



# PROCEEDINGS

## Water Efficiency Conference 2015

5-7 August 2015  
University of  
Exeter

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## **Proceedings of the Water Efficiency Conference 2015**

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### **All enquiries to:**

Dr Kemi Adeyeye

University of Bath, UK. Web: [www.watfnetwork.co.uk](http://www.watfnetwork.co.uk)

Email: [kemi@watfnetwork.co.uk](mailto:kemi@watfnetwork.co.uk)



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## Preface

This volume contains the proceedings of Water Efficiency Conference 2015 held from 5-7 August, 2015 at the University of Exeter, Exeter, UK.

This is the Third Annual Water Efficiency Conference organised by The WATEF Network. The network, *to be based at the University of Bath from this autumn*, is a global group of academics, industry, NGOs, interest groups and members of the public who share an interest in promoting water resource efficiency, progressive water policy, useful and usable codes and standards and general best practice. The WATEF Network is funded by the Water Efficiency policy team at Department of Environment, Water and Rural Affairs (DEFRA) UK, led by Alison Maydom. DEFRA has funded the network since its inception in 2011 and we graciously acknowledge the support of all members of the team.

In all, the committee received about 60 submissions; 30% more papers compared to last year. All papers were administered and managed through the Easy Chair Conference System. Each submission was blindly reviewed by at least 2 program committee members. After the review process, the committee decided to accept 34 papers representing work undertaken by academics and industry practitioners. This is another significant increase from last year and further demonstrates the growth and reach of the conference year on year.

Papers are presented verbally or through posters. *A big thank you to all the authors and presenters for the time and effort dedicated to preparing their quality contributions.* This has helped to achieve a conference that is educative, interesting and enlightening.

The program also includes keynote lectures by UK and international speakers. We are grateful to Mr David Rose of South West Water, Prof. Armando Silva Afonso of ANQIP Portugal, Prof Kevin Tayler, Prof Zoran Kapelan of the University of Exeter and, Dr Cara Beal of Griffith University, Queensland, Australia. I will particularly like to thank Dr Beal and colleagues at Griffith University for committing the time and resources to travel all the way from Australia for this event.

A very special thank you to all the members of our international Scientific Committee. The quality of the proceedings is a testament of your time and effort, and we are very grateful indeed.

I would personally like to say a big Thank You to the conference chair: Prof Fayyaz Ali Memon for the time and effort he put into the proceedings and for his valuable contribution to the success of the conference.

Thank you also to all network members and strategic partners, our network will not be a success without your support and contribution. *I encourage those who are not yet members to do so; membership is still free.*

And thank you to Suzy Armsden, our network Administrator for doing an excellent job in organising another successful conference.

Welcome to our conference. I wish you all a pleasant time and I hope we meet again soon at one or all of our future network events.

Kemi Adeyeye, Lead WATEF Network

July, 2015

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## Program Committee

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## EDITORIAL

This volume presents a collection of papers selected for presentation at the 3rd Water Efficiency International Conference organised by the Water Efficiency Network. The network aims to facilitate the promotion of water efficiency and sustainable management of urban water by bringing together the research community and water industry.

The conference has become one of the key events to disseminate research and innovation in water sector particularly at a time when we are witnessing relatively frequent droughts and floods. Whilst the conference has attempted to bring in some focus on energy efficient urban water management via dedicated keynote presentations, wider issues pertaining to integrated/sustainable water management are also given consideration. The selected papers have been grouped into five categories. These are:

- Domestic Water Consumption
- Integrated Water Management
- Water Reuse Systems
- Surface Water Management
- Water and Wastewater Treatment

The selection of papers was via peer review process and we would like to thank the scientific committee and the network members for their timely constructive feedback to the authors of the papers. We have also encouraged the upcoming generation of young researchers to present their research as "work in progress" with a hope for them to not only learn along the journey but enjoy it too!

We would also like to extend our thanks to the conference sponsors, the organising committee and in particular Suzanne Armsden for her hard work and humour to make this conference happen.

We very much hope that the presented papers and discussions at the conference would help to cross fertilise research ideas and advance our understanding of challenges and opportunities to address global water insecurity.

**Fayyaz Ali Memon**

Chair, Watef Conference 2015

## **Keynote lecture: "Meeting longer term goals for greenhouse gas reduction"**

*At a not insignificant 5 million tonnes the UK water industry is accountable for around 1% of all the UK's reportable greenhouse gas emissions. For the past fifteen years or so the industry has taken upon itself to measure, report and actively manage its greenhouse gas emissions and most UK water companies have set ambitious longer term goals for emissions reduction. The approach to target setting is not consistent across the industry however, with some companies aiming for carbon neutrality whilst others have set much more modest targets. South West Water's strategic aim is to match the Government's longer term target of an 80% reduction by 2050 as set out under the 2008 Climate Change Act. But is this scale of reduction technically possible for a water and sewerage company? What steps will the company have to take on its journey towards 2050 to stand a fighting chance of achieving this aim? Does the future impact of even higher standards of treatment, population growth and climate change pose such a threat to the outcome to make the setting of long term goals an exercise in strategic naivety? David's presentation will attempt to answer some of these key questions and show how significant reductions are possible over time if vital effort and investment is applied to the goal of emissions reduction.*

### **DAVID ROSE**



David is Energy and Carbon Manager at South West Water Ltd where his role includes responsibility for the strategic and tactical management of carbon along with managing the company's energy efficiency and renewable energy programmes. David has more than 20 years of professional experience in energy and its impacts on the environment. He has spent the past 17 years working for South West Water after moving to the South West from his former role in London as a Research Associate at Imperial College's Centre for Energy Policy and Technology. He holds a degree in Environmental Engineering from Cardiff University and an MSc in Environmental Science from Bath University. David is both a Chartered Engineer and a Chartered Environmentalist.

## Keynote Lecture: “Pathways to achieving energy efficiency in urban water management”

*In the last decade south east Queensland (SEQ), Australia, has been subject to extreme weather events (droughts and floods), a growing population and a fluctuating political landscape. These factors have dictated the changing focus of urban water research resulting in a variety of applied research projects being undertaken by Griffith University. This presentation will cover research projects that have emerged as a response to the growing need for SEQ water businesses to improve their water and energy efficiency. It will include an overview of research on a variety of projects including:*

- *the application of smart metering technology to improve our understanding of peak demand patterns and subsequent network optimization*
- *assessing energy consumption of water heating systems with empirical information*
- *residential rain tank pump performance at an end use level*
- *using smart meter data to identify the key indoor and outdoor end-uses that contribute to water-related energy demand; and*
- *the water-energy nexus in remote and Indigenous communities*

### CARA BEAL



Dr Cara Beal is a Senior Research Fellow at the Smart Water Research Centre & School of Engineering, at Griffith University, Queensland, Australia. Her research covers topics such as water resource management, remote and regional water-energy efficiency, and smart asset management. She is internationally recognised for her research on decentralised water treatment systems and, more recently, intelligent water metering, water end-use studies, the water-energy nexus and demand management. As a member of the Qld Government appointed Water Expert Panel she is responsible for identifying innovative research and development to help implement the 30 year water strategy for the Queensland water sector. She is the current recipient of a mid-career Accelerate Fellowship for her work on sustainable water and energy management in remote Indigenous communities.

## **Keynote Lecture: “Energy, the water sector and rapid urbanisation in the ‘South’”**

*The cities of the ‘South’ are growing rapidly, creating demand for water supply, sanitation and wastewater disposal services. Meeting this demand requires both high capital investment and resources to fund ongoing operational costs. Energy-related costs usually constitute a high proportion of those operational costs so action to reduce energy-related expenditure must be central to any strategy to reduce operational costs while maintaining adequate service levels. Drawing on lessons learnt from various internationally and locally funded projects and programmes, the presentation will explore available options for reducing energy use in both the water supply and wastewater management sectors. In both sectors, the aim will be to go beyond theory to identify the practical challenges to be met if efforts to reduce energy demand are to be successful. The presentation will distinguish between immediately implementable measures and those that, while bringing significant benefits, are dependent on better information, additional funding or both. In the water supply sector, it will focus on the need to reduce high levels of leakage and wastage in order to reduce pumping costs. On the wastewater management side, there will be a strong focus on options for reducing energy requirements for both wastewater pumping and treatment.*

### **KEVIN TAYLER**



Kevin Tayler trained as a civil engineer. Early experience with consultants and water sector organisations in the UK was followed by two years as Adviser on Water Supply to Sudan’s Southern Regional Government. This led to work for consultants and international agencies, mainly in the urban sector and covering services upgrading in low-income areas, water supply and sanitation. His work has covered over twenty countries, including Pakistan, Egypt, India, Indonesia and several African countries. He is an Honorary Professor in the School of City and Regional Planning at Cardiff University and an Associate of WEDC at Loughborough University.

## Keynote Lecture: "Water Efficiency in Buildings: A Portuguese Approach"

*In Portugal, despite the severe water stress problems that are anticipated for the Mediterranean basin, the promotion of water efficiency in buildings has essentially been carried out by ANQIP, a non-profit technical and scientific association composed essentially of universities and companies, rather than by the Government.*

*This presentation describes the path that has been pursued by ANQIP since 2008 and the various measures taken, which were essentially of a technical character, such as the labelling of the water efficiency of products, the development of technical specifications for rainwater harvesting and reuse of greywater in buildings (including certification systems), the development of a specific program for audits of water efficiency in existing buildings (AUDITAQUA), the development of a hydric classification model for buildings, and additional studies such as the water-energy nexus in Portuguese buildings.*

*Reference is also made to how these civil society initiatives have been accepted and embraced by citizens and companies, and to ANQIP's efforts toward incorporating them within national laws and regulations.*

### ARMANDO SILVA AFONSO



Prof. Armando Silva Afonso is a retired Full Professor in the Department of Civil Engineering at the University of Aveiro (Portugal), where he still collaborates as Visiting Professor in the field of water efficiency and building hydraulics. He is also Chairman of the Board of ANQIP, a Portuguese technical-scientific association for the improvement of building installations, with about 200 members (universities, companies, water authorities, etc.). His current research interests include efficiency and sustainability related to water supply and drainage, and he is an invited expert of the European Commission (DG Environment) for water efficiency in buildings.

## **Keynote Lecture: "Toward Improved Water and Energy Efficiency in Urban Water Systems"**

*Urban water systems are integral part of our daily lives. These typically complex systems comprised of large pipe networks and many other components were developed largely during the era of low cost of energy and water, i.e. without much consideration given to the energy used and water lost. This, of course, is not acceptable anymore. The lecture will start with recent work on modelling principal flows of water and energy in urban water systems, followed by the presentation of several technologies leading to more efficient use of energy and water, both in the operational context and from the point of view of long-term management of these systems. All this will be illustrated using suitable real-life examples from Prof. Kapelan's research work. The lecture will conclude with future work recommendations in the field.*

### **ZORAN KAPELAN**



Prof. Zoran Kapelan is a professor of Water Systems Engineering and leader of the Water and Environment Group at the University of Exeter. He has 25 years of research and consulting experience in various water engineering disciplines, both in the UK and abroad. His research interests and expertise are centred around the development of novel technologies addressing a wide range of issues in urban water systems including water and energy efficiency. Prof. Kapelan is an IWA Fellow and a chartered engineer with CIWEM. He is currently serving as an Associate Editor for the Journal of Water Resources Planning and Management (ASCE) and has over 300 technical publications.

# CONFERENCE PROCEEDINGS

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# WATEF NETWORK TECHNICAL GROUPS

# Water Sector Service Innovation: what, where and who?

Sarah Ward<sup>1\*</sup>, Steve Brown<sup>2</sup>, Aaron Burton<sup>3</sup>, Kemi Adeyeye<sup>4</sup>, Noel Mannion<sup>5</sup>, Siraj Tahir<sup>6</sup>, Craig Gordon<sup>7</sup>, George Chen<sup>8</sup>

<sup>1</sup>Centre for Water Systems, University of Exeter

<sup>2</sup>Centre for Environmental Strategy, University of Surrey

<sup>3</sup>Amec Foster Wheeler

<sup>4</sup>University of Brighton/WATEF

<sup>5</sup>Mace Group

<sup>6</sup>UCL

<sup>7</sup>Oxford Innovation

<sup>8</sup>Heriot-Watt University

## ABSTRACT

**Aims:** Changes in water law and policy, in the UK and further afield, are promoting social and service innovation, as well as technical innovation in the water sector. In particular, the separation of wholesale and retail water and sewerage services for English and Welsh commercial water systems customers is leading to a focus on service innovation. But what do we mean by 'service innovation'? To whom does it apply and how do these parties interpret it? To answer these questions, this paper presents the findings of recent interviews undertaken by and case studies presented to the Water Efficiency (WATEF) Network Service Innovation Technical Committee.

**Study design:** The paper explores definitions and interpretations of service innovation (SI) and discusses case studies where SI is already being realised in the water sector.

**Methodology:** The study was conducted using interviews and case studies.

**Results:** A tree-branch model of SI is proposed, emphasising the placement of the customer as the focus of SI. A revised definition of SI was also provided to assist water service providers in enhancing the services provided to their customers.

**Conclusion:** The study revealed that the water sector offers scope for improvement in fundamental business services. These include billing, customer relations, communication (information services) and data provision and visualisation.

*Keywords: change, client, concept, delivery, service innovation, technology, water efficiency*

## 1. INTRODUCTION

The Water Act received Royal Assent on 14th May 2014 [1], ushering in wholesale and retail separation and opportunities for non-domestic (business) customers to change their supplier. Previously only the largest water users in England and Wales could switch suppliers. However, the process of deregulation will take place between 2014 and 2017, when all non-domestic customers will theoretically be able to switch water service providers (WSPs). In the context of this deregulated water market, WSPs are becoming more focussed on recruiting new, and retaining existing customers. It is unlikely that the unit cost of water between water companies will be a large enough differential to encourage organisations to switch their provider [2].

Within the Water Act a number of measures are highlighted as potentially catalysing change: price limits, social tariffs, WaterSure (for low-income customers), water metering and concessionary schemes for surface water drainage charges. In the past, the variability of service across more than 22 WSPs has led to non-standardised billing, customer service

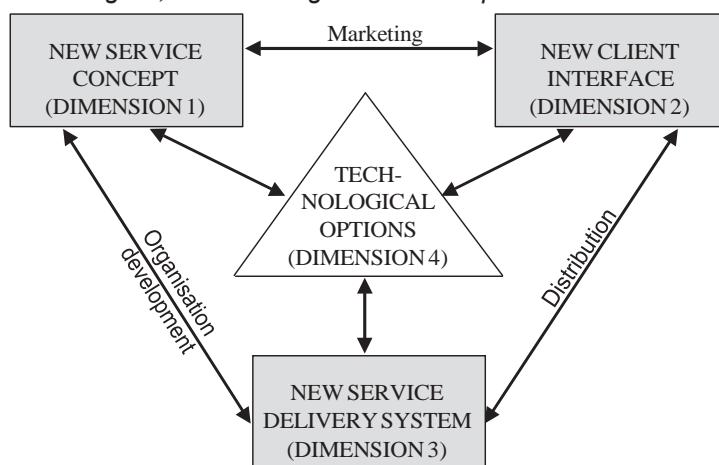
\* Tel: +44(0)1392 723730

Email: sarah.ward@exeter.ac.uk

dissatisfaction and high cost transactions (time and money). Non-domestic customers in Scotland are already within a deregulated market, where efficiencies have been made by standardising and improving certain aspects of service provision [2]. But has deregulation led to *service innovation*? And what is meant by this term? Innovation is broadly defined by Ofwat as the application of new technology, business processes or management expertise that delivers any improvements to customer service, the environment or cost efficiency [2]. However, "Service Innovation" within the context of the UK water industry is widely discussed but often not defined further. More generally this has been broken down into innovation around service products, service processes and service organisational change. The need for a definition emerges in order to benchmark whether different options are indeed innovative and service-focused. Without at least a working definition, almost anything could be deemed SI, which would not facilitate useful assessment of how WSPs are performing [2].

### 1.1 Definitions of service innovation

First documented in 1993 by Miles [3], service innovation (SI) as a concept began by characterising the features of services associated with innovation, usually of a technological or expertise-based product. This early research covered innovation in services, products, processes and firms (organisations and industry) and was broader than just looking at the novel aspects of the services themselves. A useful typology of SI was elaborated by [4] and is illustrated in Figure 1. The four dimensions of den Hertog and Bilderbeek's typology represent the SI concept, the client, the delivery system and technological options. Further to this, Van Ark *et al.* [5] proposed the following definition of SI: "*a new or considerably changed service concept, client interaction channel, service delivery system or technological concept that individually, but most likely in combination, leads to one or more (re)new(ed) service functions that are new to the firm and do change the service/good offered on the market and do require structurally new technological, human or organizational capabilities of the service organization.*"



**Fig. 1. A four dimensional typology of service innovation (adapted from [4])**

With regard to small to medium enterprises (SMEs), the European Commission [6] sees SI as having transformative (disruptive) powers in relation to economic change and as being a catalyst of cross-sectoral enrichment and new business models. Similarly to the aforementioned definition by [5], the EC defines SI as comprising: ".*new or significantly improved service concepts and offerings as such, irrespective of whether they are introduced by service companies or manufacturing companies, as well as innovation in the service process, service infrastructure, customer processing, business models, commercialisation (sales, marketing, delivery), service productivity and hybrid forms of innovation serving several user groups in different ways simultaneously.*" The EC goes on to elaborate on its definition of transformative power, by asserting that SI should enhance customer experience by disrupting existing channels to market, processes and models, acting on the whole value chain. Consequently, emerging sectors, industries and markets are shaped influencing modernisation and change at the activity concept, company client, sectoral system and market levels. Ten 'dos' and 'don'ts' in relation to SI are suggested, which include:

- Don'ts: focusing purely on research and technological innovation, supporting individual specialised firms, copy-pasting best practice, following without reflecting, not having specific targets, launching pilots in isolation, match a problem to an innovation;
- Do's: focusing on all knowledge and innovation, support transformation, support firm clusters and networks, focus on manufacturing and services, search for next best practice, capitalise on regional competencies, be systemic and cross-sectoral, launch large-scale demonstrations, match an innovation to a problem.

Additionally, ideas for support instruments include:

- For companies: innovation clinics/incubation centres, vouchers, management guidance, access to finance;
- For sector: design centres, living labs, cluster support and assistance;
- For market: awareness raising, cooperation incentives, vouchers, procurement initiatives.

Whilst these have been developed with SMEs as a focus, it is asserted that they could be useful at other levels and across a range of sectors via the 'spill-over' effect (where events in one context occur because of events in a seemingly unrelated context). The EC definition fits well within den Hertog and Bilderbeek's 4D typology and therefore this research uses the typology as a framework for considering SI by WSPs in England under deregulation.

A sector in which deregulation has taken place includes the energy sector, where deregulation has resulted in realignment from a cost-based to performance-based focus considering satisfaction and security of supply [7]. Innovation to services for domestic (residential) customers have included information services (receiving consumption information by email, digital TV or instant message to a mobile phone), consumption simulation (to estimate future demand based on a range of practices), smart measurement (metering, monitoring and response), smart control and delegation (whereby customers enable their retailer to electronically control their equipment (e.g. white goods) to reduce consumption), roaming (customer can access the system via an 'app') and payment (wide variety of environment-independent options incorporating customer preferences).

## **1.2 A working definition of service innovation for water efficiency**

With the previously outlined options and typology in mind, the research presented in this paper was undertaken to develop an understanding of what SI could look like for the water sector and the types of options WSPs could consider offering to their customers. The paper forms part of the annual report of the Water Efficiency (WATEF) Network's Service Innovation Technical Committee (SITC), which is tasked with scoping:

- Retail competition service innovation for water efficiency;
- Innovative approaches to delivering services with customers and considering aspects such as the hydro-social contract and who is thought to be responsible for water efficiency delivery and messaging;
- Delivering partnership working for water efficiency (energy and social housing retrofit programmes – lessons learned, extent of implementation, further roll-out);
- Ensuring water efficiency is part of wider integrated service innovation such as Water Sensitive Cities.

This paper focuses on the first two objectives and proceeds as follows. The next section outlines the data collection and analysis methods used to refine the working definition of SI presented below. The following section presents the results and a discussion that recontextualises the findings in relation to the literature presented. A final conclusion section reiterates the main themes of the paper. Based on the literature presented above and discussions held at WATEF SITC meetings, the following working definition of SI for water efficiency is considered within the research presented in this paper: "*Service innovation for water efficiency represents the concepts, clients, delivery systems and technological options available to the water sector through which to develop new or improved service functions resulting in an enhanced customer experience and requiring structural organisational change.*"

## 2. METHODOLOGY

In order to test and refine the working definition of service innovation for water efficiency (SIWE) and gain insight into how SIWE is perceived within the water sector, a mixed methods approach comprising the following data collection methods was utilised:

1. Links to an online questionnaire-based survey form and separate case study template form were circulated to WATEF SITC member's networks;
2. Informal semi-structured interviews were held with experts in the field of water management either in person or by phone, with notes taken, which were anonymised to comply with standard ethical practice.

The online case study template form consisted of 8 questions (7 open, 1 closed) regarding the participant's SIWE initiative. The closed question consisted of a list of types of service innovation, from which the participant was invited to match their initiative to a type. The types listed were: pricing, inset, competition, rental/lease agreement, partnership, target, technical, service, research, asset delivery, customer engagement and other. These types were developed *a priori* by the WATEF SITC, not as an exhaustive prescriptive list, but to guide participants in thinking about how they would categorise their initiative. The open questions orientated around the features of the initiative, such as its name, how long it had been in operation (or if not yet operating, when the concept was first registered), the outcomes of the initiative (such as costs, water savings and wider benefits), ongoing monitoring, partnerships and dissemination. The interview pro forma consisted of an introductory section on the context of the Water Act and deregulation, followed by questions regarding reimagining service models for water provision and examples of SI from other sectors. Questions were designed to help prompt and funnel the participant into suggesting a definition of SI. For each data gathering method participants gave their informed consent for any information provided to be used in an analysis to be presented in this paper. The information gathered was triangulated [8] into the analysis that follows in order to refine the working definition of SIWE.

## 3. RESULTS AND DISCUSSION

In total the details of five SI initiatives were registered by participants through the online case study template, four interviews were held with water management experts and only two participants completed the questionnaire. The low participation rate, particularly for the questionnaire, could be explained by a current lack of understanding regarding what comprises SIWE or participants were constrained by not being able to find time to submit their information. A further explanation could be that of 'innovation protectionism', a concept that emerged from the data and that is explained in more detail later in this section.

### 3.1 Service innovation for water efficiency – Initiatives

The real and hypothetical initiatives described by case study and interview participants are summarised in Table 1 and represent a small snapshot of the types of SIWE that could be or are already in practice. Interview discussions across all the participants are summarised for each question in the following short sub-sections.

#### 3.1.1 Q1. What do you imagine could be an alternative service model to maximise water efficiency (WE)?

Some participants suggested an alternative model where WSPs do not operate in silos, but facilitate water management in an integrated and holistic approach. Also, a new method of financing water efficiency projects to offset the low cost of water was highlighted. In contrary to this view, one participant suggested that water efficiency in a retail market is counterproductive and WSPs will be reluctant to maximise water efficiency. However, overall, participants agreed that the existing service model of water supply and treatment is very good.

**Table 1. Real and hypothetical service innovation initiatives for water efficiency/the water sector**

<b>Initiative</b>	<b>Type (listed in Section 2)</b>	<b>Details/Outcomes (potential or actual)</b>	<b>Known impact to date (stage of initiative)</b>
Rainwater harvesting or greywater reuse equipment leasing	Rental/lease agreements	Reduction in potable water use, access to alternative sources, reorientation from product to practice, changing social norms	N/A (hypothetical)
Runoff capture and sharing	Partnership (social/community), Other	As above	N/A (pilot)
Retail competition in Scotland	Competition, service	Efficiencies in billing, smart metering reducing water use: 5% of businesses switched supplier, but 50% renegotiated beneficial supply terms	34KtCO <sub>2</sub> , 16bn litres water saved (completed)
Reverse auction	Service, technical, partnerships	Ability to directly support implementation of customer-selected options to improve source water quality, reduce polluted runoff and source control	Fowey catchment - £360K distributed to farmers for improvements on a value-for-money basis (completed)
Water efficiency retrofit	Technical	Improving facilities and service delivery whilst achieving better water and cost savings	35% water savings (ongoing calculations), positive guest feedback, behaviour transfer to home (completed: 28-room hotel)
Combining water & energy efficiency in Wales	Partnerships, targets, service, technical	Agreement between multiple water/energy stakeholders to provide equipment for free if records of installations were maintained	£30M spent across a 6K home uptake (completed: see <a href="http://arbed.org/en/about-arbed">http://arbed.org/en/about-arbed</a> for more info)
Enhanced service	Service, pricing, other	Reduced price water efficiency fittings, quicker failure response times and access to other services (flood protection & SuDS)	N/A (hypothetical)
Green tariff	Service, pricing, other	Similar to energy companies – customers pay to support alternative water supply system infrastructure (rainwater, greywater, wastewater reuse)	N/A (hypothetical)
Service rather than product access	Rental/lease agreements	Similar to services provided in the music streaming, transportation device and floor covering industry – lease the associated service rather than the product (CDs/cars-bikes/carpets) – water efficient fittings?	N/A (hypothetical)
Examine B2B* operations	Service, pricing	Getting billing, metering and monitoring right is key – paying for equipment? SI is solving these issues	N/A (ongoing)
Enhanced communication with subsidised monitoring	Service, technical, customer engagement	Already undertaken by some energy companies to facilitate low daily consumptions	N/A (cross-sectoral)
Rising block tariff	Service, pricing	Including threshold allowance for certain segments	N/A (proposed)

\*Business to Business

**3.1.2 Q2. Thinking about other services where you are free to choose your provider, such as gas and electricity, can you think of examples of ways organisations operate their services that you consider to be innovative?**

Energy and Gas suppliers were cited as examples of innovative organisations with strong parallels to the water sector. All participants suggested that WSPs should look to energy companies for inspiration and direction with innovative schemes such as green tariffs, providing water monitoring equipment at no cost to the customer, improved communication channels, shorter billing cycles and on-demand water usage data available. However, one participant expressed a strong view that for the WSPs: "*innovation is a million miles away*" and they should focus on getting the basics right, such as correct billing, before attempting to be innovative. The same participant also suggested that WSPs should look at any Business to Business (B2B) retail operation for guidance on the basics of business.

**3.1.3 Q3. Water is a key ingredient of life, and yet most take this precious resource for granted. If you had to reinvent the way water is sold, distributed and valued as resource: what would it look like?**

A common sentiment was that WSPs perform their water treatment and supply operations to a very high standard and overall run the water network exceptionally well. Therefore reinvention of the water supply system is not particularly useful or needed. However, one participant suggested this effective and centralised supply system also serves to perpetuate an emotional disconnect between the water from a tap and the source of the water. In a similar vein, the same participant asserted that the use of potable water for sanitation purposes (toilet flushing etc.) would not prevail in a reinvented water network. The majority of participants expressed the low cost of water as significant barrier to reinforcing the true value of water. One participant expressed this sentiment by stating: "*people do not value anything that is cheap.*", and suggested the use of rising block tariffs, as: "*when it [water] costs more, people will consider water efficiency products more*". In addition, it was suggested that WSPs should also consider alternative models of financing water efficiency products.

**3.1.4 Q4. Focusing on a wide range of services, such as staying in hotels, buying food or going to the doctors: can you think of examples of ways in which services are provided that you feel are innovative?**

Participants provided existing examples of innovation in other sectors, such as: high fidelity music rental via internet streaming; short-term vehicle rental (bikes and motor vehicles) and floor cover leasing, as opposed to buying a carpet. These examples followed a common theme of accessing a service instead of a product. In addition, examples of innovation followed an efficiency theme, such as: touchscreen patient arrival to avoid queuing; free time-limited Wi-Fi and countdown buzzers to alert and placate hungry (infant) diners.

**3.1.5 Q5. Returning to our focus on water efficiency, please try to design your own definition of Service Innovation.**

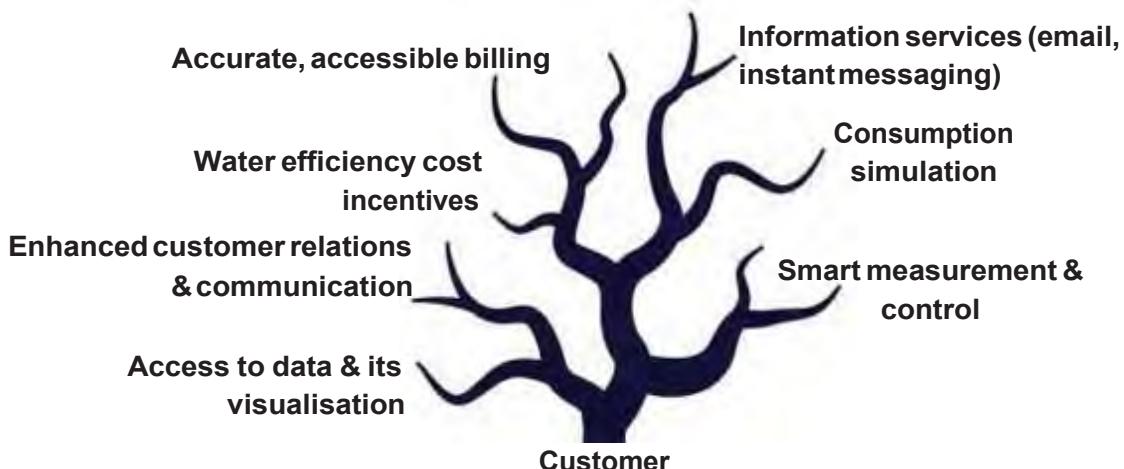
All participants struggled to design their own definition, instead preferring to suggest requisite components of a SI definition. The components have been grouped into broad themes, labelled Fundamentals, Cost and Collaboration and are shown in Table 2.

Fundamentals	Cost	Collaboration
Better communication	A true cost of water reflected	Integrated water management
Monitoring & measurement	Water efficiency cost incentives	
Improved access to WSP		

**Table 2. Key phrase components given by participants for a working definition of SI**

In summary, all participants agreed that WSPs already provide high quality water through an effective distribution network, which did not require innovation per-se. The overwhelming

message was that WSPs, in innovating, need to focus on business fundamentals. These include billing, customer relations and improved provision of data and its visualisation. It was apparent that the customer should be the beneficiary of the result of any SI and therefore elements of SI should orientate around enhancing the provision of services to them. In interpreting these discussions, the authors visualised this interaction as being a tree, with the customer as the trunk and the SI initiatives as the branches (Figure 2). This is in contrast to the typology presented in Figure 1, which locates technological options at the junction of concepts, interfaces and delivery systems. However, these processes are still fundamental to achieving SI in the tree-branch model, as some of the options suggested represent interfaces (customer relations, data visualisation) and delivery systems (billing, information services), which may or may not require technology to support them.



**Fig. 3. The tree-branch model of SI for the water sector**

Additionally, most participants agreed that the energy sector could provide a blue print for the water sector to follow, particularly with respect to customer relationship management and providing consumptive data in line with initiatives described at the end of Section 1.1. These have also been added to Figure 3. Furthermore, the low financial cost of water was identified as a barrier to engaging people with water efficiency. This barrier was identified by the majority of participants and all largely agreed an alternative pricing required further investigation and testing. The final question, asking participants to suggest a definition of SI, was in hindsight a very challenging question. However, all participants provided elements of such a definition, which enabled the working definition to be further developed. Participants kindly provided insightful data, however the volume of data was lower than anticipated. A low participation rate, due to a myriad of reasons, is common in research. In this instance it is hypothesised that the low rate could be attributed to the emergent concept of *innovation protectionism*, as previously discussed.

### 3.2 Innovation protectionism or protecting intellectual property?

As briefly mentioned previously, a further concept that was elucidated through the informal conversations with potential participants is that which the authors have termed 'innovation protectionism'. The main feature of this concept is that a SI (or other initiative) exists, but the owners of the initiative are reluctant to share or disseminate information about it before they themselves have. This concept emerged initially as a way of explaining the low survey and case study participation rate. Through discussion it then became apparent that it was a wider phenomenon than has perhaps been documented in the innovation literature to date. It is understandable that the owners of a perhaps novel or previously untried initiative would be reluctant to release information into the public domain before they have had a chance to release such information. It is also a process that would probably parallel the protection of intellectual property that has not been formally protected via a patent, copyright or other mechanism of 'know how' registration. However, the practice of innovation protectionism could result in the impeded and delayed diffusion of innovation, which is a recognised problem within the water sector. For example, innovation activity in water-related technologies has been increasing over the last two decades; however there is a bias towards supply-side technologies [9]. Indeed, a

special volume of the *Journal of Cleaner Production*, due for publication in March 2016, will focus on the 'dynamics of water innovation' to document the application of a range of innovations in ICT, structural change, learning and strategizing, competence and capacity building and social innovation [10], within the water sector and between the water sector and other sectors. Additionally, a recent European Commission report [11] identified that a significant barrier to innovation is the widespread reluctance to trial new initiatives. It may be that trials are being undertaken, but are not being widely publicised due to innovation protectionism or fear of losing rights or ownership of unprotected intellectual property (ideas/initiatives). This echoes standard WSP practice, where techniques and data may be for internal use only and not shared across the sector, often leading to a number of different processes for achieving the same goal or objective.

### **3.3 Refining the SIfWE definition – what, where, who?**

This paper began by suggesting a working definition for SIfWE of: "*Service innovation for water efficiency represents the concepts, clients, delivery systems and technological options available to the water sector through which to develop new or improved service functions resulting in an enhanced customer experience and requiring structural organisational change.*" However, the results guided the definition from a narrow focus on water efficiency toward a more holistic view of SI. Accordingly, a refined definition is proposed:

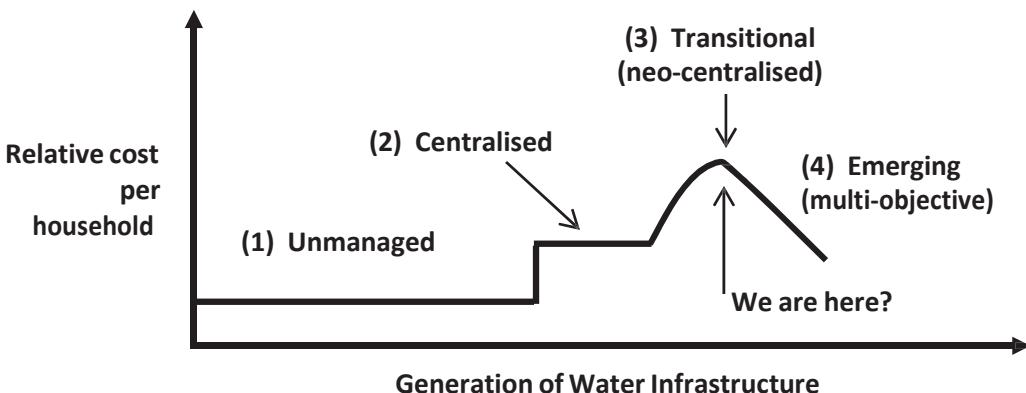
*"Service innovation for the water sector places the WSP customer as the focus of service innovation. The customer is both the catalyst and recipient of transformative change in concepts (ideas and initiatives, such as alternative tariffs, data visualisation), technological solutions (especially ICT), delivery systems (for example accurate billing, email, instant messaging) and supple organisational structures (for instance responsible processes, people and teams). Service Innovation enables the customer to select the appropriate options to enhance their experience, leading to a valued integrated water management service."*

The 'what' is represented by the concepts and initiatives, the 'where' is represented by the WSPs and organisational structures and the 'who' is represented by WSP customers who are the focus of SI concepts, initiatives, interfaces and delivery systems. However the proposed definition cannot be the 'final' word. Definitions should always change and evolve in response to new knowledge, ideas and context. Additionally, the triangulation of the findings highlighted that SI should not focus solely on water efficiency, for example service enhancements could be realised through improvements in many aspects of the water management process.

### **3.4 Beyond Service Innovation for Water Efficiency**

It is also useful to situate SI in the wider sustainability transitions movement that is being commented on in the urban water sector [12]. These are often focussed on transition occurring *within* the WSP rather than looking at the wider hydro-social contract that WSPs have with the community. From a water efficiency perspective, the move from a supply-led to demand-led planning paradigm has shaped much of the water resources planning in the UK based on a twin track approach. In parts of Australia, the need for more integrated water management has led to the concept of water sensitive cities and the transition towards these is based on socio-political drivers and service delivery functions. Although not explicit features of the water cycle/water sensitive city, there is a need for cross-sectoral SI in order to deliver new decentralised sources and to reinforce water sensitive behaviours [13].

A further conceptual approach incorporating elements of SI has been presented by Sydney's Institute of Sustainable Futures [14]. This associates the relative cost per household of water infrastructure provision with a certain generation of water infrastructure (Figure 4). The third generation in particular focuses on alternative but centralised supply options such as desalination or wastewater reuse. In Australia, the high cost associated with such options was justified by the short time-frame in which to make planning decisions to address the Millennium Drought (1995-2012). However, the fourth generation focuses on integrated service provision and customer service, with the aim of meeting multiple objectives. For example, green infrastructure could be regarded as fourth generation as it can deliver water saving, stormwater management, heat island mitigation and health benefits, which have been realised in projects such as the Olympic Park in London [15].



**Fig. 4. The ‘Four Generations of Water Infrastructure’ and their associated relative cost per household (adapted from [14])**

Considering how SI fits within fourth generation infrastructure provision enables us to think beyond services provided directly to the customer. An example of this is innovative permitting and licensing, where discharges from treatment works to receiving water bodies are controlled based on dynamic risk-based operational variables depending on a range of indicators rather than set levels. Such practices are SIs that allow the needs of the customer and the environment (both requiring good water quality to survive) to be met, potentially with a lower cost (monetary and energy/carbon) [16]. Whilst not directly implemented at the customer or building-scale where water efficiency products would be, these approaches still enable water to be treated and used more efficiently than under current practice.

#### 4. CONCLUSION

The Water Act will (from 2017) enable wholesale-retail separation and in turn, should create competition in the market. From the present day and in the future, Water Service Providers (WSPs) will be challenged on services other than the supply and cost of water (the product). Retail competition is unlikely to result in a lower-cost price war between WSPs and therefore service innovation (SI) offers WSPs an alternative way to retain and recruit new customers. SI has previously been a loosely-defined and slightly intangible concept, but the research presented in this paper has led to an empirically derived revised version for the water sector. Case study information and interview discussions revealed that the water sector is perceived as operating a high quality infrastructure and delivering an exceptional product. In addition the water sector offers scope for improvement in fundamental business services. These include billing, customer relations, communication (information services) and data provision and visualisation. A tree-branch model of SI is suggested, emphasising the placement of the customer as the focus of SI and a revised definition of SI has been developed in order to assist WSPs in enhancing the services provided to their customers. The definition is: *"Service innovation for the water sector places the WSP customer as the focus of service innovation. The customer is both the catalyst and recipient of transformative change in concepts (ideas and initiatives, such as alternative tariffs, data visualisation), technological solutions (especially ICT), delivery systems (for example accurate billing, email, instant messaging) and supple organisational structures (for instance responsible processes, people and teams). Service Innovation enables the customer to select the appropriate options to enhance their experience, leading to a valued integrated water management service."* Future discussions on and research relating to SI should focus on further elucidating lessons from parallels with the deregulation of the energy industry and other sectors in which clearly defined SI has yielded success. Additionally, further social science-based research is warranted to investigate what is important to non-domestic customers and how they would visualise an enhanced service from WSPs. Developing this understanding would enable WSPs to innovate accordingly.

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# WATER EFFICIENCY - PEOPLE AND COMMUNITIES

Sarah Bell<sup>1</sup>, Eleni Tracada<sup>2</sup>

<sup>1</sup>Civil, Environmental and Geomatic Engineering, University College London, Gower St,  
London WC1E 6BT, s.bell@ucl.ac.uk

<sup>2</sup>Engineering, University of Derby, Kedleston Rd, Derby DE22 1GB, e.tracada@derby.ac.uk

*Keywords:* social factors, water efficiency, behaviour change, culture, socio-technology

## 1. INTRODUCTION

How and why people use water in their everyday lives is central to the challenge of improving efficiency and reducing consumption. Approaches to water efficiency have evolved in recent years to recognise that water use is shaped by technology, infrastructure, culture and the environment, and that these factors underpin individual choices and habits about water using behaviours. Interventions to change how much water people use and waste include education of individuals, households and school children, water metering and pricing, provision of water saving technologies, social marketing and changing social norms, highlighting environmental impacts of water use, and community scale engagement campaigns. Research and practice in engaging with people and communities in water efficiency are constrained by a lack of data and evidence to evaluate impacts and identify factors for success, and inconsistency in theoretical approaches that underpin interventions and strategies. Debates amongst academics and practitioners about the validity of conceptual models that focus on individual behaviour change compared to those that emphasise wider social and cultural change have enabled a richer understanding about how people use water and how to achieve change, but have contributed to confusion and inconsistency in approaches.

The People and Communities technical committee was formed to address these challenges. It brings together academics and practitioners from different sectors and disciplines to provide evidence and develop strategies for addressing social, behaviour and cultural elements of water efficiency. This note provides an update of activities since the committee was formed in February 2015, and plans for future work.

## 2. ACTIVITIES IN 2015

The People and Communities technical committee is the most recent addition to the work of the WATEF network, with the first meeting held at UCL in London on 16 February 2015. The network members include water efficiency practitioners and educators, engineering consultants, housing providers, designers and academics.

**2.1 Scope of Activity:** The focus of the committee for its first year is on clarifying different approaches to the role of people and communities in achieving water efficiency, and developing case studies of best practice.

**2.2 Technical Committee Meetings:** The inaugural meeting of the committee confirmed its scope and membership. A subsequent meeting on 23 April discussed a conceptual framework developed by Alison Browne and Claire Hoolahan at the University of Manchester to clarify how different approaches to human and social issues at different scales of water efficiency, from individual behavior to large scale socio-technical change (figure 1). Committee members agreed a template for case studies of water efficiency at different scales, with the framework

\* Tel.:

E-mail address: [s.bell@ucl.ac.uk](mailto:s.bell@ucl.ac.uk); [e.tracada@derby.ac.uk](mailto:e.tracada@derby.ac.uk)

providing a means to categorise and analyse different approaches. The minutes of both meetings are available on the WATEF website <http://www.watfnetwork.co.uk/67-333>.

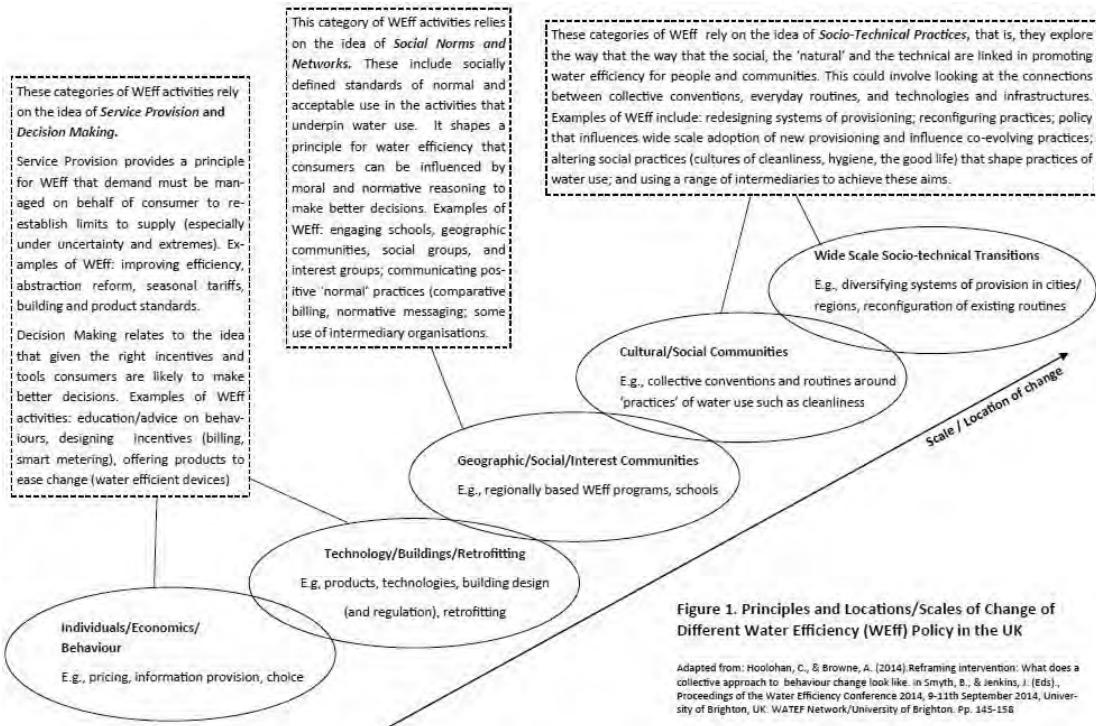


Figure 1. Principles and Locations/Scales of Change of Different Water Efficiency (WEff) Policy in the UK

Adapted from: Hoolahan, C., & Browne, A. (2014) Reframing intervention: What does a collective approach to behaviour change look like. In Smyth, B., & Jenkins, J. (Eds.), Proceedings of the Water Efficiency Conference 2014, 9-11th September 2014, University of Brighton, UK: WATEF Network/University of Brighton. Pp. 145-156

### 3. FUTURE WORK

The key objective for the People and Communities Technical Committee for the remainder of the year is to gather case studies of water efficiency to demonstrate the different approaches identified in the conceptual framework. This will draw on existing resources of water efficiency case studies and programmes, including water company, DEFRA, BRE and other programmes. However, the intention of the committee is to extend understanding of water efficiency beyond water companies and buildings, to incorporate a wider range of actors and approaches. Case studies under development include work undertaken by a housing association and addressing diverse communities including travelers and faith communities in London.

# SURFACE WATER MANAGEMENT ISSUES SURVEY

The WATEF Sustainable Surface Water Management Technical Committee:

T. Nash<sup>1</sup>, S. Charlesworth<sup>2\*</sup>, C. Booth<sup>3</sup>, P. King<sup>4</sup>, K. Bryan<sup>5</sup>, A. Crilly<sup>6</sup>, A. Burton<sup>7</sup>, D. Knaggs<sup>8</sup>, C. Snowdon<sup>9</sup>

<sup>1</sup>UK Rainwater Management Association; <sup>2</sup>Coventry University; <sup>3</sup>University of the West of England; <sup>4</sup>Ouse & Adur Rivers Trust; <sup>5</sup>University of Exeter; <sup>6</sup>Northern Ireland Water <sup>7</sup>Amec Foster Wheeler; <sup>8</sup>Albion Water; <sup>9</sup>WRcPLC

## ABSTRACT

At its first meeting on 6<sup>th</sup> February 2015, the WATEF SWMTC agreed that there were various and diverse approaches to sustainable surface water management in the UK.

**Aim:** It was therefore agreed that a large scale survey of stakeholders and practitioners across the UK be undertaken to establish their views on the status of sustainable surface water management, whether this was an approach which they use, and what their opinion was on current policy.

**Study design:** To facilitate the survey, 8 aspects of surface water management were identified as being of particular relevance; these have been identified in a 'survey note', linked to an online response form. These aspects included: scope; time frame; evolving changes; capacity building; integrated management; geography, administration; water re-use.

**Place and Duration of Study:** The survey has been undertaken electronically, during the period 1<sup>st</sup> June to 30<sup>th</sup> June 2015.

**Methodology:** The survey is being managed for the Committee by the UK Sustainable Development Association, which has circulated the *Survey Note* below to the list of organisations attached to the Note; addressees will also be asked to cascade the survey to colleagues and relevant networks. The on-line survey used automatically analyses the survey inputs, the results of which will be reported to Conference.

**Results:** The survey objective is to capture the views on selected aspects of surface water management in the UK, of more than 1,000 relevant individuals, whose views are likely to be representative of stakeholder organisations.

**Conclusions:** This study will be completed as a feature of the 2015 Conference, enabling delegates to play a key role in formulating associated conclusions and recommendations

**Keywords:** Surface water management; Sustainable Drainage; survey; practitioners; stakeholders

\*Tel: 02476 887688

Email: [s.charlesworth@coventry.ac.uk](mailto:s.charlesworth@coventry.ac.uk)

## **1. INTRODUCTION**

The Surface Water Management Technical Committee (SWMTC) first met on 6<sup>th</sup> February 2015, and recognised that sustainable surface water management is high on the national agenda. For example, there is work ongoing including publication of National SuDS Standards, and an updated SUSDRAIN Guide due to be published shortly following widespread consultation. The aim of the Committee is to avoid duplicating recent work, whilst identifying any outstanding issues that may merit further attention.

This remit is being tackled by consulting with as many stakeholders in surface water management as possible, with it being accepted that the list is not exhaustive. All those contacted directly by the Committee were asked to cascade this note through their own relevant networks and to colleagues to provide the widest possible range of inputs in order to enable valid conclusions to be reached.

The results of this information-seeking consultation will be reported at the Water Efficiency Conference 2015, Exeter University from 5 - 7 August and a summary of the results will also be provided to all contributors who provide their email address.

## **2. METHODS**

This consultation has two main components: the consultation note, which briefly identifies a number of aspects of surface water management, and invites feedback, and a quick on-line survey at <http://goo.gl/KxD419> which is the feedback mechanism for this consultation which closes on 30<sup>th</sup> June 2015. The consultation was managed on behalf of the Committee by the UK Sustainable Development Association

### **2.1 Consultation process**

The following outlines the structure of the consultation process, detailing the surface water management aspects which were considered significant and asking for considered opinions on each.

#### **1      Scope of sustainable surface management approaches**

- "Surface Water Management" is often equated to the management of surface water arising from new urban developments, referred to as "SuDS" (sustainable drainage systems) in the UK, to avoid increasing local and down-stream flood risks.
- A broader view on surface water management might also take into account the need to manage water run-off in the rural landscape, to mitigate the flood risk this causes, and to also manage surface water to ensure security of supply and to meet other criteria such as water quality, amenity and biodiversity.

**Survey question:**     The survey asks to which of these views the respondent subscribes and why.

#### **2      Timeframes for implementation**

- Published Standards tend to be time-neutral, it being generally assumed that they are designed to deal with today's environmental conditions.
- Published Organisational Plans deal with future time-frames, but often cover only the 5-to-10 year range.

**Survey question:**     The survey asks whether longer-term (20 to 30 years, or more) strategic Standards and Plans are required (or already exist) to reflect anticipated evolutionary changes that are expected to affect surface water management in the future.

### **3      Evolving Changes**

- Water-supplies are stated to be under varying degrees of stress in many parts of the UK, the worst affected region being the south-east of England. Conversely, well-publicised floods are a regular feature in many parts of the UK whenever extreme (very intense or protracted) rainfall events occur.
- Respected national and international agencies are forecasting that the risks of both floods and droughts are likely to increase over the next 30-years due to climate-induced changes to rainfall patterns. Significant predicted population growth will also exacerbate both, due to the need for associated urban development and the increased demand for water.

**Survey question:** The survey asks whether respondents accept, reject or disregard these predictions in their work, and also asks whether they have been quantified in a way that justifies any associated strategic investment needed by their organisation to respond appropriately.

### **4      Capacity-building**

- Responding to current flood risks, and maintaining security of water supplies to meet current requirements, is an expensive and time-consuming process; current investment in this respect is aimed principally at addressing the current position.
- Responding to predicted future increased risks will require an understanding of the likely economic, human and environmental impact should those risks come to pass, and strategic investment over strategic timescales to build up the additional capacity needed to mitigate those impacts.

**Survey question:** The survey asks whether their organisation is thinking in terms of long-term capacity-building in response to forecast increased risks.

### **5      Integrated Management**

- Currently, the diverse distinct aspects of surface water management (flood avoidance, drought avoidance, quality, the environment etc) tend to be addressed separately, rather than collectively.
- This serves as a barrier to the formulation of an over-arching water management strategy, potentially leading, in the worst examples, to narrowly focussed investment potentially improving the targeted aspect of surface water management, at the expense of another.

**Survey question:** The survey asks whether a more integrated approach to surface water management is desirable

### **6      Geography**

- The surface water management requirements of localities vary widely throughout the UK, making national legislation and Codes poor tools for meeting local requirements.
- Surface water management requirements also do not necessarily align particularly well with administrative boundaries, which mean that both local and down-stream factors need to be considered within a particular administrative boundary.

**Survey question:** The survey asks whether surface water management issues need to be decided on a "river basin" approach, rather than through national legislation and codes.

## 7 Administration

- The administration of SuDS requirements, in particular, has gone through a turbulent period following the 2010 Flood & Water Management Act as, for example, a new national Standard has been produced, and a review undertaken of Housing Standards (leading to the demise of the water-related aspects of the Code for Sustainable Homes).
- So far as can be determined at the time of this survey, the position is likely to be that there will be no national strategy for reducing mains-water demand, beyond the new-build requirements of Building Regulations. Insofar as reducing flood risk is concerned, oversight of the maintenance aspects of SuDS will be delegated to local Planning Authorities, with Flood Risk Management Authorities (FRMAs) becoming responsible for flood avoidance planning.

**Survey question:** The survey asks whether the administration of surface water management, at a river basin level, would be improved by re-mandating the FRMAs to take responsibility for all aspects of surface water management in their areas as, say, fully integrated "Surface Water Management Authorities"

## 8 Water Re-use

- The inclusion of water re-use, such as rainwater harvesting (RWH), in a development overlaps with SuDS to the extent that both might involve the storage of water, in the case of RWH for non-potable re-use, and in the case of SuDS for attenuated release. In the UK, the practice has been for designers to regard SuDS and RWH as two separate systems, thus incurring the capital and maintenance costs of both. Best practice is to integrate the two, looking to reduce the combined cost to no more than SuDS alone might incur, when maintenance is taken into account. This approach is also considered to deliver water-quality benefits.
- The new British non-statutory SuDS Standard does not include water re-use in its hierarchy of surface water management techniques; in contrast, the Welsh Government draft equivalent Standard lists water re-use as its preferred water management tool. It is anticipated that an updated CIRIA SuDS Guide will also include water re-use as a surface water management tool.

**Survey question:** The survey asks if there should be improved and integrated tools to allow exploitation of opportunities to reuse water within surface water management schemes.

## 9 Overall Survey question

The survey closes with the following:

- A question which invites respondents to line-up their personal responses with what they perceive to be the policies of the organisations for which they work
- A question which invites respondents to grade the aspects above in order of importance for follow-up study
- An opportunity to add any further thoughts on the subject of surface water management, not provided by the aspects listed above.

## **3.CONCLUSIONS**

Since the survey will be completed at the end of June, 2015, there are as yet no results to report. However, it is anticipated that outcomes of this study will enable understanding of the various perspectives of practitioners and stakeholders with respect to sustainable surface water management and identify their individual aims for its implementation and the barriers that are perceived. Recommendations will be made, based on these results, to better encourage approaches such as SuDS and water re-use in urban and rural developments.

**Appendix:**  
**Non-exhaustive list of stakeholders**

There are many stakeholders involved, or with a vested interest in organising the management of surface water to avoid future floods and stresses on water supplies for the general benefit, and to meet human and environmental needs; the table below shows the organisations contacted directly during the course of this consultation.

All those contacted directly will also be asked to cascade the consultation through their own networks.

**Table 1 stakeholder organisations being contacted:**

2B Landscape Consultancy	Mandate
3e Consulting Engineers Ltd	Marshalls Mono Ltd
A.L.H. Environmental Services	Mayer Brown Ltd
Aberystwyth University	Martin J Harvey
ACO Technologies plc	MCG
Alde and Ore Association	Meon Building Designs
Allen Pyke Association	Micro Drainage Ltd
Albion Water	Middle Level Commissioners
Allianz Insurance	Miller Homes Limited
All Internal Drainage Boards	Mills and Reeve LLP
All Local Authorities	Moors for the Future - Peak District National Park Authority
All Flood Risk Management Authorities	Morgan Sindall
All Parliamentary Group on sewers and sewerage	Mott Macdonald Ltd
All Parliamentary Group on Water	Mouchel
Amey	National Consumer Federation
Anglian (Central) Regional Flood Defence Committee	National House Building Council
Anglian Water	Natural England
ARUP	National Environmental Research Council
ASD Engineering	National Flood Forum
Association for Consultancy and Engineering	National Housing Federation
Association of Drainage Authorities	National Sewerage Association
Association of Rivers Trusts	National Trust
Atkins Global	Northumberland Community Flooding Partnership
Atkinson Peck Ltd	Northumbrian Regional and Flood Defence Committee
Aviva	Northumbrian Water and Essex and Suffolk Water
Barratt Northampton	OFWAT
Bedfordshire Highways	Opus Joynes Pike Ltd
Bellway Homes West Midlands	Oxford Food Alliance
Bellenden	Parliamentary Office of Science and Technology
Berwin Leighton Paisner	Peel Utilities Holdings Ltd

Bircham Dyson Bell LLP	Pell Filschmann
Black and Veatch	Pennine Water Group - University of Sheffield
Blueprint for water	Peter Brett Associates
Boston Mayflower Ltd	Peter Kite Associates
Bourne Stream Partnership	PFA Consulting Ltd
Bovis Homes Ltd	Pick Everard
Brett Associates LLP	Pipeline Industries Guild
British Geological Society	Planscill Ltd
British Hydrological Society	Plastic Pipes Ltd
British Property Federation (BPF)	Policy Consulting Network Limited
British Waterways	Portsmouth Water Ltd
Bristol Water	Ponds for Cornwall
Broadland Agricultural Water Abstractors Group	Practical Law Company
BSP Consulting	Premier Water Solutions Ltd
Callidus Transport and Engineering	QinetiQ
Cambridge Water	Ramboll UK
Capita Symonds	Regional Fisheries Ecology and Recreational Advisory Committee
Cascade Consulting	Richard Jackson plc
Catchment Change Network	Rio Tinto Alcan
Chartered Institute for Environmental Health	River Restoration Centre
Chartered Institution of Water and Environmental Management	Robert Clark Associates Ltd
Cholderton & District Water Company	Rogers Cory Partnership Ltd
City of London Planning	Rotherham MBC
CIWEM	Royal Institute of Chartered Surveyors
Centre for Ecology and Hydrology	Royal Borough of Windsor and Maidenhead
Colin Buchanan Ltd	Royal Haskoning
Committee on Climate Change	Royal Town Planning Institute
Commission for Architecture and the Built Environment (CABE)	RPS Planning and Development
Construction Products Association	Royal Society for the Protection of Birds (RSPB)
Consumer Council for Water	Sandwich TC
Consumer Focus	Scott Wilson Ltd
Corylus Planning and Environment Group	Sembcorp Bournemouth Water
Costain Group Ltd	Severn Trent Water
Country Land and Business Association	Severn Valley CLG
Coventry University	SKY-Garden Ltd
Crestwood Environmental Ltd	SMP Ltd
Croudace Homes Limited	Society of British Water & Waste Water Industries
Davies Arnold Cooper LLP	Solent Protection Council
E&M West Consulting Engineer	South Staffordshire Water
Eden Young Associates Ltd	South West Water
English Heritage	Southern Housing Group

Environment Agency	Southern Water
Environments for people	Stephen Daykin Consulting Ltd
Environment, Food and Rural Affairs Committee	Sutton and East Surrey Water
Environment Industries Commission	Technical Advisory Group
Essex and Suffolk Water	Telford Homes Metro
Essex County Council	Thames Consulting LLP
Eversheds	Thames Water
Farming and Wildlife Advisory Group	The Crown Estate
Flood Hazard Research Centre - Middlesex University	The society of County Treasurers
Flourish Homes	The Wildlife Trust for Lancashire, Manchester & North
Foundation for Water Research	The Wildlife Trust for Staffordshire
Friends of the Earth	The Wildlife Trusts
FP McCann Ltd	Thomas Consulting
Genever and Partners	TPS Consult
GeoMarine and Land Ltd	Trinity House
Glenwood Property Investments	TRM Technologies Inc
Green Alliance	Turfgrass Growers Association
Great London Authority	Tyne Rivers Trust
Guy Linley-Adams Solicitor	UKELA
H20K Systems Limited	UK Water Industries Research Ltd
Halcrow Group Ltd	United Utilities
Hannah-Reed	Unity Partnership
Hartlepool Water	UK Contractors Group
Hasker Architects Limited	University College London
Health and Safety Executive	University of Kent
HR Wallingford	University of Leeds
Homes and Communities Agency	University Sheffield
House Builders Association	University of the West of England
Home Builders Federation	Upton McGougan Ltd
Hyder Consulting UK Ltd	URS Corporation
Hydro-International	Van Oord UK Ltd
Hydrock Consultants	Veolia Water UK
IDOX	Veolia Water Central
Independent Water Networks	Veolia Water East
ICE	Veolia Water South East
Infrastructure Design Studio Ltd	Vine Technical Services
Interpave	Wallingford HydroSolutions
Institute of Civil Engineers	Ward Cole Consulting Engineers
Institute of Water	Water Consultancy
J R Claydon Limited	Water Management Alliance
J&J Design	Water UK
Jacobs	Wavin Ltd
Jacobs Engineering UK	Waterwise

Joint Nature Conservation Committee	Weetwood
Kingcombe Aquacare Ltd	Wendage Pollution Control UK
Knowsley MBC	Wessex Water
KPMG LLP	West Midlands Business Community
JBA Consulting	Westlakes Engineering Ltd
JNP Group Consulting Engineers	Wildfowl and Wetlands Trust
Landmark Information Group	Wildlife and Countryside Link
Landscape Institute	Williams Saunders
LGA Coastal SIG	Wilsons Solicitors LLP
Living with Environmental Change	Worcestershire Wildlife Trust
Local Government Association	WWF
Local Government Group	WRc Plc
Logica	WYG Engineering Ltd
Loughborough University	Yorkshire Water

# A View on the Current State of the Art in Water Reuse Technologies

Phil Barnard, Kevin Reed, Katherine Hyde, Suzanne Armsden\*, Neil Pendle, Andy Wilson, Lutz Johnen, Daniel Goodwin, Phil Henry, Doug Clarke and Alan Fewkes

*Water Reuse Technical Committee, Water Efficiency Network*

## ABSTRACT

**Aims:** The Water Reuse Technical Committee of the Water Efficiency Network is a specialist group of industry practitioners and academics that focus primarily on the issues pertaining to water reuse in the UK. Four aims and priorities for the study were identified, including the collecting and sharing of information on: water reuse codes and standards; water reuse technologies, and their costs and maintenance; the practice of information sharing and awareness with respect to water reuse; the uptake of water reuse, in particular, short, medium and long term actions to promote mainstream integration.

**Study design:** The study was designed to include a consortium of members from the Water Reuse Technical Committee, and from the Water Efficiency Network. The consortium and committee held a series of meetings for reviewing: the overall scope of the study; the questionnaire study; policy and industry recommendations, and future work on the further uptake of water reuse in the UK. The scope of the research was designed to include four primary study areas; the drivers for water reuse in the UK, the barriers to water reuse in the UK, water reuse technologies and the cost/benefit evaluation of Water Reuse Systems. Recommendations for innovation and the role of stakeholders in water reuse were then circulated.

**Place and Duration of Study:** The study meetings took place between 6th August 2014 and 1st April 2015 at a range of locations including Brighton, and some members participated remotely. A questionnaire survey was undertaken by email distribution amongst the consortium of members in the UK during the period 1<sup>st</sup> June to 30<sup>th</sup> June 2015.

**Methodology:** Firstly, previous work on information and awareness of water reuse in the UK was reviewed, followed by a review of opportunities within current and future codes and standards. A sandpit was held to consider the following: firstly, what are the drivers for water reuse in the UK; secondly, what are the barriers to water reuse in the UK; thirdly, to identify suitable water reuse technologies; fourthly, to identify the costs and benefits of water reuse systems, and fifthly, to make recommendations regarding innovation and the role of stakeholders in water reuse. The findings of this sandpit report subsequently led to the formation of the Water Reuse Technical Committee.

**Results:** attitudes of key stakeholder groups with regards to its wide-scale adoption and use. The consortium meetings resulted in reflective observations that are summarised in the paper. The outcomes are described in three sections: Water Reuse Codes and Standards; Water Reuse Technologies - Costs and Maintenance; Information Sharing and Awareness.

**Conclusions:** This study will be presented during the 2015 Conference, enabling delegates to make an important contribution to further work, additional data, conclusions and recommendations.

\* Tel.: 01273 642204

E-mail address: s.m.armsden@brighton.ac.uk

**Keywords:**

*Water Efficiency, Water Reuse, Greywater Reuse Technologies, Water Reuse Codes and Standards*

## 1. INTRODUCTION

Resilient and robust water resources is a subject that those involved in the supply, management and large scale use of water are concerned about. The water industry and regulators are continuously exploring strategies to help customers use water efficiently, including new technology, information campaigns, pricing and other policy mechanisms. The technological innovations in water recycling and reuse offer one way of helping to manage water resources effectively, to reduce the demand-side water requirement per head of population. They have the potential to scale down water demand as well as reduce energy and carbon emissions associated with the centralised treatment and distribution of water, and can also reduce the pressure on surface water drainage schemes when rain water harvesting incorporated within a stormwater management system.

## 2. BACKGROUND

In April 2014 the WATEF network in conjunction with DEFRA, EA and WATER UK held a Water Reuse event at the University of Brighton. The event was well attended and delegates were given the opportunity to present questions to speakers and contribute towards future water reuse strategies. A sandpit report was produced and the main topics identified were: - "What are the drivers for water reuse in the UK"; "What are the barriers to water reuse in the UK" ; Water Reuse Technologies; Cost/Benefit of Water Reuse Systems; Recommendations for Innovation and the Role of Stakeholders in Water Reuse. The findings of this sandpit report subsequently led to the formation of the Water Reuse Technical Committee. The Committee comprises business, government and academic members.

**2.1 Scope of Activity** of the Water Reuse Technical Committee was defined under the following headings: water reuse codes and standards; water reuse technologies their costs and maintenance; information sharing and awareness; uptake – short, medium and long term actions to promote mainstream integration.

**2.2 Technical Committee Meetings:** the inaugural meeting of the Water Reuse Technical Committee was held on 6 August via teleconference.

This meeting and the subsequent meeting on 28 August focused on the Committee's output to the WATEF Conference 2014. These outputs can be viewed on the WATEF website <http://www.watfnetwork.co.uk/69-363> where a special Water Reuse session took place. Presentations on the following subjects were made: Reviewing the Evidence for Grey and Rainwater Harvesting; Scope of Work; How Do We Regulate the Water Industry; How Greywater Systems have Developed (Dispelling the Myths); Commercial Greywater Recycling; Public Awareness and Engagements.

Subsequent meetings took place on 10 October 2014, 3<sup>rd</sup> December 2014 and 1<sup>st</sup> April 2015 where the main topics following on from feedback at the WATEF Conference 2014 were discussed. The outputs from these discussions were made available in the form of meeting minutes and disseminated via the WATEF website <http://www.watfnetwork.co.uk/67-349>

**2.3 Key Findings and Conclusions:** The key findings and conclusions of the Water Reuse Technical Committee are disseminated in the next section of the paper. These findings and conclusions have been drawn from discussions during Technical Committee meetings and research data provided by the members of the Technical Committee.

### **3. RESULTS AND DISCUSSION**

The key findings of the Water Reuse Technical Committee can be summarized as follows:

#### **3.1 Water Reuse Codes and Standards**

The main issues were that codes and standards were not working, in particular barriers exist around rainwater harvesting and greywater recycling. The conclusions of the Technical Committee were:

- A mapping exercise should be undertaken to further identify these barriers and how they can be addressed.
- The simplification of codes and standards (UK and Europe) would help in building confidence that water reuse systems were reliable, fit for purpose and would provide the end user with savings.
- Environmental standards such as BREEAM and the Code for Sustainable Homes need to be embraced and maintained by both national and local authorities. This would involve a joint initiative from all interested parties.
- The main difficulties encountered with installation relate to regulations and enforcement – BS8515: 2009 RWH and BS8525: 2010GWR both require updating to avoid common problems such as cross contamination and incorrect installation of water meters.

#### **3.2 Water Reuse Technologies – Costs and Maintenance**

The lack of data available from manufacturers/industry demonstrating the cost/benefit ratio of installing water efficiency technology is a major hurdle. The industry needs to make water reuse products more desirable, and more practical, to the general public by providing them with information upon which to base their decisions. In order to do this the Technical Committee concluded:

- Water Reuse systems can be very effective in terms of water savings and cost provided they are designed properly and other benefits are linked for instance Sustainable Urban Drainage Systems. There needs to be a tangible return on investment for example the customer has to like the idea of saving rivers, slowing down surface water run-off and reducing the risk of flooding.
- Manufacturers need to provide systems which are easy to install, simple to maintain, and cost effective. The costings need to include energy costs and these need to be clearly set out so that the public can compare them.
- Manufacturers need to provide more relevant data to the public so that they are able to see for themselves the need for water efficiency (much of this data will be provided in the new Home Quality Mark which will replace the Code for Sustainable Homes).
- There is a need to identify best products available on the market in order to gain the public's confidence as there are many products out there which are "unfit for purpose" or incorrectly specified.
- Water stressed areas should receive encouragement to utilize water efficient technologies – local authorities should incorporate these technologies into their planning requirements. A Government incentive scheme could promote further uptake of these technologies
- There is a need to establish national standards for installation and maintenance – the manufacturers should withhold their guarantees until installation and maintenance standards have been agreed. An approved installers training programme needs to be established, following which a national list of approved installers needs to be drawn up.
- Water companies need to be informed of installations in order to take responsibility for dealing with any problems which occur, for example contamination of water supply.
- Some water companies do appear to be taking more interest in new schemes with RWH now and inspecting the installation before connecting to the mains supply, and this should be rolled out to all water companies

- Developers need to find value in water reuse products and to be encouraged to install pipework at the build stage rather than retrospectively.
- A survey of water reuse equipment manufacturers will be made and the results of this survey will form the basis of a future Workshop.

### **3.3 Information Sharing and Awareness**

Most of the public appreciate that they need to save water and that there is only a finite amount of water to go around, however there is a growing need to engage the public with water efficiency. The Water Reuse Technical Committee concluded:

- There is a need for more data to be made available to the general public to break down barriers against water efficiency and prove that products do work. The manufacturers need to provide relevant data which is freely available to the public.
- There is a need to demonstrate that water reuse products are both reliable and desirable to the general public. In order to achieve this objective we need to have the water companies on side.
- A Water Reuse workshop is planned where data gathered from Manufacturers will be disseminated to builders, developers and the general public.
- Water companies should look at what technology they can back or support- can this sort of information be provided with water bills?
- What are water companies doing about innovation - there is a tendency to offer customers who show an interest in water efficiency a piece of kit but one size does not fit all. Water companies need to provide more information for example around rainwater harvesting systems.
- The Environment Agency's draft report on energy and carbon implications of rainwater harvesting and greywater recycling 2010 needs updating in order that it is relevant to current developments.

## **4. CONCLUSIONS**

The Water Reuse Technical Committee's main conclusions in order to raise awareness and inform policy are:

- Manufacturers need to make available relevant data to the general public to encourage take up of water reuse systems
- The codes and practices within water reuse need to be more easily understood in order to build confidence in water reuse systems
- The Code for Sustainable Homes (CFSH) (or a similar code) needs to be maintained and environmental standards such as CFSH and BREEAM need to be incorporated within planning regulations.
- The British Standard codes for installation of greywater recycling and rainwater harvesting systems need updating;
- Water reuse equipment manufacturers need to provide systems which are easy to install and maintain, and are cost effective - there needs to be clear and informative data available
- There is a need to establish national standard for installation and maintenance. An accredited national training programme needs to be established and list of approved installers drawn up.
- Water companies need to be made aware of water reuse installations in order to take main responsibility for resolving problems
- A survey of water reuse equipment manufacturers needs to take place in order to gather data for future Workshop
- More public engagement needs to take effect, particularly from the water companies' viewpoint.
- There needs to be an updated report on the energy and carbon implications of water reuse systems in order to provide relevant data to allow informed decisions to be made.

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# DOMESTIC WATER CONSUMPTION AND IMPLICATIONS

# Difficulties in setting minimum flow rates in showers

C. PIMENTEL RODRIGUES<sup>1\*</sup>, A. SILVA AFONSO<sup>2</sup>

(1) PhD, Technical Director of ANQIP (Associacao Nacional para a Qualidade nas Instalacoes Prediais)

Rua S. Roque n° 23 1º, 3B00-257 Aveiro, Portugal ([anqip@anqip.pt](mailto:anqip@anqip.pt))

(2) Professor, University of Aveiro (Portugal), and Chairman of the Board of ANQIP  
(Associacao Nacional para a Qualidade nas Instalacoes Prediais)

Campus Universitario de Santiago, 3B10-193 Aveiro, Portugal ([silva.afonso@clix.pt](mailto:silva.afonso@clix.pt))

## ABSTRACT

**Aims:** To provide inputs for assessing minimum flow rates in showers, and to help improve water efficiency labelling systems of products, based on studies conducted by ANQIP.

**Study design:** Parametric analysis of results obtained in studies to evaluate the comfort and duration of showers with different flow rates.

**Place and Duration of Study:** One student residence in the University of Aveiro, and one residential building in Portugal, between 2013 and 2015.

**Methodology:** The first part of this study involved a student residence in the University of Aveiro, with the aim of finding the minimum shower flow for comfort, considering both gender of users and shower duration. This involved 8 male and 8 female users. The second study was conducted in a dwelling which has been subjected to an audit of water efficiency, and consisted of the analysis of diagrams of hourly consumption before and after implementation of the audit efficiency measures. This involved a 3 room apartment, occupied by a family of three persons, and the audit included placing reducers (with air emulsions) in the showers. Other studies conducted by ANQIP will be briefly discussed.

**Results:** The results show that a "break point" exists for each type of shower, i.e. a point at which reducing the flow rate implies increasing the duration of the shower.

**Conclusion:** Just indicating a flow rate on labels is an overly simplistic and inadequate indicator of water efficiency for the case of showers.

*Keywords:* showers; comfort; low-flow products; water efficiency

## 1. INTRODUCTION

One of the essential, and more relevant, measures for achieving efficient use of water in buildings is the adoption of efficient products. However, for the case of showers, the definition of efficient product based only on minimum flow raises some doubts, since behavioural factors, related to comfort, can counteract the savings resulting from application of a low-flow product.

Although the sensation of comfort varies from individual to individual, with showers there are inherent characteristics of the product that can change the feeling of comfort between different models working with equal flow rates. These include the strength of the jet or the pressure on the skin, the coverage of the spray, the vertical temperature distribution, how effective they are in removing the shampoo and soap, etc. With low-flow showerheads, the influence of these factors on comfort can encourage people to stay in the shower longer, thus increasing final water consumption.

Aiming to improve the water efficiency labelling system, ANQIP (Associação Nacional para a Qualidade nas Instalações Prediais), a Portuguese non-profit civil society association concerned with implementing water efficiency in buildings [1], undertook a number of studies in residential buildings of various types, some of which are described in this paper. The purpose was to establish the comfort factors. In fact, ANQIP believes that a labelling system based on flow rates may mislead consumers into acquiring products that, in the end, can lead to higher water consumption.

In addition to these behavioural aspects, it should be noted that the use of low-flow showerheads can introduce other issues of a technical nature, such as problems on turning on gas water heaters. This aspect is difficult to study, given the large number of models of instant water heaters available on the market, their different characteristics, and the influence of the network pipe characteristics of the building so, in this case, the minimum flow rate can only be determined through an experimental evaluation.

Placing flow reducers in showers is often, also, a bad technical option, because many high flow showers do not work properly when the flow rate is reduced significantly, giving, for example, a spray which is deficient in skin coverage or jet pressure. There are reducers that can minimize this problem (with emulsion of air, for example), but their application is not appropriate in all cases.

In spite of these issues, we feel that, in general, it is possible to define a flow rate threshold, above which the above mentioned problems arise, whatever the characteristics of the installation of the device, or the residual pressure upstream.

## **2. METHODOLOGIES**

### **2.1 Evaluation of minimum flow for comfort with flow reducers in a student residence**

ANQIP led a study in a student residence at the University of Aveiro to measure the effect of applying flow restrictors to reduce the flow rates in existing showerheads, on the minimum flows for comfort, considering the gender of users and duration of the shower. This also involved other less relevant parameters (age of student participants, etc.), that are not discussed in this communication, but did not consider temperature measurements of the shower [2].

Although the results of this study cannot be generalized, since it only involved a population within a narrow age range (university students) and the behaviour depends on the type of shower and its characteristics (spray coverage, etc.), they can give indications about the existence of comfort limits and the consequences on them of reducing the flow rates. We note, however, that a similar study carried out by ANQIP with people of different ages (between 20 and 70 years) and social situations led to similar conclusions, although a greater dispersion in the results was seen.

The study involved 16 people, 8 male and 8 female; each user was asked to record the flow rate they normally use for showering ( $Q_{\text{usual}}$ ), and to carry out a progressive reduction (around one litre minute per day) of the flow rate on subsequent days, until they found a minimum value for comfort ( $Q_{\text{min.comf.}}$ ). The students were provided with a graduated recipient (Figure 1) and a chronometer to measure flow rates, and considered the average of three measurements.

### **2.2 Analysis of water consumption diagrams before and after the implementation of water efficiency audits in buildings**

In order to study the changes in water consumption diagrams, ANQIP carried out more than 10 studies in buildings where different water efficiency measures had been implemented in the wake of water efficiency audits, with hourly recording of consumption through telemetry

systems [3]. Although these studies relate to short periods of time and a relatively limited number of households, which may affect the quality of the findings, the results provide some conclusions of interest by confirming the importance of performing more studies in this field.



**Fig. 1. Graduated recipient**

One of the audited dwellings was an apartment with 3 rooms, occupied by a family of three people, situated in a town in a rural region of southern Portugal. The average monthly flow of the dwelling was  $14.17 \text{ m}^3/\text{month}$ , before the audit, and  $12.40 \text{ m}^3/\text{month}$  after it, that is a reduction of 12,5%. The audit included placing reducers in washbasin taps, bag reducers in cisterns, and reducing flow rates (with emulsion of air) in the showers (Figure 2). The reducer used in the showers reduced the flow rate from 10.5 L/min to close to 8 L/min. It was not possible to apply a reducer in the kitchen tap because the gas heater would not start if there was any reduction in the flow rate.



**Fig. 2. Photograph of the existing showers in the apartment**

### **2.3 Other studies**

ANQIP has also performed comparative studies with other labelling systems, such as EPA WaterSense scheme in the United States [4]. In this case, the product label involves both the

value of the flow rate (less than 7.58 L/min), and compliance with minimum requirements of comfort concerning water coverage and spray intensity.

In this study, ten different showers were used, some of which did not meet the criteria of WaterSense. Consequently, several users were asked to provide their classification in terms of comfort, on a scale of 0 to 10.

### 3. RESULTS AND DISCUSSION

#### 3.1 Evaluation of minimum flows of comfort with flow reducers in a student residence

The data collected from the study conducted in the student residence at the University of Aveiro are summarized in Table 1, and average values presented on Table 2. The mean values for the duration of the shower are slightly lower than those obtained by other organizations, such as Waterwise (9 minutes, on weekdays, for persons under 35 years) or the American Standard Group (8 minutes for a typical shower).

The most important result of the study is that, below a certain value, the duration of a shower increases upon reducing the flow rate, which means that the decrease in the volume of water used does not follow the reduction in the flow rate, such that the savings may not be as significant as expected. This leads to the conclusion that, for each type of shower, there probably exists a "break point", i.e. a point at which a flow rate is not translated into an increase in water efficiency.

**Table 1. Student residence. Data collected**

Person	Age	Sex	$Q_{\text{usual}}$ (L/min)	Duration (min)	$Q_{\text{min.comf.}}$ (L/min)	Duration (min)
1	22	F	11	4	7	5
2	23	F	10	15	5	13
3	22	F	10	9	6	8
4	24	F	9	10	5	12
5	21	F	8	7	4	8
6	20	F	9	8	6	7
7	19	F	10	5	7	6
8	23	F	10	8	7	10
9	20	M	11	5	8	6
10	22	M	12	4	7	6
11	23	M	10	6	6	5
12	21	M	9	7	6	6
13	19	M	10	5	7	7
14	22	M	11	8	9	7
15	24	M	8	4	6	7
16	23	M	10	6	7	9

From analysis of Table 2, it can be concluded that males usually use a higher flow rate in the shower, and also require a greater flow for comfort. However, the values for the duration of the shower are higher for females.

We note from Table 1 that the minimum average shower flow rate of comfort for females was 4 L/min, whereas for males it was 6 L/min. However, as is clear in the table, these values do not satisfy all individuals.

**Table 2. Student residence. Averages values**

		Q <sub>usual</sub> (L/min)	Duration (min)	Q <sub>min.conf.</sub> (L/min)	Duration (min)
Averages	F	9.6	8.3	5.9	8.6
	M	10.1	5.6	7.0	6.6
	F+M	9.9	7.0	6.5	7.6

Table 3 presents the usual volumes and the volumes of minimum comfort for each person, in terms of consumed volumes (flow x duration of showering). From this it can be seen that the minimum and maximum usual volumes used by females are 44 L and 150 L, respectively, while with the volumes of minimum comfort, the minimum value is 32 L and the maximum is 70 L.

**Table 3. Volumes consumed in showering (usual and minimum comfort)**

Person	Age	Sex	V <sub>usual</sub>	V <sub>min.conf.</sub>	Person	Age	Sex	V <sub>usual</sub>	V <sub>min.conf.</sub>
1	22	F	44	35	9	20	M	55	48
2	23	F	150	65	10	22	M	48	42
3	22	F	90	48	11	23	M	60	30
4	24	F	90	60	12	21	M	63	36
5	21	F	56	32	13	19	M	50	49
6	20	F	72	42	14	22	M	88	63
7	19	F	50	42	15	24	M	32	42
8	23	F	80	70	16	23	M	60	63

Linking these two analyses, it can be noted that females consume more water in showers. In terms of the overall reduction, the effects are significant since for females the average volumes fell from 80 L/shower to 50 L/shower (37.5% decrease), while for males it decreased from 57 L/shower to 46 l/shower (reduction of about 20%). Overall, the average usage was 68.5 L/shower, while the minimum comfort value corresponds to 48 L/shower, which translates into an effective reduction potential of 30%.

Minimum volumes of comfort were plotted against flow rates, and the data fitted to a trend line (2nd degree polynomial, Figure 3). From this the 'break point' corresponds, on average, to a minimum of comfort around 5 L/min.

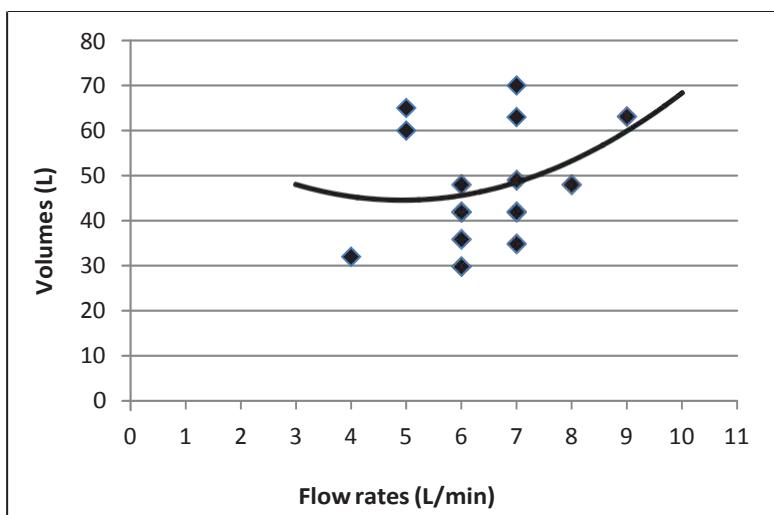


Fig. 3. Relation between flow rates and volumes for a minimum comfort

### 3.2 Analysis of diagrams of water consumption before and after the implementation of water efficiency audits in buildings

Analysis of hourly consumption diagrams (average values of monthly readings) in the study of the audited apartment showed that in two periods of the day (morning and evening), the consumption increased after the implementation of the measures contained in the audit (Figure 4). The system of registration of flow rates installed does not allow identification of the devices in use, but knowing that, from the beginning, the inhabitants were uncomfortable with the flow reduction in the shower, and that one of the residents usually showers in the morning, while the other two do so at the end of the day, the increase of the volumes consumed during these periods was attributed to an increase in duration of showers for reasons of comfort. In fact, given the type of shower installed in the building, with numerous large diameter water outlets, reducing flow to 8 L/min led to a loss of pressure and shower coverage of the jet.

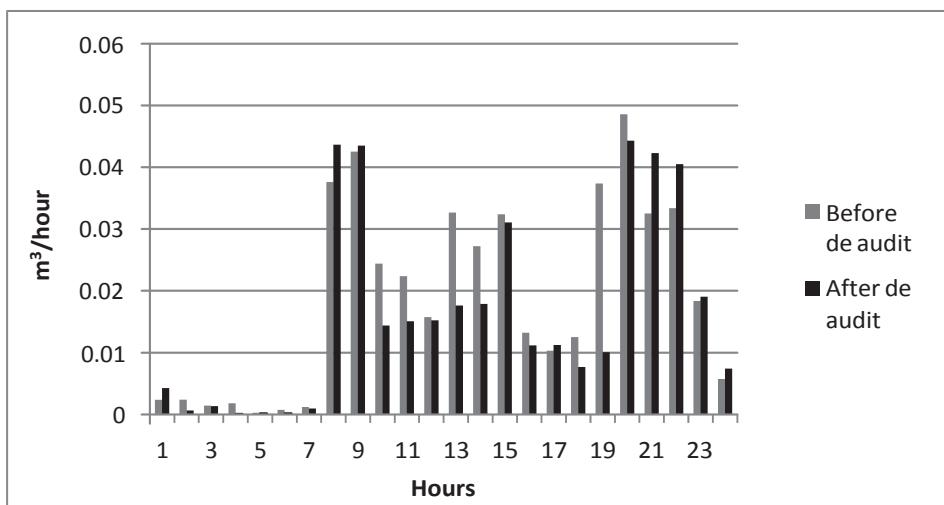


Fig. 4. Average hourly consumption, before and after the audit

### **3.3 Other studies**

As previously mentioned, ANQIP has also performed comparative studies with other labelling systems, such as the EPA WaterSense scheme in the United States, which requires both a low flow rate, and also compliance with minimum requirements of comfort concerning water coverage and spray intensity.

In the comparative study with the WaterSense scheme, ten different showers were used, some of which did not meet the criteria of WaterSense, such that several users were asked their classification in terms of comfort, on a scale of 0 to 10. The results showed the subjectivity inherent in issues of comfort, because some of the showers were well graded by the users, although they did not meet one or more of the criteria of WaterSense. Interestingly, the highest-ranked shower (8/10) corresponded to a low-flow shower of the category "A" of the ANQIP labelling system and also meets the various criteria of the WaterSense.

### **3.4 Influence of the results on establishing water efficiency labels**

The ANQIP scheme for the labelling of the water efficiency of products aims to be an easily implementable system, which guides the consumer on the best choice in terms of effective water efficiency, and not just in terms of low flow rate or volume. It was launched in 2008 by ANQIP, taking into account the risk of water stress in the country and the recommendations of the National Plan for Efficient Water Use [5], but despite being one of the oldest in Europe, it was based from the beginning on concerns of comfort, public health and proper functioning of the building networks. This has been confirmed over time, and in some cases adjusted, based on the results of many studies that have been developed by ANQIP with associated universities.

ANQIP manages the system in an independent manner. The Association has drawn up Technical Specifications (ETA) for different products so as to create and establish the necessary benchmark values to be assigned to each letter. These technical specifications also establish the certification testing conditions.

Firms signing up to the system will sign a protocol with ANQIP, which will set the conditions under which they can issue and use the labels. ANQIP controls the process by randomly testing, from time to time, labelled products on the market. These tests are performed by accredited laboratories or by laboratories which are recognized by the Association [6].

Figure 5 shows the labels adopted by ANQIP, varying between the letters "A<sup>++</sup>" and "E". The assignment authorization of labelling for showerheads and shower systems is made in accordance with the categories established in Table 4 [7]. The base colours of the labels, which cannot be seen in Figure 1, are green and blue.

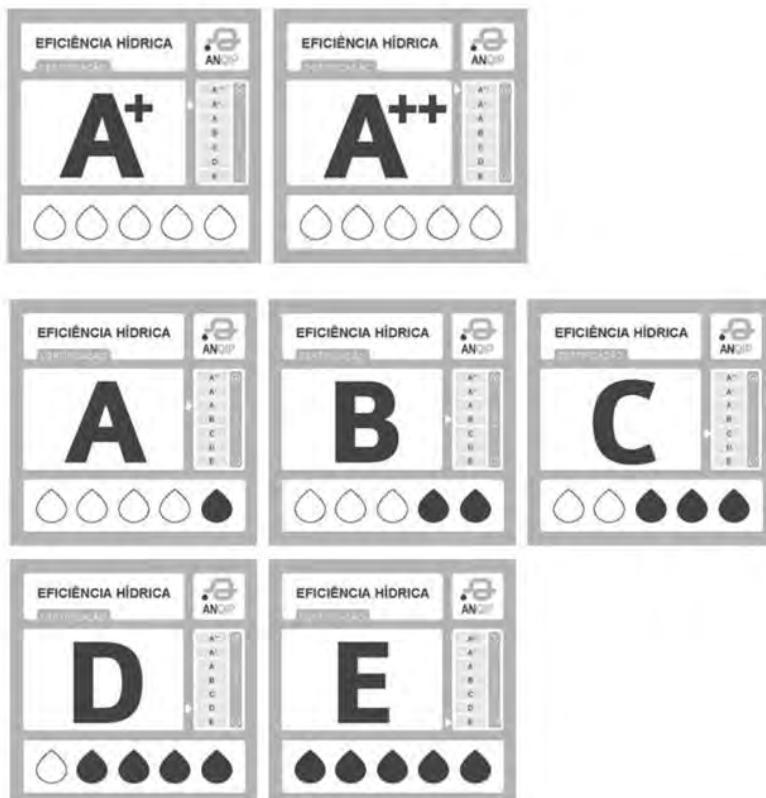
Category "A" means the ideal efficiency for several products in the current installations, considering not only the reduced flow, but also concerns of public health, the necessity of ensuring a minimum comfort and questions of functioning of the networks, such as the start-up of instant gas water heaters or the performance of drainage systems.

The minimum flow rate of 5 L/min for showers of category "A" was set by ANQIP as a result of several studies that essentially take into account aspects of comfort. It is true that, when showers are specially designed to work with low-flow rates, using solutions such as the emulsion of air or the use of a small turbine vane, those with flow rates less than 5 L/min can still be convenient for the user and so we have categories A<sup>+</sup> and A<sup>++</sup>. [8].

In relation to public health issues, it is known that shower systems with a discharge of 5 L/min or less have an increased risk of scalding, and the "A<sup>+</sup>" and "A<sup>++</sup>" labels applied to these devices must bear the indication "Recommended for usage with thermostatic taps" (Figure 6).

This aspect is very important and distinguishes it from other schemes. In fact, the ANQIP label seeks to give consumers guidance on the most appropriate product, and is not intended to be a scheme for commercial promotion for products.

In general, ANQIP considers that the mere indication of a flow rate on the label, even if accompanied by an indicative colour, is an overly simplistic and inadequate solution, because it does not prevent the above-mentioned problems and does not advise the consumer of the best option.



**Fig. 5. Portuguese water efficiency labels [5]**

**Table 4. Conditions for water efficiency labels in showers and shower systems (ANQIP) [7]**

Flow rate (Q) (L/min)	Showerhead	Shower system	Shower system with thermostatic tap or eco-stop	Shower system with thermostatic tap and eco-stop
Q < 5,5	A <sup>+</sup>	A <sup>+</sup>	A <sup>++</sup> (1)	A <sup>++</sup> (1)
5,0 < Q < 7,2	A	A	A <sup>+</sup>	A <sup>++</sup>
7,2 < Q < 9,0	B	B	A	A <sup>+</sup>
9,0 < Q < 15,0	C	C	B	A
15,0 < Q < 30,0	D	D	C	B
30,0 < Q	E	E	D	C

(1) The use of eco-stop in these cases is not considered to be of interest



**Fig. 6. Examples of ANQIP water efficiency labels for shower systems with low flow rates [7]**

#### 4. CONCLUSIONS

An efficient shower or shower system classification based only on the flow rate is an overly simplistic and inadequate solution, since it does not cover aspects of comfort, public health, or operation of building networks. The comfort aspects are particularly important and may even imply that a higher total volume is consumed in the bathroom in a shower of lower flow rate because of the effect of extending its duration.

This fact should be considered in water efficiency labelling schemes, and including parameters of comfort in the classification of products along with the flow values, as is done in the WaterSense scheme, could be an appropriate solution even though these parameters are fairly subjective. Further studies are needed to determine whether the comfort criteria would increase the complexity of the schemes and labelling, but fail to lead to the desired objectivity.

With the ANQIP system, a relatively simple solution was adopted to give consumers the most appropriate guidance on products, opting to set a minimum reference category, which hopes to safeguard aspects of comfort, public health (risk of scalding) and the operation of the installations in buildings (start up of instant water heaters). The system accepts categories of better water efficiency, but warns the consumers of the need for a proper installation for low volumes or flow rates, in addition to adopting solutions that avoid risks in use (such as thermostatic taps), together with the importance of considering solutions that compensate for a possible decrease in comfort in use.

#### COMPETING INTERESTS

The authors are members of ANQIP, a non-profit, technical-scientific civil society association, which brings together universities, companies and water authorities, working in favor of increasing water efficiency in buildings. With about 200 members, ANQIP is not financed by the government or by any company and its financing is the result of membership fees and services provided to the community.

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# Objective measurement of showering behaviour in the UK and a behavioural intervention to reduce water use in the shower

Hilde Hendrickx<sup>1</sup>, Doug Clarke<sup>3</sup>, Rhian Davies<sup>2</sup>, Katherine Fuller<sup>4</sup>, Chris Noakes<sup>5</sup>, Adam Russell<sup>2</sup>, Lorraine Sassano<sup>1</sup>, Richard L. Wright<sup>2</sup>

<sup>1</sup>Unilever R&D, Sharnbrook UK

<sup>2</sup>Unilever R&D, Port Sunlight UK

<sup>3</sup>Severn Trent Water, Coventry UK

<sup>4</sup>Essex and Suffolk Water, Chelmsford, UK

<sup>5</sup>Wessex Water, Bath UK

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## ABSTRACT

With the growth in popularity of power showers and the trend for more frequent and longer showers, the use of water for showering will become a more sizeable component of domestic water consumption and an increasingly important target for water efficiency improvements. Limited data is available on showering and existing data is often based on self-report, a method with drawbacks. Similarly, evidence on the efficacy of water efficiency interventions for showering is scarce.

In this study, a shower monitor based on sensor technology was used to gather objective data on showering behaviour in the UK. Secondly, a behavioural intervention was developed to reduce shower duration and water use using a low flow feedback showerhead combined with other behavioural techniques (commitment and social comparison). 319 households participated in the study run in three UK water company area's. During the first 'baseline' month all households were monitored under their normal usage condition. Households were then randomly assigned to either the 'Control' or 'Intervention' group. In the intervention group, the low flow feedback showerhead was installed and the other elements of the intervention were administered. All households were monitored for a further month.

Study results will be reported at the conference. The study will provide objective data on UK showering behaviour and give insight into people's environmental attitudes and beliefs about showering (questionnaire data). The study results will also show whether a water efficiency intervention based on behavioural principles resulted in shorter showers and a decreased water use.

*Keywords:* Showering, behaviour monitoring, behaviour change

## 1. INTRODUCTION

With the growth in popularity of power showers and the trend for more frequent and longer showers (Shove & Walker, 2010), use of water for showering is likely to become a more sizeable component of water consumption of households and an increasingly important target

for water efficiency improvements. To develop robust future scenarios on domestic water use and water efficiency strategies, reliable data is needed on showering behaviour as well as a strong evidence-base on the efficacy of various water efficiency interventions in the home.

Limited published and peer-reviewed data is available on showering in the UK (Browne et al., 2013; DEFRA, 2009; Waterwise, 2009) and the existing data is often based on self-report, a methods with considerable drawbacks. Self-report is a commonly used method for recording information about behaviour. However, social desirability can affect survey responses in environmental research (Snelgar, 2006). In particular, socially desirable responses (such as recycling) can be over-reported in surveys. Also, behaviours such as showering tend to be habitual – habits are repeated behavioural sequences that are under the control of environmental cues and often performed without much conscious thought or attention. As a consequence, respondents often lack insight into the nature and drivers of these behaviours, and will struggle to report on these habits (Verplanken et al., 2005).

#### Shower monitors

In order to gather reliable data, this study uses a monitor, developed by Unilever's R&D function, to unobtrusively record showering behaviour and water use. The shower monitor is attached to the shower hose and collects data through multiple sensors (rumble, acoustic, temperature, real time clock). Bespoke algorithms are then used to process the sensor data to derive the time, date and duration of showers. Similar monitors have been previously embedded in toothbrushes and soap bars to track tooth-brushing and hand-washing e.g. Claessen et al., 2008; Halder et al., 2010; Wright et al., in press; Zillmer et al., 2014).

The shower monitor can provide more accurate baseline information on showering and is an important tool to more objectively measure the impact of water & energy saving interventions for showering. A handful of studies mostly in Australia have previously used smart metering technologies to measure overall household water consumption. The metering data was combined with flow trace analysis software for event disaggregation to identify showering events (Wilkes et al., 2005; Willis et al. 2011). This study solely and directly captures showering events. The logger data is combined with shower diaries filled out by all members of the household which allows for fine-grained analysis of showering behaviour at the person level.

#### Changing showering behaviour

Water efficiency strategies often require water users to adopt new technologies and/or change habitual behaviours. Behaviours related to household energy/water conservation can be divided into two categories: efficiency and curtailment behaviours (Gardner & Stern, 2008). Efficiency behaviours are one-shot behaviours and entail the purchase, installation and continued use of water and energy efficient equipment, such as a low flow showerhead. Curtailment behaviours involve repetitive efforts to reduce energy use, such as reducing showering time. Adopting both types of pro-environmental behaviours requires some form of behaviour change.

The research basis for changing pro-environmental behaviour, however, is still relatively limited and needs further building. A few meta-analyses outline behavioural techniques that have proven to be effective in encouraging pro-environmental behaviour (Abrahamse et al., 2005; Osbaldiston & Schott, 2012; Steg & Vlek, 2009). In addition, behavioural economics and the 'nudge' approach (Thaler & Sunstein, 2008) give further insights into how to engage people in behaviour change and how to shape the environment in such a way as to influence habits. To our knowledge, however, very few behaviour change interventions have been tested specifically aimed at making showering more sustainable. In one study, a combination of tailored information, goal setting and tailored feedback was used to encourage households to reduce their direct energy with showering as one of the target behaviours. Compared to the control group, participants in the intervention did show a decrease in shower time but results were solely based on self-report (Abrahamse et al., 2009).

#### Showering intervention

In this study, an intervention was tested to encourage participants to adopt sustainable showering habits through the use of water efficiency tools and proven behaviour change

techniques. The design of the water efficiency tools was directly inspired by behaviour change principles to 'nudge' behaviour in the desired direction.

In the intervention group, the existing showerhead was replaced with a low flow showerhead fitted with a regulator that reduces the water flow rate to 7.6 Ltr/min. Assuming no change in showering behaviour, the low flow showerhead should result in water and energy savings. In addition, to encourage participants to shorten their shower duration, a timer and feedback light was incorporated in the showerhead. Passage of time is signalled by an LED light (powered by a turbine incorporated in the shower head) that immediately switches on when the shower is turned on. The LED light displays three colours. Initially, the light is blue (signalling low water consumption) but changes to orange after two minutes and then to red after a further three minutes (signalling high water consumption). The provision of feedback about a target behaviour is a well-established behaviour change technique. For example, giving households information about their energy consumption or energy saving has been shown to result in modest changes in energy conservation behaviour. It have been found to be particularly effective when given immediately after the behaviour occurs (Abrahamse et al. 2005; Darby, 2006; Geller, 2002), as is the case here.

To further motivate participants to reduce the duration of their shower, two additional behaviour change techniques were used. First, participants were asked to make a commitment to have shorter showers. A commitment is an oral or written pledge or promise to change behaviour and is usually linked to a specific goal. This promise can be a pledge to oneself, or can also be made public. Commitment has been found to be a successful strategy for reducing household energy use as well as for water conservation (Abrahamse et al., 2005; Osbaldiston & Schott, 2012). For example, in a large field study, hotel guests asked at check-in to make a brief but specific commitment to reuse towels were 25% more likely to hang at least one towel for re-use, and this increased the total number of towels hung by over 40% (Baca-Motes et al, 2013). In this study, before the start of the intervention period, participants in the intervention group were asked to sign a written pledge to commit to three short showers a week ('blue' light showers). As a reminder, participants received a sticker to put in their shower cubicle ('I commit to three short showers a week').

Secondly, social influence was used to entice household members to have shorter showers. Social influence refers to the ways in which our behaviour is affected by what other people do, or by what other people think. People are more likely to start engaging in a behaviour when they observe others engaging in this behaviour (Abrahamse & Steg, 2012). People also have a tendency to compare themselves to other people. Socially comparative feedback consists of providing people with feedback about their own performance, compared to the performance of other people. A number of experimental studies found that social comparison can affect people's willingness to engage in sustainable behaviours (e.g. Rabinovich et al., 2012). In this study, all members of the household were asked to 'publicly' share their efforts to reduce their showering time with each other. To that aim, the household was provided with a chart on which each household member had to indicate (by means of little coloured dots - blue, orange and red) what colour (LED light) their shower ended on. The chart was displayed in a clearly visible place in the bathroom.

In sum, this project used shower monitors to reliably and objectively measure domestic showering behaviour (shower duration, frequency, water use) in a representative samples of domestic customers of Essex & Suffolk Water, Severn Trent Water, and Wessex Water. In addition, information was gathered about participants' environmental values and attitudes and beliefs about showering. Second, the monitors evaluated the impact of an intervention that combined commitment and social comparisons with a low flow showerhead that incorporated a LED feedback light. Compared to a matched control group, we predicted that households in the intervention group would shorten their shower duration and reduce water consumption in the shower.

## 2. METHOD

### 2.1 Participants

319 households were drawn from three UK water company area's (Severn Trent Water, Essex and Suffolk Water, and Wessex Water) and representative across five main ACORN category groups. Acorn is a geo-demographic consumer classification tool used by the UK water companies to segment the UK population. About two-thirds of the households lived in a property with a water meter, with one third living in an unmetered property.

## 2.2 Study Materials

### 2.2.1 Shower Monitor

The shower monitor (see Figure 1) combines different sensors (rumble, acoustics and temperature) to detect timing and length of the shower. The monitor is a small device ('data logger') that is attached to the pipe or hose of the shower using a special holder, no permanent alterations to the shower are required. The data from the monitor is digitally downloaded at the end of the study. Although the logger tracks all shower events in the household, on the basis of only the logger data it is impossible to tell who in the household took a shower. To be able to identify the household member who took a shower on a certain day/at a particular time, during the study all household members were asked to fill out a short shower diary immediately after each shower. They recorded the day and time of day and indicated who used the shower. Some additional questions are also asked such as what products were used in the shower and in what order (e.g. shower gel, shampoo...) and how much participants enjoyed the shower.



Figure 1: Shower monitor

### 2.2.2 Intervention Materials

A low flow showerhead was used with a regulator inserted that limits the water flow to 7.6 litre/minute. When the shower is turned on, an LED light on the showerhead (powered by a turbine incorporated in the shower head) is coloured blue, and changes from blue to orange after 2 minutes, and from orange to red after 5 minutes (see Figure 2). The showerhead is WRAS approved [complies with the Water Supply (Water Fittings) Regulations or Scottish Byelaws] and has CE marking. Other intervention materials included a pledge sheet that captures people's commitment to shorter showering, a reminder sticker ('I commit to three short showers a week') and a sticker chart to 'publicly' keep track of the household's efforts at shorter showering (put in the bathroom/shower room).



Figure 2: Low flow showerhead with feedback lights

### **2.2.3 Questionnaires**

The following questionnaires were administered in the study:

-Demographic/dwelling questionnaire: captures demographic information about the household as well as general information about the dwelling and details about the water and heating systems.

-Showering habits questionnaire: Self-report of the participants' habitual showering behaviour and their beliefs about other people's showering behaviour. This questionnaire was used to investigate the gap between actual behaviour and reported behaviour and to better understand the practices and social norms around showering.

- Values questionnaire (van der Werff et al., 2013): Values are desirable and trans-situational goals that serve as guiding principles in one's life. The questionnaire measured participants' altruistic, egoistic, bio-spheric and hedonic values. The questionnaire was included to test to what extent bio-spheric values and environmental self-identity were drivers of observed showering behaviour.

-Sustainable showering questionnaire: The questionnaire explores the perceived acceptability of specific interventions to reduce the water and greenhouse gas impact from showering and captures participants' views on the study and/or the showering intervention.

## **2.3 Study Design**

During the first 'baseline' month all households were monitored under their normal usage conditions. At the end of this period, households were allocated to either 'Intervention', 'Control', or 'Excluded' groups.

Households were 'excluded' based on the suitability of their shower for taking the low flow showerhead. We excluded households with electric showers, power showers with a flow rate higher than 12l/min and those showers that could not physically fit the intervention showerhead.

The remaining 'suitable' households were randomly assigned to either the 'Control' group or the 'Intervention' group. In the intervention group, the low flow feedback showerhead was installed and the other elements of the intervention were administered (pledge and shower chart).

Showers in all households were then monitored for a further month ('Intervention' phase). However, for the purposes of evaluating the impact of the intervention we compared only 'Intervention' and 'Control' households.

### **2.3 Study Procedure**

For logistical reasons, the study was staggered over a 6 month period. An external agency was employed to recruit households from a defined set of postcodes within each water company area.

#### Visit 1

All participants gave informed consent before the shower monitor was fitted to the shower(s) in the participants' home. Children were asked to give assent and the child's parent signed the consent form to agree their child's participation. To measure flow rate of the current shower head, the researcher turned on the shower for 30 sec at the normal setting and measured the amount of water discharged. The researcher checked the type of shower and its suitability for installing the intervention showerhead. Shower diaries were explained to participants and handed out. The main participant in the household also filled out a demographic/dwelling questionnaire. All adults in the household were given the shower habits questionnaire and values questionnaire to be filled out during the baseline period.

Showering behaviour of all family members was monitored for approximately 1 month.

#### Visit 2

At the end of the 1 month baseline phase, the researcher returned to the participant's home to retrieve the monitor, shower diary and completed questionnaires. A new shower monitor was installed. If the household was assigned to the intervention group, the low flow feedback shower head was installed, the researcher handed out and discussed the intervention material (pledge and shower chart). Participants also received new shower diaries. At the end of the visit, the researcher handed out the sustainable shower questionnaire which participants were asked to complete before visit 3.

#### Visit 3

At the end of the one month 'intervention' phase, the researcher retrieved the shower monitor and collected the shower diaries and questionnaires. All participants were debriefed, thanked for their collaboration and remunerated for their participation in the study. (£50 voucher per household and three complimentary shower gels). Participants in the low flow showerhead condition were given the option to keep the shower head.

## **3. RESULTS AND DISCUSSION**

281 households completed both study phases (baseline monitoring and intervention phase). In total 507 adults and 87 children over 7 participated in the study. At the time of writing this report the data analysis was still underway so full results will be available in the presentation at the conference. Results from the logger data (close to 20, 000 shower events) that will be discussed in the presentation are as follows:

1. At the level of the households: descriptive statistics (central tendency and spread) for shower duration, shower frequency, timing of the shower. Across the sample or split by group e.g. based on Acorn category or metered vs unmetered properties.
2. Test the hypothesis that the intervention resulted in shorter shower times and reduced water use. To that aim, for the intervention phase, shower time duration for households in the intervention group will be compared to the control group, taking the baseline monitoring period into account.
3. Using shower diaries shower events captured by the logger can be assigned to different people in the household. This will allow for more fine-grained analysis of shower duration either using demographic variables (gender, age) or questionnaire information (e.g. environmental values).

4. Again, the effect of the intervention will be tested at the participant level which may provide insight into whether certain participant groups are more responsive to the intervention than others.
5. Finally, questionnaire output will be reported

#### **4. CONCLUSION**

Study results will be reported at the conference. The study will provide objective data on UK showering behaviour and give insight into people's environmental attitudes and beliefs about showering (questionnaire data). The study results will also show whether a water efficiency intervention based on behavioural principles resulted in shorter showers and a decreased water use.

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# A Tool for Urban Water Efficiency – Smart Metering for Detailed Analysis of Long-Term Diurnal Water Use Patterns

Caryssa Joustra<sup>1</sup>, Paul Stanek<sup>2</sup>, Pacia Diaz<sup>1</sup>, Daniel Yeh<sup>1\*</sup>

<sup>1</sup>Department of Civil and Environmental Engineering, University of South Florida,  
4202 E. Fowler Avenue, Tampa, FL 33620, USA

<sup>2</sup>Public Works and Utilities Department, Water Division, City of Dunedin,  
1401 CR #1, Dunedin, FL 3469B, USA

## ABSTRACT

**Aims:** To evaluate the validity of smart water metering to capture long-term diurnal water use patterns and develop a set of attributes that capture temporal trends.

**Place and Duration of Study:** City of Dunedin, between March 2014 and November 2014.

**Methodology:** We collected water use data from on-site smart meters at four building locations (multi-residential neighborhood, commercial business, elementary school, and community center) for the period from March 11, 2012 through August 16, 2014. The smart meters logged data an hourly time step with a resolution of between 1 gallon and 100 gallons depending on the size of each meter. A set of attributes (average hourly flow, peak hourly flow, peak factor, time to peak flow, time to 50% consumption, duration that hourly flow exceeds average hourly flow, number of peaks exceeding average hourly flow) was developed to track changes in diurnal curve characteristics.

**Results:** Raw meter data produced 889 24-hour diurnal water user curves for each of the four sites. The multi-residential neighborhood had the least variation in water use attributes over time, while the remaining sites exhibited larger deviations due to fluctuations in occupancy.

**Conclusion:** Smart meters adequately collect, record, and display water use data at an hourly resolution capable of detecting diurnal water use trends unique to each building location. Diurnal water use patterns impact system efficiencies and illustrate a nexus of water, energy, and land use.

**Keywords:** Automated meter reading (AMR), diurnal water demand, data mining, water demand profiles, potable water, time series, urban water, water management

## 1. INTRODUCTION

Utilities ensure the timely delivery of water of adequate quantity and quality to end-use customers, but the difficulty of utilities maintaining the needs of their customers is amplified due to population growth, increasing urbanization, and climate change variability. These factors stress available water quantities by increasing the demand for water resources and altering the amount available over time, thereby threatening the security of water supplies managed by the utility. Water delivery accomplished by distribution and storage components within the infrastructure network must successfully meet peak flow demands while ensuring quality standards are maintained throughout the system. The development and maintenance of water supply systems must optimally balance the economic production of water to meet user's demands with efficient land, energy, and chemical utilization [1].

The focus of operations undertaken by utilities has expanded from exclusive supply-side supervision to widespread demand management strategies, such as water accounting, conservation, pricing, and education [2]. Managing urban water from the demand side often

proves to be cost-effective compared to supply side options which require expensive capital investments for the construction and maintenance of large installations necessary for the movement, treatment, and storage of supplementary water sources. The increased emphasis on demand-side management drives the need for economic data recording, collection, and interpretation which may be accomplished using meters than allow utilities to account for water demands and losses throughout the network [2]. In particular, sustainable urban water management encourages the implementation of widespread metering that produces data at a higher frequency with increased resolution that is remotely accessible in order to promote system efficiency through timely and detailed data analysis [2].

Water metering links customers to the utility resulting in shared benefits for both parties, such that the customer receives potable water access and compensates the utility appropriately, whereby the responsibility of water management is distributed among all stakeholders [2,3]. A smart (intelligent) meter has the ability to capture, store, and communicate detailed water use data more frequently than can be accomplished by traditional meters [2]. Smart metering implementation is driven by water scarcity, conservation support, identification of system losses, utility operation schemes, energy use, climate uncertainty, and financial costs; and includes benefits regarding water savings, economics, customer satisfaction, and community engagement [4,5]. The ability to capture flows at higher time resolutions, such as at the hourly intervals, allows constant water consumption to be flagged as potential leaks in the system, thereby reducing water loss and improving customer relationships by preventing potentially inflated water bills [5]. In addition to leak detection, smart metering improves customer service by producing more accurate billing amounts and aiding in the response to bill inquiries. Remote reading prevents the need for water meters to visit each individual property site, and thus is a less intrusive and labor intensive method for water consumption data collection. Utilities reduce expenditures due to operating costs, deferral of capital project costs, quicker meter reads, and less frequent customer complaints while increasing revenue as a result of the improved accuracy of meter reading and identification of deficits between water produced and water billed, e.g. non-revenue water (NRW). NRW is a result of pumping, treatment, and distribution efficiencies throughout the municipal water system; up to 20% of source water consumption is lost as NRW in the developed world, and the value may reach up to 50% (60%) in the developing world [5]. Traditional meters identify the difference between water produced by the utility and water that reaches customers, but smart metering allows for proactive loss prevention through leak detection and response, reduction in data reading errors, and confirmed meter operation and accuracy calibration.

It is recognized that water demanded by utility customers is dynamic, resulting in a diurnal water use pattern based on the composition of structures served by the urban water infrastructure. The regional diurnal water use pattern provides water utilities with necessary design criteria, such as peak factors, necessary for ensuring that user demands are matched with an adequate supply throughout the network. However, evaluating the diurnal pattern at the system-level does not capture the variable demand patterns produced by individual customers which may greatly differ from the observed cumulative pattern [6] and contribute to the creation of unique microsystems within the water network. The impact of different building types (residential, commercial, industrial) on the utility demand is disguised without a tool capable of capturing water use at the scale and resolution necessary to reveal unique diurnal patterns over time.

Previous studies focused on measuring building water demands include limitations by the resolution of collected data and reporting of aggregate results. Studies conducted over long time durations often report findings at low resolutions, such as in monthly averages or aggregate end-use distributions, whereas studies that collect data more frequently are limited by the short duration of the data collection period [7-9]. The data-logging intervals achieved by meter readings restrict the detail of demand patterns and usability of collected data. Water end-use disaggregation may be accomplished with frequent smart meter readings on the order of seconds, but produce vast amounts of data requiring extensive analysis and quickly deplete battery-powered loggers. When high-resolution data has been captured, trends are lost in the reporting of averages that neglect the inherent variation in water demand necessary for successful timely and efficient delivery of water supplies. The objective of this paper is to determine the validity of smart water metering to capture diurnal water use profiles

for different building types in Dunedin, Florida at an appropriate resolution and duration in order to evaluate building and temporal differences. Diurnal water use patterns will be evaluated using attributes that describe curve features in order to identify the variability and shift in water use patterns over time for each building type.

## 2. METHODOLOGY

### 2.1 Study Sites

Four locations were chosen to represent a residential, commercial, institutional (school), and multi-use case. The multi-residential complex consists of 94 owned units with either two or three bedrooms. The commercial location chosen is a single-building bank with customer transactions taking place on the first floor and permanent offices housed on the second floor. The elementary school site includes two buildings and captures water consumption not only by the student population, but also teachers and faculty who occupy the campus longer than the students. A community center was chosen as a representation of a multi-use facility due to the range of services the building provides to the population. The single-story building houses a fitness center, basketball court, dance studio, and other multipurpose rooms. Occupancy is driven by visitors that may attend scheduled events, such as summer camps or parties, or use open facility amenities as needed.

### 2.2 Data Collection

On-site collection of water consumption data occurred at each meter location. A transmitter downloaded data from the meter via an infrared connection made by direct contact with the transmitter to the meter information portal. The transmitter was then brought back to a central computer where the data was downloaded in Comma Separated Values (CSV) format. The resolution at which volumes were collected by the meter varied from 1 gallon to 100 gallons among location. The multi-residential unit, elementary school, and community center were each served by two potable water meters – one collecting small flow events and a second activated during large flow events. At these sites, both potable meter values were summed and reported as the total potable water consumption. For this study, water consumption at each location was logged at an hourly time step, which is the standard preset in most of the city's water meters. The hourly time step allows for data collection at a high enough resolution to identify diurnal trends while also providing historical data for at least two years.

### 2.2 Data Analysis

Data files in CSV format were analyzed using Microsoft Excel and Access 2010. Potable water consumption at each location was evaluated from March 11, 2012 through August 16, 2014 at each hourly time step for all locations.

**Table 1. Summary of attributes used to evaluate diurnal water use curves**

Characteristic	Notation	Units	Definition
Average hourly flow	$Q_A$	gph	Average flow over a 24-hour day
Peak hourly flow	$Q_P$	gph	Maximum flow observed in a one-hour period over a 24-hour day
Peak factor (peak to average factor)	$F_{P/A}$	-	Ratio of maximum one-hour flow to average hourly flow
Time to peak flow	$t_p$	hr	Hour at which the PHF first occurs
Time to 50% consumption	$t_{50}$	hr	Time in hours that it takes to reach half of the daily water use
Duration that hourly flow is greater than $Q_A$	$T_{Q>Q_A}$	hr	Duration in non-consecutive hours when the hourly flow exceeds the MFH
Number of peaks exceeding $Q_A$	$N_P$	-	The number of events in which a peak flow occurs and exceeds the MFH

Statistical values are necessary in order to describe and quantify the variability among diurnal water curves of different building types and temporal changes of diurnal curves produced by the same building. Attributes used to characterize diurnal patterns must represent unique traits of the resultant daily demand curves in terms of intensity, duration, and frequency [10].

The attributes identified and developed for this study are listed in Table 1 and depend on the analysis of logged flowrates ( $Q$ ) tagged for each date ( $d$ ) and hour ( $h$ ) denoted as  $Q(d,h)$  in gallons per hour (gph).

The calculations for the following attributes are developed using data for unique dates consisting of 24 flow values representing each sequential hour within that date, beginning with hour 1 representing the time between 12:00 AM and 1:00 AM.

### **2.2.1 Average Hourly Flow and Peak Hour Flow**

The total daily water demand is represented as a mean or average hourly flow ( $Q_A$ ) normalized over 24 hours as calculated by

$$Q_A = \frac{1}{n} \sum_{h=1}^n Q(d,h) \quad (1)$$

where the flow for each hour on the given date is summed and divided by the total number of  $n$  hours (24). Although the  $Q_A$  does not describe diurnal changes for the building at the given date, it is useful for evaluating seasonal trends in water use and comparing the intensity of daily water use for each building site. Furthermore, establishing a mean hourly value provides a baseline by which to compare hourly water use magnitudes in terms of deviation from the average throughout the day.

The peak hour flow ( $Q_P$ ) is determined by identifying the maximum hourly flow value within each date,

$$Q_P = \max\{Q(d,h)\}_{h=1}^n. \quad (2)$$

Peak flows are important for the design of water supply systems in order to ensure that water successfully meets customer demands at all times. Identification of the  $Q_P$  within the diurnal curve is essential to the sizing and operation of water network components such as pipe diameters and pressure thresholds.

### **2.2.2 Peak to Average Factor**

The magnitude of the  $Q_P$  may be normalized by division with the  $Q_A$  in order to accurately report the intensity of the peak for the building on that day as a peak to average factor ( $F_{P/A}$ ). While changes in the  $Q_A$  indicate a change in the magnitude of water use by the building, the  $F_{P/A}$  tracks the significance of the peak event. A low  $F_{P/A}$  indicates a steadier water use pattern with less variance from the mean, whereas a high  $F_{P/A}$  alludes to a fluctuating profile.

### **2.2.3 Time to Peak and Time to 50% Consumption**

The time at which the  $Q_P$  is reached, or the time to peak ( $T_P$ ), is marked by the hour at which the  $Q_P$  occurs. In the event that the  $Q_P$  occurs more than once in the 24-hour period, the first occurrence is marked as the  $T_P$ . The appearance of a peak requires that the flow exceed the average value, and thus  $T_P$  values were not recorded for dates that did not record measurable water flow.

Another term developed to indicate the intensity of water use is the time required to fulfill 50% of the date's total daily water use ( $T_{50}$ ). Similar to the  $T_P$ , the  $T_{50}$  marks the hour at which at least 50% of the daily water use has been achieved. The hour value indicates both the time of day at which the  $T_{50}$  is achieved and the duration it took to reach the  $T_{50}$  value. By splitting the day's water use such that half is achieved before the  $T_{50}$  and half fulfilled afterward, the value acts as a center of mass and is calculated as

$$T_{50} = \frac{\sum_{h=1}^n Q(d,h)h}{\sum_{h=1}^n Q(d,h)} \quad (3)$$

Expanding the center of mass definition to a 2-dimesional area results in the intersection of the  $Q_A$  and  $T_{50}$  summarizing the diurnal curve profile as a single point at time  $T_{50}$  with flow  $Q_A$ . It is expected that the  $T_{50}$  nears the  $T_P$  as the  $F_{P/A}$  ratio increases due to the increasing concentration of water volume around the peak. Similar to the  $T_P$ , the  $T_{50}$  was not recorded for dates with no measurable water flow.

#### **2.2.4 Duration that Flow Exceeds Average Hourly Flow**

Another indicator of water use intensity is the amount of time that the hourly flow exceeds the  $Q_A$  ( $T_{Q>QA}$ ). This value is calculated by counting each hour in which  $Q(d,h) > Q_A$ . The resulting count represents the amount of time in hours that the water use by the building exceeded the mean and may be consecutive or non-consecutive. In either instance, a shorter duration recorded as the  $T_{Q>QA}$  indicates events with higher intensity. It is expected that short  $T_{Q>QA}$  values correlate with higher  $F_{P/A}$  ratios.

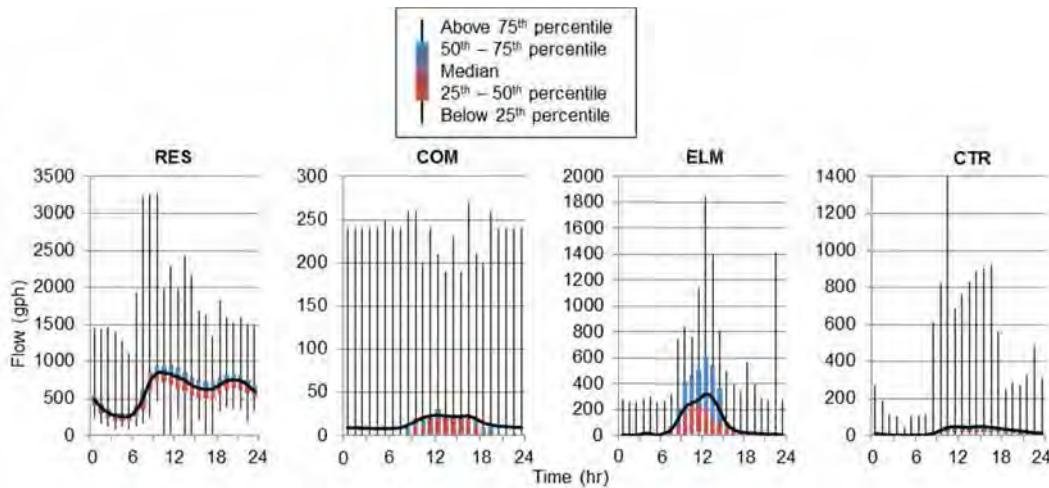
#### **2.2.5 Number of Peaks Exceeding Average Hourly Flow**

Identifying characteristics of the highest peak flow event provides designers and operators with the most severe event that the system must be able to accommodate, but the appearance of additional peak events, although not necessarily of the same intensity, increases the stress placed on the system by decreasing the amount of time available to respond and recover between events. A higher frequency of intense peak events requires increased buffering capacity in the water supply system in the form of storage and affects pressure within the pipe network. The frequency of high-intensity peak events ( $N_P$ ) is determined by counting the number of peak events that exceed the  $Q_A$  and result in a  $F_{P/A}$  greater than 1.

### **3. RESULTS AND DISCUSSION**

#### **3.1 Diurnal Water Use Curves**

As expected, a range of individual daily diurnal curves is produced from the collected data and results in an hourly-average demand profile that describes each building type. Figure 5.2 illustrates the distribution of flows for each hour of the day for each building type with the composite hourly-average demand profile drawn on top of the distribution. For all sites, the distributions plotted in Figure 1 are for all 889 days during the study period, and therefore aggregate usage patterns may be different depending on day and month. The median flow at each hour is generally lower than the average flow for each of the four building sites due to high-flow outlier events that drive up the average. The effect of outliers on the average is best presented at the commercial site where at least 75% of values indicate no flow during the early morning hours (hours 1-9 and 19-24). However, infrequent water use events presumably due to irrigation during this time period result in an average flow that represents the presence of a relatively constant use of water which is not correct. The outlier flow values cause the largest difference in median and average flows in the community center throughout the 24-hour period, thereby indicating wide fluctuations in the time and magnitude of peak flows. Fluctuating water use in the community center is a result of the dynamic population that utilizes the building's many amenities; scheduled events that influence building occupancy and water use vary seasonally, monthly, and day-by-day. The distribution of water use for the commercial site is assumed to be the result of the transient occupants comprised of people visiting the building for only a short amount of time to complete business transactions. The number of full-time occupants in the building has remained relatively constant throughout the study period. The hourly-average demand profile and median hourly flows best align at the multi-residential site and result in the expected diurnal curve. However, the high distribution of values outside of the 50% of values about the mean indicate intense flow events that greatly exceed those within the average pattern.



**Fig. 1. Box plots showing distribution of all flows by hour for each of the four building sites – multi-residential (RES), commercial (COM), elementary school (ELM), and community center (CTR)**

### 3.2 Temporal Trends

#### 3.2.1 Peak Flow and Mean Flow

The monthly average mean flow ( $Q_A$ ), peak flow ( $Q_P$ ), and peak factor ( $F_{P/A}$ ) for each day of the week is plotted in Figure 2 for each building location. The multi-residential site has the least percent variation among  $Q_A$ ,  $Q_P$ , and  $F_{P/A}$  values based on both month of the year and day of the week compared to the other sites. In all cases,  $Q_A$  and  $Q_P$  follow a similar trend over the 12 months, resulting in a relatively stable  $F_{P/A}$  over time for most days of the week; however, the remaining three building locations have  $Q_A$  and  $Q_P$  values that fluctuate depending on the time of the year.

The commercial building site has slightly higher water use in the winter months (November through January), and the average attribute values are skewed due to the unusual water usage patterns on the weekends when the building is closed. Water use captured on the weekends for the commercial site is attributed to the irrigation system and produces diurnal curves with low  $Q_A$  values compared to  $Q_P$ . The resultant high  $F_{P/A}$  values shift the average curve higher than the weekday  $F_{P/A}$  values.

Water use for the elementary school drops during the summer months (June through August) when school is not in session, but measurable water use persists during the summer due to occupancy by teachers and staff. Similar to the commercial building, the elementary school is closed on weekends and the meter captures water use for irrigation on these days.

Contrary to the elementary school, the community center has the highest water use during the summer months (June through August) which may be attributed to the array of summer programs hosted by the center to accommodate children during the summer break. The reduced number of building operating hours on Sunday results in lower water use on these days, both in terms of  $Q_A$  and  $Q_P$ . However, there is a greater difference between the average and peak values which results in higher  $F_{P/A}$  for Sundays.

#### 3.2.2 Time to Peak and Time to 50% Consumption

Figure 3 plots  $T_P$  and  $T_{50}$  values over time for each location. Residential diurnal curves are expected to peak in the morning or afternoon, and the  $T_P$  for the multi-residential location shows that the average hour of highest flow varies between hours 11 and 16 (10:00 AM – 6:00 PM). Therefore, the  $T_P$  is not constant and may shift from a morning peak to an

afternoon peak or vice versa. Despite the change in  $T_P$ , the  $T_{50}$  remains constant for all months and days for the multi-residential site around hour 14 (1:00 PM - 2:00 PM) indicating a constant time for water use symmetry.

The commercial building and elementary school also have varying  $T_P$  values, but weekend  $T_P$  values tend to occur in the morning or later in the day and coincide with common times for irrigating. The average  $T_{50}$  for the elementary school is around hour 12 (11:00 AM to 12:00 PM) for months March through October and around hour 13 (12:00 PM to 1:00 PM) for hours November through February. The average weekday  $T_{50}$  is slightly less than the average weekday  $T_P$  for the elementary school, but both still occur during the lunch hours when the highest demand for water is expected due to a break in classes for students. The commercial building has the largest variation in  $T_{50}$  values of all the building sites, and average weekday values range from hour 13 to hour 17 (12:00 PM - 5:00 PM). Unlike the consistent occupancy at the elementary school, visitors to the commercial building may have a large impact on the time and intensity of water use resulting in the large range of  $T_{50}$  values. The average  $T_{50}$  values occur during the latter half of the open hours for the building, thereby inferring a higher occupancy during these hours.

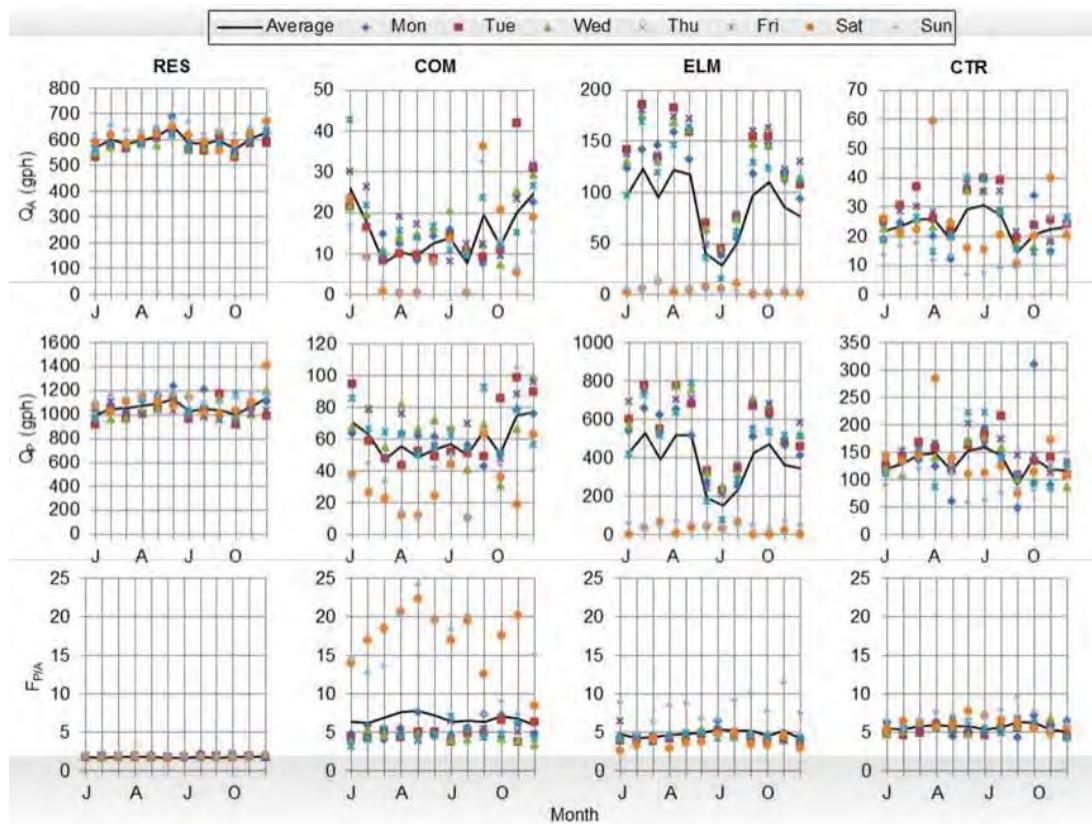
The community center has the largest average  $T_P$  and  $T_{50}$  values which indicate higher water use later in the day around hour 15 (2:00 PM - 3:00 PM). However,  $T_P$  ranges from hour 11 to hour 18 (10:00 AM - 6:00 PM), and the majority of  $T_{50}$  values fall between hours 13 and 16 (1:00 PM - 4:00 PM). The earlier closing time on Sunday results in lower  $T_P$  and  $T_{50}$  values for this day over the year.

### **3.2.3 Peak Frequency and Duration Above Mean Flow**

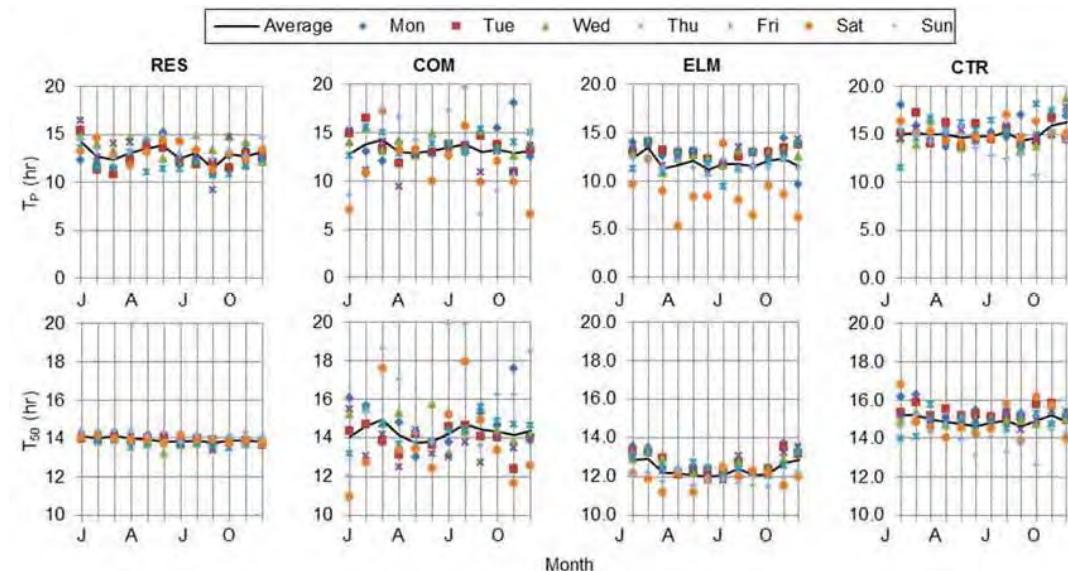
The peak frequency and duration that flow exceeds the mean flow is plotted on Figure 4. For the multi-residential site, values for  $T_{Q>QA}$  are maintained between 12 and 13 hour non-consecutive durations throughout the year which indicates that roughly half of the hours each day observe water use that is above  $Q_A$  and the remaining hours observe water use below  $Q_A$ . In the commercial setting, weekday  $T_{Q>QA}$  values vary between 7 and 12 hours per day, while weekend values are much lower and mostly fall between 1 and 6 hours per day. The low weekend  $T_{Q>QA}$  values can be attributed to irrigation that occurs on the weekend during short watering periods. Weekday  $T_{Q>QA}$  values for weekdays at the elementary school average around 8 hours per day, which coincides with the time when the school is occupied by students. Sunday diurnal patterns for the elementary school show consistent water use in the late morning between hours 10 and 13 (9:00 AM - 1:00 PM) and correlate with  $T_{Q>QA}$  values between 4 and 6 hours as a result of these events. Saturday water use captured by the meters was often above 0 gph but below 10 gph as supported by  $Q_A$  values, which is very low for the size of the campus. The low fluctuating flowrates observed on Saturdays produced  $T_{Q>QA}$  values higher than weekday values due to the relatively constant water use profiles observed. Average  $T_{Q>QA}$  for the community center is about 8 or 9 hours per day with a range of 6 hours to almost 11 hours. As expected,  $T_{Q>QA}$  values for Sundays are lower than the other days due to the reduced number of open hours for the building.

The  $N_P$  values calculated for each building location indicate that the diurnal water use patterns are not smooth curves, but rather include multiple peak events that result in craggy shapes. Although two peaks are expected for the multi-residential building,  $N_P$  values averaged about 4.1, twice the amount expected, and were relatively constant throughout the year, falling between 3 and 5. The  $N_P$  values for the commercial building averaged about 1.9, with higher  $N_P$  values occurring on weekdays and low  $N_P$  values occurring on weekends due to short intense irrigation events. Similar to  $T_{Q>QA}$ , Saturday  $N_P$  values for the elementary school were observed to be higher than on weekdays. Again, this data may infer the occurrence of many high intensity water use events, but in reality flows for these days were low (low  $Q_A$ ) and therefore slight elevated changes in water use were captured as multiple  $N_P$  events. Weekday  $N_P$  values for the elementary school were near 1.4 for months January through May and September through November; a slight increase in  $N_P$  was observed in the summer for months June through August and again in December where values were closer to 3 peaks. The multi-use functions of the community center resulted in a range of average  $N_P$

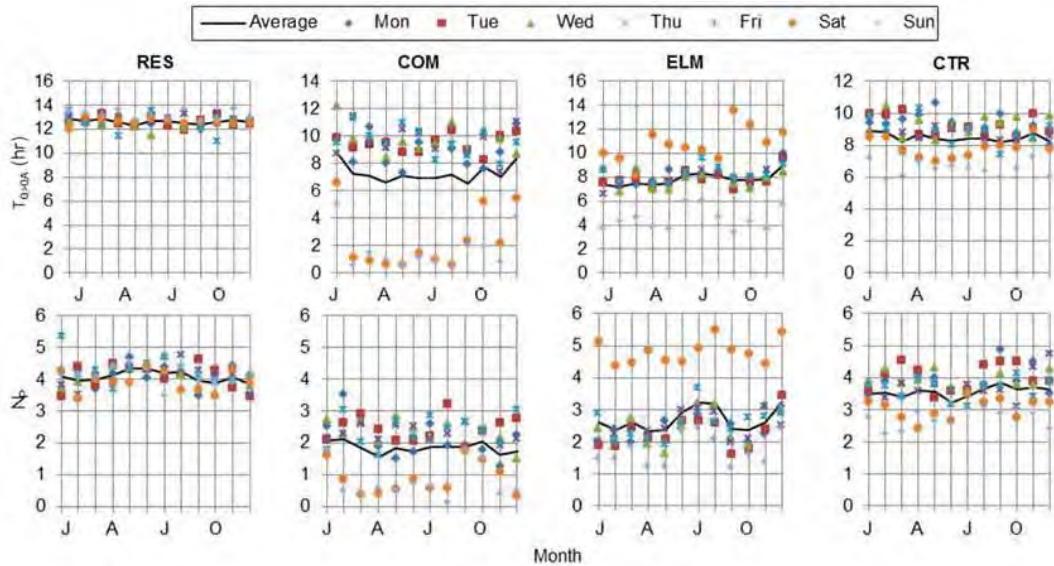
values between 2.3 and 4.9. Fewer peaks were observed on weekends than on weekdays. For all building locations,  $N_P$  was not constant and exceeded expected values.



**Fig. 2. Average hourly flow ( $Q_A$ ), peak hourly flow ( $Q_P$ ), and peak to average factor ( $F_{P/A}$ ) by day for each month for the multi-residential (RES), commercial (COM), elementary school (ELM), and community center (CTR) sites**



**Fig. 3. Time to peak ( $T_p$ ) and time to 50% water consumption ( $T_{50}$ ) by day for each month for the multi-residential (RES), commercial (COM), elementary school (ELM), and community center (CTR) sites**



**Fig. 4. Duration that hourly flow is greater than  $Q_A$  ( $T_{Q>Q_A}$ ) and number of peaks exceeding  $Q_A$  ( $N_P$ ) by day for each month for the multi-residential (RES), commercial (COM), elementary school (ELM), and community center (CTR) sites**

#### 4. CONCLUSION

The water management shift from strict supply-side provider to integrated operations regarding demand-side management has driven the need for the efficient collection and evaluation of high-resolution water data. The smart meters using AMR technology in this study have been shown to adequately collect, record, and disseminate water use data at an hourly time step, which provides sufficient resolution to capture diurnal water use trends for unique building locations for a fair time duration that may capture seasonal trends. The resultant diurnal water use curves were exclusive to each building, and hourly-average curves contained expected features that aligned with diurnal curves from literature (e.g., two-peak residential curve and plateauing commercial curve). Separating diurnal water use curves by day and month showed how water use for each building site varied over time. Throughout the year the multi-residential building had the least variation while the multi-use functions of the community center resulted in the most variation among values. Seasonal water use was clearly evident at the elementary school, where water use fell during summer months when school is not in session for students.

Smart meters allow water utilities to capture diurnal water patterns at varying spatial scales that may be used to improve the planning and operation of water supply networks [11,12]. Daily diurnal water use patterns map the temporal demand for water by unique users or clusters of users, and supplying that demand requires an energy input to treat and transport the water volume. The identification of unique diurnal patterns allows utilities to identify areas with high water use and the time of peak use with associated high energy costs. Diurnal patterns catalogued in this study show that peak flows are not the same for all water users, and therefore different water management strategies will have different effects on building water use patterns. Alternative water strategies, such as rainwater capture and greywater reuse, have been shown to reduce average daily and peak water demand via potable water offsets, and thereby alleviate stress on existing water supply networks and offset expansion needs resulting in energy and financial savings [6,11,13]. In addition, characteristics of urban areas, such as density, land use, and imperviousness, have been found to affect spatial water demands [14,15]. As a result, land use planning should be utilized as an additional tool for water management with information on location-specific water use patterns as a necessary component for an integrated decision-making process that considers the relationships among urban development, energy consumption, and water use [3].

## ACKNOWLEDGEMENTS

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## Low flow water fittings: Measurements, opinion and policy

Josephine J Prior\*, Mindy Hadi

BRE, Bucknalls Lane, Watford, WD25 9XX

### ABSTRACT

**Aims:** The response to increases in water demand is driving a move to low water use fittings including taps. However few measurements of real water use have been made. The aim of the study was to ascertain the acceptability to users of a variety of tap flow rates and presentation methods for carrying out different tasks.

**Study design and methodology:** The study was in three parts:

- an experiment using a specially designed, low flow water fittings test rig. Participants carried out three tasks, hand washing, filling a beaker and filling a kettle using a randomised series of flow rates, low, medium and high.
- a focus group study
- a literature review

**Place and Duration of Study:** BRE, Watford, UK. June to October 2009.

**Results:** 339 people took part in the experiment. All were of working age, between 21 and 65. The results showed that the acceptability of flow rates was task dependent with 86% of participants finding the lowest flow rates (1.5 litres/min) unacceptable and 85% finding the high rate of 4.2 litres/min) acceptable for filling a kettle whilst for 64% and 67% found the low flow rate acceptable for filling a beaker and hand washing respectively.

**Conclusion:** Taps are used for many activities, including drinking, cooking, bathing, laundering clothes and cleaning, that it is difficult to define a single acceptable performance level. Although low flow rates are seen as a nuisance for tasks requiring a large volume of water, such as filling a kettle, saucepan, bucket or bath due to the extra time required, there is a drive towards lowering flow rates of water use fittings. If these are seen as delivering poor performance, consumers will change them for those with higher flow rates.

**Keywords:** water efficiency, taps, consumers, low flow fittings, water use

### 1. INTRODUCTION

Concern about water supply and quality has gripped Europe for the last 40 years. 60% of the water supplied in England and Wales is used for domestic purposes, amounting to an estimated 9.2 billion litres per day across all buildings [1].

Many thousands of pounds have been invested researching water use, but without measuring it. Many opinion surveys question whether or not people think water efficiency is important and how they choose water fittings. Many existing predictions of future water use are based on extrapolation from a small database of real measurements, and computer modelling.

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\*Tel.: +44 (0) 1923 66 4468

E-mail address: priorj@bre.co.uk

Original data from the Anglian Golden 100, which underpins many of the predictions, are not available for independent study.

Population growth and competing uses (domestic, agricultural and industrial) have put water resources under increasing strain [2]. Between 1976 and 2006 the areas and number of people affected by droughts increased by nearly 20%. The droughts of 2003 affected a third of European Union land and 100 million people [3]. European and UK policy, legislation and regulation have evolved steadily over the last 40 years in response to steady increases in demand. Since 1973 almost all United Kingdom environmental legislation has been driven by or developed closely with the European Community (EC) or international bodies [4].

In 2010 the UK Government introduced for the first time in Building Regulations a 125 litre per person per day limit on the design water consumption for new domestic buildings [5]. In October 2015 amendments will be made to the water use efficiency requirements set out in Part G (Sanitation, hot water safety and water efficiency) of the Building Regulations [6]. In particular, an optional requirement of 110 litres/person/day will be introduced where this is required by planning permission, with an alternative fittings-based approach to demonstrating compliance. The amendment also includes the water-efficiency calculation methodology for new dwellings, approved by the Secretary of State.

A literature review [7] revealed both a drive to develop low flow taps to meet Code for Sustainable Homes standards and a gap in knowledge concerning their acceptability to users. It also appeared that very few measurements of real water use have been made. The work in this study therefore comprised a mixture of measurement and opinion gathering. It concentrated on low flow taps because so little is known about how people use taps, how much water they use, and what is important to consumers in tap performance [8]. An opportunity arose in June 2009 to conduct an experiment with members of the public at the BRE Insite09 exhibition. A low flow water fittings test rig was designed and built to test opinion on using low flow rates for simple everyday tasks. A focus group of local people canvassed opinion on low flow taps, using the low flow water fittings test rig [7]. In 2012 the BRE Trust funded further experimental work to test the effectiveness of tap flow regulation valves in office toilets [9]. The experiments were accompanied by a behavioural change campaign.

## **2. MEASUREMENTS WITH THE BRE LOW FLOW WATER FITTINGS TEST RIG, FOCUS GROUP OPINION AND BUILDING REGULATIONS POLICY**

### **2.1 Experiment with the BRE low flow water fittings test rig**

The experiment aimed to test, record and analyse consumer reactions to using low flow rates when performing three water-related tasks that most of us do several times per day. The experiment was conducted at the BRE exhibition Insite09 in June 2009. The test rig was mounted outdoors in a thoroughfare and participants were recruited as they passed. A total of 339 people took part. All were of working age, between ages 21 and 65. The authors acknowledge that participants were self-selecting professionals with an interest in buildings and sustainability.

The low flow water fittings test rig was simple, robust and portable. It only required access to mains water and drainage. No electricity supply was needed. Unheated water was produced from one of three outlets, with a plain, spray or aerated flow. The outlets were hidden from view. The water flow rate was controlled by the experimenter from behind the rig. The test rig was calibrated before and after the experiment. Figure 1 shows a schematic diagram of the test rig.

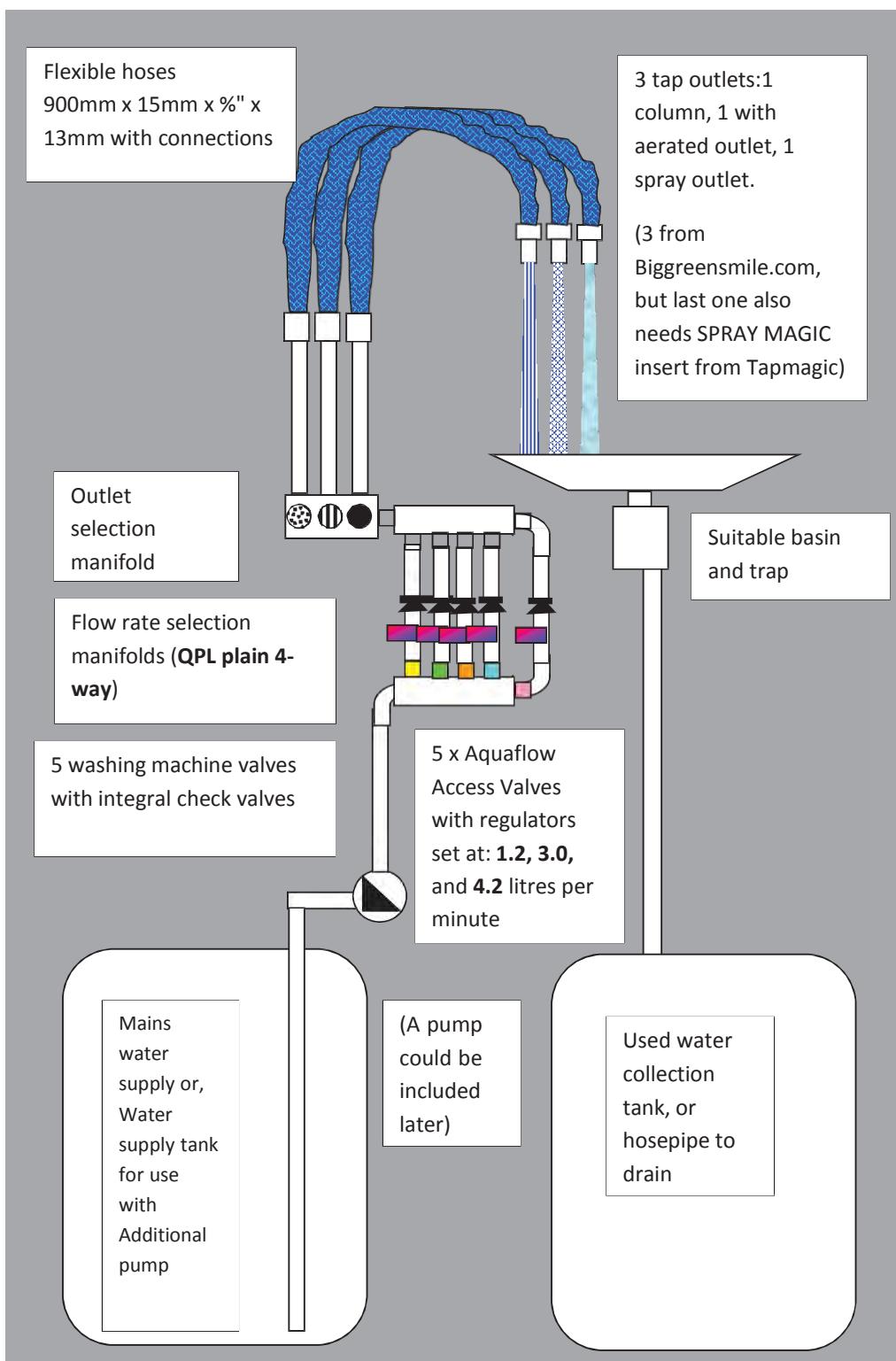


Figure 1. Schematic design of the BRE low flow water fittings test rig

The flow rates were chosen to reflect the extremely low water flow rates being encouraged at the time to meet the highest standards under the Code for Sustainable Homes [10]. After

the research (but independently from this) the new calculation method was introduced [11].

The experiment was statistically designed using a Latin square arrangement to maximise both the control of variables and confidence in the analysis of results. Under the supervision of an experimenter, the participants performed one task at each flow rate and using one of three water presentations (plain, spray or aerated). They were asked to judge the water flow rate as *acceptable* or *unacceptable*.

The tasks were to wash their hands with liquid soap, fill a 300 ml beaker, or fill a 1.7 litre kettle. The flow rates were low (1.5 litres/min), medium (3 litres/min) and high (4.2 litres/min). The water was unheated. Each participant carried out three tasks and at each flow rate. The order of flow rate was randomised (e.g. high-low-medium, or low-medium-high). Within each flow rate, the flow presentation was randomised (plain, spray, aerated). Some participants had all three flow presentations, some had two and others only one. The order of tasks (beaker filling, kettle filling, handwashing) was randomised between participants. An experimental worksheet was used by the experimenter to record results and anecdotal comments.

## **2.2 Opinion from the focus group**

Several large-scale public opinion surveys have been carried out examining public attitudes to water economy and water efficient appliances. These have been discussed in detail elsewhere [7]. A focus group with members of the public was carried out at BRE to test opinions on the acceptability of low flow taps and specifically on the lower flow rates being recommended to reduce water consumption in domestic buildings. The focus group also assessed the reactions of individuals carrying out four tasks at a low flow rate (1.5 litres/min) on the BRE test rig. Nine participants took part. Ages ranged from 21 to 70; there were four females and five males; four participants had a water meter and five did not.

A pre-set script was followed, which covered:

- attitudes to water saving
- experiences of standard and low flow taps
- factors governing tap choice
- flow rates
- acceptability of low flow taps.

During the workshop, participants were invited to use the low flow water fittings test rig to experience a low flow. The test rig was calibrated in advance, to a rate of 1.5 litres/min (plain flow), reflecting the situation being encouraged in new homes through the earlier Code for Sustainable Homes water calculator [11].

Participants were invited to do one of four tasks (washing hands, filling a cup, filling a kettle and filling a large bowl) while the others watched. Their comments and reactions were recorded. Participants were very interested in the areas discussed and all agreed that the workshop made them aware of issues that they had never considered before. It complemented the results of the Insite09 experiment by providing detailed consumer opinions on the performance of low flow taps. The qualitative experience of carrying out the four tasks using the test rig was an important part of the workshop.

The focus group showed that asking about flow rates of 6, 4 or 1 litre/min means nothing to a lay person unless they have experienced the flow rates first hand in the context of an everyday task.

Most participants were aware of recent publicity about the need to save water, and some had changed their behaviour in response to this, e.g.:

- not leaving the tap running when brushing teeth
- having a shower rather than a bath
- children sharing baths
- using washing-up water on the garden
- not flushing the WC each time they used it.

Participants described having a variety of taps at home. People preferred lever taps, particularly in the kitchen, because they were modern and were also easier to turn on and off. Participants also preferred mixer taps to two separate taps, particularly mixers with a single control. Most of the group tended to wash their hands without putting the plug in the basin, even where there was no mixer tap. Of those who did plug the basin, one began when a water meter was fitted, as they found it used less water; and another filled the basin to reduce the risk of scalding her child.

Several people reported problems with the water flow rates from their taps at home. They found this 'very irritating'. One person had had a pump fitted to their water system to increase flow rates. They felt that it might not be very water efficient, but it had improved the flow and pressure to all the taps in the house.

The group was invited to try out the low water use test rig. The 1.5 litres/min rate with a plain flow was chosen as one that was being used in new homes in 2009. Each person was randomly assigned one of four different tasks: handwashing, or filling a cup, kettle or bowl. They were asked to talk about their thoughts as they carried out the task, with the rest of the group watching. Each task was carried out at least twice. The participants were very interested in this experiment and the observers all gave their own comments while watching the task. The results are applicable for two types of tap - basin taps and kitchen taps - and are summarised in Table 1.

**Table 1. Reactions to carrying out tasks at water flow rate of 1.5 litres/minute**

Task	Reaction
Handwashing	The 1.5 litres/minute flow rate was barely acceptable.
Filling a cup	Participants would have increased the rate if they could.
Filling a kettle	People found 1.5 litres/minute flow rate much too slow for filling a kettle.
Filling a bowl	The 1.5 litres/minute flow rate was far too slow for filling a large bowl. It prompted a strong reaction from participants.

In a separate study [9] the effectiveness of installing flow regulator valves in the wash hand basins of an office building at BRE was tested and compared with a behavioural change campaign aimed at reducing water consumption. The behavioural campaign had a greater short term impact than the flow rate reduction valves.

### **2.3 3 Development of Building Regulations Policy**

An excellent account of the historical approach to managing water supplies in England and Wales from 1843 can be found in Chapter 2 of the report of the House of Lords select committee on water use [4].

Growth in water demand has threatened to become unsustainable in recent years. Between 1976 and 2006 the number of areas and people in England affected by droughts rose by nearly 20%. Droughts in 2003 affected a third of EU land and 100 million people [3]. Average English household demand increased by about 55% over the past quarter of a century and has been rising at 1% per year [12]. More recent forecasting predicts stability or small increases in water demand over the next 10-20 years. In 2007-2008, average household water use over England and Wales was 148 litres/person/day. In homes where the supply is unmetered, people used slightly more, at 153 litres/ person/day. In metered properties, people used, on average, 13% less than in unmetered homes.

Since 1973 almost all UK environmental legislation has been driven by or developed closely with the EC or other international bodies [4]. Under the Treaty of Nice, EC Directives focus predominantly on water quality, although it can be essential to address water quantity in order to meet the required quality standards. The EC has been actively concerned for many years about risks to freshwater supplies and the need to protect them. Its formal activity began with the 1980 Council Directive on *the protection of groundwater against pollution by certain dangerous substances* [13], which was enacted on 17 December 1979. There have been numerous water-related Directives that have had a profound influence on water policy in the UK, culminating in the Water Framework Directive [14]. This is the most substantial piece of EC water legislation to date. Its purpose is to improve and integrate the way that water bodies are managed throughout Europe. One of its principal aims is to promote the sustainable use of water.

Defra is responsible for water fittings policy in England and the National Assembly for Wales is responsible in Wales. On 1 July 1999 the Water Supply (Water Fittings) Regulations 1999 (Statutory Instrument No. 1148) [15] replaced the Water Byelaws in England and Wales for the prevention of waste, misuse, undue consumption, contamination and erroneous measurement of a water supplier's mains water supply. A copy of both the Regulations and the Water Supply (Water Fittings) Amendment Regulations 1999 (Statutory Instrument No. 1506) [16] can be obtained from the National Archives website at [www.legislation.gov.uk](http://www.legislation.gov.uk).

Defra published its water strategy for England in February 2008 [17]. The strategy looks ahead to 2030 and sets out practical steps to ensure the continued availability of clean water for people, business and nature. It covers every aspect of water use, from the challenges of sewage treatment to the design of buildings. The vision for 2030 includes:

- sustainable balance between demand and supply across England including:
  - high water efficiency in new homes
  - more water-efficient technology and products in existing buildings
- no seriously water-stressed areas
- cost-effective reduction of water leakage to agreed targets
- water companies protecting customer supplies and the environment
- cost-effective water use reduction to a maximum average of 130 litres/person/day
- using water well, appreciating value and the consequences of wasting it.

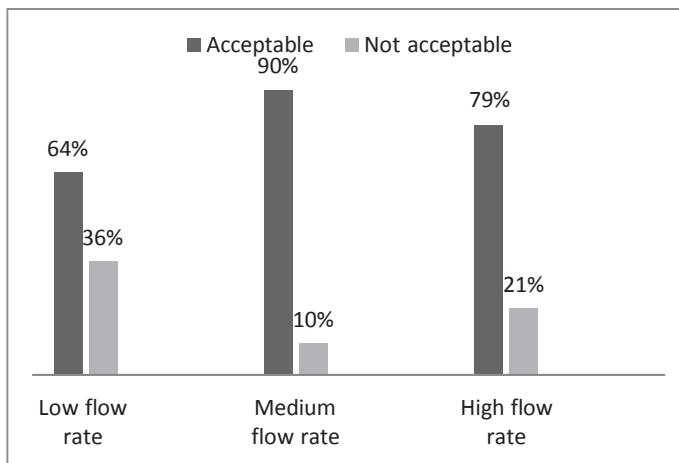
In December 2006 DCLG and Defra issued a joint consultation document setting out proposals to regulate water efficiency standards in new buildings [18]. The results (DCLG and Defra, 2007) showed strong support for a regulatory approach for domestic buildings, combining a performance standard (whole building) with standards for key water fittings.

In 2010 the UK Government introduced for the first time in Building Regulations a 125 litre per person per day limit on the design water consumption for new domestic buildings [5]. In October 2015 amendments [6] will be made to the water use efficiency requirements set out in Part G (Sanitation, hot water safety and water efficiency) of the Building Regulations. In particular, an optional requirement of 110 litres/person/day will be introduced where this is required by planning permission, with an alternative fittings-based approach to demonstrating compliance. The amendment also includes the water-efficiency calculation methodology for new dwellings, approved by the Secretary of State.

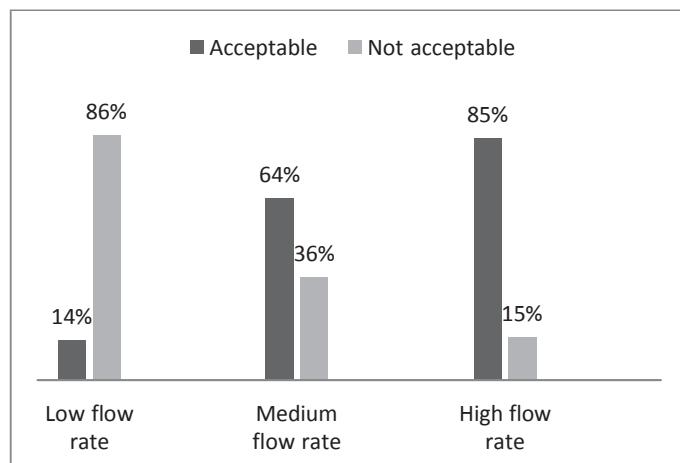
### **3. RESULTS AND DISCUSSION**

#### **3.1 1 Results**

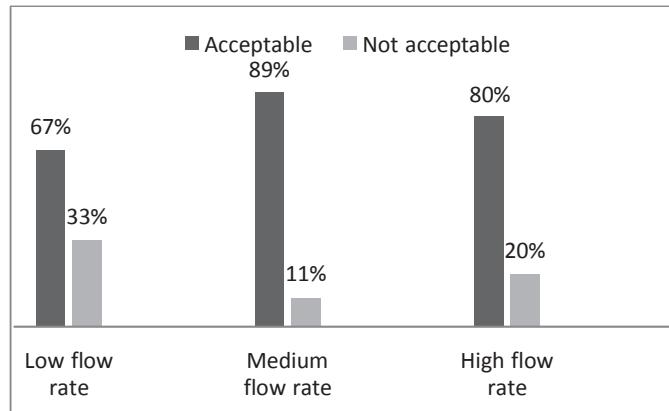
The raw results from the Low water fittings test rig experiment were analysed for each task (beaker filling, kettle filling and handwashing.). This analysis and the results are shown in Table 2, illustrated in figures E1 to E3. Further analysis of the effects of flow presentation, age and gender of participants is beyond the scope of this paper, but reported in detail elsewhere [7].



**Figure E1 Filling a beaker - Test for acceptable flow rate**



**Figure E2 Filling a kettle - Test for acceptable flow rate**



**Figure E3 Handwashing - Test for acceptable flow rate**

Task	High 4.2 litres/min Acceptable response		Medium 3.0 litres/min Acceptable response		Low 1.2 litres/min Acceptable response	
	Fraction	Percentage %	Fraction	Percentage %	Fraction	Percentage %
Beaker filling	64/81	79	73/81	90	52/81	64
Kettle filling	69/81	85	52/81	64	11/81	14
Handwashing	65/81	80	72/81	89	54/81	67

**Table 2 The effect of flow rate on acceptable response**

### 3.2 2 Discussion

The factors that affect the acceptability of low flow rates can be summarised as:

- the time it takes to do tasks
- whether or not the flow rate is sufficient for a given task
- whether there is splashing or mess as a result of water use
- the compatibility of low flow fittings with local water pressure
- the gender of the user.

From the comments made during the test rig experiment, and later in the focus group when the test rig was used, it was clear that the main objection to very low flow rates (1.2-1.5 litres/min) was the long time required (and the consequent inconvenience) for tasks using a substantial volume of water, such as filling a kettle or a washing-up bowl. Members of the focus group were shocked that anyone might think a flow rate as low as 1.5 litres/min could be acceptable for general use.

The amount of water people use through their taps depends on the frequency of use, flow rate and duration of flow. Activities requiring a large delivered volume of water take an unacceptably long time if the flow rate is too low. Tasks requiring the scouring action of water, for rinsing or cleaning, are unacceptable if the water flow rate is too low. The experiment with the low flow water fittings test rig and the focus group showed that for some tasks a low flow rate was more acceptable than a higher one because of splashing at the higher rate. Later work in the BRE office showed the same. Where only a small amount of water is required for a short time, such as with handwashing, reducing flow rates with limiters has no effect on reducing the amount of water used. There are implications for providing small-volume basins and low flow taps in certain areas, such as wash basins in downstairs toilets. This is being reflected in the 2015 revision of Part G of the Building Regulations (October 2015) [6] in which water fittings are being specifically considered for the first time.

## 4. CONCLUSION

Given the importance of domestic water use, understanding of its details in the UK is surprisingly poor. Very few actual measurements of water use are made at all. Most estimates are made using computer models, or via questionnaire surveys of local people. A comprehensive review has been published [7] of 18 studies made by the water companies. None of the original data are published in detail.

The only way to be confident about water use is to carry out real experiments. The focus group showed that opinions of water flow rates are meaningless outside the context of everyday tasks. People have almost no appreciation of water flow rates expressed in litres per minute; only by doing familiar tasks at prescribed flow rates can honest and accurate responses be achieved. Asking people for opinions without direct experience is useless.

60% of all the water supplied in England and Wales is used for domestic purposes. This is about 9.2 billion litres/day (MTP, 2008a) [1] across all buildings. Taps account for 34% of all

the domestic water supplied in England and Wales (21% for basin taps and 13% for kitchen taps). The work in this study has concentrated on low flow taps because so little is known about how people use taps, how much water they use or what is important in tap performance. The main objections to very low flow rates (1.2-1.5 litres/min) are the long time required (and consequent inconvenience) for tasks using a substantial volume of water, such as filling a kettle or a washing up bowl. It is interesting that a recent report by the NHBC Foundation [20] reports user dissatisfaction with low flow technologies but rather than advising that these systems are designed to meet the needs of the user, the suggestion is for user education to 'develop realistic expectations' ie to expect the user to adapt to the technology and accept less than adequate performance rather than delivering a win/win solution that satisfies the user and saves water at the same time. The actual flow rates and amounts of water people use in everyday life need to be better understood, including variation from task to task and the limits on performance that people are prepared to accept. The importance of this type of research can hardly be overestimated.

## ACKNOWLEDGEMENTS

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# Examination of Domestic Cold Water Systems

Richard. K. Beattie (1)\* and Damien Kane (2)

(1) Mechanical Engineer, AECOM Edinburgh, UK

(2) Principal Engineer, AECOM Edinburgh, UK

## ABSTRACT

The design of domestic cold water systems is inherently based upon the fixture unit or demand unit method. Therefore, it is fundamentally necessary to understand these water demand units and how to interpret them in order to design efficient water systems that enable a balance between capital cost (where oversizing leads to elevated capital cost) and engineering good practice. Recent sustainability initiatives aimed at reducing water usage encourage the uptake of devices such as flow limiters, spray and percussion taps and low flow appliances and have driven peak water demands down in buildings. Maintaining water movement within the cold water system prevents overheating and helps to maintain a healthy hygienic system. Stagnation exacerbates overheating and may contribute to contamination by micro-organisms. To promote movement of cold water within pipework systems there has been a recent move towards adopting strategies that were not traditionally incorporated into cold water pipework design such as, a secondary cold water return circuit and end of line solenoid flush (dump) valves. These are an added expense, contribute to wasted water or energy and should therefore be carefully considered when incorporating into domestic cold water systems taking cognisance of the other contributory factors such as the building water usage and turnover, building air tightness standards and sanitary ware specification. Also water conservation in buildings is another reason to have an appropriately sized system for the potential water consumption as older appliances had larger flow rates than present; this subsequently has a knock-on-effect on the buildings drainage pipework, for example WCs.

This paper presents an examination into the importance of sizing a cold water distribution system appropriately and the effect of modern building design standards on operational performance. Finally, through the experience of multiple engineers from many consultancies over several years a summary of cold water services issues caused in modern buildings is presented and potential strategies to mitigate against excessive temperatures and promote water movement and turnover is given.

*Keywords:* Frequency, water hygiene, stagnation.

\* Tel.: 0131 451 8600 , E-mail Richard.Beattie@aecom.com

## 1. INTRODUCTION

It would be reasonable to assume that the '*out of sight out of mind*' adage often applies to building services systems which may potentially lack the appropriate design and maintenance attention they deserve until an apparent defect or issue with system performance transpires. In most buildings, domestic water services represent a small percentage of the total construction cost, however their design and installation should not be underestimated given the potential cost and disruption from future remedial works and retrofit measures required in the event of the system failing to provide a hygienic potable water source.

This paper will look at issues with domestic cold water systems (DCWS) in recent years through the experience of several building services engineers. There has been a growing trend in rising cold water temperatures in systems and a number of examples where temperatures greater than 20°C have been recorded which exceed Health and Safety Executive requirements. Generally, the Health and Safety Executive's L8 document [1] is seen as the authoritative document within the construction industry, setting a maximum permissible temperature of 20°C within domestic cold water systems. In a number of instances it has proven difficult to achieve temperatures of less than 20°C due to the temperature of the incoming mains water supply and the associated heat pick-up from the site boundary to the points of connection within the building.

This paper starts by summarising the current design methodologies and codes of practice, followed by a review of the relevant standards and regulatory requirements with respect to cold water temperatures and the contributing circumstances and risk factors that would enable bacteria to proliferate within the domestic cold water system. Finally, causes of elevated temperatures are acknowledged and potential mitigation measures presented.

## 2. DESIGN METHODOLOGY

The design of domestic cold water systems should always be in accordance with local Water Bylaws guidance, current design guides and industry good practice. However it is acknowledged that sometimes the quality of the potable water has degraded due to one or many external influences. Tracing the domestic cold water systems pipe routes can help highlight the potential parameters that could affect water quality. The potable water supply will originate from the local water authorities 'town' main. The point of connection of a buildings potable water supply is normally at the water authority meter located at the site boundary, where it will then be routed to the potable water storage tanks or supplied directly to mains water outlets within the building. From the cold water storage tank, the cold water feed normally serves a cold water booster set which distributes 'boosted' cold water around the building to the various cold water outlets and cold water feeds to hot water generation plant. Additionally, direct mains water may be distributed throughout a building to appliances or outlets deemed to be 'potable' such as drinking fountains; this is deemed as industry good practice and often a requirement to satisfy sustainability assessment methods such as BREEAM.

In the UK the Institute of Plumbing (IoP) - Plumbing Engineering Services Design Guide [2], British Standard 6700 [3] or BS EN 806 [4] are the recognised methods for designing and sizing domestic cold water systems. The industry practice of using loading units to size pipework is based on the 1940s methodology created by Hunter of the USA. These loading units are based upon; probability theory, time between uses of an appliance, duration of use and flow rates when in use. Dr Hunter knew most appliances are intermittently used, from this he theorized the loading of a single appliance didn't just depend on the rate of flow to the appliance but also the frequency of use and duration of use [5]. Konen [6] reviewed part of the Hunter method based on the probability theory and also established that the frequency of use is the most critical parameter for water turnover rather than flow rate. However at present, with the use of water conservation measures, the flow rate may now become just as important, if not more than, the frequency of use if we are to size pipes appropriately to the lower volumes of water now being used.

From a building services industry perspective it is important to highlight that many of the design guides for domestic pipe sizing have not been updated to reflect current domestic water services approaches particularly with regards to water conservation measures and building design standards and strategies. This has been investigated by Tindall *et al* [7] where the study undertaken compared three typically used design guides and found that one more than doubled the over sizing of pipework when compared to the actual recorded site data in relation to water consumption and frequency of use. They also highlighted BS EN 806-3 as the more accurate standard in predicting DCWS flow rates.

In academia, Goncalves *et al* [8] presented a paper that summarised the mathematical models of the design of water systems within buildings. This included a review of Webster 1972 (a generalized binomial distribution function), Courtney (1976) a probabilistic model to determine flow rate but also the use of different types of appliances. Konen (1980) and Holmberg (1981) a dimensioning formula. Nowhere within his study did Goncalves highlight microbial contamination as an issue or if design consumptions changed would the models verify. However if design demands change then consideration should be given to reviewing pipe sizes. As such, if pipe sizing does not consider potential consumption and turnover within a building, the potential of water stagnation increases and associated issues of elevated temperatures in services distribution voids may contribute to cold water overheating and bacterial growth within the cold water system.

### 3. WATER QUALITY STANDARDS AND REGULATIONS

To give some context to the health issues regarding water quality there are several standards and regulations that are applicable to cold water supply temperature within the UK, these are:

- UK Health and Safety Executives L8: 2013, Approved Code of Practice and Guidance, '*The control of Legionella Bacteria in Water Systems*' [1].  
This requires that temperatures between 20°C and 45°C are to be avoided.
- UK Water Regulations (WRAS) [9].  
This requires temperatures to be kept below 25°C.
- BS 8580:2010 '*Water Quality – Risk Assessments for Legionella Control*'[10].  
This requires the temperature of a cold water outlet to be below 20°C after the outlet has been opened for 120 seconds.
- CIBSE TM13:2013, '*Minimising the Risk of Legionnaire's disease*'[11].  
This requires the temperature of a cold water outlet to be below 20°C after the outlet has been opened for 120 seconds.

For bacteria such as Legionella to proliferate within cold water systems several factors need to be present; these include a suitable temperature and a source of nutrients, e.g. sludge, scale algae and other organic matter. The Chartered Institute of Building Services Engineers Technical Memorandum TM13 '*The Control of Legionella*' [11] identifies the following as temperatures for Legionella growth:

- Dormant; 0°C to 20°C;
- Will multiply; 20°C to 45°C;
- Will not multiply and will die in time; 50°C to 70°C;
- Not active; 70°C to 100°C.

The ideal temperature, based on empirical data suggests that the ideal microbial growth and proliferation is 36°C. Typical appliances such as, WHBs, sinks, WCs, drinking fountains, bib taps and urinals are not typically associated with aerosol sprays which is the understood transfer route for Legionella bacteria through inhalation. Also, certain groups of people are

known to be more susceptible, for example; men are more open to contract the disease than women, over 45 year olds, smokers, alcoholics, diabetics, immune compromised and those with cancer or respiratory or kidney disease. Therefore the obvious building where infection would prove catastrophic and potentially fatal is a hospital. The Department of Health have the Technical Memorandum HTM 04-01 [12] for their own facilities to ensure a hygienic water source to the patients, it states there should be no greater than a 2°C rise between the storage tank and the appliance within 2 minutes. BS 8580:2010 provides detailed guidance on how to conduct a Legionella risk assessment; the risk assessor should however have an in depth understanding of water systems.

#### **4. POTENTIAL CAUSES OF COLD WATER OVERHEATING**

There are several potential factors within new-build constructions that may contribute to overheating of DCWS. The main factors generally relate to the modern day drive to conserve energy, these factors include:

##### **4.1 FROM THE MAINS WATER SUPPLY NETWORK**

- Mains water authorities should have a requirement to provide water at less than 20°C;
- A rural location of a building on a radial service, due to the distribution routes from the reservoir/pumping station and potential low rates of water draw-offs water temperatures can increase;
- In a new-build there is a standard burial depth for the incoming water mains however sometimes in older buildings incoming mains water pipeline from the site boundary to the cold water tank room can be at a shallower burial depth, as such during a warm day the incoming water could receive heat pick-up;
- Water storage tanks located above ground or in semi-buried configurations.

##### **4 .2 FROM WATER CONSERVATION MEASURES**

- The introduction of rainwater/grey water/black water recycling provided for water conservation;
- The use of percussion taps and low-flow fittings;
- A lack of regular flushing of the system as a management procedure.

##### **4.3 FROM HIGHER VOID TEMPERATURES**

With the drive to reduce energy costs, changes in the building standards and client aspirations to reduce carbon emissions, buildings have become very well insulated and constructed to a higher level of air tightness compared to older buildings. This can result in higher services distribution-void temperatures. In a non-ventilated void, in a well sealed building, temperatures could easily elevate to 30°C and above. Although the change to reduce carbon emissions by reducing water consumption and insulating buildings is seen to be good for the environment, there is evidence to suggest they can have a negative effect on the quality of building potable water supplies. The result is that buildings cannot guarantee to keep cold water temperatures below 20°C during spells of low or no use unless sufficient design mitigation measures are implemented.

##### **4.4 FROM DESIGN AND MANAGEMENT**

There are design and management/operational factors that also contribute to potential elevation of DCWS temperatures:

- A lack of temperature monitoring within the cold water tank, incoming mains and at the extremities of cold water pipe distribution;
- The possibility of over sizing the cold water storage tank;
- Reduced periods of occupancy and demand such as at weekends and holidays. Seasonal variations in the occupancy of the building can result in longer standing times of water within the cold water storage tanks;
- Heat generating plant and equipment within ceiling voids such as recessed light fittings, current carrying cables, radiant panels and heating pipework. Although heating pipework and plant may be insulated, over time this will emit heat to the void space if adequate ventilation is not provided;
- The DCWS pipelines should be kept a minimum distance from any hot water and LTHW heating pipelines within void spaces, however spatial restrictions for building services often result in DCWS pipes running in parallel heating pipelines;
- If the plant room where the cold water storage tanks are located and unventilated there may be the potential for cold water storage temperatures to increase when there are periods of low usage;
- A lack of quality control of legislation particularly with regards to thermal insulation of plant and equipment may contribute to elevating plant and void space temperatures if sections remain un-insulated;
- Insufficient separation between the heat generating plant and equipment e.g. boilers, hot water storage cylinders and the cold water storage tank room and a lack of appropriate ventilation within the plantroom housing heat generating plant and equipment;
- If the occupancy levels within the building after handover is less than envisaged at design stage a lack of domestic water draw-off due to unoccupied spaces and infrequently used outlets may cause elevated temperatures;
- The end user not implementing risk assessments and procedures to control the risk of Legionella.

It is possible that the above factors may, in some part, contribute to elevating water temperatures in any domestic water installation.

## **5. MITIGATION MEASURES**

The previous section discussed several factors that may contribute to an elevated domestic cold water services temperature. The following highlights the potential mitigation measures that could be considered and adopted where appropriate and also areas where further investigation would be recommended:

- Ensure pipe sizing is carried out as close as possible to the expected demand to ensure good flow, to minimize stagnation and potential heat gain;
- Implement an appropriate management strategy which includes manual flushing of mains and cold water pipework to all remote outlets on a daily routine and identifies infrequently used outlets that should be included within a regular flushing regime;
- Conduct a detailed testing and commissioning of DCWS and LTHW systems to monitor domestic cold water temperatures and ensure heating system set points and time schedules are set appropriately;

- External MWS pipework between the site boundary and plant room should be at a depth of 750mm in accordance with industry standards. Also avoid if possible running under asphalt surfaces or surfaces with a low albedo, this would minimise heat gains to below ground pipework;
- Isolate and drain down one cold water storage tank section if it is a sectional tank as in hospitals. This will improve water turnover-to-demand;
- The addition of chlorine dioxide tablets to the domestic water services systems. This is an eco-friendly micro biocide. This solution will assist in eliminating Legionella within systems but will not address the issue of water temperature. However, it is recognised water temperature is directly related to the ability of microbial bacteria to exist within water supplies, therefore by eliminating the bacteria increased water temperatures may be acceptable;
- Improve quality control on site with regards to thermal insulation of pipes, valves, flexible pipe connections and LTHW radiant panels;
- Increase the thickness of insulation on the cold water system pipework. Whilst this may eliminate overheating of pipework it will also help to further delay the temperature pick-up over time;
- Provide a delayed action adjustable height ball valve within water storage tanks to allow stored volumes to be adjustable;
- Ensure appropriate controls and sensors are provided for monitoring domestic cold water consumption and cold water temperatures throughout the system;
- Consider reducing cold water storage levels within buildings appropriate to the building type and anticipate demand (reduce from 24hr to 12hr storage);
- Incorporate a 'soft landings' approach to help building users and operators adjust to their new facility and help them understand the building and associated systems design intent and operation;
- Include for seasonal commissioning within the contract to allow the systems to be adapted to seasonal variations and changes in user need;
- Enhance void ventilation movement by introducing high and low level grilles to induce airflow through the ceiling voids. This may be achieved by installing natural or automatic ventilators to reduce heat build-up and resulting temperature elevations to cold water pipework, particularly during periods of low water use. However this would not mitigate the issue if high incoming mains water temperatures and storage tank temperatures were being achieved, an analysis study may also be undertaken into whether void vents may increase temperatures within corridors or adjoining spaces;
- Introduce a cold water return circuit combined with automatic balancing valves to maintain water movement within the system;
- Install automatic dump valves at the system extremities/sentinel points. These operate by temperature controlled solenoid valves which will remain open until acceptable temperatures are detected. This will result in water being wasted, however the dump valves will assist in water movement and subsequently cold water temperatures;
- Install a refrigeration system with pumps and a plate heat exchanger to chill water within the cold water storage tanks to ensure that the water is stored at an appropriate temperature or connect to a building chilled water circuit if one is available. This solution would deal with the issue if there is high incoming water

temperature. This would require additional energy consumption and costs to the building. Remote outlets may still be flushed regularly as heat gains could still occur to cold water pipework in ceiling voids, as such a secondary cold water return loop could also be added;

- Encourage clients to include for post occupancy evaluation to learn how the systems and building are performing including encouraging the logging of live data which can be shared with the industry to help inform trends and future updates to standards and guidance;
- Industry review of current standards in relation to the design and sizing of cold water systems, drawing on the experience of industry professionals and available live data across a wide range of building types and sectors;
- Encourage an environment that would promote the sharing of data logged and lessons learned.

## 6. SUMMARY

This paper has reviewed potential causes of domestic cold water elevated temperatures, potential system mitigation measures to maintain water temperatures below 20°C and recommendations for future investigation. The paper has outlined the history of the existing design methodology and presented the supporting guidance and legislation associated to maintain a hygienic cold water supply, potential causes of water degradation and proposed mitigation measures.

Additionally, in order to allow the client to make informed decisions on appropriate management strategies for the building water supplies the FM team need to be provided with sufficient training and background information relating to the running and operation of the DCWS systems. Also, the client should be made aware of potential benefits of seasonal commissioning and soft landings.

Also, promoting a culture of collaboration and knowledge sharing with the ultimate goal of benefiting both the building services industry and our clients should be an objective for all. As such, harmonizing industry experience and academic research should be enforced if we are to achieve this objective.

## COMPETING INTERESTS

The issues raised in this paper have accumulated through several resources and in no way reflect any one specific project or AECOM design. The issues and mitigation measures have been compiled through the experience of multiple engineers from many consultancies over several years.

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# An Investigation into Domestic Water Consumption and Water Use Habits in Indian Urban Areas

Seyed MK Sadr<sup>1\*</sup>, Fayyaz Ali Memon<sup>1</sup>, Andrew P Duncan<sup>1</sup>, Arpit Jain<sup>2</sup>,  
Shilpa Gulati<sup>2</sup>, Wa'el Hussein<sup>1</sup>, Dragan A Savic<sup>1</sup>, David Butler<sup>1</sup>

1: Centre for Water Systems, University of Exeter, Exeter, EX4 4QF, UK

2: Department of Civil Engineering, Malaviya National Institute of Technology, Jaipur,  
Rajasthan 302017, India

## ABSTRACT

**Aim:** To explore the relation between water consumption and water use behaviour and attitudes, and devices applied in households in urban areas in India.

**Methodology and study site:** This paper presents the results of a domestic water consumption survey carried out in Jaipur, India. A questionnaire containing over 60 questions was developed to collect information on households' characteristics (e.g. family size, household type, and number of children), indoor and outdoor water use activities and their respective frequencies and durations. Information was also gathered on the volume of water used in each of these activities. Over 90 households of different types (standalone houses and apartments in a university campus and Jaipur city) participated in the survey. The survey results were analysed using cluster analysis.

**Results:** The results show that the per capita consumption varies considerably with household type and size. The average water consumption was 183 and 215 litres/person/day for standalone households and apartments, respectively. Water used in bathing and WC's represent the highest proportion of water consumption in both stand-alone houses and apartments. Over 40% of the households reported no use of showers. The per capita water consumption is inversely related to family size especially in stand-alone houses.

**Conclusion:** The information pertaining to water use habits and the qualitative and quantitative analysis can be used as an input to a proposed domestic water efficiency tool (DoWET) which can generate optimal water efficient composite strategies keeping in view a range of sustainability indicators including water saving potential, cost and associated energy consumption of the water saving devices and fixtures available in India.

**Keywords:** Water-use habits; efficient household micro-component devices; water consumption; water demand management; developing countries

## 1 INTRODUCTION

Water crisis referring to scarcity of freshwater resources has become one of the major challenges throughout the world. This has resulted from many interrelated issues such as population explosion, and climate change. The global population has increased from 3 to 7 billion people in five decades [1], placing considerable pressure on water resources. It is estimated that by 2025, 67% of the global population will face moderate to high water stress and half of the population will be suffering constraints in their water supply [2]. India, as one of the largest countries in the world with a population of 1.2 billion, can be classified as a hot tropical country. A large proportion of the Indian population lack access to safe drinking water, and as a result of growing population, this situation has deteriorated. UNICEF [3] reported that

\* Tel: +44 1392 724075

E-mail: address: s.m.k.sadr@exeter.ac.uk

the utilisable water for human use (654 billion cubic metres (BCM)) is very close to the current actual water use (634 BCM); these figures indicate an imminent alarming situation in this country. Poor management and overexploitation of groundwater by all sectors in the absence of adequate regulation and effective pricing instruments severely impact water-scarce areas [4]. Domestic water demand accounts for 80 percent of groundwater use, and GR [5] projects the situation to worsen over the coming years. Additionally, an increase in disposable income is projected to change consumption patterns towards more water intensive products which will lead to a significant increase in household water demand [5].

Although the existing urban water systems and technologies provide reliable services at reasonably low costs, over the last decades there has been widespread criticism of their level of environmental sustainability [6, 7]. The question of greenhouse gas emissions and the associated global warming, contamination of groundwater, eutrophication, nutrient depletion and other environmental degradations are among the many challenges associated with conventional urban water management approaches [8]. Therefore, innovative water management approaches should be employed to influence demand by augmenting water supply in a way that is both cost-effective and favourable for the water environment whilst still meeting consumer demand [9]. A range of sustainable water management practices and principles can be introduced to ensure the secure supply of urban water. Water demand management (WDM), which can be defined as the practical development and implementation of strategies aimed at influencing demand, are utilised globally to assist in shifting consumers towards sustainable water consumption behaviour.

WDM aims at reducing average water consumption in order to improve sustainable use of water resources [10, 11]. WDM measures emphasize reducing end use consumption hence offsetting the need for additional water supply and wastewater treatment measures which are costly and can be environmentally and socially detrimental. The WDM approach relies greatly on consumers to understand how to reduce their water consumption and to apply this understanding to everyday activities to consume sustainably. Reducing demand by improving the efficiency of water use requires an understanding of how water is used and in what ways water savings can be realized [12]. Sofoulis [13] believe an understanding of the cultural domain and the complex world of everyday life experience is crucial for understanding water use and vital to the adoption of more sustainable urban lifestyles. If utilised effectively, WDM can also reduce water and energy cost for households and water operators, so could have a positive impact on wastewater infrastructure by delaying/reducing peak inflow into wastewater systems, reduce pollution loads and thereby increase water supply, and extend the life of ageing water infrastructure [9].

Another approach is micro-component based WDM which has been identified as a way forward to reduce per capita water consumption without necessarily changing user behaviour [8]. The actual volume of water consumption for a given service is believed to be considerably lower than that provided by conventional water-use micro-components. This concept forms the basis for the micro-component oriented water demand management approach, which seeks to meet water efficiency targets without compromising the quality of the services provided [8]. Based on what has been discussed above, two potential solutions for reducing the water stress imposed by population growth and human activities especially at household level can be identified: (1) water efficiency-conservation attitudes and (2) water saving microcomponent and devices. Therefore, this research aims to explore the relation between water consumption and water use behaviour and attitudes, and devices applied in households in urban areas in India. A survey conducted to understand some of the behavioural aspects of water consumption in Jaipur is presented as an example of an Indian urban area.

### **1.1 Factors influencing domestic consumption**

In the context of urban areas in India, two types of buildings, where water consumption takes place, can be considered: residential and non-residential. In residential buildings, water is

usually used for WC flushing, washing clothes and dishes, showering, bathing and satisfying a variety of other uses (such as cooking and drinking). Since the residential sector represents the largest urban water use sector [14], water saving measures targeting the residential sector could play an important role in reducing the total domestic water consumption. There are significant variations of water consumption in this building type, and level of water consumption varies from building to building depending on type, size, functions, construction age and class of buildings.

The water consumption of a building, which is standardised as “litres/capita/day”, is determined by a number of factors: (1) climate and weather condition; (2) the types and characteristics of water use micro-components installed in a building; and (3) water use habits. The first two have been, to some extent, defined and understood in different parts of the world, while the understanding of water use habits is still incomplete since water use habits vary from region to region, and country to country. Household water use habit itself depends on a number of factors, including household occupancy, household types, household income, and water prices. In England, EA [15] reported a strong and clear relationship between household occupancy and water use, with per capita consumption decreasing as occupancy increases. Additionally, water use habits can significantly differ between households, depending on socio-economic, cultural, and/or religious factors [9]. Since water use devices/appliances play important roles in water consumption/conservation, here the main appliances will be described.

## **1.2 Household water-using appliances**

A clear understanding of household types and household water consumption breakdown leads to better understanding of water consumption trends; subsequently, more efficient use of water and better forecasting of future water demand would be possible [9]. It is therefore necessary to break down domestic water consumption and study the individual water consumption elements within the household which leads to better understanding of household water consumption patterns and trends [16]. Breaking consumption into different micro-components of demand has been considered in a number of studies. Fidar [8], for example, focused on six micro-components (e.g. showers, WCs, baths, internal taps, washing machines, and dishwashers). Shaban and Sharma, [17] mainly focused on five micro-components and assessed per capita household micro-component water use in 7 major Indian cities. They showed that on average cooking and drinking account for only 10 percent of water use, with bathing, WC flushing, clothes washing, and utensil washing accounting for much higher water use in households. Since the focus of the survey is mainly on bathing/showering and clothes-washing, here a summary of these two appliances is presented.

## **1.3 Bath and Shower**

Bathing currently accounts for about 55 percent of household water use in India [18], with modern plumbing, en-suite bathrooms, and changes in lifestyle all potentially contributing to the increase in water use for bathing and showering [19]. Baths are available in a wide range of shapes and volumes, and the main variables which determine how much water is used to fill a bath are its volume and shape. Water use in bathing can only be reduced through extensive awareness raising campaigns on the need to save water by the use of efficient shower heads. In India, bucket bath practice seems to be rather common with ownership of western style bath tubs mainly evident in upper class (high income group) households. There is considerable difference between old and new properties, in terms of water consumption through showers [8]. Defra [20] estimated that water consumption through showers in standard new built houses is about 20% of the total household water consumption. MTP [21] estimated the proportion of water used for showering in old and new homes as 8.6% and 23.1%, respectively; the increase being due to the move away from baths towards showers in newer properties. In addition, en-suite bathrooms and changes in lifestyle are contributing to the trend towards use significantly more water for showering [17, 22]. There are divergences on shower types and categories; Grant, [23] and Elemental Solution, [24] reported the availability of three types of showers in the

international market: low-pressure gravity fed showers, mains-pressure/power showers, and electric showers, whereas, Critchley and Phipps [25] divided the showers into electric showers, mixer showers and pumped showers. The type of shower and the duration for taking a shower directly impact on the amount of water consumption. Water consumption in showers also depends on heating mechanism, type of shower control (fixed/adjustable), the shower spray pattern, and even the pressure of the water droplets on the skin.

### **1.3.1 Clothes washing**

Clothes washing represents 20 percent of per capita household water use in India [18]. In general, higher income households wash clothes more frequently. However, no information has been found on how this water is used (washing machine, hand washing, etc.) or how this demand can be reduced in India. In general, washing machines can be divided into two types: (1) front-loading (horizontal axis) and (2) top-loading (vertical axis washing machines). Front-loaded washing machines are reported to be more efficient, both in terms of energy consumption and water use [26]. Lifetime can be considered as the most important factor in determining efficiency of washing machines. The average lifespan of washing machines found in the literature varies widely ranging from 8 years to 16 years [22, 27, 28, 29]. However, it is reported that the average lifespan of washing machines has recently reduced ranging from 4.5 to 10 years [8, 30, 31].

## **2 METHODOLOGY**

The environment created by the interaction of society and economy in urban centres is a complex system of social and environmental interactions. Urban water consumption can be also considered as a parameter heavily dependent upon social, environmental and financial aspects. As mentioned earlier, water use habit is one of the most important factors influencing domestic water consumption. Yet acquiring information on water use habits in India and most developing countries is still problematic and no reliable data on water use habits has been found in the literature [32]. Therefore, here in this study we conducted a survey on water use practices in households targeting Indian urban areas.

### **2.1 Technical notes on the survey and study site**

This survey includes the development and distribution of a questionnaire to about 100 households of different types in the Indian city of Jaipur. This city, which has a population of 3.1 million, is facing a significant problem with drinking water. The survey was administered to the city dwellers with a view to improving our understanding of typical water consumption habits in India and to obtain a more holistic and representative sample of data regarding frequency and duration of use of micro-components for use in a water efficiency technology selection tool. The developed questionnaire consists of two main sections:

#### **2.1.1 Household characteristics**

This section includes nine questions, and aims to categorize and filter information based on household characteristics e.g. household location, household type, number of occupants in each household, number of washrooms in a household, time/duration of water supply, monthly water bill, and household income. This information is aimed at helping to categorize the responses for further analysis. In the survey, 63 number of stand-alone houses and 27 number of flats/apartments participated.

#### **2.1.2 Water use characteristics**

This section is composed of 11 subsections and aims at identifying/classifying water consumption habits in a household in urban areas in India. The information on water use patterns focuses on middle to high income households in urban areas of India. Low income groups (e.g. slums and informal settlements) were excluded, since the water consumption for those areas is already very low and do not offer significant water saving potential. This section

focuses on different water use devices/appliances (e.g. how many showers/bathrooms in a household, duration and number of showers per day, approximate amount of water used for showering). This information will help in analysing water use habits and finding some patterns of water consumption in urban areas.

## 2.2 Clustering approach

Cluster analysis is the art of finding groups in data [33]. The classification of similar objects into distinct groups is an important part of any analysis. A population can be divided into entire unrelated groups pertaining to which variables are selected upon which to define categories [34]. In other words, before engaging in any group classification, a clear theoretical understanding of relevant variables for groupings which represent distinct categories is required. In this research, an attempt to consider recognisable dimensions of water use practices by which a number of clusters can be created has been made. The main focus of analysis is on water consumption for different types of households based on different appliances. In addition, for further analysis, three clustering dimensions have been created (Table 1) with focus on showering/bathing and clothes washing.

It is worth noting that the analysis method used in this study follows that of Browne et al. [34] with some modifications. This analysis method is commonly in use and tries to maximise the chances of identifying real groups in the data where these exist [35]. In addition, scale values are normalized between 0 and 1 for all dimensions of each practice. The focus of analysis is mainly on household type, family size, and water use appliances.

**Table 1: Dimensions of bathing/showering and cloth-washing practices used for clustering analysis**

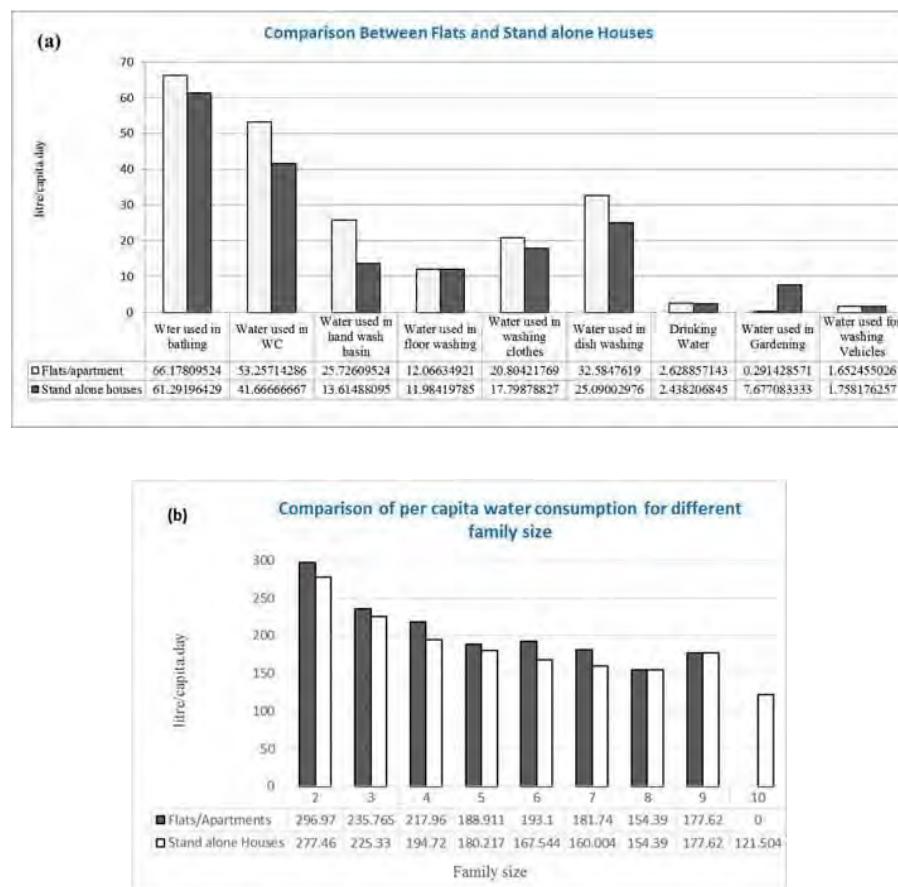
Water using practices	Dimension	Description	Normalized scale values
Bath and shower	Frequency	Number of baths and showers per week per person	0 – 1 per week or fewer 1 – 14 per week or more
		Duration of each shower or number of buckets (15-20 litres) used for each bath	0 – 1 minutes or fewer / 1 bucket or less 1 – 30 or more / 6 buckets or more
	Diversity		0 – always taking showers 0.5 – taking baths and showers
		Bath to shower ratio	equally 1 – always taking baths
	Technological preference	Number of times clothes are washed per week per household	0 – 1 per week or fewer 1 – 12 per week or more
		How much water used for clothes washing per week	0 – 3 buckets / 60 litres or less 1 – 40 buckets / 800 litres or more
Clothes washing	Frequency	Manual washing to washing machine ratio	0 – always washing manually 0.5 – equal manual washing & using washing machine 1 – always using washing machine

### 3 RESULTS

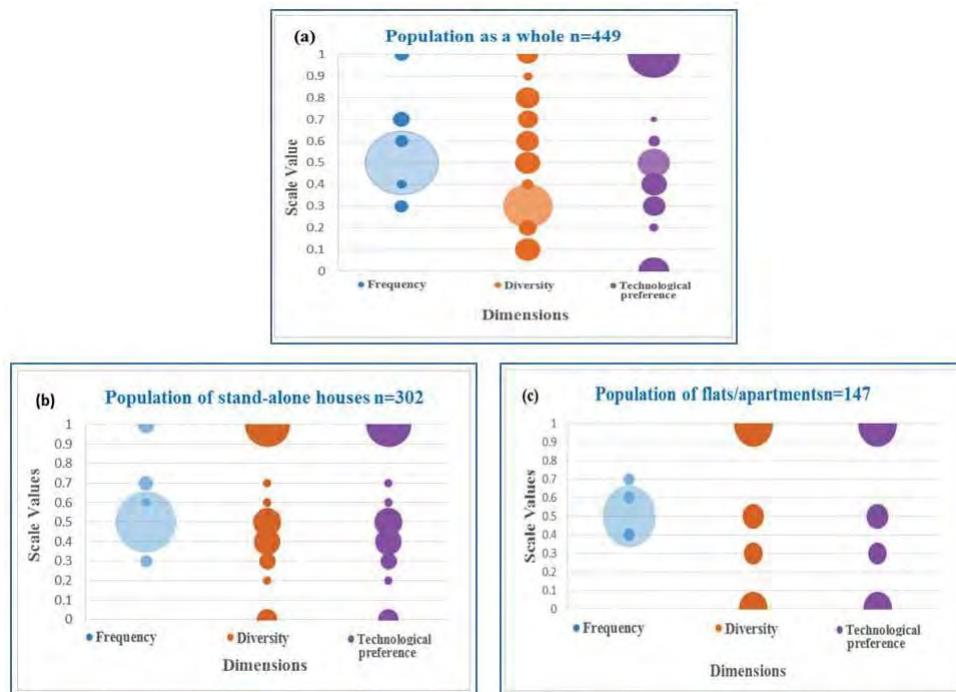
Questionnaire and interview responses provide the quantitative and qualitative household water values and cultural/behavioural information. Figure 1(a) compares the per capita water consumption of different water use practices in stand-alone houses and flats/apartments. It shows that bathing has the highest water consumption and it is followed by water used in WC, dish washing, and clothes washing. It is interesting that similar trends can be seen for both flats and stand-alone houses. However, generally water consumption in flats/apartments is a slightly higher than that in stand-alone houses, except water used in gardening which is nearly zero in the flats/apartments. This trend can be explained by the fact that the quality of life is higher in the areas where the flats are located. In addition, nearly three quarters of the flat/apartment population have a family size of six or smaller. It is shown in Figure 1(b) that per capita consumption is higher in smaller families and vice versa. According to the result of the survey, the majority of households have only one person earning for the whole family; it can be assumed that generally smaller families have higher life quality. Since changes in water use habits in bathing/showering and clothes-washing could considerably change household water consumption, here in this section, the focus will be on these two water use practices.

#### 3.1 Analysis on bathing and showering

Showering/bathing has changed substantially for the majority of the population in many places in the last few decades [34]; in many countries, taking showers is becoming the norm representing a transition from bucket bathing and flannel washing [25]. In India, although taking showers is becoming more common, generally bucket bathing is still the preferred way of having a full body wash. It is widely believed that the frequency of taking showers/baths has significantly increased [36]. The results from the questionnaires illustrated in Figure 2 reflect this change with approximately 70% of the whole population having daily showers/baths. 15% of participants never have a bath, while 43% never have a shower. Figure 2(a) shows the distribution of all respondents in the population on the three dimensions by which clusters are defined. The bubble sizes represent the weighted percentages of respondents having value on that particular dimension. Figures 2(b) and 2(c) illustrate the distribution of members of two clusters in turn on these same dimensions. It can help in better comparing bathing/showering behaviours in stand-alone houses (Cluster 1) and flats/apartments (Cluster 2) with the overall population. The proportion of baths and showers is varied, with a fair share of baths, and a variety in the duration of the bath/shower and the amount of water used at each time, based on a number of reasons. It was shown in the survey that daily baths/showers, which represent about 70% of the total do not usually take more than 10 minutes. Families with children are shown to have more frequent and longer bath/showers. By comparing Figure 2(b) and Figure 2(c) it can be concluded that in stand-alone houses generally taking bucket bath is still the preferred way of washing the whole body, while taking a shower is slightly more common in flats/apartments.



**Figure 1: The average per capita water consumption (a) versus different household water usage; (b) versus family sizes**



**Figure 2: Population and cluster results for bathing/showering (a) whole population; (b) stand-alone houses; (c) flats/apartments**

### 3.2 Analysis on clothes-washing

There are a number of ways to analyse water use in households. In the previous section, the data on bathing/showering was mainly analysed based on the type of household. Here in this section, the data analysis on clothes-washing will be focusing mainly on family size. In the area of the study, 40% of the households have families with four members, and families of five and six, respectively, account for 11% and 21% of the whole population. Therefore, three separate clusters have been considered for these family sizes (Figure 3). Water Consumption rates for clothes-washing, 20.80 l/capita/day in flats/apartments and 17.79 l/capita/day in stand-alone houses, indicate that, on average, residents of flats consume more water for clothes-washing in the households than people living in stand-alone houses. This may be due to number of reasons including family size: the majority of the participants living in flats have small families, and as mentioned earlier, water consumption (per capita) is higher in smaller families (Figure 1(b)). The other reason would be the family salary class; a large proportion of the flats/apartments in this study are located in the upper middle class areas. Generally people in this class are more concerned about sanitation and hygiene [37].

Figure 3(a) illustrates the water use behaviours for clothes-washing across the whole population. It is shown that 50% of the households wash their clothes on a daily basis (seven times per week), while, less than 1% wash their clothes less than 2 and more than 10 times per week. It is interesting that nearly 30% of the population consume 700 litres per week only for clothes-washing; this figure is concerning and can be decreased by applying water conservation practices and some changes in water use habits. According to the results of the survey, only 23% of the participants never use washing machine; it means that more than 70% have washing machine in their properties. Washing clothes with fully loaded washing machines is more efficient than manual clothes-washing. Even among the families using a washing machine, water consumption is relatively high. One reason is that more than 78% these households have top-loading washing machines which consume nearly twice as much water than front-loading machines. Figure 3(b) shows that smaller families preferred manual clothes washing mainly on a daily basis. The washing preference in families with four members is similar to the previous group (Figure 3(c)). However, this group consumes a higher amount of water in clothes-washing compared to the families with one to three members. By comparing different bubble plots in Figure 3, it can be seen that water consumption in clothes washing is lower in larger families. Larger families preferred using washing more than the smaller families, while, manual clothes washing is still in practice in all the households



**Figure 3: Population and cluster results for clothes-washing (a) whole population; (b) stand-alone houses; (c) flats/apartments**

#### 4 DISCUSSION: HOW TO IMPROVE WATER USE HABITS AND SWITCH TO A WATER CONSERVATION MODE?

The qualitative and quantitative analysis provided in the previous sections should help in highlighting opportunities and conceptual approaches resulting in improved water use habits. Browne et al. [34] believe that these approaches should be less reliant on changing people's attitudes towards water and the environment and more focused on the different elements that make up practice. On the other hand, Randolph and Troy [38] stated that policies and rules play an important role in reducing household water consumption. They also argued that for acquiring better responses, the complexity of the forces shaping demand needs to be understood in the context of the socio-demographic composition of households in different kinds of dwellings, as well as the cultural, behavioural and institutional aspects of consumption.

Changing human habits is a long process [39] which means that it needs time and resources to build new habits, whereas, water scarcity is a current and existing concern in India. Therefore, both long term and short term plans should be considered in this situation. The best long term plan would be community capacity building (CCB) or educating people. CCB is basically a conceptual approach to development focusing on understanding the obstacles that inhibit people and governments from realizing their development goals while enhancing the abilities that will allow them to achieve measurable and sustainable results [40]. A number of studies suggested that water use habits can be improved by educational campaigns and dissemination of knowledge in changing behaviour together with the effect of consumerism on water consumption through the daily routines and awareness of entitlement [13, 41, 42]. People can be informed of the water scarcity, its associated issues and any inappropriate water use habits/behaviours; then they can be guided through appropriate direction towards more efficient water consumption. Randolph and Troy [38] proposed 13 actions for reducing household water consumption e.g. taking shorter showers, filling washing machine before using, reducing garden watering, and reducing car washing; it was shown that almost all of these actions are to some extent efficient. In the previous sections it was shown that water consumption for bathing/showering and clothes-washing is relatively high in Jaipur; the average shower time of nearly 25% of the participants is between 15 and 30 minutes. This can be reduced by at least a few minutes which will help to improve the city's water consumption efficiency.

Applying water saving devices and microcomponents would be the best short-term plan, as some of these can reduce water usage by 50% or even more [8, 30, 31]. However, most of these water saving appliances/devices are rather expensive for the majority of the population. It means that in order to encourage people to apply water saving devices and thereby effect a general lowering of water use, subsidising these technologies is required. In a survey in Australia, it was shown that 77% of the participants were willing to fit these devices if the price was subsided by 50% [38]. More studies are required to investigate the impact of each water saving device in improving water efficiency in Indian cities. Conducting a longitudinal diary-based study on water use habits would be worthwhile in order to derive even more useful evidence.

## 5 CONCLUSION

Indian water demand is projected to very soon overtake the availability of water. Household water using habits and water demand in particular is growing as a result of increased water use for personal hygiene and use of water consuming appliances as a result of increasing standards of living. This growing demand will impose additional strains on ageing and deteriorating water and wastewater infrastructure, which could further reduce per capita mains water supply. Climate change and climate variability will also likely challenge the resilience of the water sector by adversely affecting the water resources in this country.

Given the above challenges and the role water efficiency can play in mitigating some of the challenges, this paper presented the findings of a domestic water consumption survey carried out in Jaipur, India. A questionnaire containing over 60 questions was developed to collect information on households' characteristics as well as the volume of water used in different water use practices. To analyse the results of the survey, cluster analysis was undertaken. The results showed that the per capita consumption varies considerably with household type and size. Water used in bathing/showering represented the highest proportion of water consumption in both stand-alone houses and apartments. Family size and income were also found to be important indicators in estimating household water consumption; it was shown that small families have higher water consumption in general. Water Consumption rates for clothes-washing indicated that, on average, flat residents consume more water for clothes-washing in

the households than people living in stand-alone houses. Analysing the results of the cloth-washing, it is shown that 50% of the households wash their clothes on a daily basis; water used in clothes-washing can be significantly reduced by using and filling washing machines.

The findings of this study draw the conclusion that although changing water use habits of any city dwellers seems to be a long and complex process, it would substantially reduce the household water consumption. In addition to that, several water saving devices/micro-components can be adopted in household levels to improve the domestic water efficiency. As a final note, in order to undertake further research, conducting a diary study on water use habits would be worthwhile.

## ACKNOWLEDGEMENTS

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# Feasibility study of water saving measures in university campuses buildings: A case study of the University of Aveiro

A. Silva Afonso<sup>1,2</sup>, C. Pimentel-Rodrigues<sup>2</sup>, I. Meireles<sup>1\*</sup>, V. Sousa<sup>3</sup>

<sup>1</sup> Department of Civil Engineering, University of Aveiro, Campus Universitario de Santiago, 3B10-193 Aveiro, Portugal

<sup>2</sup> ANQIP (Portuguese Association for Quality and Efficiency in Building Services), Rua de S. Roque, 23-1° 3B00-257 Aveiro, Portugal

<sup>3</sup> Department of Civil Engineering, Architecture and GeoResources, University of Lisbon-IST, Av. Rovisco Pais 1049-001 Lisbon, Portugal

## ABSTRACT

**Aims:** Evaluate the water savings potential and financial viability of water saving measures in university campuses buildings

**Study design:** The study follows an observational approach to characterize the current performance of existing buildings in terms of water consumption and evaluate the potential for increasing water efficiency.

**Place and Duration of Study:** Buildings of the Chemistry, Civil Engineering, Communication and Arts, Environment and Planning, and Mathematics Departments and the Pedagogic Complex of the University of Aveiro, Portugal, between May 2013 and July 2014.

**Methodology:** Water efficiency audits complemented with limited monitoring and simulation of investment scenarios.

**Results:** The payback period of the investment required to implement the measures was found to be less than 7 months in all the cases, with average water savings potential of 29% and ranging from 9% up to 39%.

**Conclusion:** Water savings measures are attractive solutions for university buildings in Portugal, particularly the older ones, because of their environmental and financial performance and the low investment required.

*Keywords:* financial viability; sustainability; university buildings; water efficiency

## 1. INTRODUCTION

Since their genesis with the publication of the Brundtland Report [1], the concepts of "sustainability" and "sustainable development" have become increasingly present in the majority of human endeavors. In particular, the environmental dimension of the sustainability concept became an issue of deep global concern throughout the latter half of the 20th century and continued into this new millennium. Amongst the various environmental issues, fresh water shortages and pollution are two of the most critical global problems, furthermore with the growth in population and demands, and the effects of global warming scenarios. Many organizations and conferences concerning water resource policy and issues have reached the consensus that water shortages may cause war in the 21st century [2].

The substantial water consumption increment recorded during the XX century was due to an increase in both the population and water demand for various purposes [3]. This was not

\* Tel.: +351 234370049

E-mail address: imeireles@ua.pt.

uniform throughout the globe, with the more developed countries accounting for the biggest share. In addition, making water available for consumption requires significant amounts of other resources to build, maintain, operate and rehabilitate/replace the supporting infrastructures [4-5]. Consequently, even in countries with favorable conditions in terms of water demand and availability ratio, there is an interest in evaluating and exploring alternatives for improving the efficient use of water resources.

In order to optimize water management, two main categories of solutions can be identified: i) efficient water use; and ii) exploitation of alternative water sources. At a building level, the former includes solutions that promote changing consumption habits (non-structural solutions) and/or the adoption of lower consumption devices (structural solutions), whereas the latter includes exploring alternative sources of water.

These vectors underpinned the stabilization or even reduction of the water use over the last years in various sectors (urban; industry; agriculture) of the developed countries due to the combined implementation of structural (e.g., use of alternative water sources; reduction of water losses; use of more efficient equipment and fixture) and non-structural (e.g., information and education campaigns; consumption based water charges) measures [6-7].

Nonetheless, the per capita water consumption in developed countries is still extremely high and water is considered to be a key at-risk resource. Improved water management is essential to tackle the water challenge due to the economic advantage of dealing with it by optimizing the available resources rather than by increasing the volume of supplied water [8]. The advantages of an optimized water demand management are not restricted to economy, but extend to the environment and the society, being considered the most sustainable option [9].

In Portugal, urban consumption represents only 8% of the total volume of water consumed, but its cost accounts for 48% of the total expenses on water supply. Within urban consumption, water consumption in buildings represents the largest share [10]. In Portugal, despite the various initiatives of ANQIP (Portuguese Association for Quality and Efficiency in Building Services), a Portuguese non-governmental organization dedicated to the promotion of quality and efficiency in water, wastewater and stormwater systems in buildings, very few studies have been published in international journals dealing with the Portuguese context [11-14]. Following previous studies by the authors [15], the present study evaluates the viability of system optimization and water conservation measures in the buildings of the Chemistry, Civil Engineering, Communication and Arts, Environment and Planning and Mathematics Departments and the Pedagogic Complex of the University of Aveiro, Portugal.

## 2. WATER CONSUMPTION

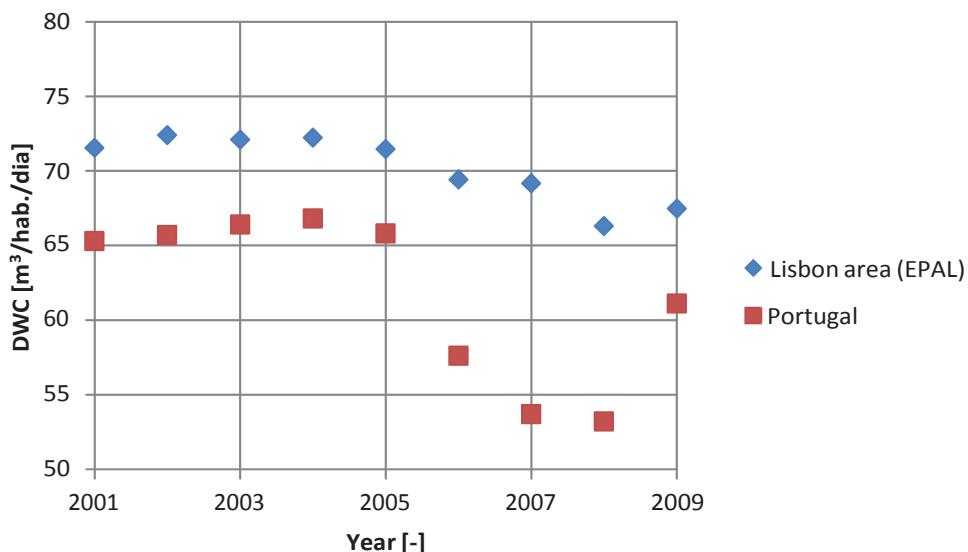
Water consumption depends on economic, social and environmental variables both at an individual or group level. Within the scope of the present paper, it was considered that a group represents a community or society sharing common features (e.g., socio-economic, cultural, educational) and responding similarly to the variables affecting water consumption. Complementarily, it is assumed that an individual consumer can be a single individual or a group that share the same facility and/or activity. This option introduces some cross effects, since a facility can be used by a group of individuals from different community or society backgrounds, but allows to break the analysis into the overall water performance of a community or society .

At country, region or community level, the water consumption depends on factors such as the development level (e.g., underdeveloped, developing or developed country; technical innovation), the weather and climate (direct - temperature; indirect - evapotranspiration and precipitation amount), the type (e.g., rural, urban) and the characteristics (e.g., population; housing type) of the community, the activities (e.g., tourism; industry; services) and technology (e.g., equipment; fixture), the water availability (e.g., losses; pressure; service level; sources; treatment required) and policies (e.g., pricing; regulations), amongst others [16-18].

An important indirect factor that can be used to characterize water consumption at a country, region or community level is the economy. According to the OECD [19], the economic growth was one of the most important factors underlying the water consumption increase in the last decades since it allowed an improvement in terms of the buildings served by public water supply and wastewater drainage systems and enhanced access to water consuming appliances (e.g., dishwasher; washing machines). Using this as a starting point, Florke and Alcamo [20] related the average domestic water consumption (DWC, in  $\text{m}^3/\text{h/year}$ ) in the European countries with the corresponding Gross Domestic Product (GDP, in Euro-Base 2000/hab) obtaining high correlations in most cases. For Portugal, these authors obtained an index of agreement of 0.73 in the relation between DWC and GDP using the following sigmoid function:

$$\text{DWC} = 18 + 99.71X[1 - e^{-1.96 \times 10^{-8} X \text{GDP}^2}]$$

The validity of the previous relationship is limited to a development stage of the community or society. For instance, the water consumption in Portugal has stabilized or decreased since 2000 (Fig. 1), despite the increase of the GDP until 2009. Furthermore, the economic crisis since 2008 resulted in a decrease of the GDP which was not reflected on a decrease on water consumption. This may be partially due to the fact that the level of service was already high in 2000 (90%) and increased to 96%. Since the major water supply infrastructures already existed in 2000, this increase resulted from small investments and the migration of part of the rural population without public water supply to the large urban centers where the service level is virtually 100%. This maturity in the water supply system allowed a shift in priorities from increasing the service level to improving the service performance, in particular, reducing losses and using the water more efficiently.



**Fig. 1. Evolution of the domestic water consumption (DWC) in Lisbon area and in Portugal between 2001 and 2009 [21].**

Despite the decreasing trend of the water consumption with the water price [22], the dispersion of the water consumption for the lower water prices is very significant. For residential buildings, recent research demonstrates that, in most cases, water demand is largely price inelastic because of its low relative cost when compared to other life essential goods [23-25]. Nevertheless, water price is invariably a statistically significant determinant in water consumption studies and there are several examples demonstrating a strong influence, but the reported results are extremely variable [18] and, thus, must be considered highly context specific. In addition, the effect of water price depends on the interaction with several other factors, being the income the most relevant. In fact, water demand is found to be most

often elastic regarding income and as the income increases the water demand becomes even less more inelastic regarding water price [18].

Within the scope of the present paper, it was considered that an individual consumer can be a single individual or a group that share the same facility and/or activity (e.g., household, school). As such, the characteristics of the group (e.g., family; staff; students) and the nature of the activity (e.g., domestic; academic) will determine the water consumption. No studies were found dealing with the determinants for water consumption in university buildings at an individual consumer level, but in residential buildings the water consumption is influenced by the occupants and the house characteristics. The former include factors such as the number, the age, the education levels and the attitudes, beliefs and behaviors of the occupants, and the latter include the lot size of properties, the number of bathrooms, the existence and size of the garden, the existence of a swimming pool and the efficiency of water consuming devices (i.e. clothes washers, shower heads, tap fittings, dishwashers and toilets, irrigation solutions) [18] [20] [26-29]. Since in university buildings the users do not pay for the water directly, these factors gain relevance.

### **3. PRESENTATION OF CASE**

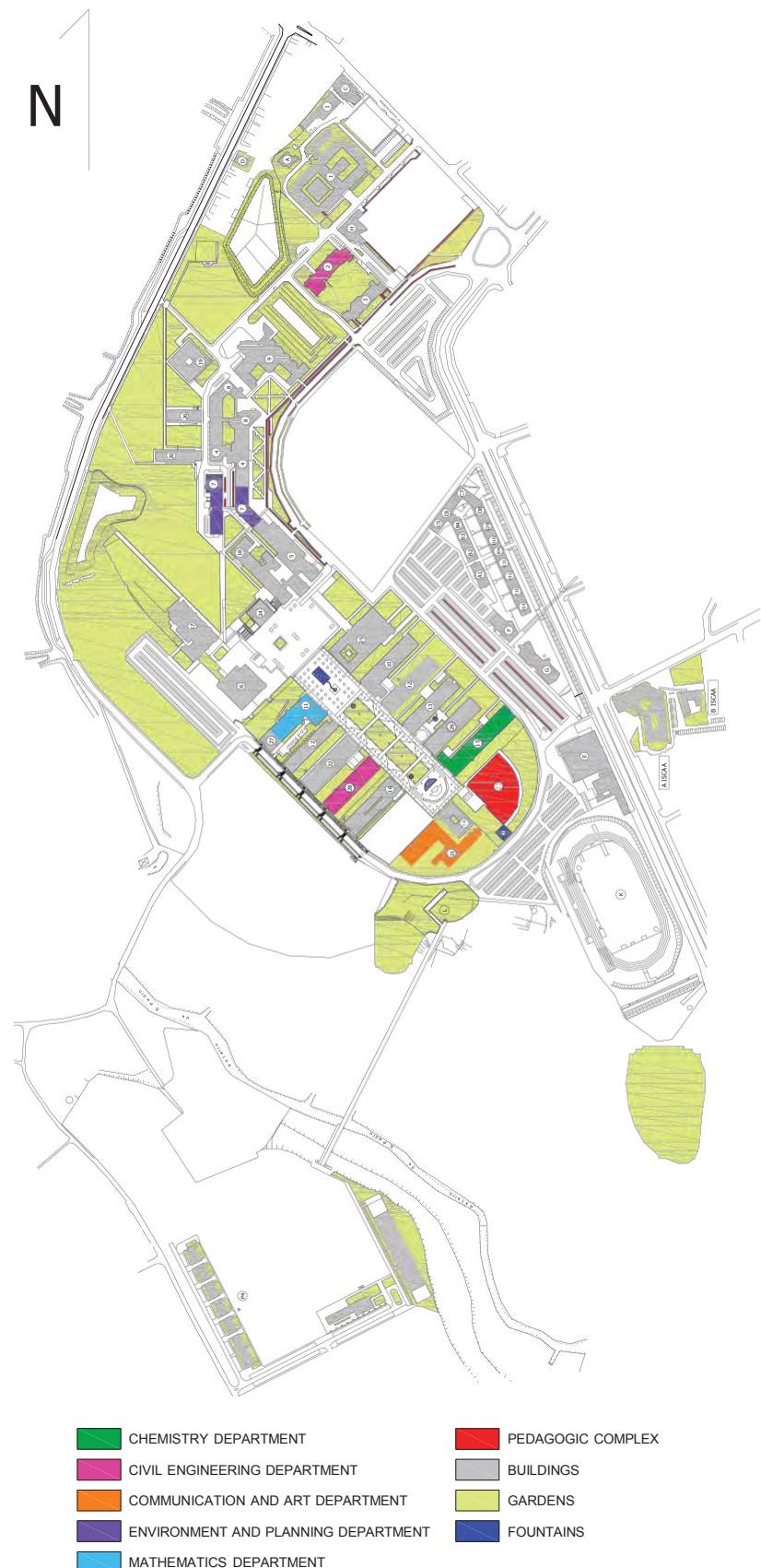
According to EPA [30], approximately 6% of the total water used in commercial and institutional facilities in the United States takes place in educational facilities. EPA [30] and Meireles et al. [31] indicate that, in the United States and in Portugal, respectively, the main consumption of water in education facilities takes place in the restrooms. In order to achieve campus sustainability, several universities already implemented environmental management systems to improve their water efficiency [32].

These numbers, along with the expected scenarios of water stress and scarcity in the near future, justify the development of new strategies for water conservation in universities, as part of an environmental management system, and are the motivation of the present study, focused on the study of water saving measures in university restroom.

The Santiago campus of the University of Aveiro extends for an area of over 460 000 m<sup>2</sup> and is composed by 42 buildings. Each department has its separate building and there are also individual buildings for other services in the university (e.g., library, sports, central administration, student's dormitory, refectory).

#### **3.1 University of Aveiro Buildings**

The buildings of the Chemistry (built in 1993), Civil Engineering (built in 1997), Communication and Arts (built in 1996), Environment and Planning (built in 1979), and Mathematics (built in 1993) Departments and the Pedagogic Complex (built in 2000) of the University of Aveiro were chosen for the present study (Fig. 2). Since the focus of the study was to capture the behavior of the students, the administrative buildings and sport facilities were ruled out since they have a much distinct type of occupation. The buildings cover a wide range of construction dates (from 1979 to 2000) and the two major groups of programs in the University: i) exact sciences and engineering; and ii) social sciences. The range of construction dates relates to the technology of the water appliances and fixtures, while the different studied fields reflect the type of activities and the cultural differences between the occupants.



**Fig. 2. Santiago campus of the University of Aveiro layout with location of the audited buildings.**

### 3.2 Methodology

The first stage of the audits was a detailed visual inspection of the facilities to identify the fixtures characteristics (e.g., brand; type) and conditions (e.g., defects/malfunctions). Afterwards, measurements were made to determine the discharges/volumes: i) taps discharges were measured either directly, using a flow meter, or indirectly, by measuring the time to fill a container, depending on the maximum discharge; ii) flushing cisterns water consumption were measured by determining the flushed volume; and iii) urinal flushing volumes were directly measured, in the Civil Engineering (CED) department building, or, in the Chemistry (CD), Communication and Arts (CAD), Environment and Planning (EPD) and Mathematics Departments (MD) and the Pedagogic Complex (PC) buildings, considered equal to 2.5 l, which corresponds to the average flush volume of 258 urinals measured in an audit to 26 public buildings of the region of Aveiro. The results are presented in Table 1.

**Table 1. Number of consumption points and consumption per use in each building.**

DATA	BUILDINGS					
	PC	EPD	CAD	CD	MD	CED
Number of consumption points						
Restrooms						
Washbasins	21	15	43	15	22	22
Toilets	23	15	32	17	31	17
Urinals	12	12	18	6	7	14
Laboratories						
Sinks				39		
Water consumption per use						
Restrooms (l)						
Washbasins	1.7	4.3	1.5	5.0	3.6	2.4
Toilets	6.0	7.8	9.3	12.0	5.8	7.2
Urinals	2.5	2.5	2.5	2.5	2.5	1.5
Laboratories (l/min)						
Sinks				15		

Consumption patterns were determined using a hybrid approach. The detailed study performed in the Civil Engineering Department building [31] was used as the base to determine the distribution of water per type of use (in restrooms, in laboratories, cleaning and others) and the number of uses per type of fixture, as a function of the building total water use. The extrapolation of the results to the remaining buildings was complemented with limited direct observation and information from hourly water consumption records, users and managers.

In the Civil Engineering Department, 70% of the water is consumed in the restrooms. According to the characteristics of the buildings, types of use and occupants the average restroom water consumption in the other studied buildings ranged from 70% to 96% of the total water use, with exception of the Chemistry Department where, due to the large number of laboratories and highly intensive laboratory activities, only 30% of the water consumed in the building is allocated to restroom usage.

Due to the large amount of water consumed in the laboratories of the Chemistry Department building, this study also focused on the water consumed in that particular activity. In this regard, the water consumed in these laboratories was divided in water consumed in activities where the volume of water is relevant and in activities where the volume of water is irrelevant. For instance, to fill a bucket is an activity where the volume of water is relevant and for the

activity of washing hands the volume of water is irrelevant. According to the characteristics of the lab activity, a proportion of 4:3 was selected based on staff sensibility.

The water volume determined for each building based on the previous information and considering a relation between occupancy and the total number of uses was compared with the water consumption records and the distribution for each type of use was adjusted in proportion (Table 2).

**Table 2. Annual number of uses per type of fixture.**

NUMBER OF USES (x 1000)	BUILDINGS					
	PC	EPD	CAD	CD	MD	CED
<b>Restrooms</b>						
Washbasins	217	45	142	203	71	71
Toilets	100	21	66	94	33	33
Urinals	84	17	55	79	27	27
<b>Laboratories</b>						
Sinks					156	
Average total consumption (m <sup>3</sup> )	1679	497	1007	7784	535	636

Since most consumption takes place at faucets and toilets, only water efficient solutions for these fixtures were evaluated. Considering the water efficiency labelling scheme developed by ANQIP [33], the discharge of water efficient fixtures and their corresponding cost (including the installation) were obtained from manufacturers with factories in the Aveiro region.

With the results from audits as a basis, it was possible to identify potential water efficiency interventions. Since the majority of the consumption in most buildings was in the restrooms, the measures considered in the scope of this study were mostly focused on reducing the domestic water consumption type in the buildings. The evaluated water efficiency measures were the installation of discharge reducers (cost: 9.50€) in the faucets, and toilet flushing volume reducer bag (cost: 5.00€) in the toilets cisterns.

#### 4. RESULTS AND DISCUSSION

The water savings resulting from the water efficiency measures are presented in Table 3. Water saving potential ranged from 9% to 39%, with most of the buildings presenting over 30% water savings potential.

**Table 3. Water savings potential.**

WATER SAVINGS (m <sup>3</sup> /per year)	BUILDINGS					
	PC	EPD	CAD	CD	MD	CED
<b>Restrooms</b>						
Washbasins	145	149	78	810	209	96
Toilets		36	225	563		40
Urinals						
<b>Laboratories</b>						
Sinks				1401		

Due to the low investment cost of the water efficient measures, they are also highly viable in financial terms (Table 4). The yearly saved amount is not very significant in most cases, but

the low payback period (less than 7 months for every building) and the low investment (less than 600€ in each building) makes it a very attractive investment in terms of relative performance.

**Table 4. Financial appraisal potential.**

FINANCIAL APPRAISAL	BUILDINGS				
	PC	EPD	CAD	CD	MD
<b>Investment (€)</b>					
Restrooms					
Washbasins	200	143	409	143	209
Toilets		75	160	85	85
Urinals					
Laboratories					
Sinks				371	
<b>Savings (€/per year)</b>					
Restrooms					
Washbasins	542	559	283	3038	695
Toilets		136	819	2110	152
Urinals					
Laboratories					
Sinks				5253	
Payback period (months)	4.4	3.8	5.7	0.7	3.6
					6.9

#### 4. CONCLUSION

The study shows that investment in water efficiency, namely in water efficient fixtures, in university buildings in Portugal has the potential to be highly viable, both in financial and environmental terms. In fact, the low payback period and low investment indicate that investment in water efficient solutions is a very attractive and achievable option. In addition, considering the long life cycle of these buildings, the total savings may be significant depending on the building scale. Furthermore, the environmental benefits are far more relevant if the climate changes scenarios for the Mediterranean region are taken into consideration. In fact, despite the stabilization or even reduction in both population and per capita water consumption, the changes in the hydrologic patterns predicted for Portugal (more extreme events and slightly drier climate) may induce significant water stress.

As expected, the most recent building presents the lowest saving potential with the installation of water efficient fixtures, since it already has the most efficient fixtures amongst the audited buildings. Also, it is interesting to notice that the Civil Engineering Department building presents the next lowest potential, despite the construction date being similar to the buildings presenting the highest potential. This may be due to some behavior change resulting from both the topics lectured and the works carried out in the topic of water efficiency in buildings.

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# Suitability of Log-logistic Distribution to Model Water Demand Data

**Seevali Surendran<sup>1,2\*</sup>and Kiran Tota-Maharaj<sup>1</sup>**

<sup>1</sup>University of Greenwich, Faculty of Engineering & Science, Department of Civil Engineering,  
Medway Campus, Kent, ME4 4TB, United Kingdom

<sup>2</sup>Environment Agency, Kings Meadow house, Kings Meadow Road, Reading, RG1 8DQ,  
United Kingdom

## ABSTRACT

A major unresolved problem in the water consumption modelling is the identification of a statistical distribution which best represents the water consumption pattern. There is a general assumption that potable water consumption is stochastic in nature and hence water demand is best addressed by fitting water demand into a suitable probability distribution. Previously, some studies were done in the UK to conclude the suitability of the Log logistic distribution in modelling water demand. The purpose of this study is to extend the studies to Canada and investigate the possibility of establishing a standard probability distribution function to apply in simulating water demand. Daily water consumption data for the last five years from 2009 to 2013 were obtained from a water company in Canada and was analysed by fitting into the normal, log normal, log logistic and Weibull distributions. Statistical modelling was performed using the MINITAB statistical package. The Anderson Darling (AD) statistical test was used as the goodness of fit parameter in the analysis.

### **Aims:**

The purpose of this study is to establish a standard probability density function to apply in simulating water demand models, using real water consumption data.

### **Study design:**

To obtain water demand data from a water company in Canada and analyse to find out the best probability distribution to use as a standard model.

### **Place and Duration of Study:**

University of Greenwich, Faculty of Engineering and Science, Department of Civil  
Engineering, Medway Campus, Kent, United Kingdom between January 2015 and April 2015

### **Methodology: Results:**

A water company in Canada was contacted and daily water consumption data for 3 zones was obtained for the last 5 years. The water company generated the data at the Water Treatment Plant and collected the data by the Water Services team, using data loggers and data was stored in a data base. Each data set consisted of 365 samples for the whole year. In this research, graphical methods were selected for the analysis along with the Maximum Likelihood method to draw the probability plots using MINITAB statistical package. The data were analysed using a 95% confidence interval (5% significance level). The goodness of parameter used is the Anderson Darling test.

**Conclusion:** The general conclusion from these results is that normal, lognormal and Log logistic distributions would appear to be appropriate for the modelling of water demand data. It

\* Tel.: +4401189533147

E-mail address: [seevali.surendran@environment-agency.gov.uk](mailto:seevali.surendran@environment-agency.gov.uk)

could be concluded that log logistic distribution provided the best distribution out of all three statistical model, and this could be used as a standard model for modeling water demand. The Weibull distribution had high AD values and thus, was not suitable for modelling water demand.

*Keywords: Water demand, stochastic nature, probability distribution function, log logistic distribution, Minitab, Anderson Darling*

## 1. INTRODUCTION

A major unresolved problem in the water consumption modelling is the identification of a statistical distribution which best represents the water consumption pattern. The aim of this research is to study real water consumption data and to find out a standard distribution to use in water demand modelling to address the probabilistic nature of water demand. Water companies are facing challenges to increase or manage water demand to cater government housing targets, water efficiency targets, population projections and technological changes. The advantage of modelling real water consumption data is that it will permit forecasting the probability of occurrence in any demand value and assist planners in future projections. Water demand data from 3 zones were obtained from a Canadian Water Company for this study.

Water demand varies with time of use, season and socio economic pattern of the consumers and hence defined as a continuous random variable. Therefore incorporating probabilistic nature of demands in modelling will lead to more realistic assessments of the performance of water distribution systems. However, few studies can be found in which the random variations of demands have been considered.

Goulter and Bouchart [1], Xu and Goulter [2, 3, 4] made an assumption that the demands have a normal distribution. Mays [5] used randomly generated water consumption data using a range of distributions to study the sensitivity of the system's performance to changes in water consumption patterns. Khomsi et al. [6] stated that the demand is behaving as having a normal distribution based on the Kolmogorov-Smirnov test. Surendran and Tanyimboh [7], Tanyimboh and Surendran [8] addressed the issue of the modelling of short term demand variations in a comprehensive way using UK water demand data and concluded; water demand data fits well in to log logistic distribution than a normal distribution.

American Water Works Association (AWWA) Research foundation sponsored a study (Bowen et al., [9]) in residential water demand use patterns in USA results, revealed that the demand data was not distributed normally. Several data transformations to improve the data analysis were investigated and it was found that the log transformation was only mildly effective in reducing the positive skewness of the frequency distributions of the data, making them more nearly normal.

## 2. METHODOLOGY

Daily water consumption data for 3 demand zones in Canada were obtained and analysed. The water company collected the data using data loggers at the water treatment plant by the water services division. The data were obtained from 01.01.09 to 31.12.14. This particular Water Works system delivers an average of 225 million litres of water to approximately 270,000 households and businesses across approximately 297 square kilometres (114 square miles) of the developed portion of Canada.

In this research a suitable statistical distribution was selected using a series of applications. Data were screened and sorted by plotting raw demand data against time. This provided a quick reference to check the accuracy of data. If the points were homogeneously distributed and there were no negative points, this meant that the data is almost accurate. Similarly, if

there was any inconsistency in distribution, this would allow us to remove all abnormal data points.

Following sorting out the data, the data were then analysed using MINITAB statistical package to fit into a probability distribution. Continuous distributions such as, normal, Log-normal, Weibull and log-logistic were applied to find a suitable distribution.

## 2.1 Analysing Data

Analysing univariate data (single column of data such as water demand) with a specific probability is one common application in modelling. Once data has been fitted into any distribution, the goodness of fit method should be used to see how well the data will fit into the particular distribution. The appropriateness of the Log logistic distribution for water consumption data was assessed by comparison to the normal and lognormal distributions using the Anderson Darling goodness of fit parameter. The Anderson Darling (AD) statistical method is a measure of how far the plot points fall from the fitted line in a probability plot. A smaller AD value indicates that the distribution fits the data better. R Johnson [10] stated that as a guide line, the large sample 5% point is 2.492 and the 1% point is 3.857 could be used to assess the data.

## 3. RESULTS AND DISCUSSION

### 3.1 The graphical method

There are various numerical and graphical methods used in estimating the parameters of a probability distribution. In this research, graphical methods were selected for the analysis along with the Maximum Likelihood method to draw the probability plots (Fig 1-4). The data were analysed using 95% confidence interval (5% significance level) and fitted to normal, lognormal and log logistic distributions to establish the parameters of the particular distribution. The middle line in the probability plot shows the normal line and other two lines show the 95% confidence interval. Normal probability plots are useful in identifying distributions that actually fit to the normal distribution and the distributions which have tails heavier and lighter Montgomery and Runger [11]. The normal probability plots for the Canadian water consumption data shown on Figure 3. It shows that for Zone 2 and 3 data, the points on the left and right are above the normal line. This explains that the data has a heavy tailed distribution. Zone 2 data lies on the normal line. It was observed that by analysing water demand data, the water demand have a normal or heavy tail distribution.

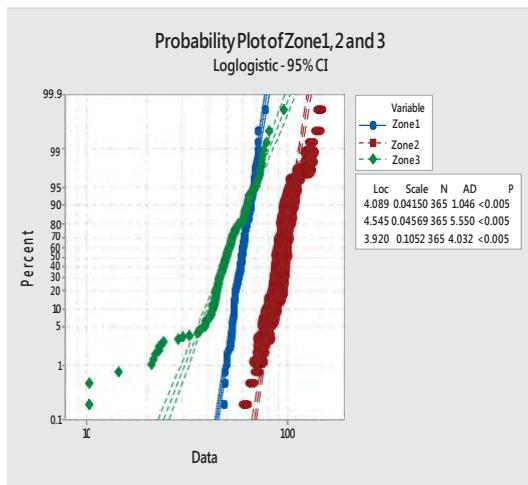


Fig. 1. Probability plots for Log logistic

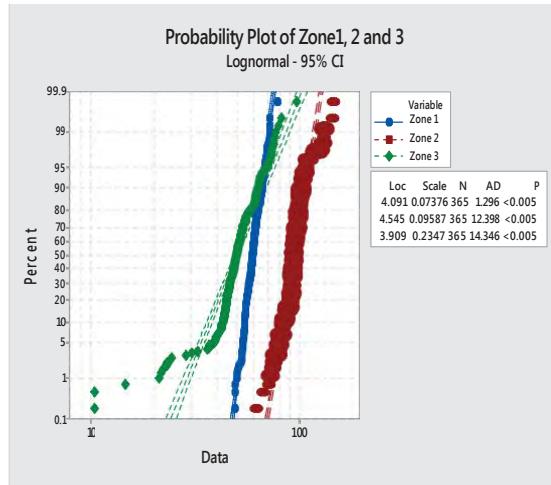


Fig. 2. Probability plots for Lognormal

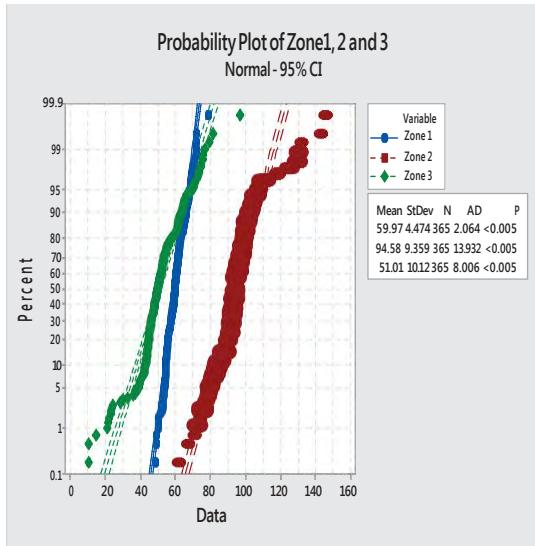


Fig. 3. Probability plots for Normal

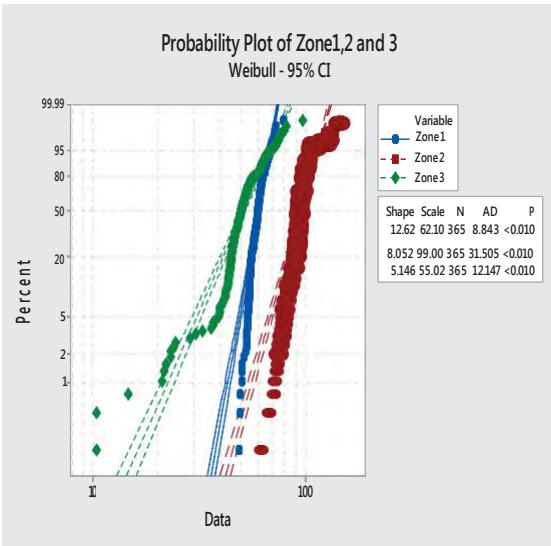


Fig. 4. Probability plots for Weibull

### 3.2 The goodness of fit

The goodness of fit used for this analysis is Anderson Darling test. AD values were obtained for all 3 zones for normal, lognormal, Log logistic and Weibull distributions and are shown in Fig.5 to 7. It can be seen that Log logistic distribution has the lowest AD values when compared with the normal, Weibull and log-normal distribution.

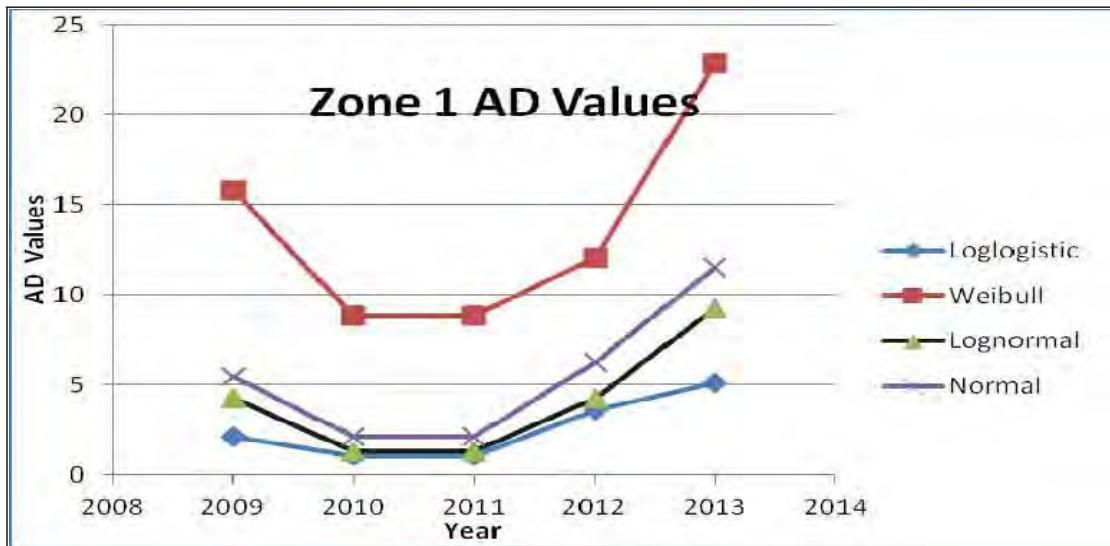


Fig. 5 AD values for Zone 1

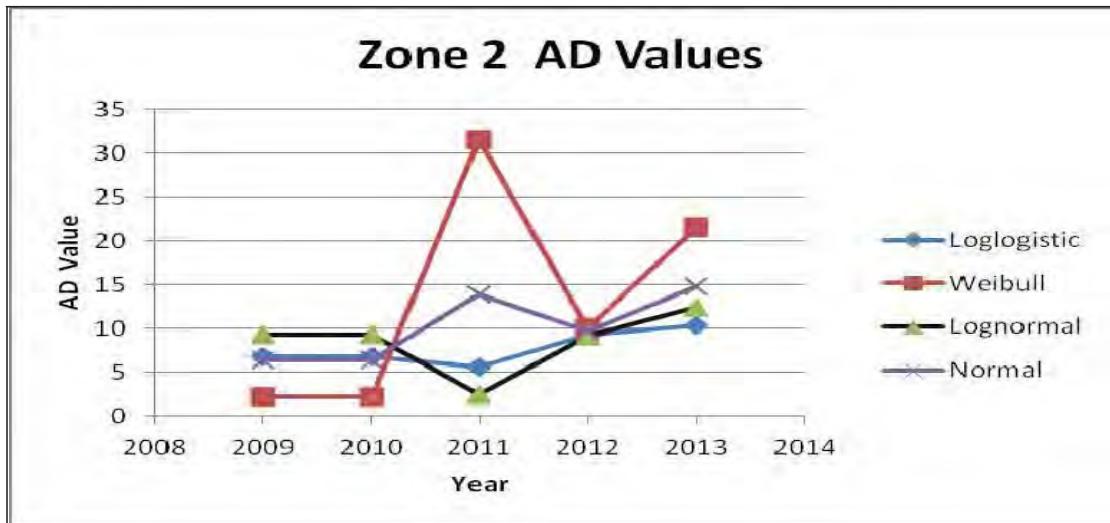


Fig. 6 AD values for Zone 1

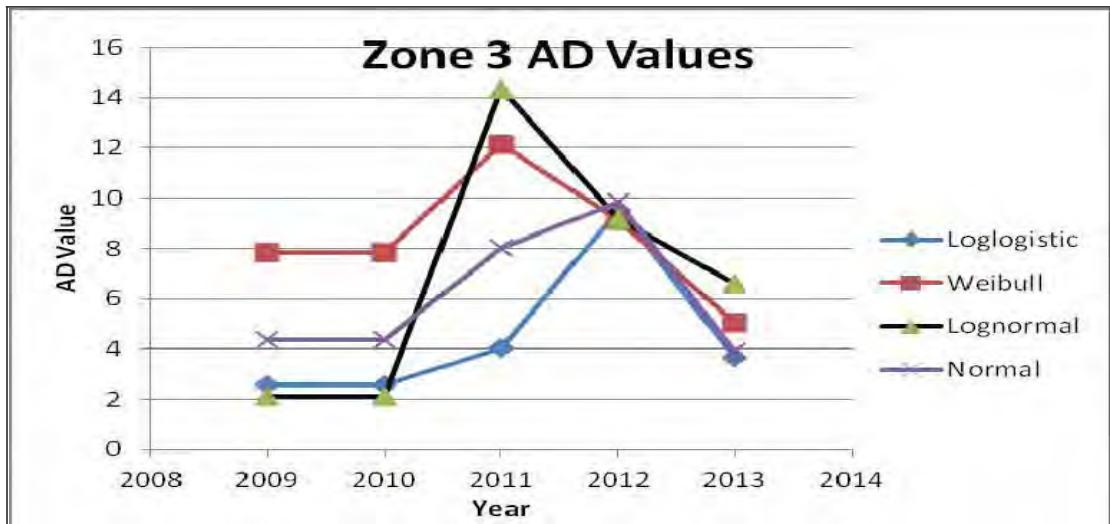


Fig. 7 AD values for Zone 1

### 3.3 parameter estimates

The parameters of the particular distribution such as location, shape and scale are also essential to describe the distribution. The lowest location parameter obtained for log logistic is 3.92 and the highest figure is 4.562. Similarly the lowest scale parameter is 0.0296 and the highest is 0.389.

Parameters for Normal distribution are mean and standard deviation, though Lognormal, Log logistic and Weibull distributions, they are location, shape or Scale parameters. These parameters will allow the distribution to have a flexibility and effectiveness in modeling applications. Scale parameters allow a distribution to take on a variety of shapes depending on the value of the shape parameter. The effect of the location parameter is to simply shift the graph to left or right on the horizontal axis. The scale parameter describes the stretching capacity of the probability distribution function. If the scale parameter is greater than 1 then it will stretch the probability distribution function. Table 1 shows the parameter estimates for the obtained data.

Table 1. Shape and Scale parameters for Log logistic distribution

	Zone 1		Zone 2		Zone 3	
	Location	Scale	Location	Scale	Location	Scale
2009 data	4.089	0.0415	4.545	0.0457	3.920	0.105
2010 data	4.089	0.0415	4.545	0.0457	3.920	0.105
2011 data	4.187	0.055	4.446	0.063	4.308	0.142
2012 data	4.098	0.389	4.361	0.041	4.152	0.092
2013 data	4.115	0.0296	4.562	0.054	3.992	0.088

## 4. CONCLUSION

If water demand fits the normal distribution, then applying the mean value in designs would make no difference to the existing method. However, due to the positive extreme values in the demand data it is certain that the demand data would not fit the normal distribution.

Findings from this study show that distribution patterns for Canada is very similar to UK studies completed in 2002 by Surendran and Tanyimboh [7]. The AD values obtained for the Weibull distribution has higher values than other 3 distributions and it is not suitable to model water demand data. The study shows that out of four distribution patterns studied, the log-logistic seems to have the lowest AD values and it was the most suitable distribution pattern to standardise when modelling water demand. However, normal and the log-normal distribution also have marginally acceptable AD values.

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## COMPETING INTERESTS

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# WATER EFFICIENCY EVIDENCE BASE STATISTICAL ANALYSIS

**Rob Lawson, Dene Marshallsay, Victoria Ashton\*, Keith Ponsonby**

*Artesia Consulting & Callidus, Unit 2, Badminton Court, Station Road, Yate, BS37 5HZ*

## ABSTRACT

**Aims:** This project updated the Water Efficiency Evidence Base with 25 water efficiency projects and two metering projects. This is the most comprehensive review of water efficiency evidence completed to date in the UK.

**Results and Conclusions:** The body of evidence from water efficiency studies indicates that reductions in consumption are likely to occur as a result of water efficiency activity, and that overall, an average saving of 13.5 litres per property per day can be achieved.

This is an important finding from this project, which confirms that suitably designed water efficiency programmes will reduce household water consumption.

A compulsory metering programme analysed was shown to deliver statistically significantly more water than any of the water efficiency programmes.

Projects and data of greywater and rainwater harvesting systems are very limited.

**Keywords:** water efficiency, water saving, consumption, retrofit, metering, greywater, rainwater, devices, evidence, statistical, analysis.

## INTRODUCTION

The Water Efficiency Evidence Base was created to help water companies identify the most effective approach to water efficiency retrofit programmes. The evidence base was initially started by Waterwise in 2008. In 2012 the Environment Agency led an independent review of the evidence base in order to test its robustness and reliability and to give increased confidence to the data it contains. A follow up project was commissioned to update the evidence base with new water efficiency studies which have been completed by water companies. In addition water companies now have increased levels of metering and in a few cases have also tested greywater and rainwater harvesting systems, and these will be analysed as well.

## METHODOLOGY

The project objectives were to carry out a review of large scale water efficiency projects, studies quantifying the impact of metering on demand and any results from rainwater and greywater recycling harvesting projects.

The overall approach we took to deliver the project consisted of four key steps:

1. The identification of suitable water efficiency projects and datasets. This was achieved by contacting all water companies and asking them for information and then compiling an exhaustive list.
2. Select a short list of projects and data for review and statistical analysis. This was done by scoring and ranking the projects against defied criteria.
3. Detailed analysis of the short listed projects. A range of statistical, contextual and qualitative analysis was applied to the project data sets. An output from this step was statistical tables and summary information in a consistent format.
4. Reporting and dissemination. This report shows the findings and results from the analysis.

Twenty water companies were contacted of which eleven responded detailing the projects they had undertaken which may be suitable for inclusion in the analysis. Five water companies responded to the initial information request but they did not have any projects to contribute and four companies did not respond at all. In total, information was given on about fifty water efficiency, metering and grey and rain water recycling projects.

Projects were selected for inclusion in the evidence base by applying a set of selection criteria on the projects supplied by the water companies. Criteria included; availability of raw data, data type and form, size of the project etc. The project team used professional judgement to decide whether the projects should proceed to further analysis. We wanted a good range of projects and a good geographical spread if possible.

The final list of projects to proceed to detailed statistical analysis consisted of: nine water efficiency projects, three domestic metering projects and one greywater recycling project. In addition, the data from the previous Phase of the evidence base was revisited so that all of the analyses were consistent.

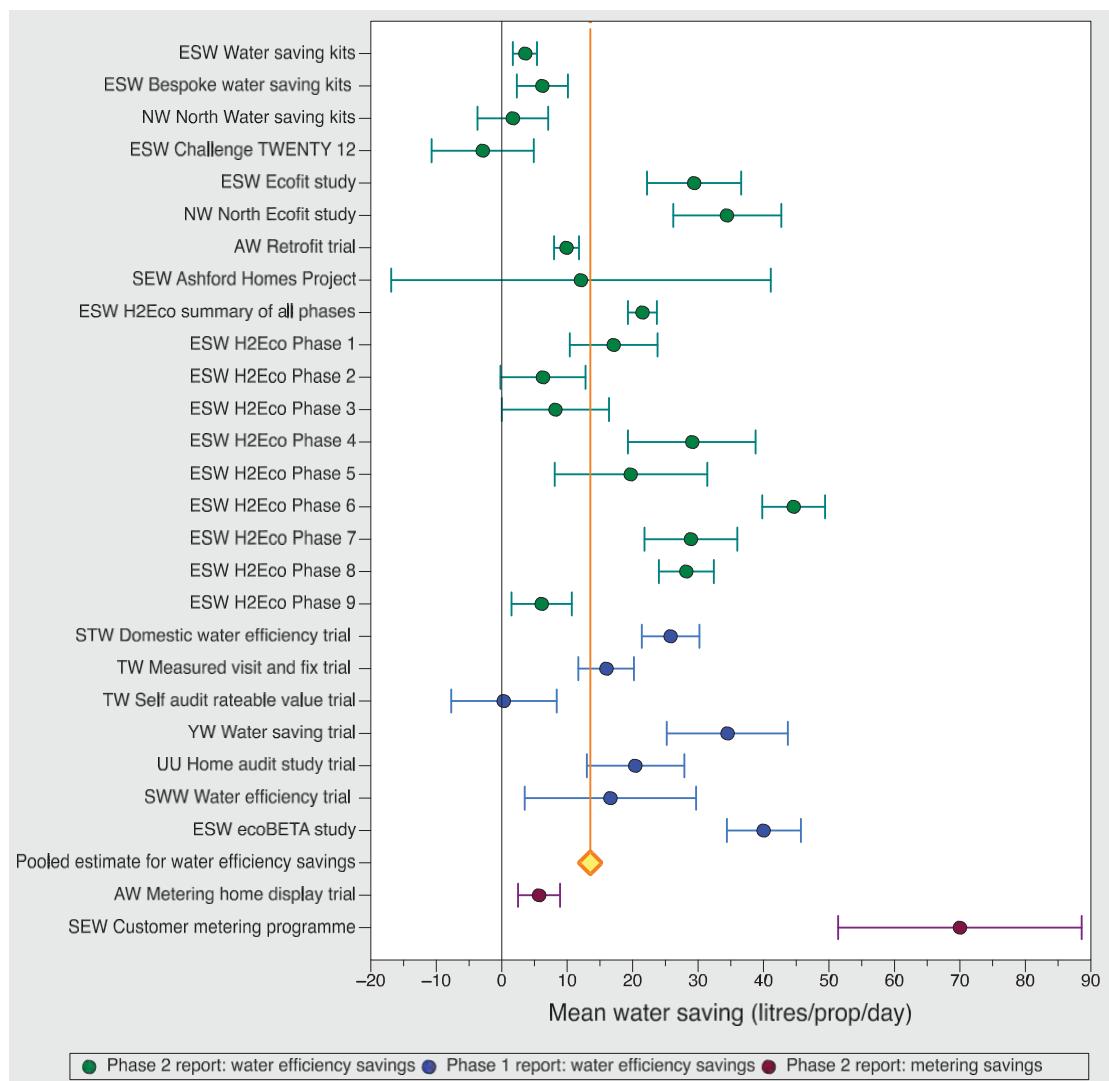
A consistent analytical approach was taken for the analysis of projects. Firstly, two different types of statistical approaches were used; descriptive statistics and inferential statistics. Secondly, a set of control data and study data were identified. Thirdly, a consistent statistical test has been used in this project, where possible to infer if the data sets are statistically significant or not from another data set.

For all projects analysed a table of results was produced to enable a consistent comparison for all results.

## RESULTS

This project presented statistical analyses for 25 water efficiency projects and three metering projects. The body of evidence that is now available from water efficiency studies indicates that reductions in consumption are likely to occur as a result of water efficiency activity and that overall and average water saving of 13.5 litres per property per day can be achieved. This

is equivalent to around 3.5 per cent of consumption (assuming 150 litres per head per day average per capita consumption and an average occupancy of 2.5). The figure below is a meta-analysis chart allowing the comparison of the results from all of the projects analysed in this project.



By comparing the means of each project (dots in the centre) it is possible to use this graph to look at the most likely and range of water saving for different types of study. By looking at any bars which cross the zero line also gives information about the statistical significance of the water savings. Any project with bars that cross the zero line (e.g. SEW Ashford Homes) are not statistically significant unlike H2eco Phase 6 which has returned statistically significantly high water savings. These results are also presented in tabular form below.

Project title	Sample size	Sample mean (l/h/d)	Lower CI (l/h/d)	upper CI (l/h/d)
ESW Water saving kits	7,678	3.6	1.7	5.4

ESW Bespoke water saving kits	610	6.2	2.3	10.1
NW North Water saving kits	423	1.7	-3.7	7.1
ESW Challenge TWENTY 12	902	-2.9	-10.7	4.9
ESW Ecofit study	330	29.4	22.2	36.6
NW North Ecofit study	177	34.4	26.2	42.7
AW Retrofit trial	12,231	9.9	8	11.8
SEW Ashford Homes Project	52	12.1	-16.9	41.1
ESW H2Eco summary of all phases	7,296	21.5	19.3	23.7
ESW H2Eco Phase 1	663	17.1	10.4	23.8
ESW H2Eco Phase 2	626	6.3	-0.2	12.8
ESW H2Eco Phase 3	146	8.2	0	16.4
ESW H2Eco Phase 4	361	29.1	19.3	38.8
ESW H2Eco Phase 5	748	19.7	8.1	31.4
ESW H2Eco Phase 6	1,042	44.6	39.8	49.4
ESW H2Eco Phase 7	545	28.9	21.8	36
ESW H2Eco Phase 8	1,507	28.2	24	32.4
ESW H2Eco Phase 9	1,658	6.1	1.5	10.7
STW Domestic water efficiency trial	717	25.8	21.4	30.2
TW Measured visit and fix trial	823	16	11.7	20.2
TW Self audit rateable value trial	525	0.3	-7.7	8.4
YW Water saving trial	359	34.5	25.2	43.7
UU Home audit study trial	246	20.4	13	27.9
SWW Water efficiency trial	341	16.6	3.5	29.7
ESW ecoBETA study	238	40	34.4	45.7
AW Metering home display trial	427	5.7	2.5	8.9
SEW Customer metering programme	44,576	70	51.4	88.6

Individually, some water efficiency retrofit schemes delivered greater water savings than others and not all water savings were statistically significant. South East Water's customer metering programme saved statistically significantly more water (l/property/day) than any of the water efficiency programmes.

This range of water savings within the results is due to three main factors:

- The variety of water efficiency interventions analysed in this report;
- The effectiveness of individual water efficiency programmes; and
- The design of projects to quantify the effectiveness of water efficiency programmes.

Greywater and rainwater harvesting recycling and systems can yield water savings but evidence to support this is still very limited. It is clear that systems are more cost effective when incorporated into the design phase as retrofitting is more difficult and costly and consequently the uptake is very small and the payback prohibitive of widespread installation.

The review of RWH and GWR undertaken in this project highlights the lack of empirical data on the extent to which these systems reduce potable water use in UK household settings. The limited data that are available suggest that the cost-effectiveness of RWH and GWR systems depend on key system design factors that can be optimised (e.g. rainwater tank size); and the careful selection of appropriate properties for installation. The Berlin case study suggests installations in apartment blocks (or similar) may be the most promising option. However the case for such systems remains unproven without significant further research. One of the barriers to such research is the lack of drivers to install more of these systems in the UK.

## DISCUSSION

This project confirms that suitably designed water efficiency programmes will reduce household water consumption.

The actual saving that will result from any individual water efficiency activity will depend on a number of factors but it is important to think about data and measurements at the design phase.

It is recommended that anyone designing a water efficiency programme should discuss their plans with colleagues and peers in the water industry, in order to achieve the best savings possible. The engagement and sharing of ideas that already occurs within the water industry should continue, and this will ensure that over time, water efficiency programmes become increasingly effective.

Whilst the evidence base for water efficiency is now large and broadly conclusive, there is more work required on metering. The studies completed to date are limited in the way that consumption pre-meter installation is estimated. It is recommended that the water industry develop approaches to monitor consumption at the individual household level prior to meter installation. This will enable a more accurate estimate of the savings due to metering to be estimated. There are likely to be challenges in achieving this, but these can be overcome if the industry works together.

# Demystifying the Showering Experience: Understanding current shower behaviour and showerhead preferences

Kemi Adeyeye<sup>1</sup>, Kaiming She<sup>\*2</sup>

<sup>1,2</sup>School of Environment and technology, University of Brighton

## ABSTRACT

**Aims:** The aim of the project on which this paper is based is broadly to demystify the performance criteria that inform the user's expectation of 'a good shower' experience. The objectives are to begin to define and empirically quantify the conditions and range of acceptability of water efficient shower-heads using physical and socio-psychological factors, and the effectiveness of the shower product to promote sustained water efficiency practices.

**Study design:** The results in this paper are based on a preliminary sampling stage of a 2 stage study.

**Place and Duration of Study:** The study was conducted in Brighton from March to April 2015

**Methodology:** This is an ongoing two stage study involving laboratory experiments and in-home user studies. A survey of the current showering practice and showerheads is carried out and the survey data is examined to gain some insights into showerhead choice, habit and behaviour as a first step in demystifying the showering experience.

**Results:** The paper presents an overview of the variables utilised in this study as well as the preliminary user feedbacks on their current showering practice and showerheads.

**Conclusion:** The findings present valuable insights in showering practices which can be used as a basis for further in-home user studies.

**Keywords:** Showerhead, Showering, Shower experience, Water efficiency

## 1. INTRODUCTION

The literature on the sociological use of water suggests dimensions to water use beyond the need to keep hydrated or stay clean e.g. water use for fun, leisure and relaxation or the increasing popularity of power showers.

At present, showers and showering account for between 25-30% of daily per capita water use [1, 2] and the demand for separate shower cubicles has increased at an average of twenty per cent per year since 1999 [3], a figure that suggests that the composition of UK bathrooms is on the move and that showering is being positioned as a normal everyday activity [4]. The recent EST data shows that the shower, using over two billion litres of water per day, is now the highest water use function in the home, overtaking the toilet [1]. This has led to various studies looking at different aspects of shower use, including the use of efficient showerhead fixtures in relation to reductions in water use [5, 6], shower performance in the context of awareness and

\* Tel.: +44 1273642257

E-mail address: k.m.she@brighton.ac.uk

habits [7], influence of shower monitors on water usage [8] and comfort, lifestyles, performance or perceived needs against new efficient products [9]. However, no study has explored in any detail the performance parameters that define the degree to which products are accepted or rejected. For example, some studies show that the ambient conditions e.g. the sound produced by the shower affects the perception of the quality of the experience - synonymous to the experience from singing in the shower. A bathroom product manufacturer, Kohler, now produces a shower head with integrated speakers to exploit this premise. [10] also found that a colder bathroom may result in a longer shower, as the hot water warms the room to make the shower more comfortable.

Water use in a building consists of water obtained directly from its fixtures and fittings e.g. taps, showers, garden hoses, toilets, washing machines and dishwashers, and indirectly in building service systems e.g. water-based central heating and cooling. Water use is largely an individual decision that is based on a need, which in turn is shaped by knowledge and beliefs on pricing, water scarcity, and water saving technologies, personal characteristics, water usage level and other social, economic and psychological factors.

There are therefore a number of factors that affect domestic water efficiency:

- i) Physical/technological – focusing on the impact of physical or technological changes to achieve water savings, or promote efficient water use by water users;
- ii) Sociological – a social service approach to understanding distribution and use;
- iii) Psychological – understanding the factors and influences that inform water use behaviours and the propensity to adopt new solutions, interactions and to alter behaviour to suit;
- iv) Action/activity – deconstructing water use activities to target and reduce waste whilst preserving the benefits, and to some extent, pleasures derived from such activity.

The study focuses on the first and last approach and aims to define physical (e.g. temperature, pressure, spray patterns), physiological (size, shape and form) and sociological action (cleaning, relaxation) and performance benefits that water users derive from the showering experience. The objective is to define the extent to which these physiological and sociological factors inform the user's propensity to choose and maintain prolonged use of water-efficient shower heads.

## **2. METHODOLOGY**

This is an ongoing study involving 12 water efficient showerheads and the overall project includes two separate stages, with stage 1 being a series of laboratory experiments on the showerheads and stage 2 being an in-home user study. The over-arching aim of stage 2 is to explore the user acceptability (condition, rate and range of acceptance) using key performance, preference and habitual criteria and the propensity of the shower-head to result in water savings (time in shower, amount of water used etc.). Stage 2 may be further divided into three sequential parts: a) A user survey of the current showering practice and showerheads followed by a detailed analysis of survey data, b) a 12-showerhead in 12 week challenge and c) analysis of user preferences with respect to the physical quantities obtained via laboratory experiments. This paper is concerned with part (a) of Stage 2 of the project. The method of study is in the form of participatory action, which is ideal for testing theoretical constructs that examine knowledge, behavior and experiential realms. An advantage of this methodology is that a smaller (focus-group) size sample can be used with more emphasis placed on 'depth' instead of 'breadth'. The participatory action methodology utilized in this study is underpinned by the Theory of Planned Behaviour [e.g.11], Theory of Reasoned Action [e.g.12] and the Technology Acceptance Model [e.g.13].

12 adult volunteers are involved in stage 2 over a period of 12 weeks. Each volunteer is issued an eco-showerhead on a weekly basis and asked to provide feedback of their experience. A range of parameters are examined including for example showering habits and frequency, times/duration of shower, shower function (cleaning, relaxation, amount of water used), heuristics for choosing shower types,, environmental values, and physical characteristics of the shower provision (design, shower-head type, enclosure, and metering). Each participant/volunteer takes part in the part (a) survey before proceeding to the 12 week challenge. The 12 showerheads are rotated between the participants in their home use over

12 weeks and a feedback form of specific questions is provided for the participants to record their experiences for each use of the showerhead in their possession. The showerheads are swapped at the end of each trial week with blank feedback sheets to go with them.

## **2.1 Sampling**

The key statistical sampling question is how many, and for how long? The traditional approach to the quantitative study is to conduct large n-studies to test the statistical significance of variables. However, this brings the researcher no closer to understanding the logic behind the phenomenon; what are the influences, dependencies, causes and effects. This proof-of-concept study therefore aims for depth instead of breadth, with the view to start to understand the motivators behind choice, preference and use of water efficient showerheads.

The quick-fire approach to the user i.e. one week per showerhead was aimed at capturing feedback that is yet to be influenced by habit, relative perceptions of others or the 'rebound effect'.

Two stages of sampling were used. First was random sampling by sending an open call (an email to all staff employed by the University of Brighton) for participants for a 12 shower in 12 weeks challenge. Interested participants were then asked to complete an online survey for the second stage of purposive sampling.

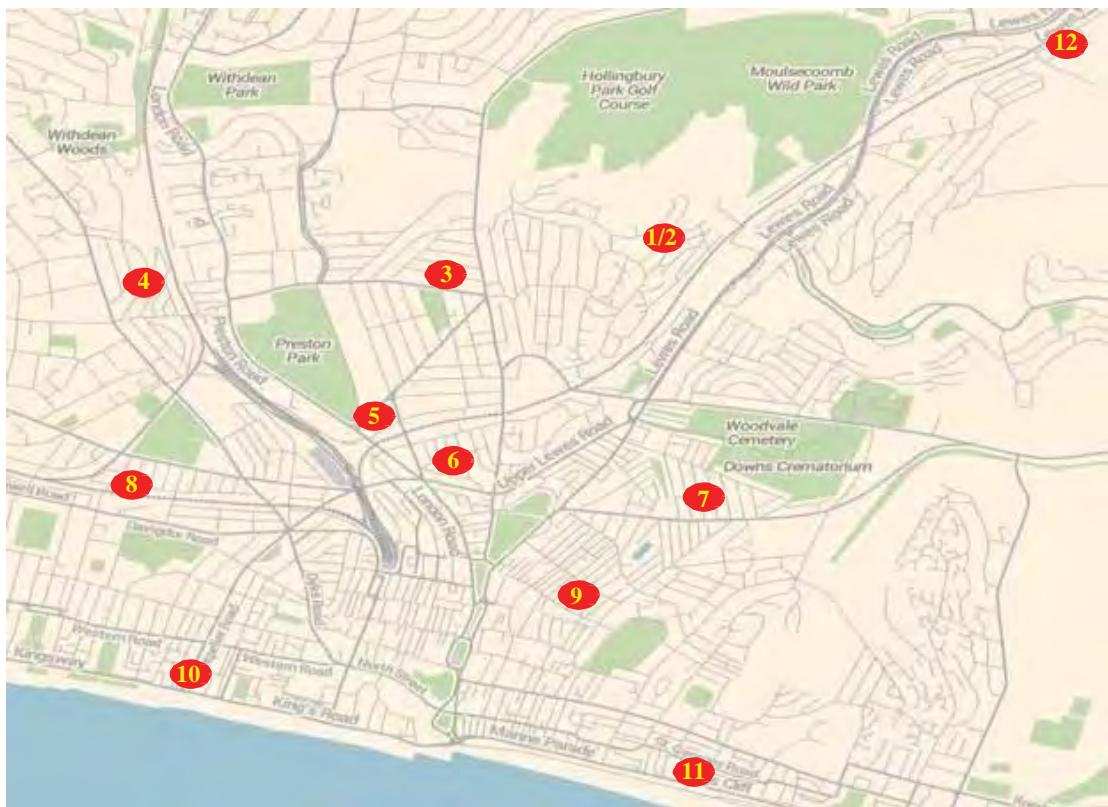
This survey was used to shortlist the final 12 participants: 6 male and 6 female. It was also useful to gather the required socio-demographic, anthropometric and other background data required for the analysis stage of the study. Summary data on participants are presented in the following pages.

## **2.2 The selected participants**

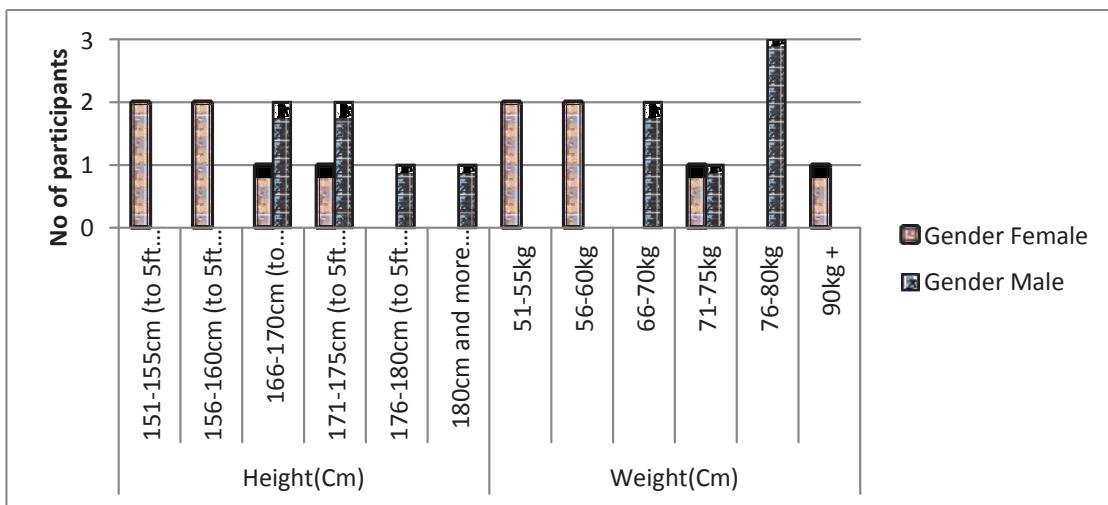
All the participants in the study live and work in Brighton, UK. This is primarily because of the time and logistics of the weekly shower swaps. In addition, a wider geographic spread of such small sample will impact on the quality of the resulting analysis of the data. As it stands, all participants reside within 5 miles of each other (Fig. 1), have the same water supplier and are all metered; universal metering was recently implemented by the water supplier in the city.

Demographically, there is an equal spread of male and female participants for the age range 25-34, 35-44, 45-54 years old. Half of the female participants are living with one other adult, whilst 2 are living with two other adults and one has no information provided for this. Only one female participant has 2 children aged less than 18 years old. Similarly, 4 of the male participants are living with one other adult and 1 with two others. One has one child, and two others have two children under 8 years old.

Of the female participants, 3 have full-time employment, 1 works part-time, 1 is a full time student whilst one works and studies part-time. 5 of the men work full-time whilst 1 studies full-time. 5 of the 6 women have post-graduate or doctorate degrees, and one a Bachelor degree. Apart from the one currently studying, 2 of the male participants have post-graduate or doctorate degrees, 2 professional qualifications and 1 further education/college. There is also good representation of the income brackets but this are slightly skewed towards the lower and higher range. 9 of the 12 participants stated that they have no religion, 2 stated that they were Christians and 1 selected 'all'. One is divorced, 9 married or cohabiting, 1 single. Other demographic data is shown on Table 1.



**Fig. 1. Relative location of participants in Brighton, UK**



**Fig. 2. Anthropometric distribution**

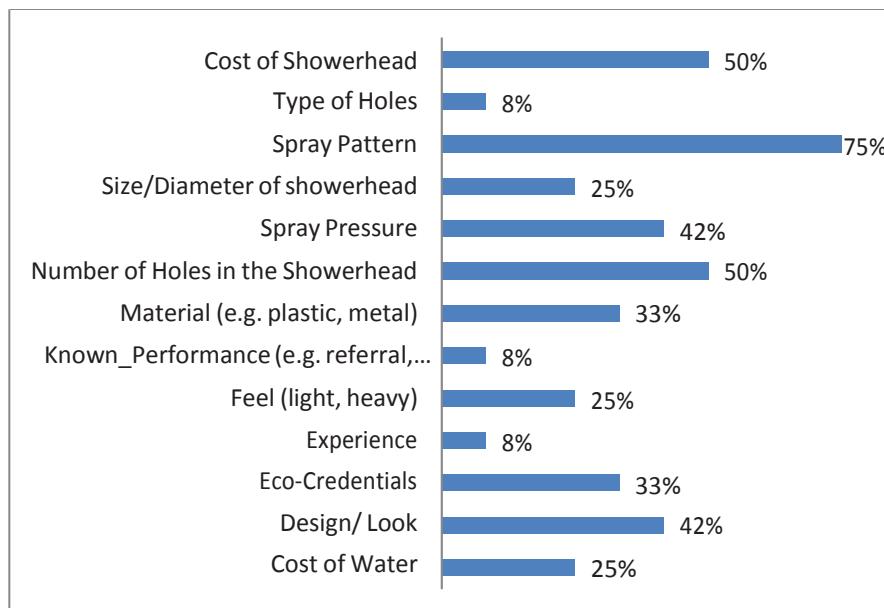
The demographic distribution presented above is important for understanding the data generated during the study. However, the pertinent factors for achieving the goals of this study are gender, height and weight distribution in comparison to the national average and used as the benchmark for the first part of this project: the laboratory experiments . Fig. 2 shows that the height and weight distribution is representative [14].

**Table 1. Demographic representation of participants**

		Gender				Gender	
		Female	Male			Female	Male
Adults in Household (Age_18+)	1	3	4	Children in Household	1	0	1
	2	2	1		2	1	2
	Bachelor Degree	1	0		£20,000 - £29,999	3	2
	Currently studying	0	1		£30,000 - £39,999	1	0
	Further Education/ College	0	1		£40,000 - £49,999	1	0
	Posgraduate degree, Doctorate	5	2		£50,000 - £59,999	0	1
	Professional qualification	0	2		£60,000 or more	1	2
	Employed (full-time)	4	5	Relationship_	Divorced	1	0
	Employed (part-time)	1	0		Married or domestic partnership	3	5
	Student	0	1		Single, never married	1	1
Ethnicity	employed and student	1	0		cohabiting	1	0
	Asian/Asian British	0	1	Religion	All	1	0
	Mixed/Multiple ethnic groups	1	1		Christian (all denominations)	0	2
	Polish Catholic & Jewish	1	0		No religion	5	4
	White	4	4				

### 3. RESULTS AND DISCUSSION

The demographics and anthropometric data obtained from the survey helps to understand the characteristics presented in the study sample and provides a basis for the analysis of the weekly feedback data from the shower challenge. It also provides some information and trends for choice and preferences of showerheads as well as showering trends and practices.

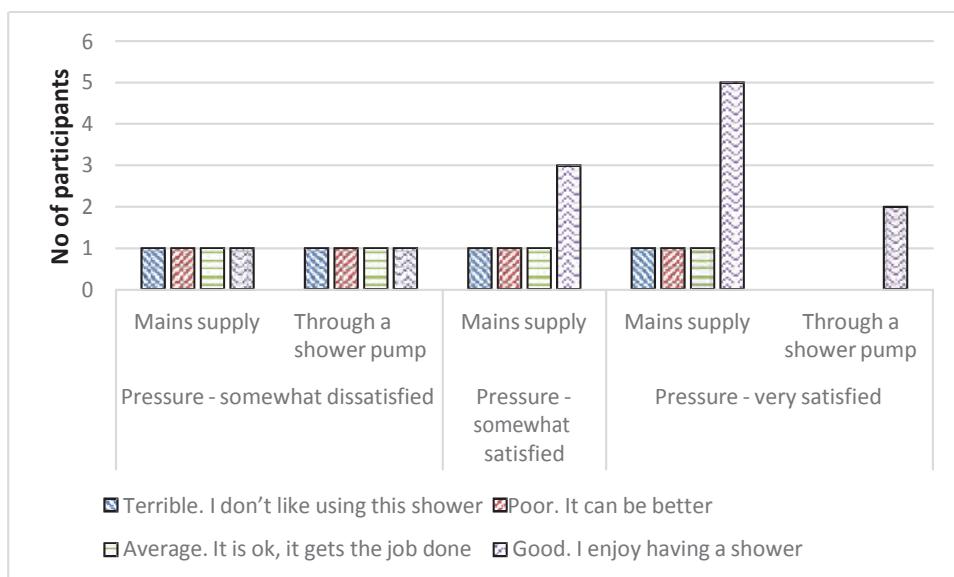


**Fig. 3. Factors that inform the choice of a showerhead**

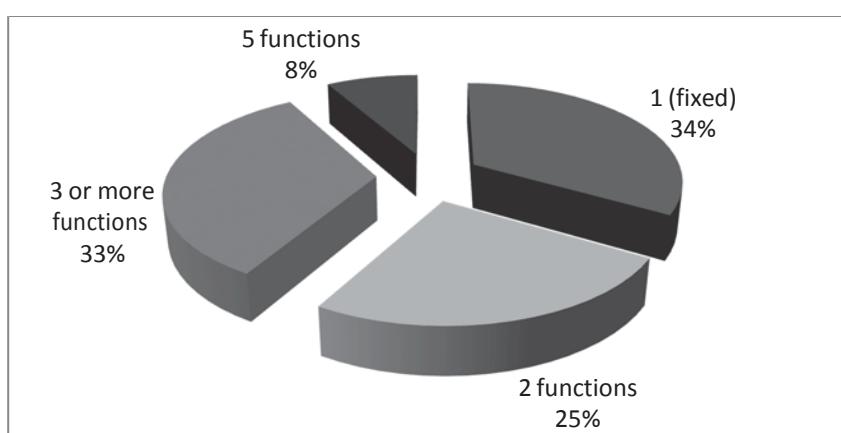
Fig. 3 shows that in terms of the showerhead product, majority of the participants will primarily consider the spray pattern and distribution of water by the showerhead. This is followed by the cost of the showerhead, number of holes, design and look of the product as well as the spray

pressure. Of the 12 participants, 8 purchased their current showerhead within the past 5 years, 2 are using the showerhead provided for example as part of a rented property, and 2 do not know if their showerhead is water efficient or not. The non-selected options are also noteworthy: for example, none of the participants stated that their showerhead is water efficient. The analysis found no correlation between choice and satisfaction with shower.

On water supply specifically to the showerhead, 75% has mains supply and 25% supply via a shower pump. When asked about their overall shower experience using their current showerhead, the 3 participants with the pumped supply to the shower were consistently somewhat satisfied or satisfied with their shower experience. Whilst there was a wider range of response for those supplied directly from the mains. However when compared as a subset of satisfaction with the mains water pressure (Fig. 4), those that were somewhat or very satisfied with their mains supply were also more likely to be happy with their shower experience and the enjoyment of having a shower.



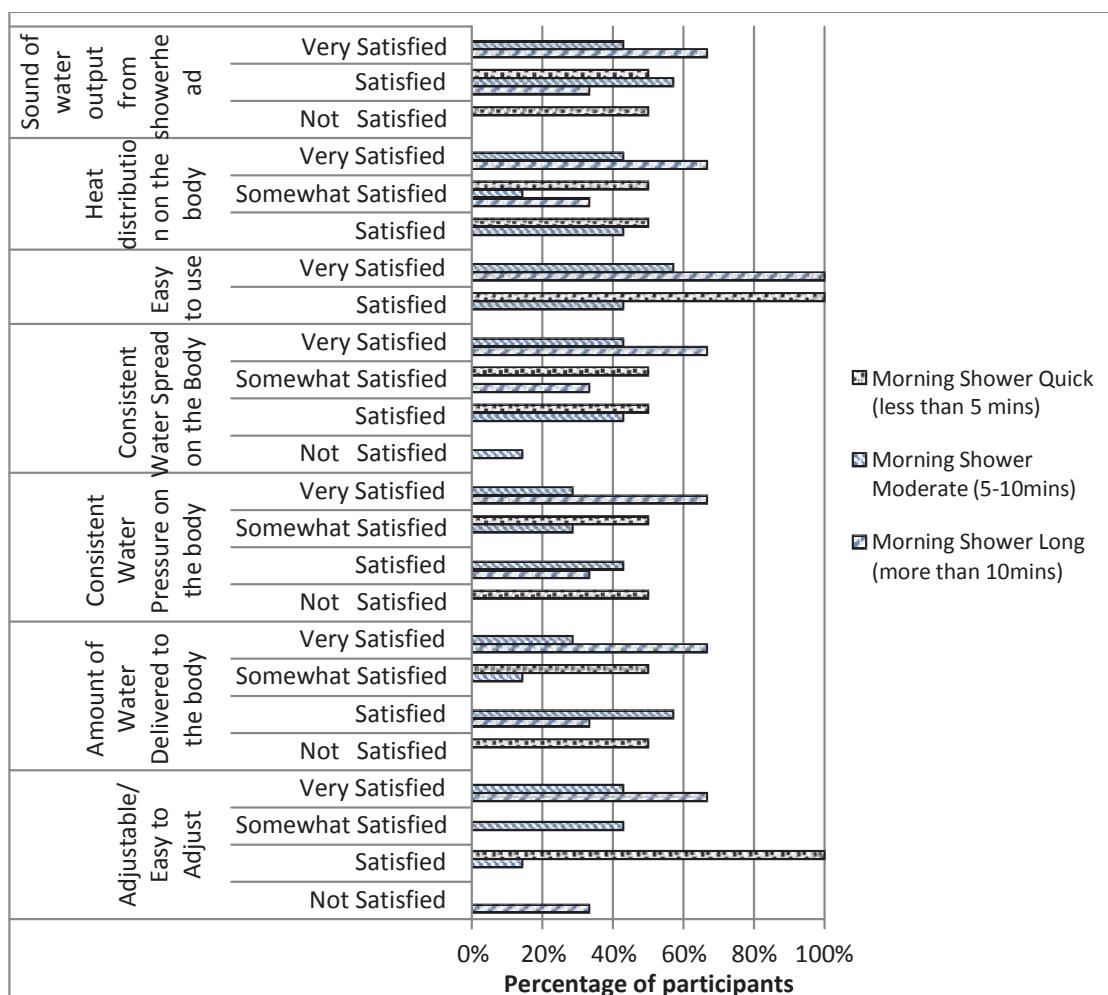
**Fig. 4. Water supply pressure and overall shower experience**



**Fig. 5. Spray functions in pre-study showerheads**

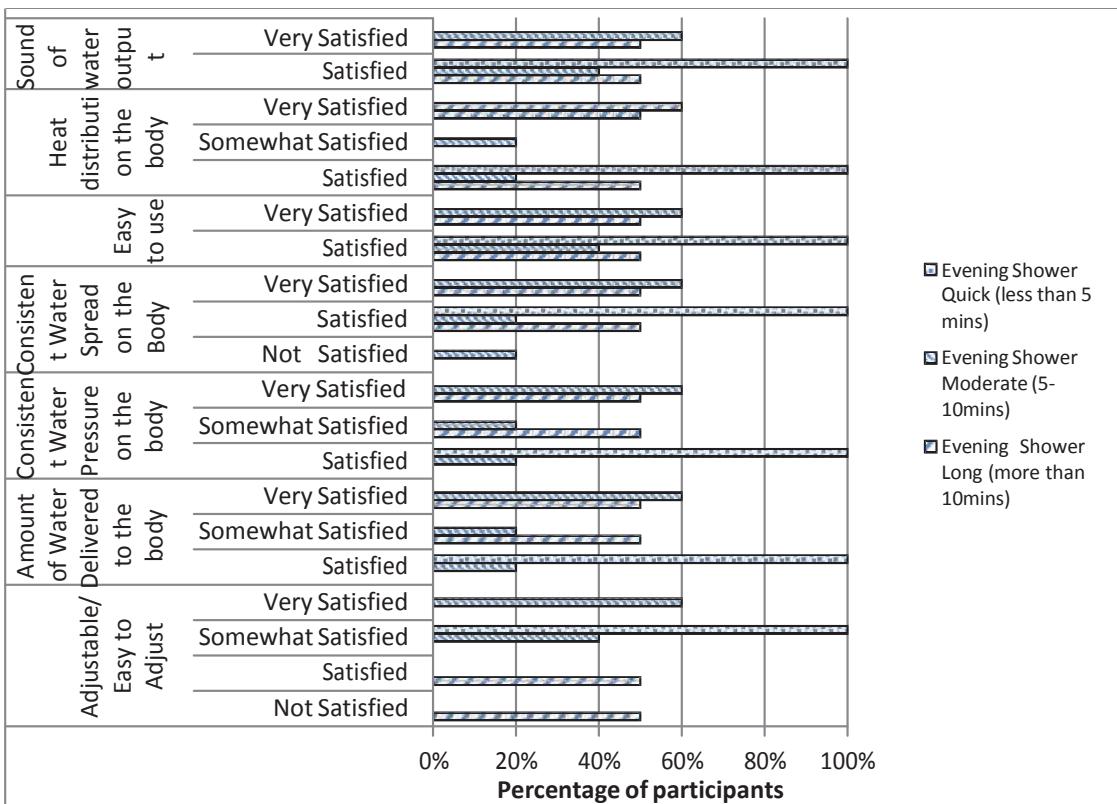
It was also found that three quarters of the participants prior to the study had showerheads with more than one spray function (Fig. 5). However, none of these participants stated that they regularly vary the function of the showerheads to take advantage of these additional functionalities.

The degree of satisfaction of the performance of showerheads were also rated based on quantifiable criteria and metrics utilized during the first experimental stage of the study. This is to aid benchmarking and comparison. These criteria include: pressure, temperature, spray distribution etc. Results show that criterion such as ease of use, adjustability, temperature, acoustics, and amount of water delivered to the body derived higher levels of satisfaction in their showerheads. When compared with the duration of their morning and evening shower (Fig. 6 and 7), it was found that the ease of use and adjustability of the shower was the key criteria for promoting a quick shower in preparation for the work or study day. Similarly, those not satisfied with the other criteria were more likely to take shorter showers. The long shower duration shown under ease of use in Fig. 6 was curious, and initial findings from the shower challenge has shown that one of the participants takes really long showers (up to 40-50 minutes) in the morning. This provides interesting dimensions to the study and will be further explored in more detail.



**Fig. 6. Performance and duration of morning shower**

However, in the evening, the tendency was split. Those that are satisfied are more likely to take quick showers of less than 5 minutes. Those that are very satisfied are more likely to take moderate to long showers. The shorter duration may also be due to awareness of the impact this additional shower may have on water bills; all participants are metered, and the longer duration may be informed by the purpose of the shower which will be presented next. These findings will be explored in more detail at the end of the 12 week challenge.

**Fig. 7. Performance and duration of evening shower**

Routine, habit and purpose also informs the procedure, location, and duration of the shower. Therefore, it was useful to examine when and where the participants shower during the week and whether there is some correlation with how long they spend in the shower. To fully understand these sets of results, it was important to first review the 'at home/out of home' routine of the participants which shows that majority had a regular e.g. 9am to 5pm out of home hours during weekdays with 4 out of 12 having irregular patterns during weeknights e.g. to accommodate for social activities. As expected, this trend changed at weekends with majority having a more ad-hoc routine.

**Table 2. The influence of the shower purpose on the duration of the shower**

	Morning (before noon)	Afternoon (noon - 6pm)		Evening (after 6pm)	
		As part of my daily routine	As part of my daily routine	To refresh (e.g. after leisure activities)	To relax (e.g. after a work day)
Duration_Morning	Long (>10mins)	27%			
	Moderate (5-10mins)	64%			
	Quick (< 5 mins)	9%			
Duration_Afternoon	Long (>10mins)		0%	0%	100%
	Moderate (5-10mins)		0%	50%	0%
	Quick (< 5 mins)		0%	50%	0%
Duration_Evening	Long (>10mins)			20%	33%
	Moderate (5-10mins)			60%	67%
	Quick (< 5 mins)			20%	0%

Table 2 shows the findings. Note that the data shows percentage distribution and not percentage of frequency. Expectedly, morning showers are primarily taken as a hygiene, routine activity in preparation for the day ahead.

None of the participants stated that the purpose of their morning shower was to refresh or relax and majority of the study participants spend between 5-10 minutes undertaking this activity. As previously stated, one participant takes significantly longer. Some participants sometimes undertake an afternoon (from noon to 6pm) shower to refresh e.g. after some leisure activity or to relax. If the activity was to refresh, the duration was either quick or moderate. If the purpose was for relaxation, then the duration of the shower was much longer. Again as expected, none of the participants indicated that the purpose of evening showers was for hygiene, routine purposes. Similar to afternoon showers, the purpose was to relax or refresh. The data, when only correlated with shower purpose, shows a tendency towards a moderate or longer shower in the evenings.

Lastly, the duration of the shower was compared with where the shower activity is undertaken (Table 3 for morning and evening showers only). Of particular interest is the duration of the shower in the periods when the participants state that they seldom or sometimes shower at home. Note that the data shows percentage distribution and not percentage of frequency. It was found that the shower duration was quick to moderate during the weekdays and moderate to long at weekend. A tendency toward a long shower is also shown even when the participants are at home in the evenings, whether weekday or weekend.

**Table 3. The influence of the shower activity on the duration of the shower**

		Morning (before noon)			Evening (after 6pm)		
		>10mins	5-10mins	< 5 mins	>10mins	5-10mins	< 5 mins
Weekday Morning	I always shower at home	30%	60%	10%			
	I seldom shower at home	0%	0%	100%			
	I sometimes shower at home	0%	100%	0%			
Weekday Evening	I always shower at home				100%	0%	0%
	I never shower at home				0%	0%	0%
	I seldom shower at home				0%	50%	50%
	I sometimes shower at home				20%	80%	0%
Weekend Morning	I always shower at home	13%	75%	13%			
	I never shower at home	100%	0%	0%			
	I sometimes shower at home	0%	100%	0%			
Weekend Evening	I always shower at home				100%	0%	0%
	I seldom shower at home				33%	33%	33%
	I sometimes shower at home				0%	100%	0%

#### 4. CONCLUSION

This paper presents some of the findings from the preliminary survey participants of an ongoing shower study. The study is underpinned by a participant action methodology which supports the use of a small participant sample to explore knowledge, behavioural and experiential phenomenon. In addition to the findings presented in this paper, other analyses were carried out on the initial participant selection survey data e.g. variations due to gender anthropometrics etc. However, the scope of this paper limits the extent to which the full extent of the findings can be discussed.

So far, this indicative survey has helped to identify the baseline factors that inform or influence user choice of showerhead products, showerhead performance preferences and the influence of routine, habit and location of shower activity on the duration. All of which could start to produce a global picture for understanding what defines a 'good' shower experience. The findings from this survey also raises interesting questions which can be further explored during and at the end of the 12 week showerhead challenge.

## ACKNOWLEDGEMENTS

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# WC and Urinal Use in Schools: Reducing WC flush volumes in schools – are we overestimating the water savings?

Cath Hassell\*, Trevor Jarvis

<sup>1</sup>ech<sub>2</sub>o consultants ltd, 27 Holywell Row, London EC2A 4JB

## ABSTRACT

Aim: When advising schools on whether to fit water efficiency measures in WC cisterns or to upgrade taps at the washbasins in toilet blocks, the cost of the measure is offset against the water savings that will result. It is therefore imperative that savings are estimated as accurately as possible based on quality data. It is the industry norm to assume that pupils use the WC an average 3 times a day, the same figure that is used for office workers. And yet schools toilets are very different to office toilets.

Methodology: Throughout 2012 ech<sub>2</sub>o collected data from 609 school pupils, (457 at primary school and 152 at secondary school) about their use of school toilets or urinals. The results showed that over 75% of pupils use the toilets less than three times a day with over 50% of students using the toilets either once or not at all. The average number of times the pupils use the toilet across both secondary and primary schools is 1.34 times a day.

Findings: Within secondary schools 65% of pupils do not use the toilets at all and average use of the toilets or urinals is just 0.6 times a day, with girls using the toilets just 0.5 times a day. Therefore savings from upgrading WCs or retrofitting flush reduction measures in the girl's toilets in secondary schools are over calculated by a factor of six.

*Keywords:* Pupils use secondary school toilets 0.6 times/day; Water efficiency in schools; WC flush savings over calculated in schools

## 1. INTRODUCTION

Over the past five years working with a range of stakeholders about how they use water, we began to realise that certain stated facts (such as the average shower in the UK is 5 minutes long) were being disproved from anecdotal evidence (1).

Therefore, since 2010 ech<sub>2</sub>o have been collecting data about how people use water at home, at school and in the office. We work with school pupils to collect data about themselves and their families, and also question housing association tenants, students, design professionals and members of the general public. We collect data across the whole range of different cultures and economic classes found in the UK today. We then robustly analyse that data to understand people's behaviour around water.

\* Tel.: +44 (0) 20 7183 1908.

E-mail address: cath.hassell@ech2o.co.uk>

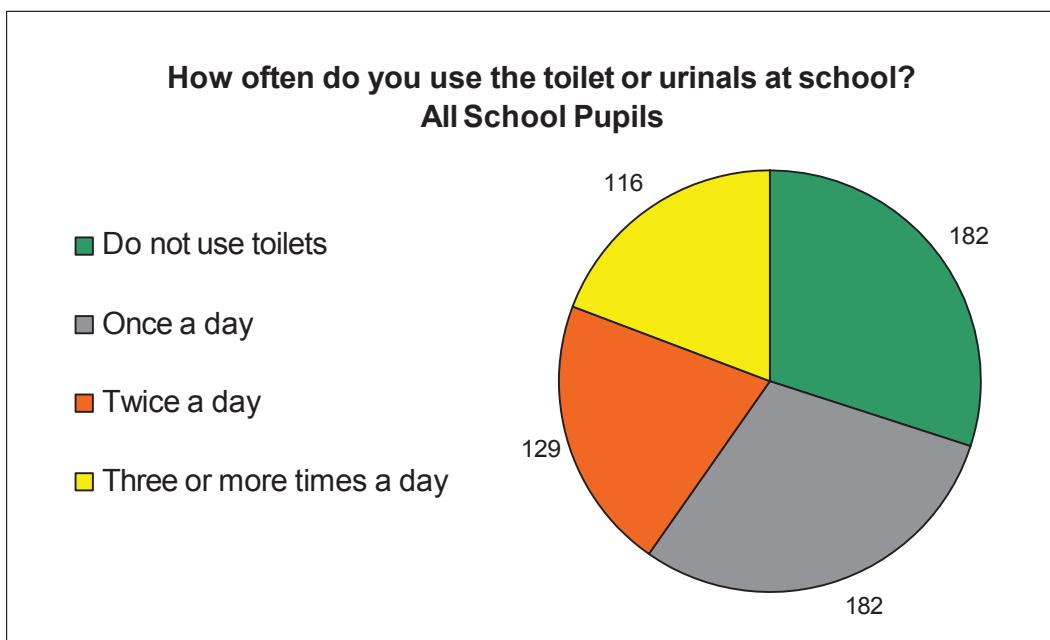
## 2. WATER SAVING FROM WC FLUSHING

When calculating water savings from efficiency upgrades in schools, it is the industry norm to assume that pupils use the WC on average 3 times a day. During our work in schools we began to realise that most pupils use the toilets less than this.

We thought it was important to find out the actual amount of WC (and urinal) usage to ensure we did not overestimate water savings from various efficiency measures such as save-a-flush bags or Hippos in WC cisterns, or reduced flow rates at washbasin taps.

In 2010 we began to formally collect and analyse data from pupils in relation to their usual patterns of using the toilets or urinals when at school (2).

This report analyses data from 609 school pupils, 457 of who were attending primary school when they answered the survey, and 152 of whom were at secondary school.



Approximately 65% of the respondents live in London, with the majority of the rest from south east England.

## 3. RESULTS AND DISCUSSION

The results were even starker than we realised and it immediately began to inform the savings we were calculating when retrofitting water efficiency measures in schools, or calculating what percentage of WC flushing demand a rainwater harvesting system will supply.

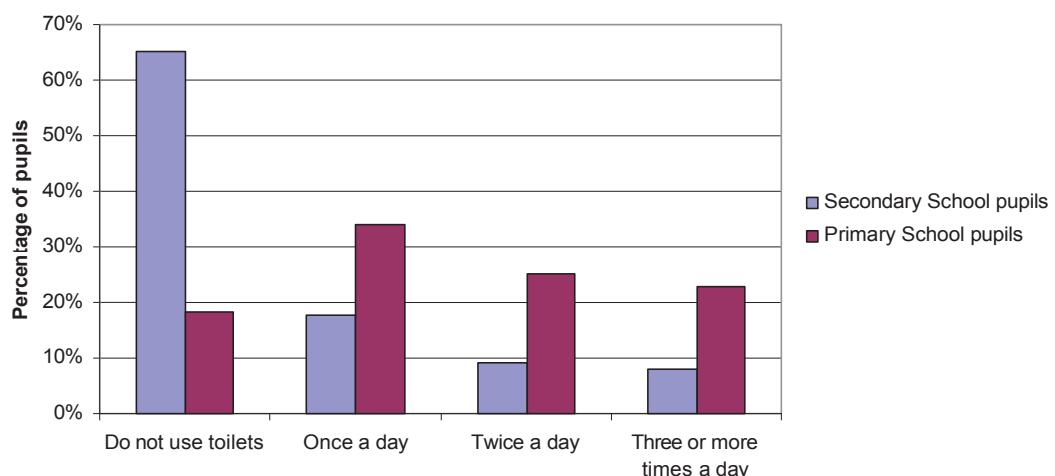
Over 75% of the pupils we surveyed do not use the toilets three times a day. In fact well over 50% either do not use the toilets at all or use them just once a day.

In our survey, the average number of times pupils use the toilets or urinals at school is 1.34 times a day (3)

### 3.1 COMPARISON BETWEEN SECONDARY SCHOOL AND PRIMARY SCHOOL PUPILS.

We thought it was important to analyse whether there was any difference in patterns of use between primary and secondary school pupils and between girls and boys. Once we split the data the difference in patterns of use is clear.

### **Comparison of Urinal and Toilet Use of Secondary and Primary School Pupils**



Of the 152 secondary school pupils we asked, 65% of them do not use the toilets at all at school, compared to 18% of primary school pupils (4).

Secondary school pupils use the toilets or urinals and average of just 0.6 times per day compared to an average of 1.6 times for primary school pupils.

In this survey girls at secondary school use the toilets just 0.5 times a day on average meaning that water savings from upgrading WCs or retrofitting flush reduction measures are over calculated by a factor of six.

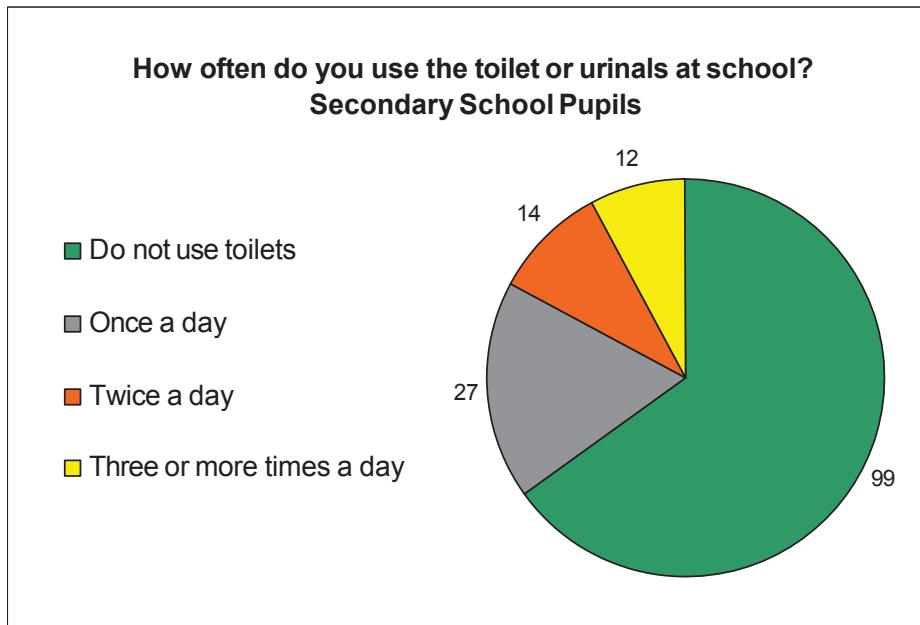
When advising schools on whether to fit water efficiency measures in WC cisterns or to upgrade taps, the cost of the measure is offset against the water savings that will result. It is therefore imperative that savings are estimated more accurately.

Most of the water savings after controls are fitted to urinals occur because the urinals no longer flush when the school is closed. Therefore in schools where bays have access to urinals, the number of times they use them is not significant when calculating savings.

## **4. CONCLUSION**

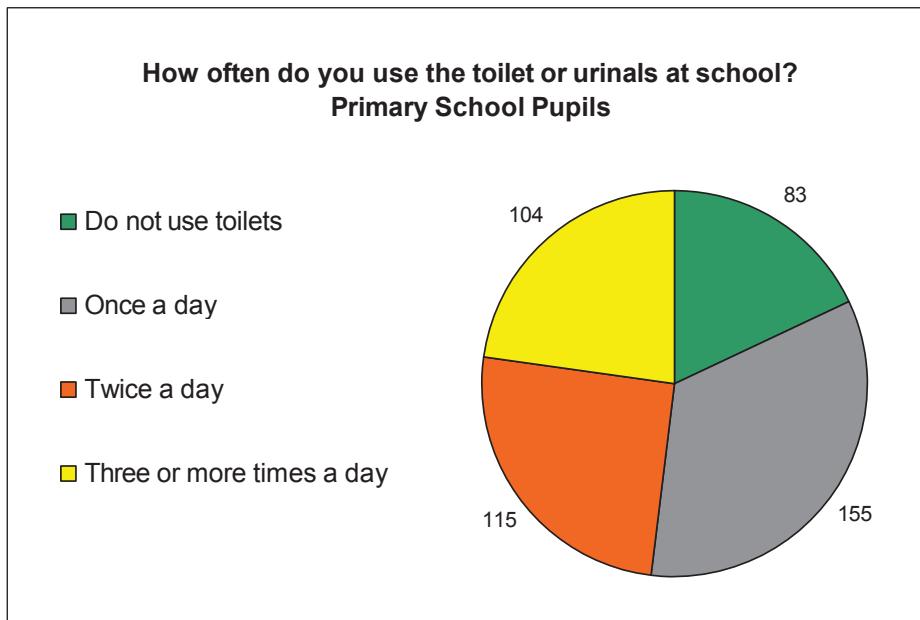
The following pages of this report break down the data we collected in more detail.

### **1. Comparison of toilet and urinal use between secondary and primary school pupils**



Of the 152 secondary school pupils questioned, just 8% use the toilet three or more times a day compared to 65% who do not use the toilet at all.

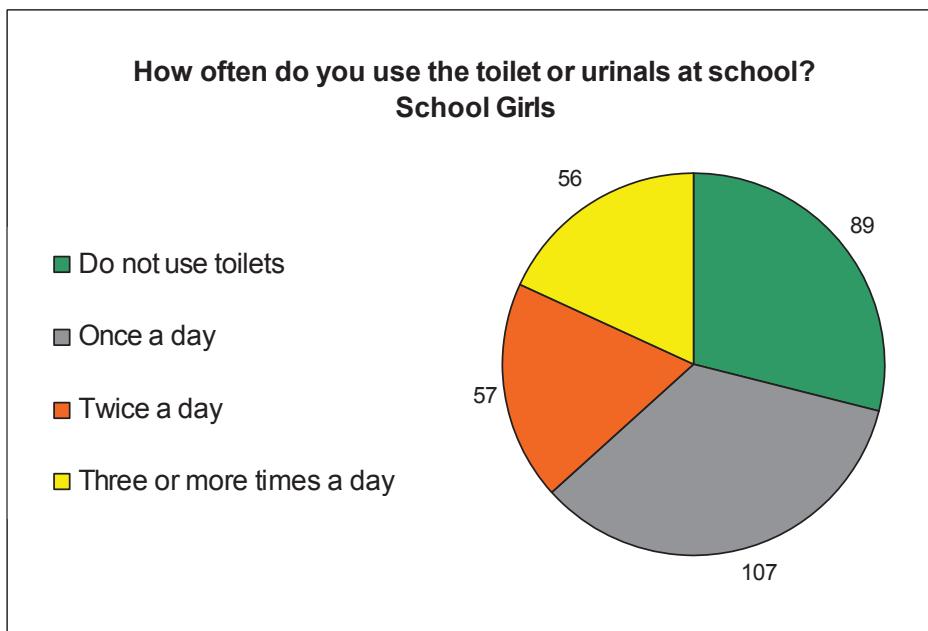
In our survey, the average number of times secondary school pupils use the toilets or urinals at school is 0.6 times a day.



Of the 457 primary school pupils questioned, 23 % use the toilet or urinal three or more times a day and 18% do not use the toilets at all.

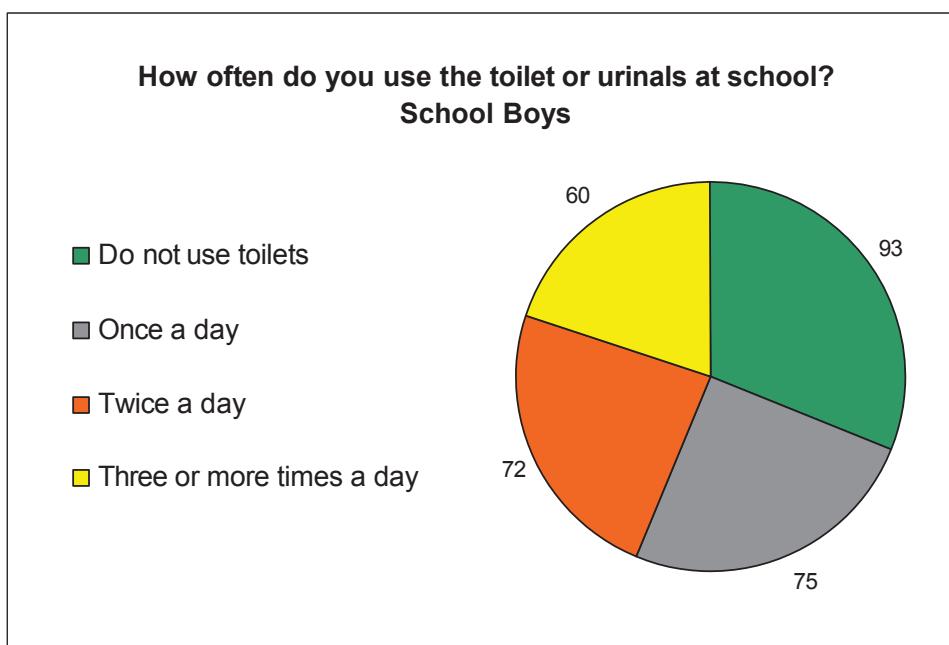
In our survey, the average number of times primary school pupils use the toilets or urinals at school is 1.6 times a day.

## 2. Comparison of toilet and urinal use between girls and boys



Of 309 girls questioned, 82% use the toilet less than three times a day.

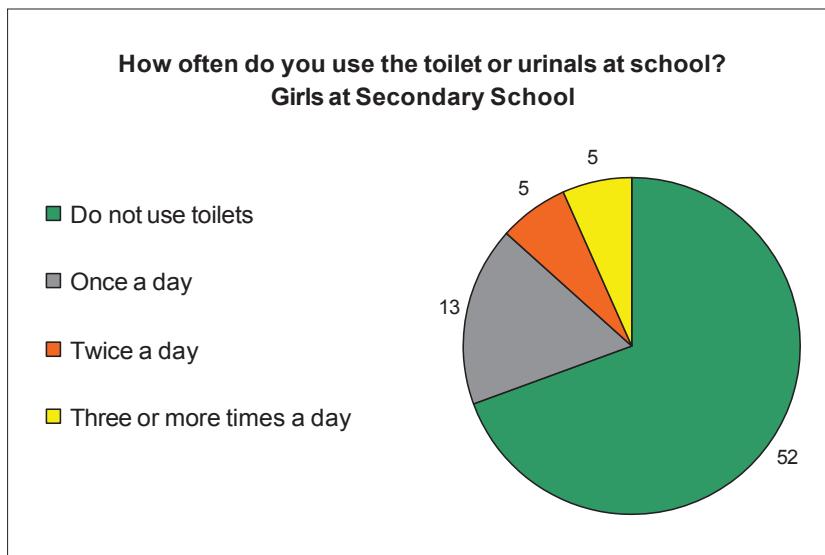
In our survey, the average number of times schoolgirls use the toilets at school is 1.3 times a day.



Of 300 boys questioned, 80% use the toilet less than three times a day.

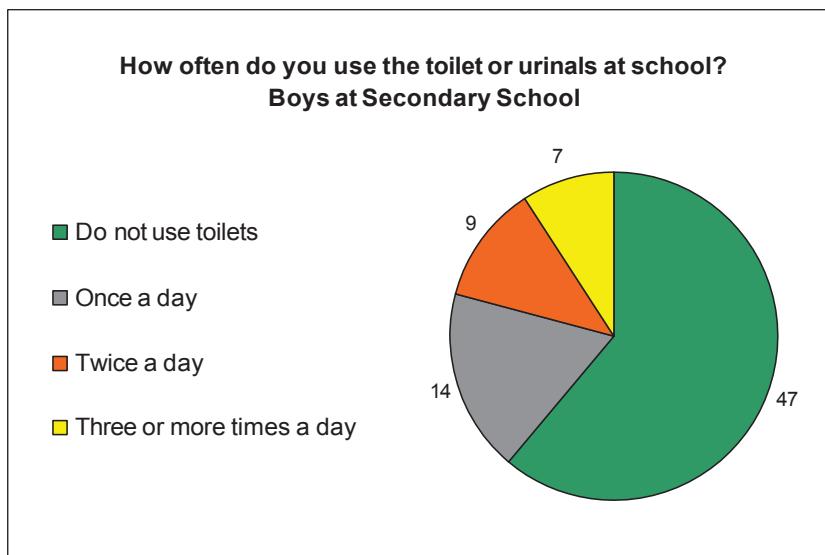
In our survey, the average number of times schoolboys use the toilets at school is 1.4 times a day.

### 3. Comparison of toilet and urinal use between secondary school girl and boy pupils



Of 78 secondary school girl pupils questioned, 67% do not use the toilets at all at school

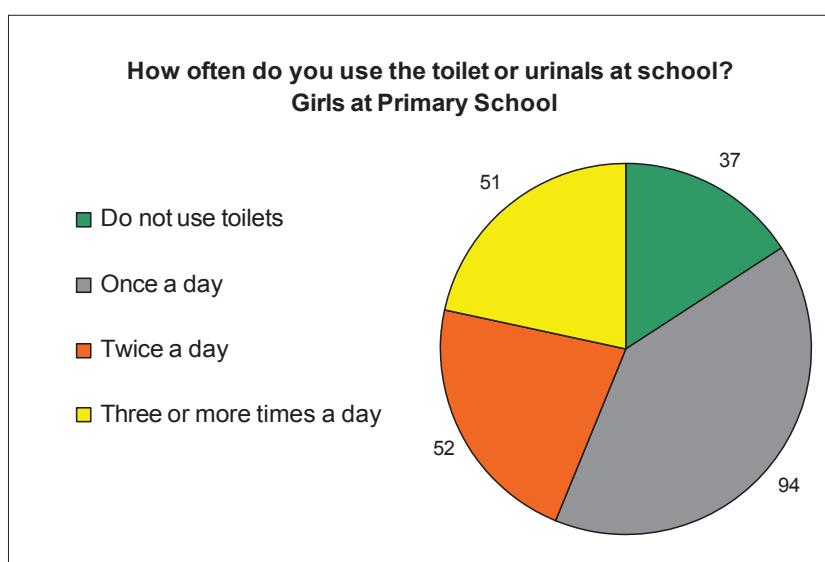
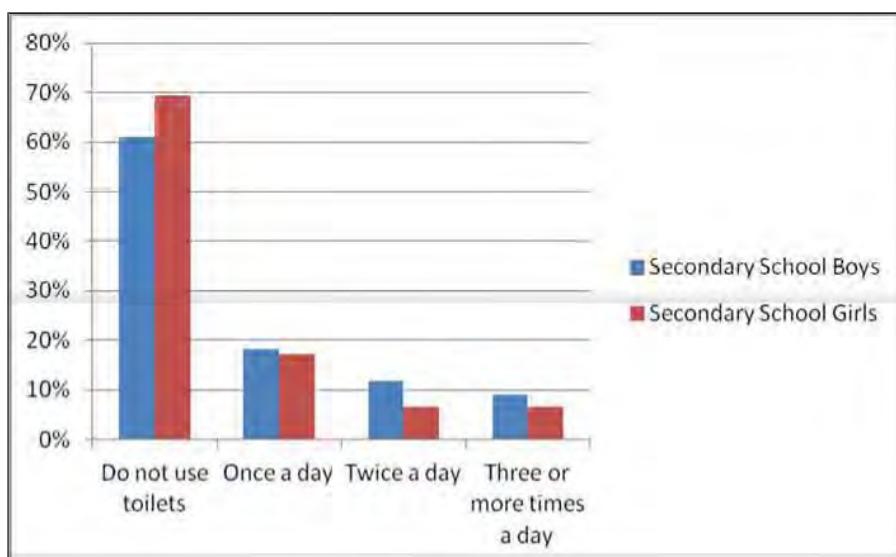
In our survey, the average number of times girls at secondary school girls use the toilets at school is 0.5 times a day.



Of 77 secondary school boy pupils questioned, 61% do not use the toilets at all at school

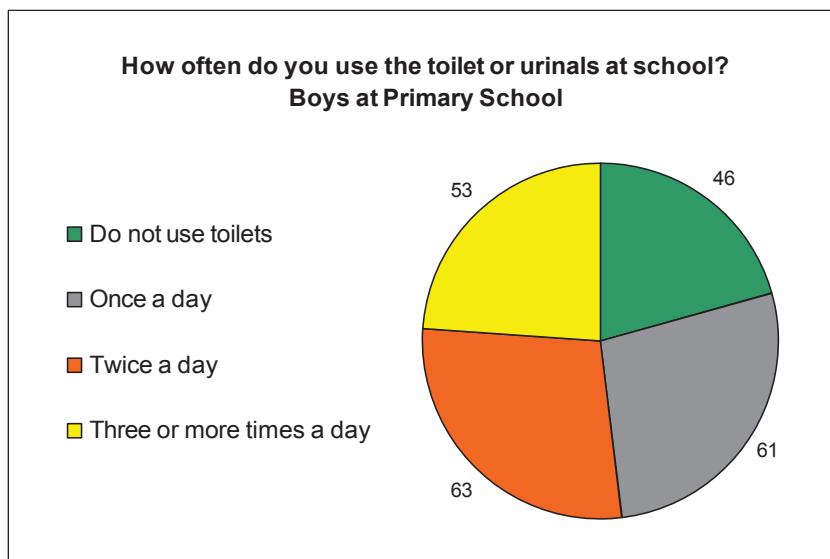
In our survey, the average number of times boys at secondary school use the toilets at school is 0.7 times a day.

#### 4. Comparison of toilet and urinal use between primary school girl and boy pupils



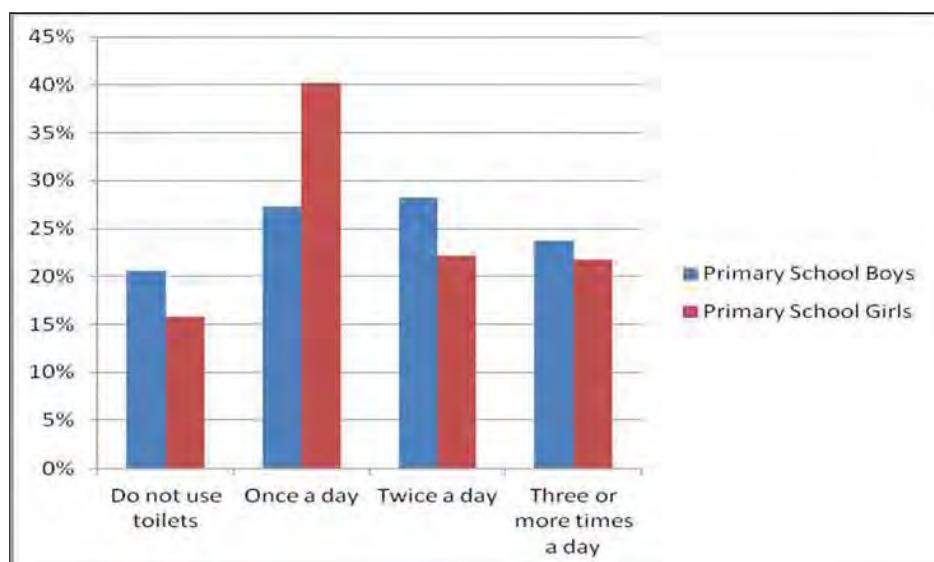
Of 234 primary school girl pupils questioned, 56% either do not use the toilet or use it just once a day.

In our survey, the average number of times girls at primary school use the toilets at school is 1.6 times a day.



Of 223 primary school boy pupils questioned, 48% either do not use the toilet or urinal or use it just once a day.

In our survey, the average number of times boys at primary school use the toilets at school is 1.6 times a day.



How often do you use the toilet or urinals at school?	Do not use toilets	Once a day	Twice a day	Three or more times a day	Totals	Average times use the toilet
Boys Secondary	47	14	9	7	77	0.71
Girls Secondary	52	13	5	5	75	0.52

Boys Primary	46	61	63	53	223	1.61
Girls Primary	37	94	52	51	234	1.55
All pupils	<b>182</b>	<b>182</b>	<b>129</b>	<b>116</b>	<b>609</b>	<b>1.34</b>
Secondary Schools	99	27	14	12	152	0.62
Primary Schools	83	155	115	104	457	1.58
Boys	93	75	72	60	300	1.38
Girls	89	107	57	56	309	1.30
All pupils	30%	30%	21%	19%		
Secondary School pupils	65%	18%	9%	8%		
Primary School pupils	18%	34%	25%	23%		
Boys	31%	25%	24%	20%		
Girls	29%	35%	18%	18%		
Secondary School Boys	61%	18%	12%	9%		
Secondary School Girls	69%	17%	7%	7%		
Primary School Boys	21%	27%	28%	24%		
Primary School Girls	16%	40%	22%	22%		

## REFERENCES

- (1) Read the analysis of our shower data at : [www.ech2o.co.uk/reports\\_shower.shtml](http://www.ech2o.co.uk/reports_shower.shtml)
- (2) We do not ask any girl pupils to differentiate between WC usage when they are menstruating and when they are not, (as when girls are having their period they may have to use the toilets more often than usual). We are very clear it is about their normal pattern of WC use.
- (3) In the early surveys we asked pupils to identify the total number of times they used the toilet with no upper limit. Out of 183 pupils, less than 10 used the toilet/urinal four times and just four used the toilet/urinal five times. In later surveys we changed the question to three times or more. Therefore, when calculating average WC use per pupil per day we calculate that 25% of pupils who tick the "three times or more" column have used it four times a day. We consider this is a valid figure based on our earlier research.
- (4) Secondary school pupils give two main reasons for not using the toilets at school. That the toilets are "dirty" (a perceived or real statement) and that they are not safe. In many new secondary schools the problem of bullying in toilets is addressed by providing single cubicle toilets accessed directly from the corridor, and we would expect in these schools that WC use would be much greater than in our survey.

# Assessing and modelling the influence of household characteristics on per capita water consumption

Wa'el A. Hussien\*, Fayyaz A. Memon, Dragan Savic

*Centre for Water Systems, College of Engineering, Mathematics and Physical Sciences, University of Exeter, Exeter, Devon EX4 4QF, UK*

## ABSTRACT

**Aims:** To investigate and model water consumption trends in Duhok, Iraq.

**Study design:** The survey carried out for 407 households in Duhok, Iraq, to estimate water consumption by different end uses and identify the influence of household characteristics, water use behaviors and per capita income.

**Place and duration of study:** The survey was carried in Duhok, Iraq during February 2015.

**Methodology:** The end uses investigated include indoor and outdoor water using activities and the water use behavior was captured through recoding the frequency and duration of each water using activity. To investigate the influence of per capita income on the household water consumption, the collected data was divided into three groups with respect to their income (low, medium and high).

**Results and conclusions:** The survey analysis shows that the per capita water consumption increases with the household income: 241, 272 and 290 l/capita/day for low, medium and high income households, respectively. Additionally, the results suggest that the per capita consumption increases with the number of adult female members in the household and almost one-third of consumption is via taps.

A detailed statistical analysis of the collected data has been presented and the data used to develop statistical models using two different techniques: STEPWISE and EPR. The inclusion of demographic parameters in the developed models considerably improved the prediction accuracy.

**Keywords:** Water end-use; household characteristics; per capita water consumption; regression.

## 1. INTRODUCTION

Water scarcity is a major issue in many developed and developing countries. Rapid population growth, urbanization and climate change related uncertainties are some of the factors need to be considered during water resources management planning. Emphasis is growing on the implementation of demand management measures, water reuse and better understanding of our water consumption behaviors and factors influencing or contributing to domestic water consumption. This paper describes a survey carried out to investigate water consumption trends in an urban area of Iraq, Duhok.

Duhok city is located in northwestern Iraqi Kurdistan. It has a population of around 295,000 inhabitants and spreads over 577km<sup>2</sup>, accounting 0.13% of total area of Iraq (Kurdistan Regional Statistics Office (KRSO), 2014). The city witnessed a rapid expansion in the area and growth in the population during the last decades and it has led to further urbanization growth in the city. This is due to the high fertility (5%) and the movement from rural areas to the city (Kurdistan Ministry of Planning, 2014).

One of the water sources in the city is Duhok earth dam with storage of 47.5 Million m<sup>3</sup> and is mainly used for agricultural purposes (Kurdistan Ministry of Water Resources, 2014). Domestic water ( $66.1 \times 10^6$  m<sup>3</sup>/year) is supplied by the national water supply board through a water supply pipe from Khrabdeem, the main water treatment plant in Duhok. In addition, up to 100 wells pump around  $8.3 \times 10^6$  m<sup>3</sup>/year for domestic use (Duhok Directorate of Water and Sewerage, 2014). Water is supplied to households from 3 to 4 times every week with each supply session lasting not more than 6 hours. People store water in overhead tanks and consume it for different activities including drinking.

## 2. METHODOLOGY FOR DATA COLLECTION

A detailed survey was prepared in the native language (Kurdish). The survey was distributed to 419 randomly selected households in Duhok, in February 2015. The replies were received from 407 households.

The number of questions included in the survey was over 40. A multiple-choice format was used to answer some of the questions. Household characteristics, such as number of occupants, children, elders, adult males and females, household type, total built up area and monthly income were surveyed. As well as, questions were included to get information on the *frequency, duration of use and flow rate* of each water end-use (e.g. showering, hand wash basin, toilet flushing, dishwashing, laundry, house washing, cooking, garden watering and vehicle washing).

## 3. RESULTS AND DISCUSSION

The analyses of collected data using IBM SPSS Statistics 22 are summarised in the following sections (3.1 to 3.3).

### 3.1 Household characteristics

The analyses of household characteristics of 407 residential units (92% houses and 8% apartments) are summarized in Table 1. It shows that the average household size is 7.04 persons, which is approximately equivalent to the average standard family size (6.7 persons) in Duhok as reported by KRSO (2014). In terms of family composition, the average number of adult females, adult males and children are 2.33, 2.27 and 2.22, respectively. The average number of elders was very low (0.22), accounting only 3.2% of the survey sample.

The socio-economic characteristics of the households show that the average built up area of all floors is between 100 and 500 m<sup>2</sup> with approximately 30 m<sup>2</sup> occupied by the garden. Of the 407 households, 58% where single-story, 36% where double-story and 6% where triple-story. The average number of rooms is over 4. The variation in the family income was significantly high and ranged from 3x10<sup>5</sup> ID/month (= £150) to 44.7x10<sup>5</sup> ID/month (= £2200) with average per capita income equivalent to 25x10<sup>4</sup> ID/month (= £125).

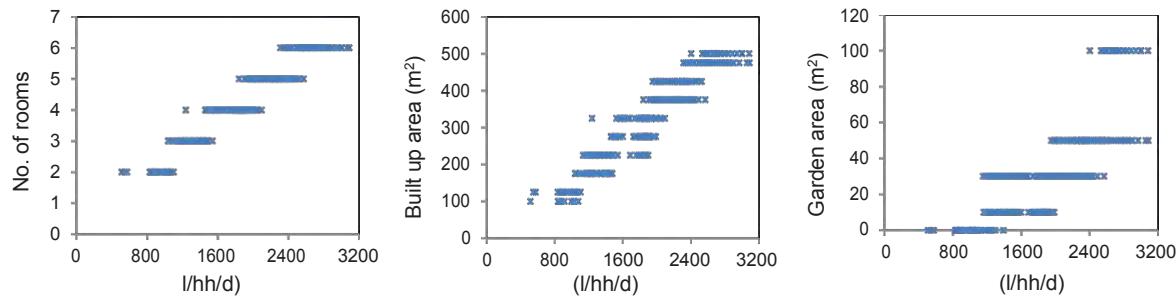
**Table 1. Summary of household characteristics (407 households)**

Household characteristics	Unit	Mean	Median	Standard deviation	Minimum	Maximum	Skewness	Kurtosis	Confidence interval (95%)
Household size (occupancy)	No./hh	7.04	7.00	2.35	2	13	0.24	-0.55	0.23
Number of children (<15 years)		2.22	2.00	1.74	0	7	0.53	-0.35	0.17
Number of adult males members (15-65 years)		2.27	2.00	1.07	0	5	-0.13	0.24	0.10
Number of adult females members (15-65 years)		2.33	2.00	1.01	1	5	0.45	-0.72	0.09
Number of elders (>65 years)		0.22	0.00	0.49	0	2	2.12	3.77	0.05
<i>Household type</i>	%	<i>Houses (91.9%)</i>			<i>Apartments (B.1%)</i>				
Total built up area of all floors	m <sup>2</sup> /hh	314.6	325.0	114.5	100.	500.	-0.10	-1.03	11.2
Garden area per household		29.56	30.00	24.38	0.00	100.	1.26	1.81	2.38
Number of rooms in the household	No.	4.19	4.00	1.18	2	6	-0.16	-0.82	0.11
Number of floors in the household	No.	1.48	1.00	0.61	1	3	0.89	-0.21	0.06
Monthly family income/household	1000 ID/month	1857	1570	1105	258	4470	0.5	-0.9	108

\* hh = household, ID = Iraqi Dinar (1000 ID = £ 0.5)

### 3.1.1 The influence of household characteristics on the total average water consumption (l/hh/day)

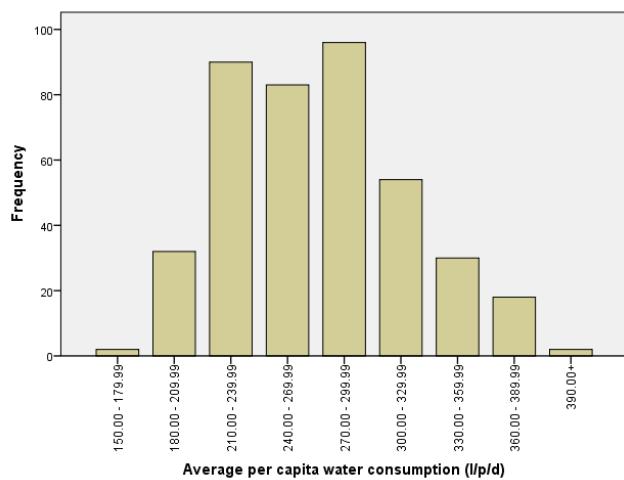
The analyses of the survey data suggest a strong positive relationship between household occupancy (i.e. the number of people in the household) and total water consumption ( $R^2 = 0.75$ ) whilst there is a negative relationship between per person usage and household occupancy. Water consumption increases with the increase in the total household built up area, number of rooms and garden area with a correlation coefficient of 0.89, 0.92 and 0.6, respectively (Figure 1).



**Fig. 1. Relationship between household water consumption (l/hh/d) and household characteristics**

### 3.1.2 The Influence of household characteristics on the average per capita water consumption (l/p/d)

The average daily per capita water consumption distribution for the whole survey is shown in Figure 2, suggesting that it is about 271 l/p/d. For houses it is approximately 274 l/p/d and that for apartments is about 247 l/p/d. The higher consumption for houses is mainly because of additional outdoor water use. Daily per capita consumption increases with increase in the total built up area of the household; however it decreases with increase in the number of household occupants. The decline in per person usage suggests household uses of water such as clothes washing, dish washing and water used for cooking and cleaning are more efficient on a per person basis for higher occupancy households. The influence of children is higher than elders. In other words, increased number of children in the household leads to a higher reduction in per capita consumption than elders. On the other hand, increased number of male adults in the family reduces per capita consumption and the increase in female members increases per capita consumption.



**Fig. 2. Frequency distribution of average per capita water consumption (l/p/d)**

### 3.1.3 Influence of per capita income on the average per capita water consumption (l/p/d)

In Iraq, a household socio-economic survey was conducted by Central Statistical Organisation (CSO) and KRSO in 2012. In the Iraqi survey, the monthly family income was divided into three groups (Table 2). This classification was based on the average family size of 6.7 persons. The last column in Table 2 shows per capita income for respective household groups and has been obtained by dividing

the household income by the average family size. Using per capita figures of column three, the surveyed 407 households were divided into three income groups (Table 3).

**Table 2. Income groups classification for Iraq (CSO and KRSO, 2012)**

Income group	Income range in Iraqi Dinar (ID)	
	Per household	Per capita
Low	$<1 \times 10^6$	$<15 \times 10^4$
Medium	$1 \times 10^6 - 2 \times 10^6$	$15 \times 10^4 - 30 \times 10^4$
High	$>2 \times 10^6$	$>30 \times 10^4$

**Table 3. Number of surveyed households at different income groups**

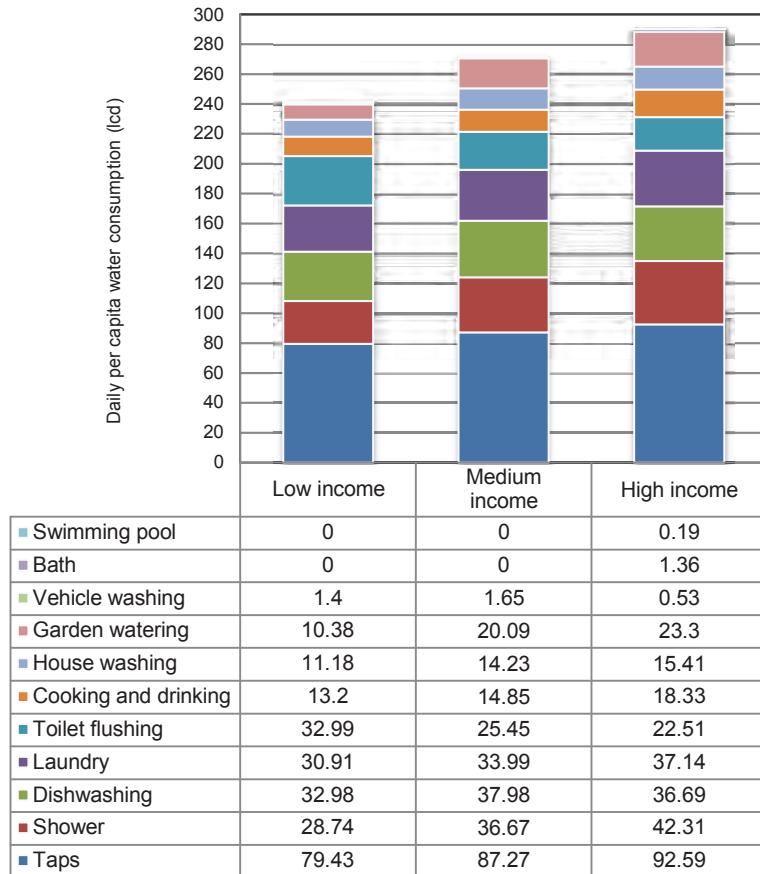
Income group	Low	Medium	High
Number of households	92	176	139

The survey analysis shows that the average per capita consumption increases with the household income (i.e. 241, 272 and 290 lpd in low, medium and high income group, respectively). Although the average per capita water consumption is increasing with the increase in the household income, the fraction of water used for different activities broadly remains the same in all the surveyed households regardless of the income group (Figure 3). The figure shows that most of water consumption is via taps. This is in contrast to many countries in the developed world where about one-third of water is used to flush toilets (Post, 2000).

**Fig. 3. Summary of percentages of water end-uses in all income groups**

### 3.2 Average per capita water use for different end-uses (micro-components)

A household's total water consumption is disaggregated into a number of end-uses: showering, bath, hand wash basin, toilet flushing, dishwashing, laundry, cooking, house washing, garden watering, car washing and swimming pool. The average daily use of each of these components in all income groups is illustrated in Figure 4. A notable feature in this figure is the considerable variation in daily water end-use per person between income groups. It is apparent from this figure that the swimming pool use in all income groups is significantly low (less than 0.2 lpd). Of the 407 surveyed households, only two houses were found to have swimming pool and therefore, they will not be included in any further analysis. Another finding is per capita water consumption for outdoor purposes (garden watering, car washing and swimming pool) is less than 10% of total daily usage in all income groups. However, the consumption may become much higher in the summer season for outdoor purposes.



**Fig. 4. Impact of per capita monthly income on water end-use in Duhok**

### 3.3 The influence of per capita income on water end-uses

The summary of average values of water end-use parameters per person (e.g. frequency, duration of use and flow rate) is illustrated in Table 4. It shows the comparison between these parameters in low, medium and high income households. The key findings are explained in the following sections.

#### 3.3.1 Shower and bath

Shower and bath use are positively related to family income (Gato, 2006). Throughout the survey, there were no baths recorded in low and medium income families. The number of baths recorded was only 10 baths in high income households with a very low frequency (once a week) in use.

The daily per capita water use for showering is the function of the frequency, the duration and the flow rate of shower. Although, the frequency of showering is high (0.61 showers/p/d) in the high income group, the flow rate of shower (8.39 l/min) is lower than that what was recorded in the low and medium income groups (Table 4). Most of the high income households were found to be constructed recently and therefore they are likely to have more water efficient appliances (e.g. shower heads). The duration of shower was found to be less sensitive to income groups. However, frequency of showering tends to increase with increase in the per capita income.

#### 3.3.2 Hand wash basin (taps)

In all income groups, hand wash basin uses are the most intensive water users accounting for approximately 32% of the total water use. Similarly to showering, hand wash basin water consumption is influenced by the same parameters with the number of times the basin is used rather than the number of showers taken.

As with shower, the flow rate from hand wash basin taps decreases with the increase in the household income. Confirming that the high income group households are relatively new and fitted

**Table 4. Summary of mean values of water end-use parameters**

End-use	Parameter/variable	Unit	Overall survey	Low income	Medium income	High income	Comparison with past studies
Bath	Frequency of taking bath per capita per day	Frequency/day	0.004	0	0.00	0.01	0.044 (Blokker et al., 2010)
	Volume of water use in each bath	Liter/bath	132.00	0.00	0.00	9.50	100 in France (EEA, 2001)
Shower	Frequency of showering per capita per day	Frequency/day	0.49	0.34	0.47	0.61	0.73 (Athuraliya et al., 2012)
	Duration of each shower	Minutes/shower	8.64	8.87	8.72	8.38	7.55 (Gato, 2006)
	Flow rate	Liter/minute	9.02	9.48	9.27	8.39	16 in France (OFWAT, 1997)
Hand wash basin	Frequency of using taps per capita per day	Frequency/day	10.46	9.96	10.31	10.98	4.1 (Blokker et al., 2010)
	Duration of tap use	Seconds/use	60.81	58.31	61.02	62.20	21.3 (Gato, 2006)
	Flow rate	Liter/minute	8.14	8.13	8.24	8.02	2.6 (Athuraliya et al., 2012)
Toilet	Frequency of toilet use per capita per day	Frequency/day	4.65	5.39	4.66	4.14	4.2 (Roberts, 2005)
	Water use in each flush (L)	Liter/flush	5.51	6.01	5.36	5.38	9.5 in the UK (OFWAT, 1997)
Dish washing	Frequency of washing dishes per day	Frequency/day	3.00	3.00	3.00	3.00	2.1 (Jacobs and Haarhoff, 2004)
	Duration of running water in each wash	Minutes/capita	1.47	1.16	1.50	1.64	
	Flow rate	Liter/minute	8.36	9.54	8.39	7.54	5.4 (Marinoski et al., 2014)
Laundry	Frequency of laundry per day	Frequency/day	1.48	0.83	1.46	1.93	0.69 (Athuraliya et al., 2012)
	Volume of water/washing load	Liter/load	167.32	190.02	161.01	160.28	80 in the UK (EEA, 2001)
House washing	Frequency of house washing per day	Frequency/day	0.69	0.51	0.69	0.80	
	Duration of each wash	Minutes/capita	2.13	1.79	2.1	2.38	
	Flow rate	Liter/minute	9.80	12.20	9.88	8.12	
Vehicle washing	Frequency of vehicles washing per day	Washes/day	0.07	0.06	0.10	0.04	
	Duration of each wash	Minutes/capita	1.39	1.81	1.34	1.1	
	Flow rate	Liter/minute	12.82	12.79	12.75	13.08	10.2 (Marinoski et al., 2014)
Swimming pool	Frequency of filling swimming pool per day	Frequency/day	0.001	0.00	0.00	0.002	
	Volume of water provided to fill the swimming pool	m <sup>3</sup>	36.00	0	0	36.00	
Garden watering	Frequency of garden watering per day	Frequency/day	0.13	0.07	0.14	0.14	0.4 (Roberts, 2005)
	Duration of each watering	Minutes/capita	13.01	13.11	11.88	14.49	20 (Athuraliya et al., 2012)
	Flow rate	Liter/minute	11.67	11.64	11.94	11.34	10.2 (Marinoski et al., 2014)
Cooking	Volume of water consumed in cooking	Lpd	13.66	11.20	12.85	16.33	10-20 (Gleick and Iwra, 1996)
Total water consumption		Lpd	271.39	241.22	272.18	290.36	180 in urban residential areas (Stephenson, 2003)

\*lpd = liter per person per day.

with water efficient appliances. The frequency of hand wash basin use increases with the increase in the income. The duration of use is relatively same in low, medium and high income families. The duration of tap for all income groups is about 60 seconds per use. When multiplied with the frequency of hand wash basin tap, the total daily per capita tap duration becomes 9.68, 10.49 and 11.38 minutes/capita/day for low, medium and high income households, respectively. The hand wash basin daily tap use duration obtained in this study is much higher than the values found in literature (i.e. 6.66-8.33 minutes/capita/day, Roberts, 2005). The high tap duration can be attributed to additional water using activities in the Islamic culture (e.g. ablution before each prayer time).

### **3.3.3 Toilet use**

In line with the observation made above, again high income group households appear to have water efficient toilet (5.4 l/flush) in comparison to low income households (6.0 l/flush). This increases the average daily toilet consumption per capita in low income group to 33.0 lpd and being higher than that in medium (25.5 lpd) and high (22.5 lpd) income families.

The frequency of toilet use per capita per day was higher in low income families (5.4 times/day) than that in medium (4.7 times/day) and high (4.1 times/day) income families. From the data presented in Table 4, it appears that in the medium and high income households' water consumption for personal hygiene related activities is higher reflected in higher frequencies of showers, clothes and dish washes and hand wash basin indicating an increased emphasis on cleanliness. The less emphasis (inability) on cleanliness in low income group may be a cause of increased water borne disease and the increased frequency of toilet use may be an indicator of poor hygiene. Another reason for lower toilet use frequency for high income group is the high number of people in employment working away from home during the day.

### **3.3.4 Dishwashing**

Dishwashing accounted for the second highest end-use being approximately 14% of total water use in all income groups (Figure 3). Manual dishwashing is significantly high compared to machine dishwashers. Only 7% of surveyed households own dishwasher but they still wash dishes manually. The daily water consumption for dishwashing is a function of flow rate, duration and number of washes. The frequency of washing dishes is same in all income groups that is dishwashing after each meal (breakfast, lunch and dinner). The flow rate of kitchen tap decreases with the increase in household income from 9.5 l/min in low income to 7.5 l/min in high income households (Table 4). However, the variability in total water use for dishwashing between income groups is due to the duration of each dishwashing session, which is dependent on the number of dishes and indirectly the size of the family. For example, the duration of each wash in six occupants' family size for each income group was found to be 6.3, 9.3 and 10.5 minutes for low, medium and high income group, respectively.

### **3.3.5 Laundry**

The main parameters to identify laundry water consumption are the volume of water used per washing cycle and the frequency of laundry per household. The volume of water used in each wash is fixed depending upon the brand, style, and size of washing machine in each house. The analysis shows there is a difference in the average volume of water used per wash between income groups, accounting approximately 160 l/washing load in medium and high income houses and much higher in low income (190 l/washing load) (Table 4). It looks that in comparison with lower income group; medium and higher income households have water efficient washing machines.

The second parameter (the frequency of laundry per household per week) can be influenced by the number of household occupants. From survey data, it increases with the increase in household income, indicating increased emphasis on hygiene with increased income. Therefore, the difference in total amount of laundry water consumption is significantly high between income groups. It is 145.7, 235.3 and 310.1 liters/hh/day in low, medium and high income families, respectively.

### **3.3.6 House washing**

About 5% of the total water consumption is used for house washing. The house washing activities include floor washing, washroom and kitchen cleaning. The analysis shows that the frequency and

duration of household washing increase with the increase in the household income. The frequency is 3.6, 4.8 and 5.6 times/week with duration of each wash approximately 8.4, 14.2 and 19.5 minutes in low, medium and high income households, respectively. This suggests that the emphasis on cleanliness and hygiene increases with the increase in the household income or due to the household built up area.

### **3.3.7Cooking**

According to the studies of White, et al. (1972), the NRC (1989) and Black (1990), food preparations in both developed and developing countries would require about 10 to 20 l/p/d of water. Duhok survey shows that average water required for food preparation lies within the values found in the literature. However, water consumption for food preparation increases with the increase in the family income, accounting 11.2, 12.9 and 16.3 l/p/d in low, medium and high income households, respectively (Table 4).

### **3.3.8Garden watering**

Outdoor water use (garden watering, car washing and swimming pool) is related to the size of the residential dwelling area (Gato, 2006). In terms of the frequency of garden watering, it is much lower in low income group than that in the medium and high income groups. Most of the houses recorded only one irrigation event per week. This may be because of the timing of the survey. This survey was conducted during winter time. In order to quantify the seasonality impact, the survey is being repeated at the moment to account for water consumption variations in summer.

The duration of each watering session in the high income group is the highest (approximately 2 hours). This appears to be mainly because of the average larger garden area ( $51.8\text{ m}^2$ ) in comparison with low ( $9.3\text{ m}^2$ ) and medium ( $22.6\text{ m}^2$ ) income households. However, the flow rate from the outside tap for the garden watering is broadly similar (11.5 l/minute) in all households regardless in their income group (Table 4). Therefore, the total volume of water used for garden watering in high income households is clearly the highest 192.1 liters/hh/day with less consumption in medium (134.1 liters/hh/day) and low (58.8 liters/hh/day) income houses.

### **3.3.9Vehicle washing**

In terms of water use for vehicle washing, the highest consumer is medium income families (75.6 l/hh/week), which is probably because of less ownership in low income families (47.2 l/hh/week). On the other hand, people in high income households prefer their cars washed at washing services rather than doing it themselves (28.0 l/hh/week). Because of this, water consumption for vehicle washing in high income group is low. It can be seen from the data in Figure 4 that the average per capita water use for vehicle washing is relatively small in all income groups but this may increase in the summer season due to the frequent dust storms.

## **3.4 Modelled daily per capita usage with household characteristics**

The water consumption data from the 407 surveyed households was used to develop statistical models to predict per capita consumption as a function of household characteristics. The household characteristics were divided into two groups, that is:

- Demographic characteristics: number of children, elders, adult males and adult females.
- Physical characteristics: total household built up area, garden area, number of rooms, number of floors and per capita income.

Two different techniques were used to build regression models in order to identify the models which are computationally efficient and provide reliable prediction. The two techniques applied are: multiple linear regressions (STEPWISE) and evolutionary polynomial regression (EPR).

### **3.4.1Models based on multiple linear regressions (STEPWISE)**

Multiple regression technique has been used widely to explore the relationship between the dependent and several independent variables (Abdul-Wahab et al., 2005). The technique is looking for the combination of relevant independent variables to construct the best fit model based on strong

statistical foundations. One of the multiple regression techniques is *STEPWISE*, which is a potential approach for selecting the best combination of independent variables (Cevik, 2007).

The *STEPWISE* multiple regression approach is applied using IBM SPSS Statistics 22 software to determine the best subset model for daily per capita water use estimation. The relationships between the independent variables (household characteristics) and the dependent variable (per capita water consumption) were investigated and the values of correlation coefficient are shown in Table 5. From the table, it can be seen that the strongest relationship of per capita consumption is with number of children in the household. The selection or deletion of an independent variable for the regression model is based on the strength of relationship (i.e. the magnitude of the correlation coefficient, R).

**Table 5. Correlation coefficients between household characteristics and per capita water consumption**

		Correlation coefficient value (R)									
		Demographic characteristics				Physical characteristics					
		No. of children	No. of adult females	No. of adult males	No. of elders	No. of rooms	No. of floors	Total built up area	Garden area	Income	
Per capita water consumption (lpd)	All surveyed households	-0.560	0.467	-0.474	-0.204	-0.028	-0.064	0.008	0.013	0.602	
	Low income households	-0.745	-0.279	-0.263	-0.408	-0.773	0.000	-0.664	-0.361	0.777	
	Medium income households	-0.808	0.467	-0.766	-0.270	-0.859	-0.638	-0.699	-0.330	0.844	
	high income households	-0.501	0.196	-0.807	-0.254	-0.766	-0.532	-0.678	-0.443	0.803	

\* Lpd=litres per capita per day

Using *STEPWISE*, twelve regression models were developed to estimate the per capita consumption for the whole survey, low, medium and high income group households. These models are shown in Table 6 and they were subjected to further statistical testing using F-test and t-test. The predictions from these models were plotted against the actual per capita water consumption values obtained from the survey as shown in Figure 5. From the figure it can be seen that the  $R^2$  value improves further when the full survey data was disaggregated into low, medium and high income groups.

### **3.4.2 Models based on evolutionary polynomial regression (EPR)**

The Evolutionary Polynomial Regression (EPR) is a modelling technique which combines the effectiveness of genetic algorithm with numerical regression to develop mathematical model expressions (Giustolisi and Savic, 2009). This technique has been used in evapotranspiration process, rainfall-groundwater dynamics, water distribution and wastewater networks.

EPR MOGA-XL tool<sup>1</sup> ver.1 is used to develop the evolutionary polynomial regression models for daily per capita water use estimation. The objective functions that used for the evolutionary search of EPR are:

- The minimization of the number of inputs, and
- Maximization of the accuracy of the model (i.e. minimization of the summation of square errors) (Giustolisi and Savic, 2009).

Using EPR MOGA-XL tool, twelve nonlinear regression models are developed for the whole surveyed households and each household income group (low, medium and high) as shown in Table 7. These models have been chosen due to their highest coefficient of determination ( $R^2$ ). The predictions from EPR models were plotted against the surveyed per capita water consumption values as shown in Figure 6. From this figure it can be concluded that the  $R^2$  value increases when the models were developed for each household income group. Moreover, the  $R^2$  value increases significantly when all (demographic and physical) household characteristics were included in the model rather than only demographic or physical characteristics.

<sup>1</sup>[http://www.hydroinformatics.it/index.php?option=com\\_docman&Itemid=105](http://www.hydroinformatics.it/index.php?option=com_docman&Itemid=105)

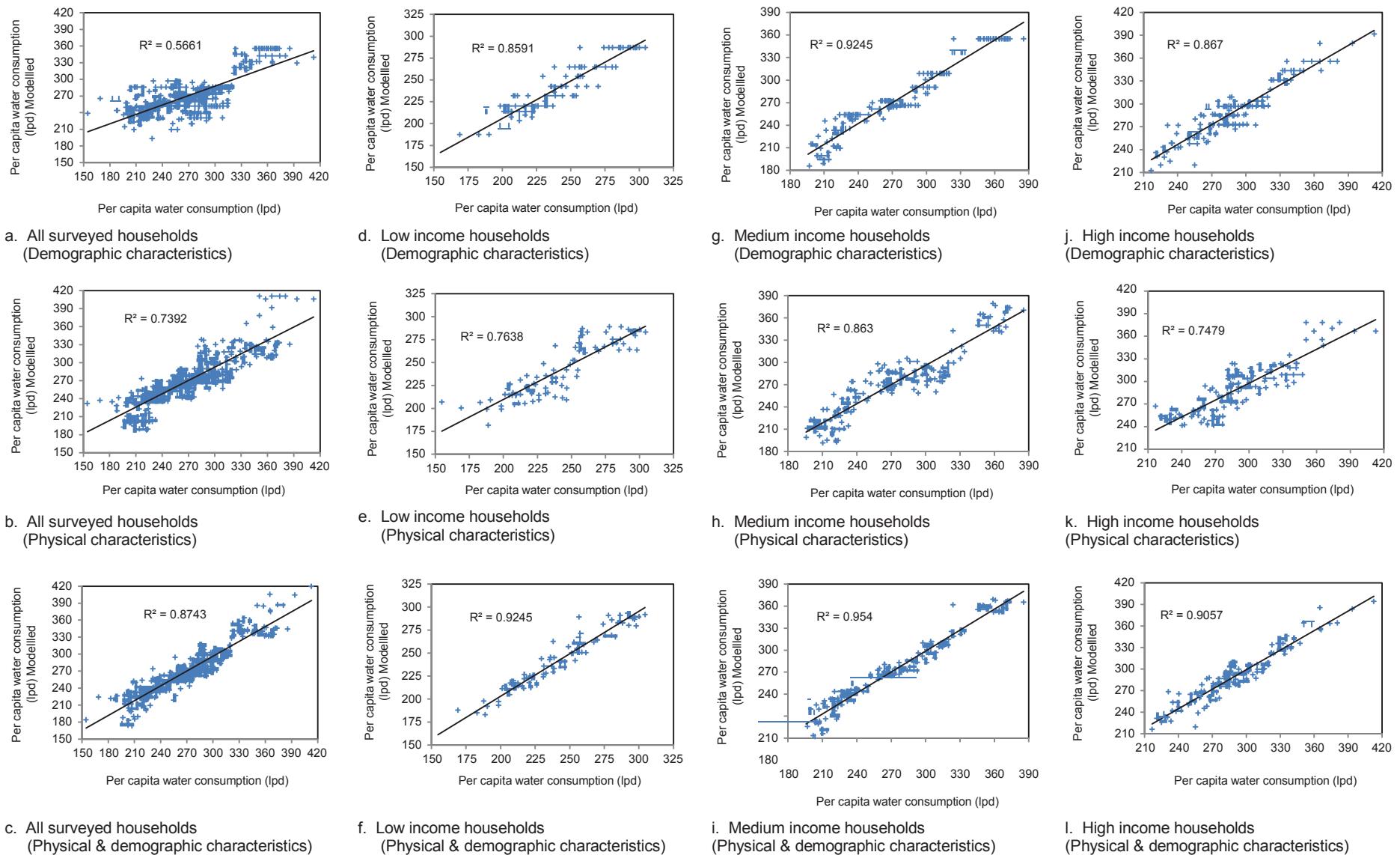
**Table 6. Models and coefficients of determination ( $R^2$ ) using multiple regression method (STEPWISE)**

	Model	$R^2$
All surveyed households	Model based on demographic characteristics of the household $TW_w = 291.92 - 10.57 \times NC_w + 15.95 \times NAF_w - 13.51 \times NAM_w - 15.91 \times NE_w$ ..... (1)	0.566
	Model based on physical characteristics of the household $TW_w = 290.87 - 26.72 \times NR_w - 29.99 \times NF_w + 0.5 \times AG_w + 0.48 \times I_w$ ..... (2)	0.739
	Model based on all (demographic and physical) characteristics of the household $TW_w = 281.9 - 15.1 \times NC_w - 10.34 \times NAF_w - 24.26 \times NAM_w - 21.02 \times NE_w + 13.2 \times NR_w - 12.74 \times NF_w + 0.3 \times AG_w + 0.24 \times I_w$ ..... (3)	0.874
	Model based on demographic characteristics of the household $TW_l = 319.52 - 22.23 \times NC_l - 32.71 \times NAF_l - 28.56 \times NE_l$ ..... (4)	0.859
Low income households	Model based on physical characteristics of the household $TW_l = 222.93 - 39.92 \times NR_l + 0.44 \times AG_l + 0.98 \times I_l$ ..... (5)	0.764
	Model based on all (demographic and physical) characteristics of the household $TW_l = 271.45 - 19.06 \times NC_l - 29.05 \times NAF_l - 25.43 \times NE_l - 0.14 \times AHH_l + 0.84 \times AG_l + 0.44 \times I_l$ ..... (6)	0.924
	Model based on demographic characteristics of the household $TW_m = 404.47 - 18.17 \times NC_m - 12.42 \times NAF_m - 26.46 \times NAM_m - 23.75 \times NE_m$ ..... (7)	0.924
Medium income households	Model based on physical characteristics of the household $TW_m = 339.46 - 51.83 \times NR_m + 0.63 \times AG_m + 0.6 \times I_m$ ..... (8)	0.863
	Model based on all (demographic and physical) characteristics of the household $TW_m = 413.19 - 16.55 \times NC_m - 17.5 \times NAF_m - 19.65 \times NAM_m - 22.05 \times NE_m - 36.29 \times NR_m + 30.83 \times NF_m + 0.14 \times AHH_m + 0.25 \times I_m$ ..... (9)	0.954
	Model based on demographic characteristics of the household $TW_h = 428.62 - 12.26 \times NC_h - 12.34 \times NAF_h - 23.55 \times NAM_h - 17.41 \times NE_h$ ..... (10)	0.867
High income households	Model based on physical characteristics of the household $TW_h = 287.96 - 26.74 \times NR_h + 0.38 \times I_h$ ..... (11)	0.748
	Model based on all (demographic and physical) characteristics of the household $TW_h = 333.66 - 10.73 \times NC_h - 11.74 \times NAF_h - 20.61 \times NAM_h - 12.95 \times NE_h + 0.16 \times AG_h + 0.19 \times I_h$ ..... (12)	0.906

\* where:

TE = daily per capita energy consumption (l/p/d),  
 NC = number of children in the household,  
 NAF = number of adult females in the household,  
 NAM = number of adult males in the household,  
 NE = number of elders in the household,  
 NR = number of rooms in the household,  
 AG = total garden area ( $m^2$ ),  
 AHH = total household built up area ( $m^2$ ),  
 NF = number of floors in the household,  
 I = per capita monthly income (Thousand ID)

w = whole survey,  
 l = low income households,  
 m = medium income households, and  
 h = high income households



**Fig. 5. Relationship between actual and predicted daily per capita water consumption using STEPWISE method**

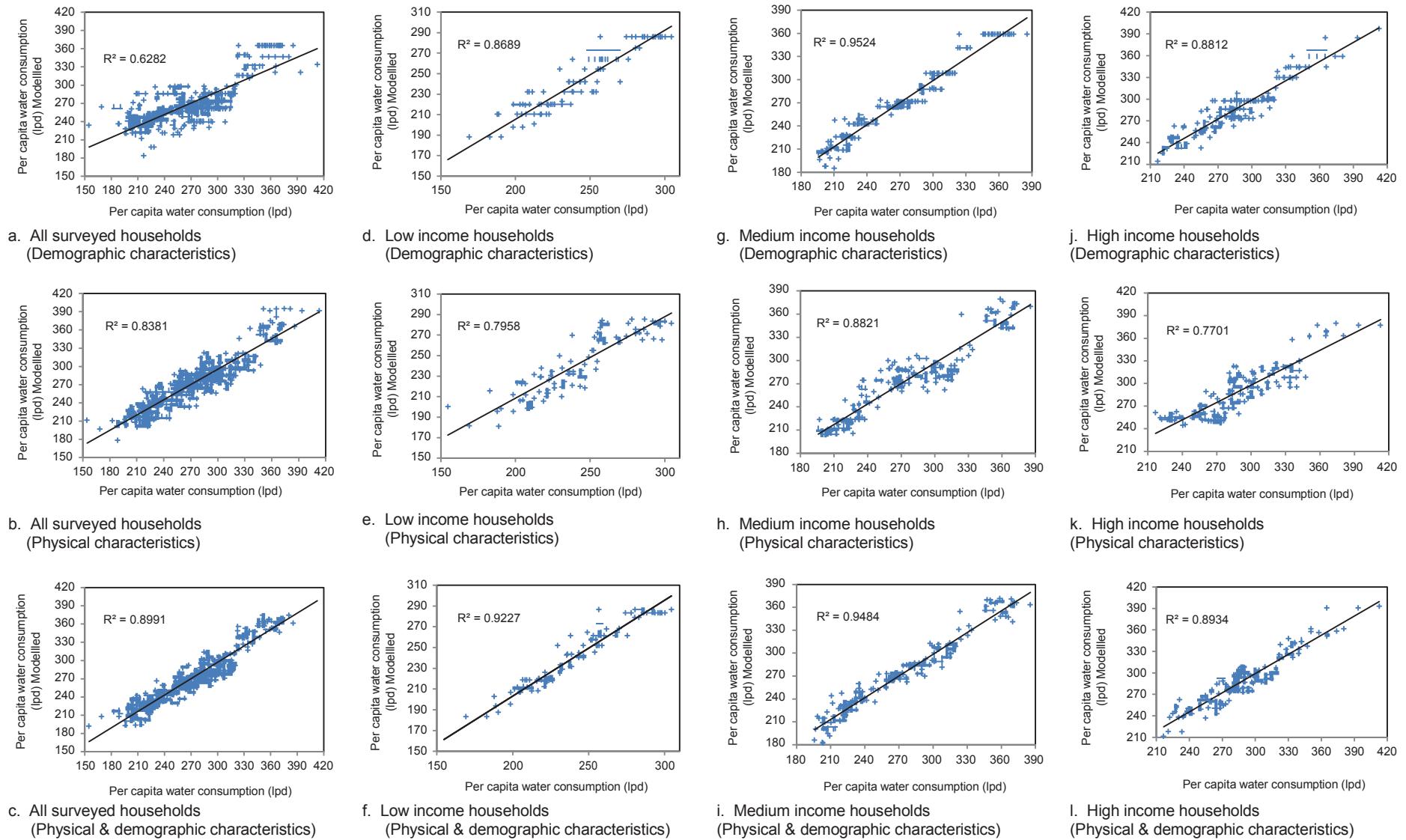
**Table 7. Models and coefficients of determination ( $R^2$ ) using evolutionary polynomial regression method (EPR)**

	Model	$R^2$
All surveyed households	Model based on demographic characteristics of the household $TW_w = 241.46 + 30.86 \times NAF_w - 0.58 \times NAF^{2.5} \times NAM - 19.9 \times NE^{0.5} - 7.63 \times NC \times NAF^{0.5}$ .....(1)	0.628
	Model based on physical characteristics of the household $TW_w = -74.80 + 31.83 \times I^{0.5} + 0.072 \times NR^{0.5} \times AHH^{0.5} \times AG^{0.5} - 0.048 \times NR^2 \times I + 91.31 \times 10^{-6} \times NR^{3.5} \times I^{1.5}$ .....(2)	0.838
	Model based on all (demographic and physical) characteristics of the household $TW_w = 147.98 + 12.79 \times I^{0.5} - 1.43 \times NAF^{0.5} \times NAM^{0.5} \times I^{0.5} - 15.15 \times NE - 10.78 \times NC$ .....(3)	0.899
Low income households	Model based on demographic characteristics of the household $TW_l = 303.21 - 17.32 \times NAF^{1.5} - 31.48 \times NE^{0.5} - 11.00 \times NC \times NAM$ .....(4)	0.869
	Model based on physical characteristics of the household $TW_l = 18.03 + 4.15 \times I + 0.69 \times AG \times I^{0.5} - 0.03 \times AHH \times AG - 0.14 \times NR^{0.5} \times I^{1.5}$ .....(5)	0.796
	Model based on all (demographic and physical) characteristics of the household $TW_l = 314.53 + 59.31 \times 10^{-6} \times NAF^{0.5} \times AG \times I^2 - 2.79 \times NAF \times AHH^{0.5} - 2.33 \times NE^{0.5} \times AHH^{0.5} - 7.76 \times NC \times NAM^{1.5}$ .....(6)	0.923
Medium income households	Model based on demographic characteristics of the household $TW_m = 358.89 - 13.58 \times NAF^{0.5} \times NAM - 7.75 \times NE^2 \times NAF^{0.5} \times NAM^{0.5} - 8.97 \times NC^{1.5} \times NAF^{0.5} + 0.13 \times NC^3 \times NAF \times NAM^{0.5}$ .....(7)	0.952
	Model based on physical characteristics of the household $TW_m = -221.44 + 48.85 \times NF^{0.5} \times I^{0.5} + 20.36 \times 10^{-6} \times NR^{0.5} \times AHH^{1.5} \times I - 0.31 \times NR \times NF \times I$ .....(8)	0.882
	Model based on all (demographic and physical) characteristics of the household $TW_m = 49.22 + 18.80 \times I^{0.5} - 83.06 \times 10^{-10} \times NAF \times NAM^2 \times I^{3.5} - 0.0017 \times NE^{1.5} \times NAM^{1.5} \times I^{1.5} - 0.053 \times NC \times NAF^{0.5} \times I$ .....(9)	0.948
High income households	Model based on demographic characteristics of the household $TW_h = 397.13 - 19.83 \times NAF^{0.5} \times NAM + 0.70 \times NAF^{0.5} \times NAM^{2.5} - 15.52 \times NE - 7.28 \times NC \times NAF^{0.5}$ .....(10)	0.881
	Model based on physical characteristics of the household $TW_h = 234.00 + 40.68 \times AG^{0.5} - 0.00011 \times AHH^{1.5} \times I - 64.33 \times NF^{1.5} + 0.013 \times NR^{0.5} \times NF^{0.5} \times I^{1.5}$ .....(11)	0.770
	Model based on all (demographic and physical) characteristics of the household $TW_h = 393.24 - 94.82 \times NAM^{0.5} + 0.0053 \times NAM^{0.5} \times I^{1.5} - 0.0015 \times NC^{1.5} \times NAF^2 \times NR^{1.5} \times I^{0.5}$ .....(12)	0.893

\* where:

- TE = daily per capita energy consumption (l/p/d),
- NC = number of children in the household,
- NAF = number of adult females in the household,
- NAM = number of adult males in the household,
- NE = number of elders in the household,
- NR = number of rooms in the household,
- AG = total garden area ( $m^2$ ),
- AHH = total household built up area ( $m^2$ ),
- NF = number of floors in the household,
- I = per capita monthly income (Thousand ID)

- w = whole survey,
- l = low income households,
- m = medium income households, and
- h = high income households



**Fig. 6. Relationship between actual and predicted daily per capita water consumption using EPR method**

### **3.4.3 Comparisons of models**

The twelve models developed in EPR and STEPWISE were compared using  $R^2$  values as shown in Table 8. From the table it can be seen that although the  $R^2$  value for EPR based model improves considerably, the complexity in the model also increases considerably and they require considerable computational effort. On the other hand, STEPWISE based prediction also offers good  $R^2$  values and models are less complex. Therefore, we conclude that implementing EPR based model do not offer considerable benefit in our case.

Both modelling approaches suggest the strong influence of demographic characteristics on per capita water consumption when the data was disaggregated into household income groups and the role of household physical characteristics is minimal.

**Table 8. Coefficients of determination ( $R^2$ ) of the final regression models**

	Per capita water consumption modelled with household demographic characteristics		Per capita water consumption modelled with household physical characteristics		per capita water consumption modelled with demographic and physical characteristics	
	EPR	STEPWISE	EPR	STEPWISE	EPR	STEPWISE
All surveyed households	0.628	0.566	0.838	0.739	0.899	0.874
Low income households	0.869	0.859	0.796	0.764	0.923	0.924
Medium income households	0.952	0.924	0.882	0.863	0.948	0.954
High income households	0.881	0.867	0.770	0.748	0.893	0.906

## **4. CONCLUSION**

The key messages from the analysis of the presented work are:

- The per capita water consumption increases with the increase in household income and decreases with the increase in the household occupancy.
- Frequency of all water end-uses increases with the increase in per capita income except for toilet usage. Toilet use frequency in low income households is higher than that in medium and high income groups.
- The duration of hand wash basin tap in Duhok is much higher than typical values in the developed world. This indicates an additional water use activities (e.g. ablution) via the hand wash basin tap.
- Flow rate from different water end-uses decreases with increase in the per capita income, suggesting that households in high income group are relatively new and fitted with water efficient appliances.
- Per capita consumption decreases with the increase in male adults, elders and children but increases with the increase in number of adult females in a household. Additionally, the change in the number of elders and children has identically effect on per capita consumption.
- Using the survey data, it is possible to predict per capita water consumption. The quality of prediction improves when the full data was disaggregated into low, medium and high income group households.
- The models based on EPR offer a marginal improvement in the predictions quality but increase the computational effort.

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# WATER REUSE SYSTEMS

# Rainwater as a domestic water supplement in Scotland: Attitudes and perceptions

Selina N. Egyir\*, Caroline Brown, Scott Arthur

*School of Energy, Geoscience, Infrastructure and Society, Heriot-Watt University, Edinburgh*

## ABSTRACT

**Aims:** Water resources in Scotland are under immense pressure despite the perception that it rains a lot and there are abundant water resources. High amount of energy is utilized for the transport and treatment of water for consumption which contradicts the UK government's carbon neutral agenda. There is the need to ensure reliable water supply to households whilst protecting the natural environment. This study therefore was aimed to explore the feasibility of rainwater harvesting (RWH) as a domestic water supplement in some selected peri-urban areas in Scotland by understanding people's perceptions, attitudes and behaviour towards RWH systems; and the preference for a community or individual system.

**Methodology:** Paper questionnaires were administered randomly to households using Private Water Supply (PWS) in three local areas: Highlands, Scottish Borders and Aberdeenshire over a period of 4 months.

**Results:** The response rates for Highlands, Scottish Borders and Aberdeenshire were 28%, 27% and 19% respectively, with the latter being marginally below target. The survey responses revealed that participants were unlikely to use RWH for domestic purposes like drinking, bathing, dishes and laundry but felt RWH would be acceptable for most uses except drinking. Respondents said that would be likely to use RWH for gardening, car washing and toilet flushing.

**Conclusion:** Most respondents were indifferent to implement RWH in their house if their neighbor had it or if it was a community set-up but were willing to in the form of grant incentives.

**Keywords:** Rainwater harvesting, private water supply, attitudes, behaviour, perceptions, community rainwater system

## 1. INTRODUCTION

### 1.1 Background

Water resources are essential for life and important not only to the society but also for the ecosystem [Forslund *et al.*, 2009] [1]. Adequate supply of clean drinking water is important to sustain human life, but it is observed that millions of people throughout the world still do not have access to this basic necessity [WHO/UNICEF, 2013] [2] and those who have access tend to take it for granted [Pass, 2013] [3]. Over the years, there has been a global increase in demand for portable water due to a growing population and a change in users' behaviour. In the UK, population increase since 1964 has been over 10 million people (18.7%) and it has

\* Tel.: +44 (0)131 449 5111

E-mail address: [sne1@hw.ac.uk](mailto:sne1@hw.ac.uk).

been projected to increase further in the coming decades [Office for National Statistics, 2014] [4]. This may lead to increase in pressure on fresh water resources and the infrastructure for managing mains water supply.

Households in the UK are the biggest users of water; approximately 55% of which 35% of the treated water for human consumption is flushed down the toilet [DEFRA, 2008] [5]. Rainwater harvesting (RWH) can be used for this non potable usage of water. RWH is the immediate collection of rainwater running off surfaces upon which it has fallen directly and excludes runoff from land watersheds into streams, rivers, lakes [Oweis and Hachum, 2006] [6]. This means controlling or utilizing rainwater close to the point rain reaches the earth and it has been known to control erosion and flood and also as an aquifer replenishment [Salem *et al.*, 2014] [7]; Brhane *et al.*, 2006 [8]; Fleskens *et al.*, 2005 [9]. It can reduce the demand for mains water supply [Ahmed *et al.*, 2014] [10] therefore reducing the amount of energy used in pumping of mains water, along with the associated pollution and carbon dioxide emissions. Examples of RWH systems can be found in all parts of the world and it has been observed to reduce water bills to meet the needs of remote communities or individual households in arid regions. Research by Basupi *et al.*, [2014] [11], discovered RWH to be more cost effective, resilient and climate-change mitigating than conventional (re)design of water distribution systems (WDSs). Also the overall energy consumption associated with RWH systems is a very minor fraction of total building energy consumption [Ward *et al.*, 2012] [12].

Moreover, climate change has been reported to likely increase the variability of precipitation and the number of flood and drought episodes [IPCC, 2007] [13]. These predictions emphasize the need to adapt water management to new and challenging environmental and socio-economic conditions [Domenech and Sauri, 2011] [14]. RWH may play a central role in widening water security and reducing impacts on the environment [El-Sayed *et al.*, 2010] [15] by turning hazards like floods and polluted water into local resources (water for non-potable uses). Even though Scotland is known for abundant rainfall, the east coast tends to be much drier with some parts receiving only 550mm of rain (UK Meteorological Office) which puts it on par with Morocco, Sydney and Barcelona; therefore there is the need to conserve water through harvesting rainwater for non-potable uses like flushing the toilet, gardening and car washing.

## 1.2 Problem statement

Despite the common perception that it rains a lot in Scotland, water resources there are under pressure. A high volume of water is taken from the environment for human use, and which requires a high amount of energy to transport and treat for human consumption. Water Supply Companies (WSCs) in the United Kingdom (UK) spend approximately £10 billion removing urban runoff from developments and importing treated water for consumption [Caffoor, 2008] [16]. In 2015, it is projected to reach approximately £12 billion [Ashley and Cashman, 2006] [17]. Within the context of changing climate and reducing carbon footprints, this situation is not compatible with sustainable development. We need to plan carefully for the future to ensure reliable water supplies are available for everyone whilst protecting the natural environment [EA, 2010] [18].

As a water saving scheme, RWH can reduce dependence on the drinking water supply, flooding and the pressure on urban drainage infrastructure. Literature is limited in Scotland with regards to RWH and receptivity of households towards this technology. Furthermore, in the context of a changing climate and reducing carbon emissions, government agencies, private organizations, and individuals are or have faced a change in the climate over the years which might have affected water resources. To achieve carbon reduction targets and be water neutral as well, organizations need to find the most cost-effective ways of achieving that. One way to achieve such a goal is to consider a water saving scheme like RWH which reduces the amount of energy used to transport and treat water, and thus reduces carbon emissions. Scottish Environmental Protection Agency (SEPA) has shown concern on Scottish water resources about the uncertainties that climate change may bring hence they need to resort to other alternatives like grey water and RWH [Scottish Water, 2012] [19].

There is the need to understand, and have a clear methodology which can define the different technologies and the risks (including financial) associated with RWH in Scotland with much

focus on the policy context, socio-economic drivers and public perception. When these real problems are considered together, it will establish a clear need for a methodology which allows the drainage and water supply needs of different development types/scales to be assessed in a way which is sustainable and efficient is demonstrated. These will limit their impact on environment whilst optimizing RWH and water consumption. According to Ward *et al.*, [2010] [12], understanding the receptivity, of water-users such as householders to RWH, is vital in facilitating the promotion, appropriate installation, end-use and maintenance of these systems. There is therefore a need for a framework which bridges the gap between socio-economic acceptance, attitudes and perceptions towards RWH in Scotland.

### **1.3 Aims**

The overall aim of this paper is to explore attitudes towards RWH among residents in Scotland. Case studies of households in rural areas with private water supplies were undertaken because it was theorized that users of PWS might be more inclined to save water because of the nature of their supply.

## **2. METHODOLOGY**

To answer the research questions a postal questionnaire survey was conducted in three study areas: Aberdeenshire (AS), Highlands (HL) and Scottish Borders (SB). These areas were selected because they had the highest numbers of PWS users in Scotland. The questionnaire consisted of 40 questions in 4 sections: water supply and source of PWS (shared or not shared), measures of water consumption, water conservation and rainwater harvesting. This paper focuses on responses about RWH.

Scottish Borders was used as a pilot study to test the response and distribution of the questionnaires. Over all a total of 1,000 questionnaires were distributed within the areas as follows (expected returns are shown in brackets): Aberdeenshire had the highest PWS users so a total of 400 questionnaires (80) was sent; Scottish Borders the second highest; 250 questionnaires sent (50) and Highlands which was the third highest was sent 350 questionnaires (70). The questionnaires were posted randomly to the selected case study areas using the list of private water users provided by their council. A small number of returned/non-delivered surveys were voided, and replaced with additional mailings. An additional 34 questionnaires were added in this way.

## **3. RESULTS AND DISCUSSION**

The expected response rate was 20% in all the case study areas. In Scottish Borders and Highlands, the actual response rate was 27% and 28% exceeding the targeted response rate; but for Aberdeenshire it was 19% response rate which was marginally below the target. The responses were grouped into: socio-economic and technical adaptations (the willingness to implement if grant was given, how easy it was to implement and the financial benefits) and behaviour which comprised of the attitudes and perceptions (awareness and experience of RWH; likelihood, acceptability of RWH). Overall, respondents were unwilling to implement RWH but if incentives like grants were given, participants were willing to implement RWH. A greater part was not likely to finance RWH installation themselves since they believed RWH not to be financially beneficial to their households.

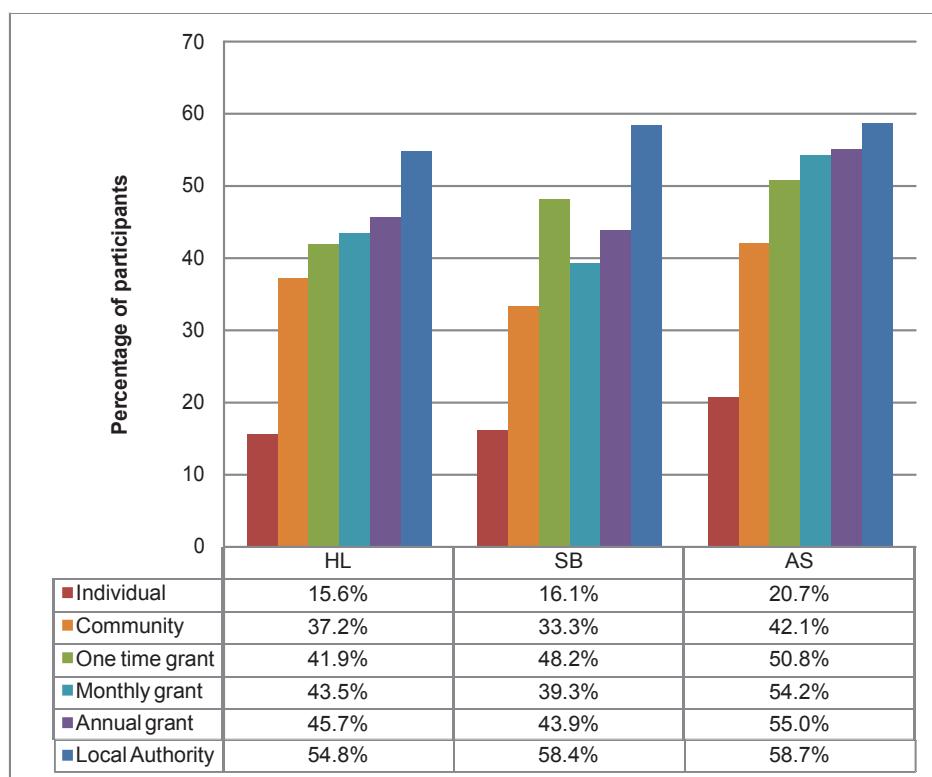
### **3.1 Socio-economic and technical adaptations of RWH in Scotland**

The issue of how environmental technologies should be paid for is an important one in understanding attitudes to, and adoption of energy and water-saving technologies. The survey asked householders under what circumstances they would be likely to adopt/implement RWH. The majority of the participants said that they would be likely to implement RWH if it was paid for by their Local Authority: HL (55%), SB (58%) and AS (59%), whereas only a minority of respondents would be willing to fund it themselves (Fig. 1). As the figure shows, there is a clear preference for some form of grant either by from a Local Authority or another organisation (Fig. 1). This result corresponds to research by Ward *et al.*, [2011] [20]; Islam *et al.*, [2011] [21] and Parson *et al.*, [2010] [22], where participants were willing to implement and or consider RWH if the government provided some incentive in the form of subsidies. Further research in the UK shows financial and economic constraints have

been a barrier to the installation of RWH in new UK houses and will remain until governmental incentives are introduced [Parson *et al.*, 2010] [22]. Therefore it was not surprising that respondents were willing to implement RWH if grants were given. New regulations and incentives that foster the use of rainwater are increasingly being developed worldwide by governments at both the local and regional levels [Domenech and Sauri, 2011] [14] and this has been successful. Governments have been known to financially support and have approved regulations and policies for RWH implementation in countries like Brazil, Belgium, India, Jordan, Sri Lanka, some American states (Arizona and New Mexico) and some Caribbean Islands [Goonetilleke *et al.*, 2005 [23]; Ministry of Urban Development and Water Supply Sri Lanka, 2005 [24]; Environmental Agency UK, 2008 [25]; Domenech and Sauri, 2011 [14].

In addition to financial grants, some countries offer rebates and tax exemptions to inhabitants to promote RWH installation. Examples include Texas in the United States where rebates and tax exemptions are offered to champion RWH [Texas Water Development Board, 2005 [26]; Australia where several initiatives (rebates) at the national and regional level promote the use of alternative water sources such as RWH to all houses installing RWH [Australian Government, 2009 [27]] and in Germany where rainwater harvesters are exempt to pay storm water taxes [Hermann and Schmida, 1999] [28]. This is also the case in the UK, but the amount of the rebate is very small and almost no one takes it up. Therefore there is the need to look into the cost of RWH installation and the feasibility installation of RWH systems so that a policy for mandatory implementation of RWH systems in the homes may be designed in Scotland.

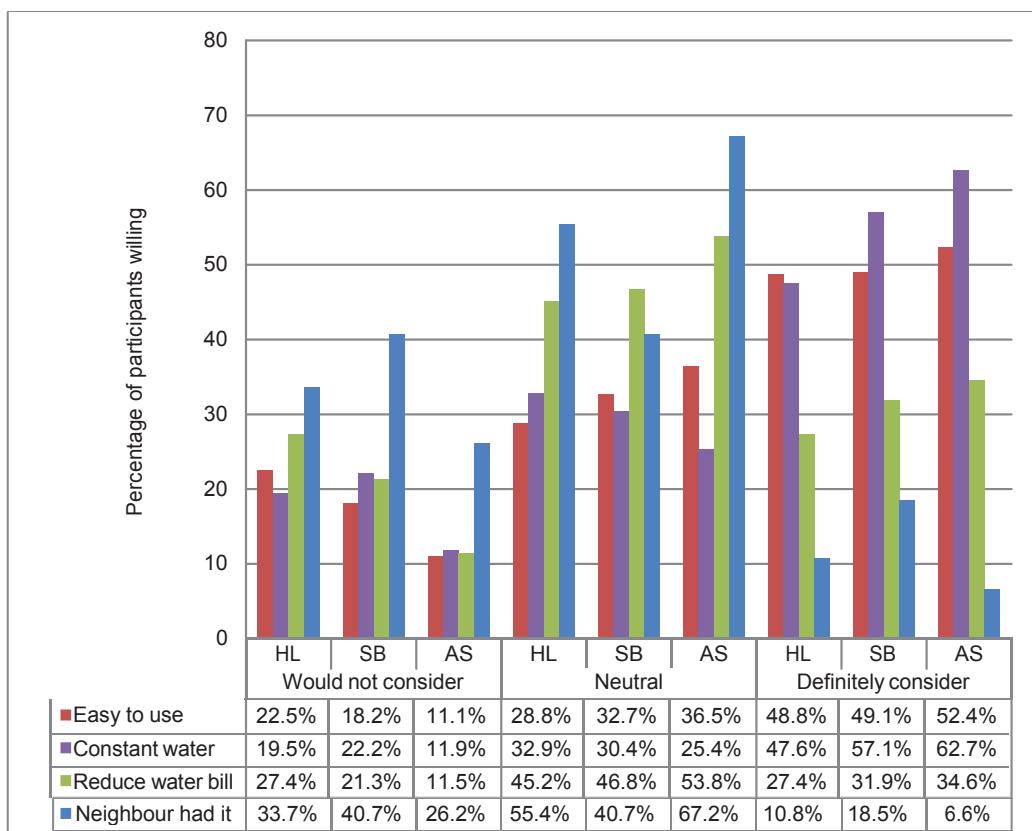
Comparing an individual setup to a community setup, most respondents preferred the idea of a community scheme.



**Fig. 1: Socio-economic incentives to implementing RWH: HL (Highland); SB (Scottish Borders); AS (Aberdeenshire)**

Most respondents in Scottish Borders (57%) and Aberdeenshire (63%) said that would also be likely to implement RWH if it would ensure there was constant water available. In but Highland the level was marginally below 50% (Fig. 2) but it should be noted the percentage willing to consider was more than the percentage willing not to consider (20%) and being neutral (33%) (Fig. 2). Therefore it can be said from the three study areas most respondents

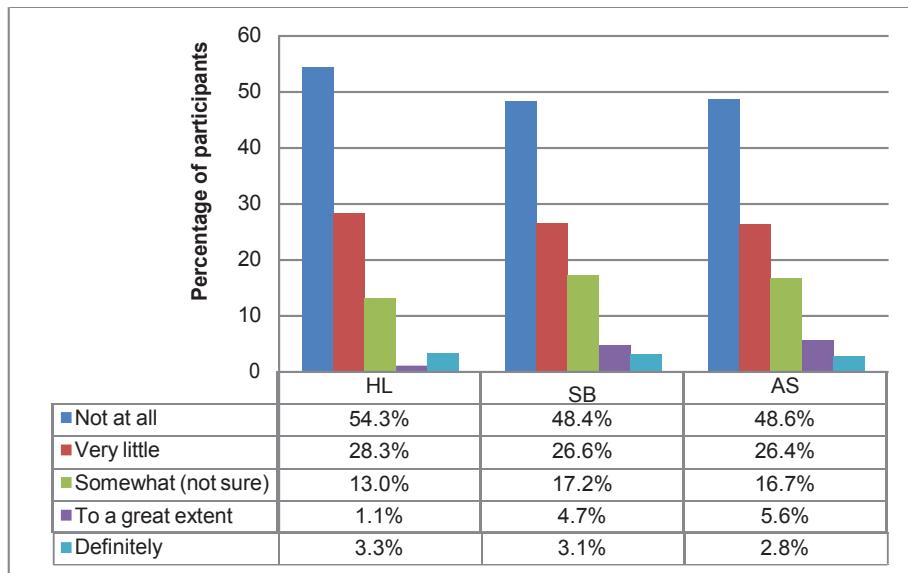
were willing to consider RWH if it will ensure there was constant water available. According to Barthwal *et al.*, [2013] [29], people are now envisaging the implications that might be associated with the negligent management of water resources and given a choice, people would choose a strategy that would help them avoid a situation of scarcity of their water resources and may be inclined and be willing to participate in a programme designed towards this cause [Sandakan Municipal Council 2008 [30]. In a RWH installation research in Brazil on subsidies, urban dwellers acknowledged the importance of diversifying the sources of water and becoming self-sufficient in terms of water supply [Domenech and Sauri, 2011] [14]. This can be attributed to the response of participants willing to consider RWH if it will ensure there was constant water was available at all times.



**Fig. 2: Adaptations and inclinations to implement RWH**

The survey explored the types of factors that would affect willingness to adopt RWH, including: a system that was easy to use; a system that improved/guaranteed water availability; that reduced bills; or was something the neighbours had.

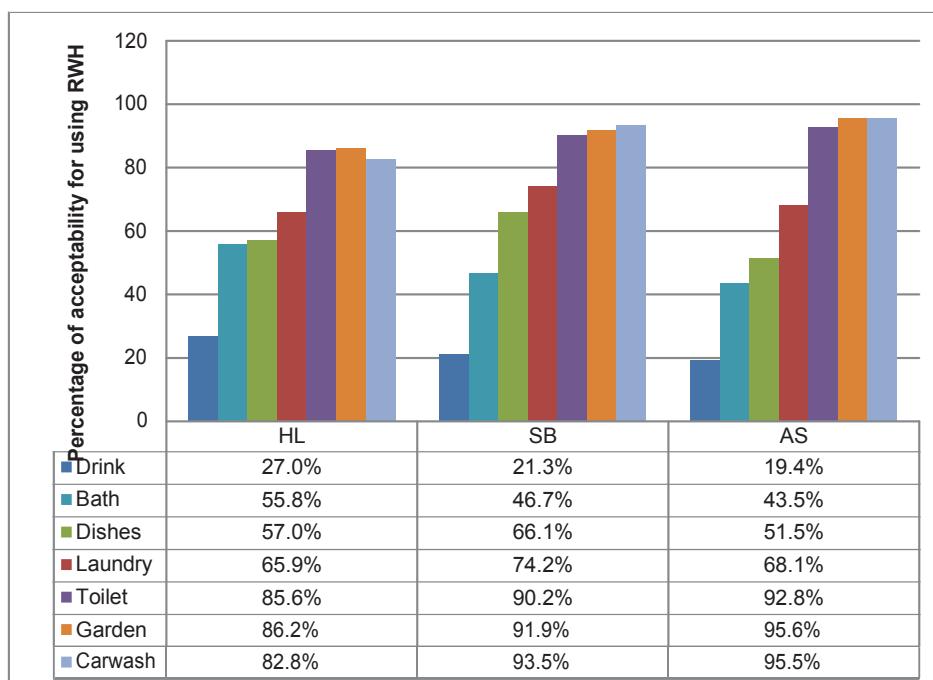
Interestingly, among these private water supply users, consistency of supply was more important to them than cost. This can be explained as a consequence of the low cost of water supply in Scotland, and the perception that water in Scotland is plentiful and free. This can be linked to the reason why participants were unlikely to implement RWH if it was to be paid by them but they were willing to consider it if it was easy to use (figs. 1 and 2). However, with regards to a communal system or personal system, the results were slightly similar in all study areas where they were not too much enthused to have it either way.



**Fig. 3: Participants response to RWH being financially beneficial**

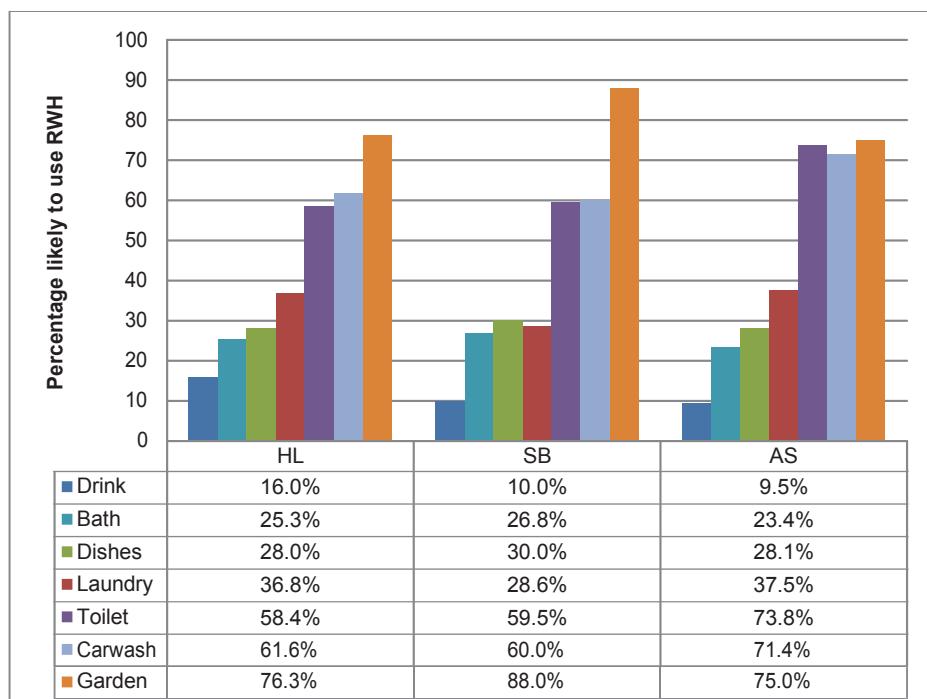
### 3.2 Behaviour, attitudes and perception of RWH in Scotland

With regards to respondents' attitude and behaviour towards RWH implementation, majority of respondents said that they thought RWH perfectly acceptable for domestic purposes like: dish washing, laundry, toilet flushing, gardening and car washing, but did not find it acceptable for drinking and bathing (fig. 4). The observed acceptability for these purposes, according to Ward *et al.*, [2008] [31], correlates to participants perceiving these uses to be less risky. Perceived risk according to Ward *et al.*, [2008] [31], is assumed when the type of use of rainwater becomes personal as in drinking and bathing therefore they do not find it acceptable. However for uses like gardening and toilet flushing where it is perceived not to be personal use they find it perfectly acceptable. And, a small number of respondents already use a water butt to collect rainwater for garden use [AS (35%); HL (26%); SB (25%)]. Similarly, studies by Hurlimann [2007] [32] identified that participants' perception of risk increased as the use became increasingly personal. Hence participants not finding RWH to be acceptable for drinking and bathing in this study can be attributed to the perceived risk of personal use of rainwater.



**Fig. 4: The level of acceptance of using RWH for domestic purposes**

Though they found RWH to be acceptable for most domestic purposes, they were only extremely likely to only use it for toilet flushing, car washing and gardening (fig. 5) which further corroborates Ward *et al.*, [2008] [31] and Hurlimann [2007] [32], where the perceived risk increases as the type of use becomes increasingly personal. Furthermore, some respondents said they would not use RWH for drinking because there was the possibility of the water being infested with crow droppings. According to Sadhu *et al.*, [2014] [33], rainwater collected and stored in domestic tanks may contain a range of microorganisms from one or more sources which might or might not be harmless but further stresses that the safety of rainwater will depend on excluding or minimizing the presence of enteric pathogens. Even though there is some health risks associated with RWH, according to Sadhu *et al.*, [2014] [33], the chemical and physical quality of rainwater may not directly cause health risk but can influence water disinfection methods and promote bacterial growth (Table 2). However, they state that "*the physical and chemical quality of drinking water directly affects its acceptability to consumers*"; this may be the reason why some participants found it unacceptable for drinking purposes.



**Fig. 5: The likelihood of using RWH for domestic purposes**

#### 4. CONCLUSION

Overall, this research revealed that Scottish respondents have a low level of awareness about RWH, with little technical knowledge or understanding of the environmental benefits relating to RWH. Respondents showed varied awareness and acceptability of installing RWH systems, but what draws out most was that they would be willing to install RWH systems if it will ensure constant availability of water and were given some form of grants by their Local Authority. However they did not know how to go about it and asked questions on how best to install RWH systems and were willing to participate in focus group discussions to learn more about RWH. Some of the participants (approximately 35%) had some form of RWH in their house in the form of water butts which they used for gardening purposes but they did not realize they were harvesting rainwater. Coupled with the lack of knowledge and technical know-how relating to the design and installation of RWH and willingness of some participants to install RWH, the following recommendations have been determined:

1. Government in Scotland should consider the introduction of new regulations and incentives that foster the use of rainwater by looking into the cost of RWH installation and the feasibility installation of RWH systems so that a policy for mandatory implementation of RWH systems in the homes may be designed.

2. Local Authorities can also create incentives and encourage RWH as most participants have been shown to be interested if grants are given at the local level.
3. Most participants felt their building design could not accommodate RWH therefore it will be good to have buildings designed in a way that supports RWH.
4. Appropriate organizations (both private and public) need to take the lead in promoting and sensitizing the public on RWH system innovation, their benefits in terms of flood control and how the water can be filtered to good quality for potable uses to make it more appealing to a wider range of householder needs.

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# Stochastic modelling of the performance of an onsite rainwater harvesting system in Mediterranean climates – North Israel as a case study

H. Muklada, Y. Gilboa, E. Friedler\*

Faculty of Civil & Environmental Engineering, Technion – Israel Institute of Technology, Haifa 32000, Israel

## ABSTRACT

**Aims:** Model the performance of onsite RWH (rainwater harvesting) system, in Mediterranean climates characterised by dry summers and winters with highly variable rainfall patterns.

**Study design:** The study is based on stochastic Monte-Carlo simulation.

**Place and Duration of Study:** 56 years daily rainfall data from Haifa, Israel was used as model input.

**Methodology:** A stochastic model was developed for quantifying the storage capacity needed, as a function of rainfall frequency and depth, roof area, number of residents, specific water use (toilet flushing and laundry) and the efficiency required from the system. Maximum volumes were calculated. Two performance indicators were defined and calculated: WSE (water saving efficiency) - proportion of water used within the house supplied by the RWH system; and RUE (rainwater use efficiency) - proportion of rainwater that was used.

**Results:** The required maximum storage capacity and WSE decreased with increasing number of residents for a given roof area, and increased with an increase in roof area for constant number of residents. For variable storage volumes, RUE increased with increasing storage capacity and reached maximum value faster with an increase in residents' number and a decrease in the roof area. The model predicted the storage capacity for avoiding extra costs (due to oversized tank volume) while keeping high system efficiency.

**Conclusion:** The model enables to determine WSE and RUE for specific storage volumes or to determine the desired WSE and calculate the needed storage. This modelling approach can be implemented to other climatic regions.

Keywords: Rainwater harvesting, stochastic modelling, water saving, Mediterranean climate

## 1. INTRODUCTION

Onsite Rainwater harvesting (RWH) is an ancient method which served as an alternative source of water in many places in the Middle East and all around the world. However, with the establishment of central water supply systems, the use of onsite RWH systems has generally stopped. Today due to increased water shortage on one hand, and urban flooding on the other, there is a renewed interest in onsite RWH. Interest in onsite RWH extends from water-scarce regions where the motivation is increasing the amount of available water, to water-ample ones where the motivation is primarily prevention and reduction of urban runoff as well as environmental awareness.

RWH has been acknowledged as a potential source to supply water and to promote significant potable water savings [1, 2]. Rainwater, which is a renewable freshwater source, could be used in various non-potable applications at the household level in urban areas. Rainwater, being the main source of freshwater in both natural and human-managed ecosystems, has significant untapped potential for being harvested [3]. Numerous studies investigating the harvested rainwater quality were conducted in Australia, Canada, Denmark, Germany, India, Japan, Spain, New Zealand, Thailand, and the United States [4, 5, 6, 7, 8]. However, less information and clear definition on rainwater tank sizing are available [9, 10, 11, 12]. The correct tank sizing is important in order to avoid extra costs when the tank is

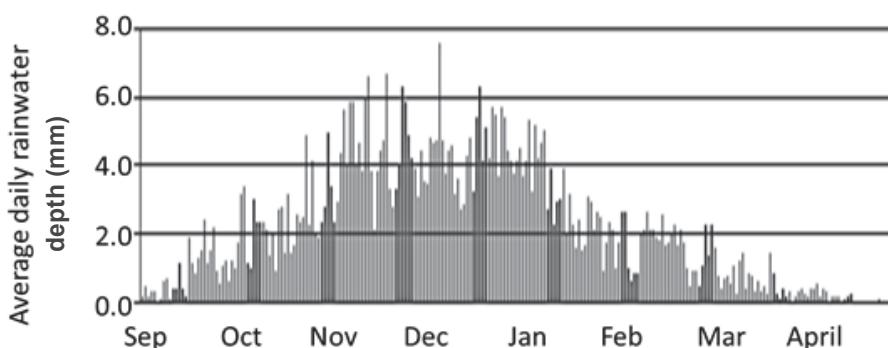
oversized and low efficiency when it is undersized. Several tools were developed for estimating the required tank size and to predict the system performance. For instances: Jenkins et al. [13] developed two behavioral algorithms to describe the operation of a RWH system during a given time interval. The first algorithm is yield after spillage (YAS), where the amount of water provided by the rainwater collection system, in which the withdrawal occurs after the rainfall has been added to the storage facility and spillage has been determined. Whereas the second one, yield before spillage (YBS) algorithm, assumes that the demand is withdrawn before spillage is determined. Fewkes [14] used collected data to verify and refine a rainwater collection sizing model based on YAS algorithm. The refined model was used to develop a series of dimensionless design curves relating collection area, demand, rainfall level, system efficiency and storage volume. Fewkes and Butler [15] evaluated the accuracy of behavioral models, for the sizing of rainwater collection systems using different time intervals and different reservoir operation. Villarreal and Dixon [16] generated a computer model to quantify the water saving potential of the rainwater collection by analyzing the water saving efficiency. The analysis of several scenarios allowed the authors to suggest suitable sizes of rainwater tanks. Khastagir and Jayasuriya [17] presented a methodology for optimal sizing rainwater tanks considering the annual rainfall at the geographic location, the demand for rainwater, the roof area and the desired supply reliability. Ghisi [9] analyzed the influence of rainfall, roof area, number of residents, potable water demand and rainwater demand on rainwater tank sizing, by using computer simulations. The author indicated that rainwater tank sizing for houses must be performed for each specific situation, i.e., considering local rainfall, roof area, potable water demand, rainwater demand and number of residents.

The objective of this study is to develop a stochastic model to estimate the optimal rainwater tank size depending on the rainwater demand, number of residents and the catchment size (roof area), when the daily rainfall at the location area was considered as the stochastic parameter. The model was developed for Mediterranean climate (Haifa, Israel), characterised by long dry summers (literally) and winters with highly variable rainfall patterns. Nevertheless, similar methodology may well be implemented to other climatic regions.

## 2. MATERIALS AND METHODS

### 2.1 Study site

Daily rainfall data was taken from Haifa Port meteorological station, located 30 m above sea level. The climate in the area is Mediterranean with an average annual rainfall of 538 mm/y (S.D.  $\pm 141$  mm/y). The data expanded over 56 years, from August 1952 until July 2007. A day started at 8 am (local time) and ended at 7:59 am the next day. A day was defined as rainy if more than 1 mm rainfall was measured. The number of rainy days was 50 d/y on average (ranging from 35 to 69 d/y), spanning from September to May. The average number of dry days within the rainy season was 151 (range: 105-220). The average number of dry days between consecutive rainy days was 4.1 (S.D. 6.2 d), with a median value of 1 d and a 75 percentile of 5 d or less. The length of the dry period was 164 d/y (range 97-217). Figure 1 shows perennial daily average of rainfall as was measured during the rainy season, at the meteorological station. The figure illustrates the fluctuations in the rainwater depth, which are significant, and should be considered when designing the storage tank size.



**Figure 1. Haifa Port meteorological station - Daily precipitation distribution- perennial average (56 years). Rainy season September-April, dry season May-August.**

## 2.2 Model description

### 2.2.1 Input data

#### 2.2.1.1 Rainwater data

As aforementioned, daily data from Haifa Port meteorological station over 56 years were analyzed, providing 56 data entries for each day, ranging from zero to the maximum rainwater value that was measured over the examined period. It was assumed that there is no dependency in the daily rainfall depth between consecutive days, although some of the rain systems in the region last more than one day. Hence, for each day, a cumulative probability function was drawn as a function of rainwater depth. Then, a sixth degree polynomial approximation function of rainfall depth vs. probability was derived for each calendar day (eq 1).

$$R(t) = \text{Max} \left\{ \begin{array}{l} a_t \cdot P(t)^6 + h_t \cdot P(t)^5 + c_t \cdot P(t)^4 + d_t \cdot P(t)^3 + e_t \cdot P(t)^2 + f_t \cdot P(t) + g_t \\ 0 \end{array} \right\} \quad (1)$$

$$P(t) = \text{Random}(0-1) \quad (2)$$

Where:

- $R(t)$  is the predicted daily rainwater depth (mm/d) for day t ( $t=1 \dots 365$ ). The *Max* function was added in order to ascertain that rainwater depth is always non-negative (the result of the polynomial approximation can become negative below a certain probability threshold).
- $a_t, b_t, c_t, d_t, e_t, f_t$  and  $g_t$  are the polynomial coefficients for day (t). These were obtained for each day by parameter estimation by minimizing the squared error function.
- $P(t)$  is the probability (0:5 P :51) - a number which is randomly chosen by the model (uniform distribution).

#### 2.2.1.2 Roof area size and type

Five roof area sizes were simulated in the model: 75,100,150,200 and 400 m<sup>2</sup>. Since the performance of the RWH systems is sensitive to the runoff coefficient, the roof type may affect the generated rainwater runoff [8, 18]. Therefore, a field experiment was conducted, during rainy seasons of 2007 and 2008, to determine the rainwater runoff coefficient for three types of roof (each having a horizontal area of 1m<sup>2</sup>) common in Israel: (1) concrete at a slope of 1%, (2) tile at slope of 30% and, (3) isolated steel sheets that are used for roofing tall buildings (*Iskoorit™*) at slope of 1%. The roofs placed at the Technion University Campus (Haifa, Israel) 1 m above the roof of one the buildings, with their slopes facing west; the dominant direction of rain events at this region. Each roof was fitted with a gutter leading to a 55 L collection tank. An automatic micro rain gauge (tipping bucket; Model 525, *Texas Electronics INC*) was placed near the system when the rainfall recorded at a resolution of 10 minutes. The results from this field experiment (55 rain events) served for developing linear empirical equations, for estimating the effect of the roof type on the correlation between rainfall and the roof runoff, as follows (eq. 3):

$$\text{runoff} = \text{Max} \left\{ \begin{array}{l} a_i \cdot R(t) + b_i \\ 0 \end{array} \right\} \quad (3)$$

Where:  $d_{i(t)}^{\text{runoff}}$  - the specific daily rainwater runoff generated (generated runoff divided by the roof area) (L/(m<sup>2</sup>·d)) for each roof type (i);  $a_i$  - the slope of the line (L/(mm·m<sup>2</sup>)), for each roof type;  $R_i(t)$  - daily rainwater depth at day t (mm/d) and  $b_i$  - the intercept with the Y-axis (L/m<sup>2</sup>·d), for each roof type.

By multiplying  $d_{i(t)}^{\text{runoff}}$  by the roof area A (simulated as 75, 100, 150, 200 and 400 m<sup>2</sup>), the

daily volume of rainwater runoff available for storage ( $V_{i(t)}$ ), is calculated as follows:

$$V_{i(t)} = d_{i(t)}^{\text{runoff}} \cdot A \quad (4)$$

$$V_{i(t)} = i(t)$$

### 2.2.1.3 Water demand and number of residents

In most countries untreated or minimally-treated harvested rainwater is used for non-potable uses, such as toilet flushing, clothes washing and garden irrigation [1, 2, 14, 16, 19]. This is practiced in order to ensure that public health is not compromised. In regions having Mediterranean climate (such as Haifa), most garden irrigation is performed during the dry summer, while the rain events occur only during the winter making the use of the harvested rain for garden irrigation is unfeasible. Hence, only toilet flushing and laundry were considered in this study. Domestic in-house water demand in Israel is evaluated as 153 litre/capita/day (L/c/d), of which 44% (68 L/c/d) can be used (toilet flushing 55 (L/c/d); laundry (13 L/c/d) [20]. This value was used as input to the model, and the cumulative water demand can be calculated by:

$$V_{(t)}^{demand} = 68 \cdot N \quad (5)$$

Where:  $V_{(t)}^{demand}$  is the rainwater demand for toilet flushing and laundry (L/d); 68 is the domestic in-house water demand used for toilet flushing and laundry (L/c/d); N is the number of residents (c).

Six possible residents population in a single house were examined in the model 4, 8, 12, 24, 48 and 64 residents.

### 2.2.2 Model algorithm

The model was written in MATLAB and based on yield after spillage (YAS) algorithm, in which the water supplied from the storage tank after rainfall has been added to the storage facility [14, 15]. The model is a daily model, i.e. it uses a daily time-step. For simplicity, it was assumed that at the end of summer (or the beginning of the rainy season), the rainwater storage tank is empty.

The daily mass balance of water in the rainwater tank is given by:

$$V_{(t-1)} + V_{(t)}^{rain} - V_{(t)}^{demand} \quad (6)$$

$$V_{(t)} = \text{Min} \quad V_{Max}$$

Where:  $V_{(t-1)}$  and  $V_{(t)}$  are the volumes of water in the tank at day t-1 and t respectively;  $V_{max}$  is the storage tank volume.

If the storage tank is completely filled ( $V_{(t)} > V_{max}$ ), the excess rainwater generated is released *overflow*) and the water volume available for the next day is  $V_{max}$ . as overflow ( $V_{(t)}$ )

If the daily rainwater demand is higher than the volume of rainwater available in the storage tank ( $V_{(t)}$ ), than freshwater from the urban water supply is provided to overcome this shortfall, and calculated as:

$$V_{(t)}^{fresh} = Ahs(V_{(t)}) \quad (7)$$

$$V_{(t)}^{fresh} = Ahs(V_{(t)})$$

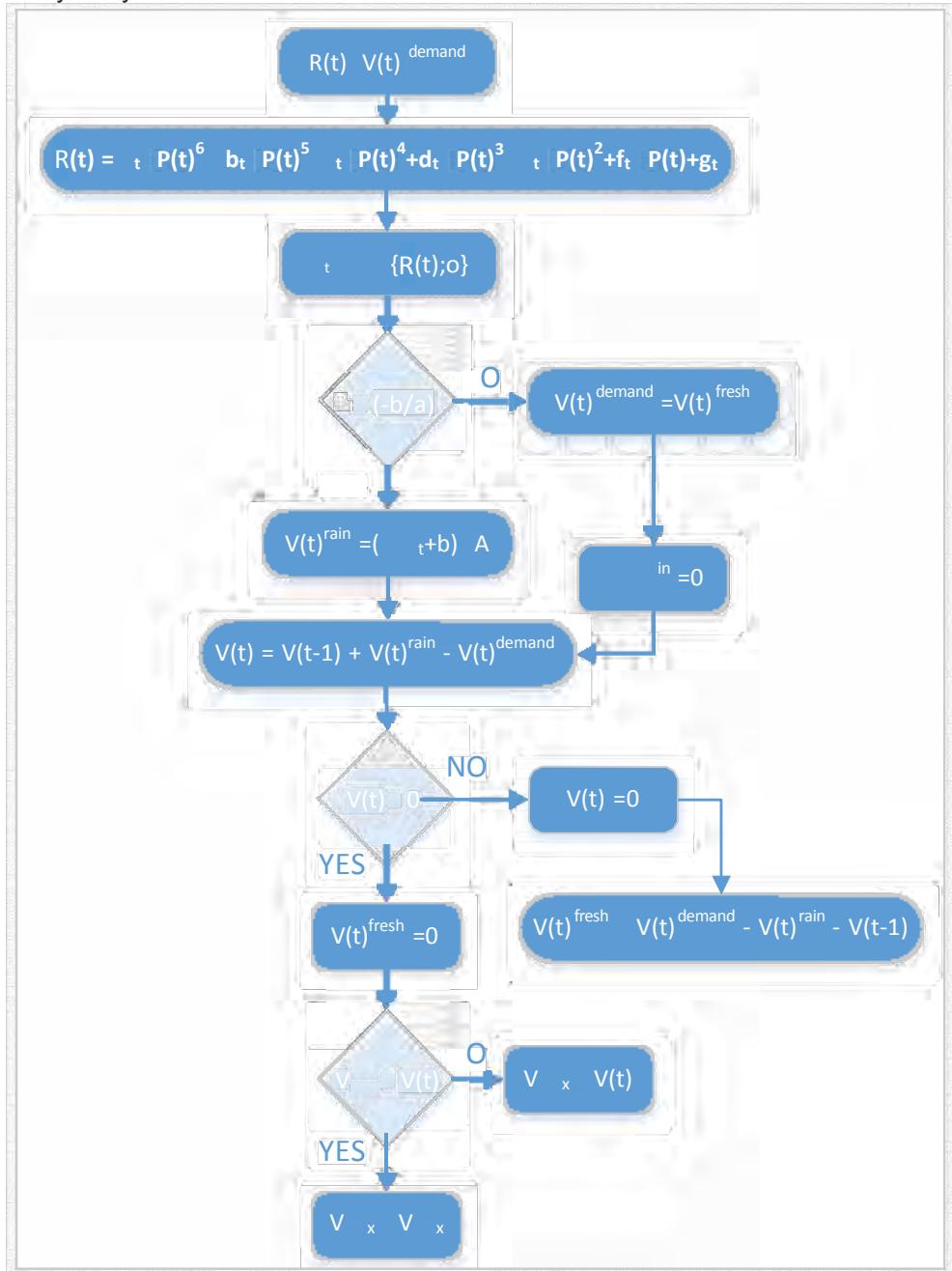
Where:  $V_{(t)}^{fresh}$  is the amount of freshwater provided; and  $Abs(V_{(t)})$  is the absolute value of  $V_{(t)}$ .

After this calculation  $V_{(t)}$  is set to 0.

### 2.2.3 Simulations scenarios

The study was divided in to two stages: In the first one the maximum volume in which all the rainwater runoff is used (in other words, system utilization efficiency of 100%) was calculated by the simulation model. Figure 2 depicts a schematic flowchart for this simulation. Thirty scenarios were simulated and analysed: five roofs sizes (75, 100, 150, 200 and 400 m<sup>2</sup>) and six number of residents (4, 8, 12, 24, 48 and 64). Each scenario was run for a whole year with a

daily time-step. 100 year-long random simulations were performed with stochastic (Monte-Carlo) rainfall input yielding 100 possible maximum storage tank volumes that were statistically analyzed.



**Figure 2. Flowchart of the simulation model for sizing the maximum volume of the storage tank**

In the second stage, lower volumes of the storage tank (lower than the maximum values found in the first stage) were set prior to the simulation for evaluating the WSE and RUE of the system. WSE (water saving efficiency) that is defined as the proportion of water demand (of the two relevant uses) that is provided by rainwater (eq. 08). It should be noted here that the WSE was calculated only for the rainy season (Sept.-Apr.) The RUE (rainwater use efficiency) that quantifies what proportion of the rainwater collected was used in-house (eq. 9).

$$WSE = \frac{V_{rain}}{V_{demand}} \quad (8)$$

$$RUE = 1 - \frac{V_{overflow}}{V_{rain}} \quad (9)$$

### 3. RESULTS AND DISCUSSION

#### 3.1 Input data

##### 3.1.1 Rainwater data

As aforementioned, the model randomly selected probability and calculated rainwater depth (eq. 1) for each day. The average simulated rainwater depth was 574 mm/y (100 model runs), fell in line with measured values at Haifa Port meteorological station (538 mm/y). The range of the simulated rain depth was 300- 00 mm/y very similar to the range of the measured data (292-925 mm/y). Further, the stochastic simulation results were not found to be statistically different from the measured data, indicating satisfactory representation of measured data.

##### 3.1.2 Roof type

The effect of roof type on the generated runoff, as calculated from the measured data, is presented in Table 1. In the table, the parameters of the linear empirical equation (eq. 3) are given. The correlations between runoff and rainfall were high for all examined roof types ( $R^2$  :: 0.93 and  $p < 0.05$ ). "a", the regression line slope, expresses the relationship between rainfall and the generated roof runoff after runoff commenced. Hence, the closer "a" is to 1, the higher the proportion of rainfall that is converted to runoff. Of the three roof materials examined tiles had the highest rain to runoff conversion rate ( $a = 0.91$ ) while concrete had the lowest one ( $a = 0.78$ ).  $R_{(y=0)}$  is the minimum amount of rainfall needed for runoff to start ( $R_{(y=0)} = -b/a$ ).  $R_{(y=0)}$  actually represents the depression storage of the roof, which is analogous to depression storage in open spaces. For the examined roof types, runoff from the concrete roof started after 2.3 mm of rain as compared with 0.37 and 0.041 mm for the tile and steel-sheets roofs, respectively. The findings were expected as steel-sheets have less and smaller crevices and less water is consumed for wetting the roof material than tile or concrete roofs. To summarise, the runoff from the concrete roof started after the largest rainfall depth as it required the largest amount of rainfall for filling small depressions in roof before runoff commenced and it generated the lowest volume of runoff for each rainfall event. The tile roof generated the largest volume of runoff for each rainfall event (largest "a"), although runoff from the steel-sheets roof started after the lowest rainfall depth (lowest  $R_{(y=0)}$ ). The high runoff generated by the tile roof is probably attributed to its high longitudinal slope (30%).

**Table 1. Values of the linear regression equation parameters for assessing the effect of the roof type on the relationship between rainfall and roof runoff**

Roof type	<b>a</b> l/(mm·m <sup>2</sup> )	<b>b</b> l/(m <sup>2</sup> ·d)	<b>R<sub>(y=0)</sub></b> <sup>*</sup> mm	<b>n</b> <sup>**</sup>	<b>R<sup>2</sup></b>
<b>Concrete</b>	0.78	-1.8	2.3	47	0.93
<b>Steel sheets</b>	0.80	-0.033	0.041	45	0.98
<b>Tiles</b>	0.91	-0.34	0.37	36	0.97

\*  $R_{(y=0)}$  Rainfall depth above which runoff commences; \*\* n – number of rainfall events (observed)

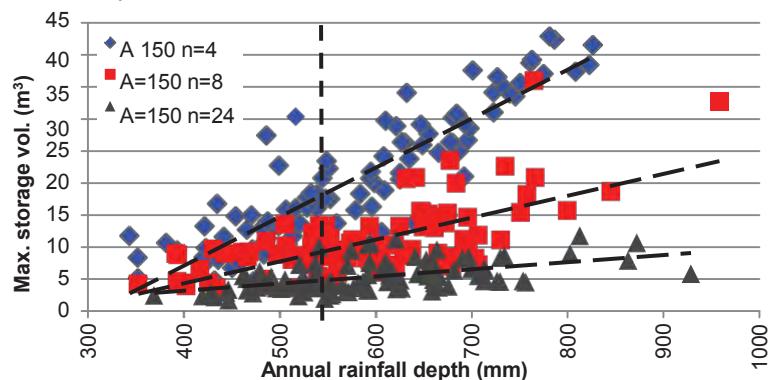
For brevity in the following sections (3.2-3.3) only the results for the concrete roof (most common roof type in Israel) is presented.

#### 3.2 Maximum volume of the storage tank and potential water saving efficiency

The maximum volume of the storage tank and the potential water saving efficiency were analysed for the 30 examined combinations (5 roof sizes x 6 population sizes in the house), each executed for 100 random runs. The maximum volume of the storage tank, is the volume that ensures harvesting and using all the runoff generated (RUE=100%, eq.9). Figure 3 depicts an example of the obtained results for a 150 m<sup>2</sup> from the 100 stochastic runs.

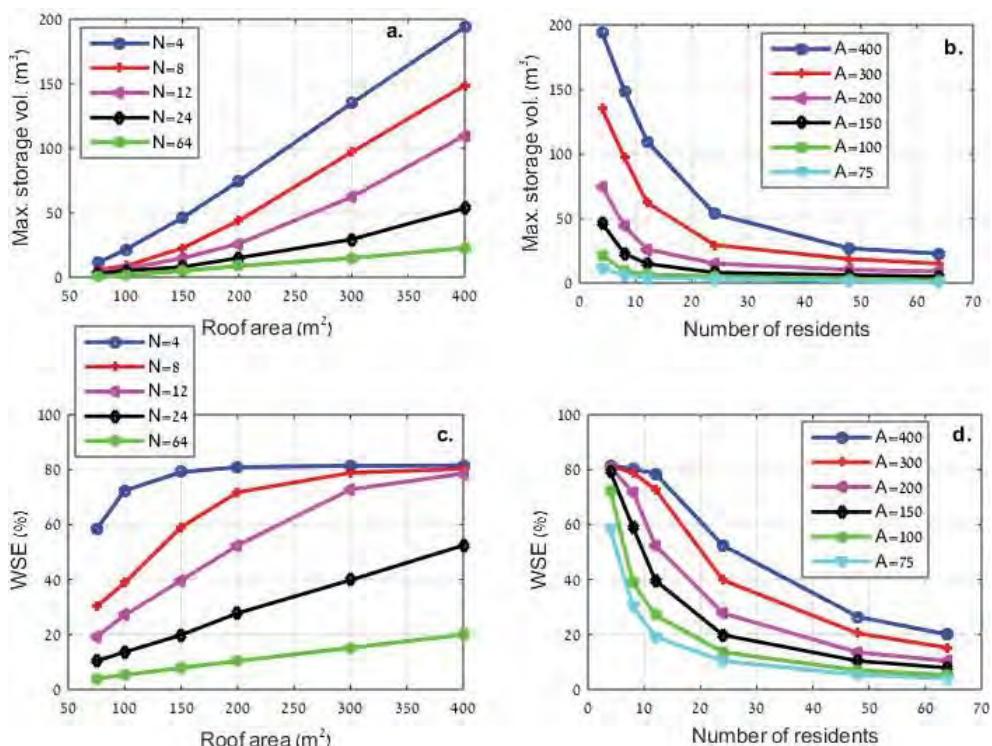
The maximum storage volume ranged from 0.46 m<sup>3</sup> and WSE of 4%, for roof area of 75 m<sup>2</sup> and 64 residents, to a maximum storage volume of 194 m<sup>3</sup> and WSE of 82% for roof area of 400 m<sup>2</sup> and 4 residents (Figure 4). As expected the maximum storage volume is highly dependent on the roof area, where larger roofs generate more runoff that required larger storage tank to increase the potential WSE (Figure 4 a, c). In other words, for the same number of residents, the maximum storage volume and the WSE increased with the roof area,

due to an increase in the generated roof runoff volume. The number of residents also has a significant effect on the maximum storage volume and on the potential WSE (Figure 4 b, d). As the number of residents increased (for the same roof area) the maximum storage volume decreased, due to higher water demand. At the same time the WSE also decreased meaning that the collected rainwater contributed smaller proportion of the water demand (although the RUE was 100% in all cases). For example, for a  $400 \text{ m}^2$  roof the maximum storage volume decreases from 194 to  $23 \text{ m}^3$  and the WSE decreases from 82 to 20% when the number of residents increases from 4 to 64, respectively. It is worth noting that in this example the number of residents increased by sixteen-fold, while the maximum storage volume decreased by 8.6-fold and the WSE only by 4.1-fold. Further, the differences between the maximum storage volumes and the WSE for varying number of residents are much more pronounced when the roof area is larger. These findings emphasise the importance of considering the roof area likewise the number of residents of each building, for calculating the volume of the storage tank and the expected WSE.



**Figure 3. Max storage volume for  $150 \text{ m}^2$  roof as a function of annual rainfall and number of residents**

Symbols - Maximum volumes obtained from each simulation (100 stochastic simulation runs). Vertical dotted line – Average annual rainfall in Haifa, Israel; Diagonal dotted lines – linear regression



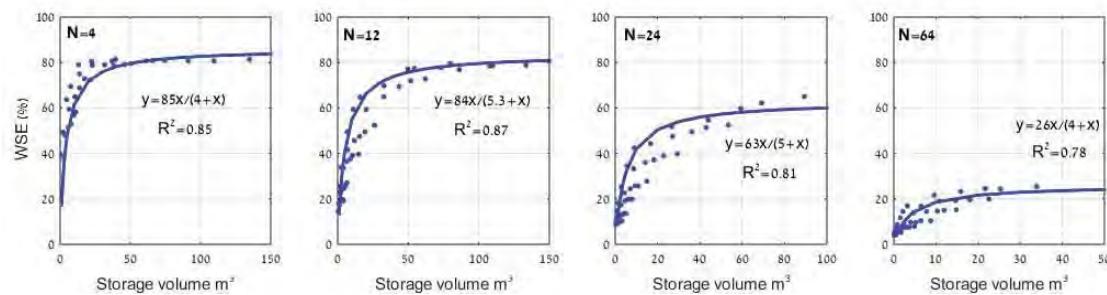
**Figure 4. Maximum storage tank volume vs. roof area (a); Maximum storage tank volume vs. number of residents (b); Water saving efficiency (WSE) vs. roof area (c); WSE vs. number of residents (d)**

Values are average values obtained from 100 model runs for each combination (roof area x number of residents)  
A – Roof area ( $\text{m}^2$ ); N – Number of residents

### 3.3 Rainwater use efficiency, water saving efficiency and storage tank volume

The above results performed for quantifying the maximum storage volume, in which all the rainwater runoff is stored and used (RUE = 100%), which in many cases leads to a large volume of the storage tank. However, rainwater harvesting systems do not always require the maximum storage volume tank and in most cases, lower volumes generate high (or at least satisfactory) WSE. Therefore, as aforementioned, in the second stage of the research the model was run with varying volumes of the storage tank and the WSE and RUE were calculated for each of the 30 combinations (roof area x number of residents).

Good correlation was obtained between the WSE and storage tank volume (Figure 5). From the figure it can be seen that this correlation follows a saturation curve, meaning that the WSE increases significantly with storage tank volume in the small volumes range and becomes much less sensitive to the tank volume as the tank volume increases. This is due to the fact that for small tank volumes the limiting factor is the volume available for storing the roof runoff, while as the tank volume increases, the limiting factor becomes the amount of water used by the residents (or in other words the number of residents). From the figure one can see that the maximum WSE (asymptotic / saturation value) decreases from ~80% for 4 person home to ~25% for 64 person home. It should be noted that WSE of 100% is never reached due to the stochastic nature of rainfall in the studied area (Mediterranean climate, as discussed above).



**Figure 5. Water saving efficiency vs. the volume of the storage tank**

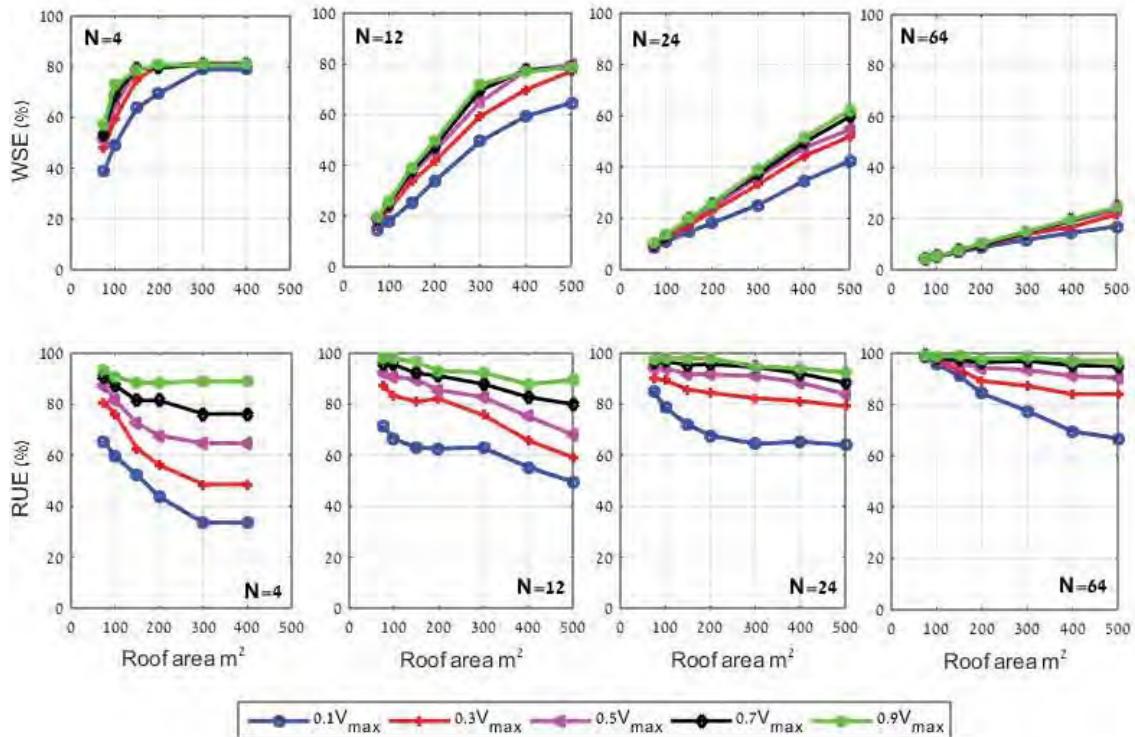
N- Number of residents

The WSE for 4, residents house ranged between 39% to 81% as the roof area increased from 75m<sup>2</sup> to 400 m<sup>2</sup> (Figure 6 top left), for the examined storage volumes (10%, 30%, 50%, 70% and 90% of the maximum storage volume). The results indicated that the WSE for a storage tank sized 10% of the maximum volume ( $0.1 \cdot V_{max}$ ) was the lowest, while no significant difference was found between storage tank sized 30-90% of the maximum volume. The same general pattern was observed for 12, 24 and 64 person houses, where storage tanks sized 10% of the maximum volume performed significantly worse than tanks sized 30-100% of the maximum volume. In other words, there was no significant advantage of the larger volume tank ( $0.9 \cdot V_{max}$ ) on the lower one ( $0.3 \cdot V_{max}$ ).

The RUE in a 4 person house generally decreased as the roof area increased, since the daily water demand is lower than the generated runoff (Figure 6 bottom left). The RUE was found to be more sensitive to tank size than the WSE, with much larger decrease of the RUE in the small tank volume ( $0.1 \cdot V_{max}$ ) from 65% to 34% (~50% decrease) than in the larger tank volume ( $0.9 \cdot V_{max}$ , from 94% to 89%, ~5% decrease). As the number of residents in the house increased the decrease in the RUE diminished, yet here again the decrease in the small tank volume ( $0.1 \cdot V_{max}$ ) became significantly larger than all other tank volumes. For example, for a 64 person house (Figure 6 bottom right) the RUE of a  $0.1 \cdot V_{max}$  tank decreased from 99% to 68% as the roof area increased from 75 to 500 m<sup>2</sup> (32% decrease), while the RUE of a  $0.3 \cdot V_{max}$

tank decreased from 99% to 84% (15% decrease) for the same increase in the roof area. It should be noted that for the combinations examined (roof area x number of residents) the WSE decreased significantly with an increase of number of residents (meaning that a lower proportion of the water consumption was supplied by the rainwater harvested, while the RUE increased (but in a less pronounced manner) with increasing number of residents, meaning that high proportion of the roof runoff was used. The results demonstrate the importance of using a model to predict the tank volume which allows determining the right tank volume

(avoiding extra costs due to oversizing of the storage tanks, while keeping a satisfactory efficiency of rainwater harvesting system).



**Figure 6. Water saving efficiency (WSE, top) and rainwater use efficiency (RUE, bottom) vs. roof area for different volumes of storage tanks (curves).**

Each graph is for different number of residents (N)

Values are average values obtained from 100 model runs for each combination (roof area x number of residents)

#### 4. CONCLUSION

A stochastic model to quantify the optimal size of rainwater storage tanks for residential homes was developed based of daily rainwater depth, water demand for non-potable domestic water uses, number of residents and roofs area, where rainfall was considered as the stochastic parameter. Daily rainwater depth was calculated from on historical data, and probability functions were derived for each calendar day. By this the effect of the variable daily rainwater was studied while keeping the seasonal patterns.

Quantifying the storage tank volume based on the WSE, emphasises the importance of considering the rainwater pattern, roof area and the number of residents. The model output exhibited good correlation between the WSE and storage tank volume, of a saturation curve pattern. This relationship is significant since it can be used for estimating the required storage tank depending on the desired WSE. It was demonstrated that in many cases it is not needed to have the maximum storage volume and smaller volumes can achieve almost the same efficiencies (WSE & RUE). For example: one can assume a specific storage tank volume and by running the model receive the predicted WSE, or determine the desired WSE and calculate the required tank volume. The model was developed for semi-arid Mediterranean environment (Haifa-Israel), the same methodology may well be implemented to other climatic regions. Further development of the model would include representation of domestic water uses in a stochastic manner.

#### COMPETING INTERESTS

We hereby declare that none of the authors has any competing interest.

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# A Laboratory Study into a Novel, Retrofittable Rainwater Harvesting System

Peter Melville-Shreeve<sup>1\*</sup>, Chris Horstman<sup>2</sup>, Sarah Ward<sup>1</sup>, Fayaz Ali Memon<sup>1</sup>, David Butler<sup>1</sup>.

<sup>1</sup>University of Exeter, Centre for Water Systems,

<sup>2</sup>The University of Arizona, College of Engineering Department.

## ABSTRACT

**Aims:** To establish the system characteristics of a novel rainwater harvesting system.

**Study design:** A laboratory test rig was used to assess the selected technology.

**Place and Duration of Study:** University of Exeter, Centre for Water Systems between June 2014 and May 2015.

**Methodology:** Previous research has identified that systems should have: 1) reduced capital costs, 2) reduced operational costs and 3) increased ease of retrofitting. To investigate the system's ability to address these requirements, two full-scale laboratory test rigs have been used to assess flow and power consumption characteristics under a range of installation scenarios.

**Results:** The system was identified to have a mean power consumption of 0.12kWh/m<sup>3</sup> during a one hour pump test. Electrical costs were found to increase when the power consumption of the 11W control board was taken into account.

**Conclusion:** Subject to reduction of the standby power consumption of the controller, the novel RWH system assessed in this study has potential to provide non-potable water supplies to households in the UK at a lower power consumption rate than existing water supply systems identified in the literature.

## KEYWORDS

Alternative water supply systems, rainwater harvesting, retrofit SuDS, water demand management.

## 1. INTRODUCTION

Rainwater harvesting (RWH) in the UK is an under-utilised technology that is often cited as a simple, low cost solution to a wide number of pressures associated with our water resources. For example, Kellagher [1] set out a range of benefits that could potentially align to see RWH become a technology that will support increased resilience to a range of potential threats such as drought, increasing energy costs and stormwater flooding. Defining and quantifying these wider benefits will become increasingly important as the magnitude and frequency of these threats increases as a result of climate change in the years ahead [2]. Internationally, RWH has been successfully retrofitted in Australia and Germany, yet it remains difficult to cost-effectively retrofit at residential properties within the UK [3][4][5][6]. At a household scale, the UK RWH market remains relatively immature and is focussed on new-build installations, although some retro-fitting has taken place [7].

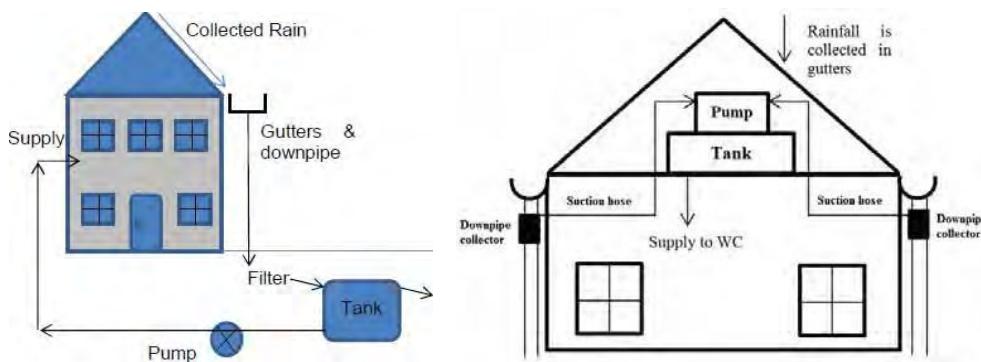
RWH systems are installed in buildings to allow rainwater from roof surfaces to be collected and stored for non-potable water applications. In developed countries, the prevalence of professionally installed RWH systems has grown in recent years [4]. This is particularly true in regions of the world that have experienced drought conditions such as Melbourne, Australia, where the installation of 25,000 rainwater tanks has been subsidised by government incentive

\* Tel.: +44 (0)1392723600

E-mail address: pm277@exeter.ac.uk

schemes since 2003 [8]. In Europe, a recent study estimates that 50,000 RWH systems are installed each year in Germany [5].

In the UK, RWH systems are typically designed to comply with the British Standard [9] with non-potable water use including; "WC flushing, laundry use and garden watering". Unlike in Australia, where RWH tanks can frequently be located at ground level, the UK's freezing temperatures during winter months requires RWH systems to be designed with tanks below ground level [9]. Roebuck *et al.* [11] illustrated that these RWH systems are expensive to install and Melville-Shreeve *et al.* [12] identified alternative configurations that can potentially be installed at a lower cost. Building on those studies, the research presented in this paper has been undertaken collaboratively with the patent holders of an innovative system marketed under the name FlushRain [13]. The research focuses on initial results from the first phase of the project in which the FlushRain RWH (FRWH) system was trialled in a laboratory setting to enable its basic performance characteristics to be assessed.



**Fig.1. Illustration of a traditional RWH system (left) and a FlushRain RWH system (right)**

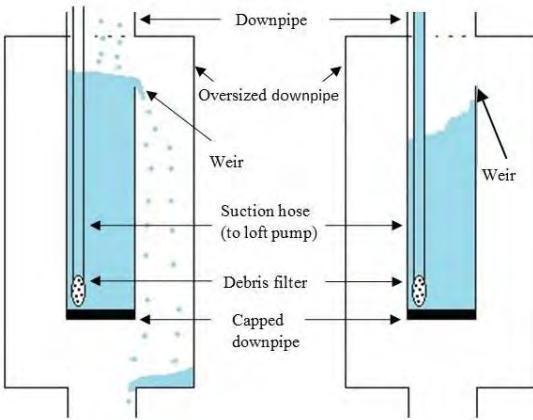
## 2. MATERIALS: THE FLUSHRAIN RWH SYSTEM

The FRWH system is described by UK patent GB2449534 and is illustrated in Figure 1. The system uses downpipe chambers, flexible hoses and a suction pump located within the loft space of a house to draw water from the downpipes into a loft tank during a rainfall-runoff event. Harvested rainwater can be supplied under gravity to non-potable end uses throughout the property. The system has been developed to address three design objectives that are perceived to be weakly addressed by existing RWH products (FlushRain Ltd, personal communication, 29 May 2015); 1) The capital cost should not exceed £1,000; 2) Electricity costs should be less than alternative water resources including traditional RWH systems and municipal water supplies; 3) The system is intended to be easily retrofitted within a single day by two installers."

Appraisal against the first two design objectives was undertaken through the construction of a FRWH system in the University of Exeter's Laboratories. Further work to appraise the third objective is underway, but not considered in this paper. Details of the system installed are described below.

### Downpipe Collection Chambers

The downpipe collection chambers allow approximately 2 litres of rainwater to pool in the existing downpipe, ready to be pumped into the loft tanks. The downpipe is capped causing it to surcharge up to the level of an overspill weir. Water spilling from this weir is re-captured in the outer chamber and returned to the lower section of the downpipe as illustrated in Figure 2.



A) Chamber connected to downpipe    B) Illustration of chamber discharging to downpipe    C) Illustration of chamber being pumped empty

**Fig.2. Illustration of the downpipe collection chambers**

#### **Debris Filter and Non-return Valve**

A debris filter is located at the inlet to each suction hose at the base of the collection chambers. It is intended to prevent leaf litter from reaching the pump and storage tank using a two stage screen with 4mm holes and a fine mesh.

#### **Water Level Sensors**

A capacitance based float switch is installed at the top of the downpipe chamber. The switch senses when it is submerged in water and closes a circuit on the control board. One switch is included at the top water level in each downpipe collector. Another sensor in the top of the storage tank is programmed to prevent the pump from activating when the tank is full.

#### **Collection Hoses**

The system uses flexible 15mm diameter hoses to collect water from each chamber. These are fed up through the downpipe and passed into the property through the roof fascia boards. The hoses are laid through the loft space and attached to the pump.

#### **Rainwater Pump**

A diaphragm pump (The Whale Gulper 220 DC) with a specified maximum suction head of 3m is installed in the loft. The pump is able to self-prime and is unlikely to experience major issues associated with short periods of dry running. The pump is controlled by a circuit board connected to the water level sensors.

#### **Tanks**

A free-flowing outlet from the pump enters the top of the storage tanks via a suspended foam filter gauze which can be washed for reuse. Standard WRAS approved [14] cold water loft tanks are used to store the water in the loft. For the purposes of this study, a tank with approximately 230 litres of storage was utilised, although in real-world installations one or more could be connected subject to the structural loading capacity and space available in the loft. Suitable insulation blankets and pipe lagging are included on the tanks and pipework. Finally, a mains water top-up is installed to allow a shallow level of water to be maintained in the tanks when no rain is available. This is designed to ensure the non-potable supply pipework is always fed with water, even when rainwater has been exhausted.

#### **System Function**

During a rainfall-runoff event, runoff fills both collectors and their water level sensors are activated. A ten second delay allows debris collected in the chamber (i.e. leaf litter) to wash through the weir into the overflow pipe. Residual sediment must be cleaned out during maintenance of the system. Following the delay, the pump is activated and the suction hoses

feed runoff via the filter into the storage tank. During low intensity rainfall-runoff events, the pump empties the runoff from the collectors and the float switches recognise they are no-longer full. The pump is programmed to continue running for 15 seconds in order to remove excess runoff from the downpipe collectors at the end of a rainfall-runoff event. Once further runoff has accumulated in the collectors, the system restarts. After heavy rain, the tank may become full and the pump stops when the top water level sensor is activated. An overflow from the loft tank provides a failsafe discharge point in case this sensor fails. Harvested rainwater stored in the loft is then plumbed directly to WCs and washing machines for reuse.

### **3. METHOD**

Two laboratory test rigs (Figures 3 and 4) using recirculated potable water were used to answer the following research questions:

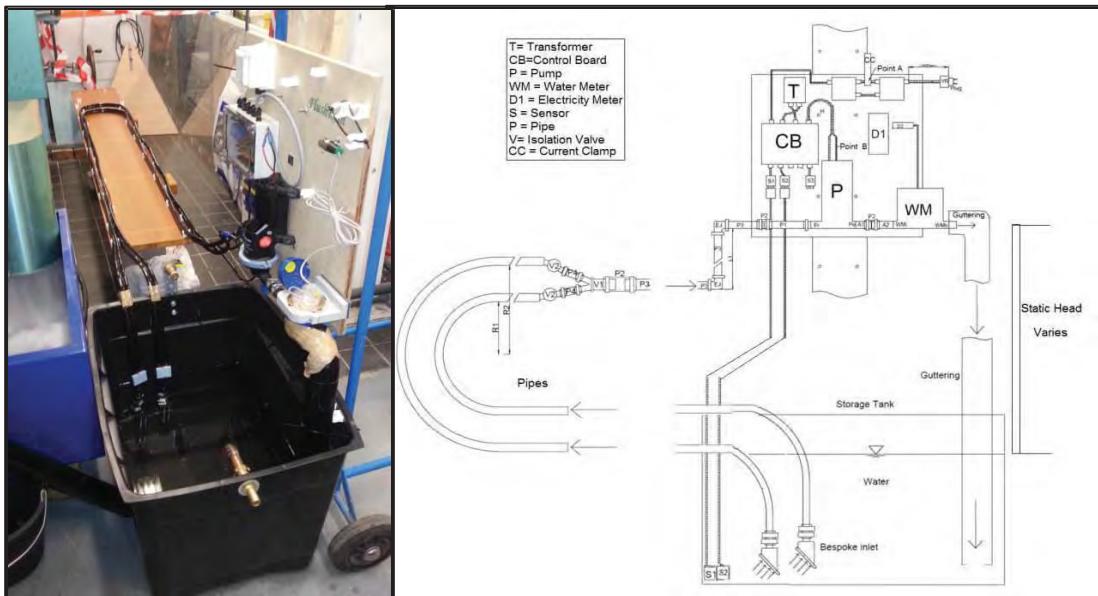
- RQ1) Can the FRWH system function with either one or two downpipes connected?
- RQ2) How does the system function when static head is increased?
- RQ3) What is the electricity consumption of the system in comparison with alternative RWH systems and municipal supplies?

#### **Test Rig 1: Assessing Head-flow Relationships**

A laboratory test rig was constructed to mimic the pipe arrangements of the FRWH system as illustrated in Figure 3. The arrangement allowed for the pump to be mounted at a range of static heads (0.26m to 2.56m) above a source water tank. At each mounting level, the system was turned on and allowed to prime with water. The flow from the pump was then routed into a tank located upon a set of scales. The mass collected in the tank over a period of time was used to establish the pump's flow rate. The equipment was used to establish a maximum static head (i.e. vertical distance) between the pump and the collection chambers, above which the pump is unable to draw water into the tank (i.e. elevation and friction head exceeds suction head). The horizontal pipe lengths were kept fixed throughout the tests using 4.85m of 15mm hose. As the static head was increased, an additional length of 22mm pipe was added to the system to allow the pump to be connected at the increased height above the water tank. Thus the measurement of static heads represents a real-world installation in which pipe lengths would increase as the vertical distance between collection chamber and the pump increases.

For Test Rig 1, tests were repeated three times at each static head and mean results recorded. Testing was undertaken by altering the following variables:

- 1) The number of pipes connected to the pump (either 1 or 2 were connected);
- 2) The static head was increased in five steps from 0.26m to 2.56m in order for a head-flow curve to be derived.



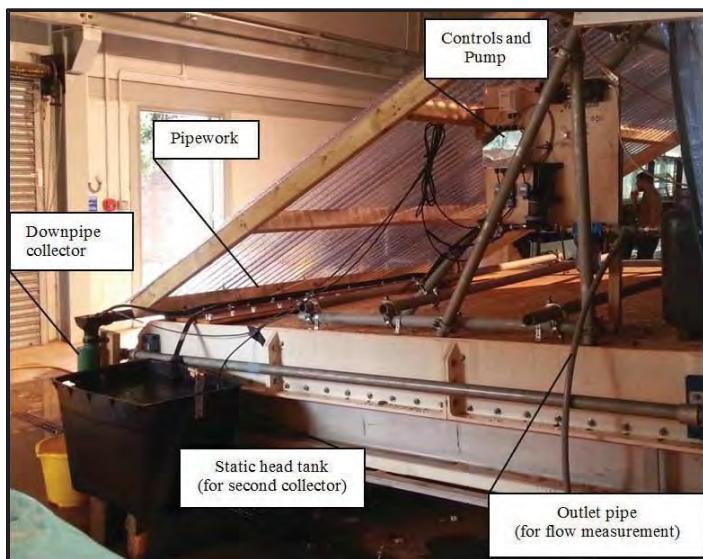
**Fig.3. Photo and layout drawing of Test Rig 1**

#### **Test Rig 2 – Full Scale Test Installation to Establish Electrical Consumption**

Test Rig 2 comprised an installation in a section of full scale roof as illustrated in Figure 4. The FRWH system was installed with 2 x 4.85m lengths of 15mm diameter pushfit pipework laid within the roof space. Pumped water was routed into a measuring vessel in order for flow rates to be monitored during testing. A control valve was used to deliver water to the gutter at a rate which exceeded the pump's maximum flow rate. The second collection hose was placed in a constant-head tank adjacent to the downpipe. This allowed both collectors to have access to an unlimited incoming flow throughout the tests.

Test Rig 2 was used to monitor the electrical usage of the system under constant incoming flow conditions from two collection hoses. Electricity usage was recorded using an EL-USB-ACT data logger in combination with a current clamp. The AC current at the pump's control board was monitored using the current clamp. The data logger required an assumed voltage to be set and following testing an average value of 230V was used. The logger was then able to record wattage of the system at a 0.25s resolution. For the purposes of identifying the energy usage, the pump was switched on and the flow routed into a collection vessel with a known volume. A stopwatch was used to record the time taken to fill the vessel. In each test this was repeated 3 times and the mean time to fill the vessel was used to establish a pump flow rate. The pump was then allowed to run for an hour and its electrical usage monitored. This data was used to calculate the average electrical consumption required to collect 1m<sup>3</sup> under optimal (pump permanently on) running conditions. These tests were then repeated with a single collection hose attached to the pump. Errors in the data collection protocols are considered in a supplementary annex available from the authors on request.

The power consumption associated with sub-optimal pump running was also investigated. The process of pump on-off switching was monitored to establish if turning the pumps on and off caused higher electricity usage per unit of water pumped. In order to assess this factor, the pumping system was switched on and off rapidly to identify any spikes in the electricity required to start the pump when the system activates.



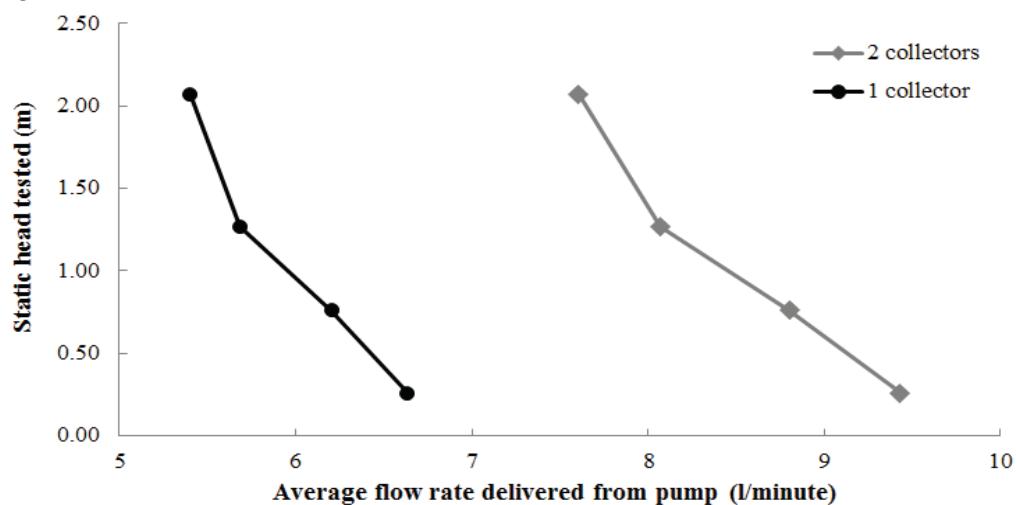
**Fig.4. Image of Test Rig 2**

#### 4. RESULTS AND DISCUSSION

The results from the laboratory testing are discussed in the following sections, along with other implications for the FRWHS and further research requirements.

##### Test Rig 1 – Assessing Head-flow Relationships

Results from the tests conducted on Test Rig 1 were used to establish the head-flow relationships that might be expected in a real-world installation. The results are illustrated in Figure 5.



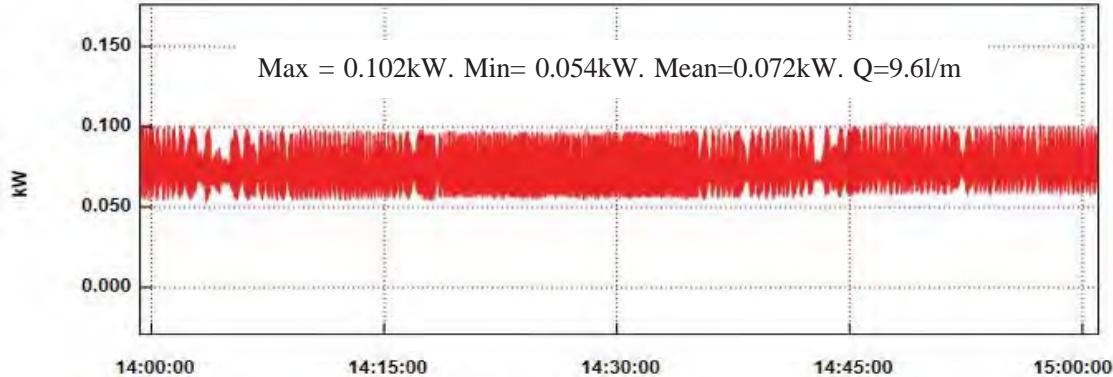
**Fig.5. Head-flow relationships for the FRWH system as identified from Test Rig 1**

Minimum and maximum values for each static head tested did not vary by more than +/- 0.1l/s from the mean value. Although a small sample set was collected, the standard deviation did not exceed 0.12. The data illustrates that the FRWH system can operate with either one or two collection chambers connected, which results in an answer of 'yes' to RQ1. As might be expected, the rate of flow decreases as the static head increases, and the system is able to deliver a greater volume of flow when pipe friction is reduced (i.e. both 15mm pipes are connected). This illustrates that the pump is able to function more efficiently when two downpipe collectors are attached (i.e. front and back of house) rather than having a single pipe connected to a single pump. Flow rates of >9l/m were observed for the lowest static head

when two pipes were connected. In contrast, the lowest flow rate recorded was 5.4l/m for a single collector at 2.08m static head (i.e. a vertical distance of 2.08m between the inlet to the pump and the water being lifted). For both one and two collectors, the system failed (i.e. the pump only drew air into the tanks and was unable to self-prime) when a static head of 2.56m was tested. As well as answering RQ2, this also suggests that installations with collectors that are installed more than 2.08m below the pump inlet would not be advisable in a real-world setting.

#### **Test Rig 2 - Electricity Usage: Constant Flow Through Pump**

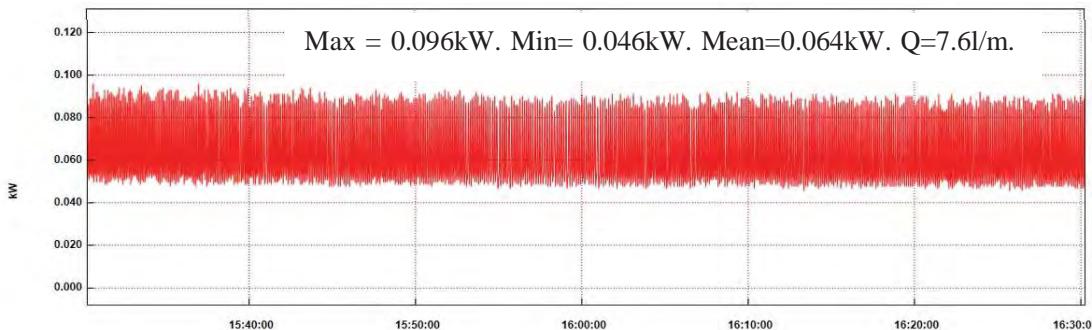
The system was run with two pipes connected to the pump for a one hour window and the resulting electricity consumption data is illustrated in Figure 6. The data shows the pump's power usage is constantly fluctuating between approximately 50-100W.



**Fig.6. Power usage at 0.25s resolution for 2 collectors pumping for 1 hour**

The average kW usage recorded was 0.072kW ( $\pm 5.3\%$ ). Scaled to an hour of usage this equates to 0.072kWh ( $\pm 5.3\%$ ). Records of the pumped flow during the one hour window (Figure 6) illustrate an average flow rate of 9.6l/m.

Repeating the above test with a single collector running for one hour yielded power usage as illustrated in Figure 7. As with the two collector scenario, the pump operates at a power usage of approximately 50-100W.



**Fig.7. Power usage at a 0.25s resolution for 1 collector pumping for 1 hour**

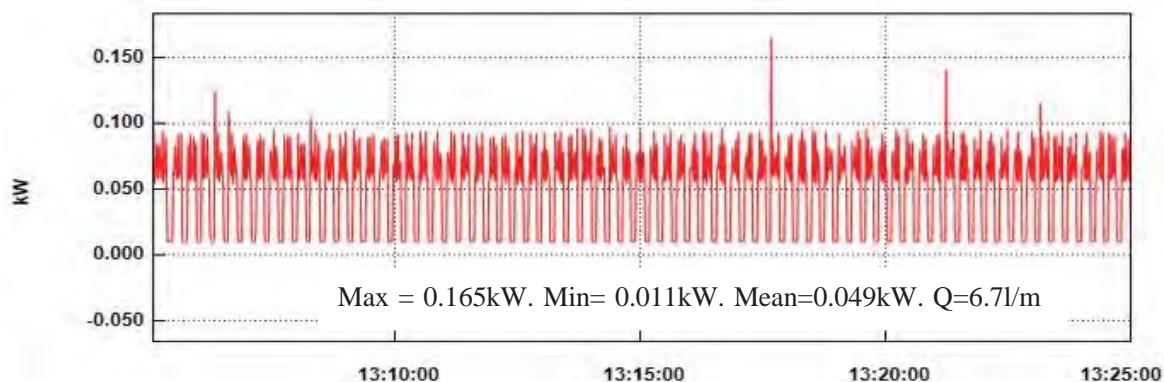
The results obtained are consistent with the findings of a number of other tests conducted using Test rig 2 which verified that the pump runs at a consistent electrical consumption rate, within a band of approximately 50-100W, regardless of the static head, friction head or flow rate. The pump's consistency allows relatively accurate estimations to be made of the electricity required to collect rainfall-runoff using the FRWH system. Taking an average electricity usage of the pump running over one hour as 0.072kWh ( $\pm 5.3\%$ ) and a recorded flow rate of 9.6l/m ( $\pm 3.8\%$ ) it is possible to assert, in relation to RQ3, that the energy usage for provision of 1m<sup>3</sup> of water equates to 0.124kWh ( $\pm 9.5\%$ ), costing 1.68p at 13.52 p/kWh [15]. This figure increases to 0.139kWh for a flow of 7.6l/m ( $\pm 3.53\%$ ) giving 1.88p/m<sup>3</sup> in the event that a single collector is operating. This compares to South West Water's [16] municipal water charge of £2.05/m<sup>3</sup>, generating a potential saving of £2.03/m<sup>3</sup> collected. However, it is

unreasonable to assume that the pumping regime would be "on" for long periods of time. In practice, rainfall-runoff events would cause the pump to switch on and off as the collection chambers filled and were pumped empty.

### **Electricity Usage: Pump Switching On/Off**

The system was allowed to run for a number of test windows with the pumps turned on and off by artificially removing the water level sensors from the water. Each time the pump activated, the switch was removed. When the pump stopped the switch was reintroduced to the water. A 20 minute window of this data is illustrated in the power curve in Figure 8. With flows starting and stopping as the pump is switched on and off, the average flow rate was less than the 'pump on' scenario and averaged  $6.7\text{l/m}$  ( $\pm 3.6\%$ ). It is evident from Figure 8 that even when the pumps are switching on and off frequently, the mean power required does not exhibit spikes in power consumption. It is possible that power spikes are more frequently experienced in centrifugal pumps which are used in most existing RWH systems [17]. Figure 8 also illustrates that a standby power of 11W was recorded when the pump was off.

The pump-switching tests illustrate that  $6.7\text{l/min}$  can be delivered at a cost of 0.049kW. This equates to a cost of  $1.65\text{p/m}^3$ , less than the cost when the pump is permanently on. In contrast to the expected outcome, this implies that pump switching on and off does not increase the overall cost of water collection.



**Fig.8. System power usage at a 0.25s resolution for 2 collectors pumping for 20 minutes with maximum pump switching**

### **Comparison with Literature on Electricity Consumption of RWH Systems**

The electricity consumption for the pump used in the novel RWH system assessed in this paper ( $0.12\text{kWh/m}^3$ ) compared favourably to electricity use data from existing RWH systems ( $0.54\text{kWh/m}^3$ ) monitored by Ward *et al.* [17] which also notes that UK municipal water supplies use around  $0.60\text{kWh/m}^3$ . This can be attributed to; 1) the low power consumption for the pump (-50-100W), the low operating head, and the lack of increased power consumption during pump start-up. A further comparison was drawn against the existing market leader for household RWH which claims a value of  $0.68\text{kWh/m}^3$  for its RainDirector system [18]. Internationally, Vieira *et al.* [19] reviewed empirical data from 10 RWH studies and identified a median power usage of  $1.40\text{kWh/m}^3$ . For contrast this study also offers a figure for global desalination of water at  $3.60\text{kWh/m}^3$ .

The annual electricity costs for pumping were projected to be very low at less than £1 per year (assuming a nominal  $30\text{m}^3$  usage consuming  $3.72\text{kWh}$  at  $13.52\text{p/kWh}$ ). In comparison, water rates for the highest-charging water company (SWW, 2014) would cost a customer £61.50 based on a rate of  $£2.05/\text{m}^3$ . However, the electronics supporting the system were found to have a mean standby power consumption of 11W (Figure 8). A total standby energy cost of  $96.36\text{ kWh/year}$  was projected at a cost of £13.41. Assuming a  $30\text{m}^3$  per annum usage, a total electricity usage of  $3.34\text{kWh/m}^3$  was projected from the results, five times higher than the operational power consumption of average municipal supplies. A reduction in the standby power consumption of the FRWH system will be necessary if the system is to achieve electrical usage that is comparable to existing water supply infrastructure. If the standby power consumption can be eliminated then the system is likely to achieve lower electricity use

per m<sup>3</sup> than existing RWH systems. Real-world pilot trials are planned in order to establish the validity of the assumptions and calculations set out in this paper and to enable empirical evidence to be collected on the capital and operational costs associated with this novel RWH technology

## 5. CONCLUSIONS

The following conclusions can be drawn;

- 1) The FlushRain RWH system can function with one or two pipe collectors connected although a greater volume of rainfall-runoff can be collected when two pipes are connected.
- 2) Flow rates reduced as the static head was increased. The system failed to operate at a static head of 2.56m and consequently, it is not recommended for installation where the static head significantly exceeds 2.00m.
- 3) Results showed the electrical consumption of the pump to be 0.12kWh/m<sup>3</sup> or 3.72kWh/year assuming 30m<sup>3</sup> of harvested water is used. This was found to be significantly lower than other consumption data in literature relating to existing RWH technologies, municipal water systems and desalination supplies. However, the control electronics were found to use 11W and as they are permanently on this contributes an additional 96.36 kWh/year. The average electricity usage for the system was therefore projected to be greater than municipal supplies at 3.34kWh/m<sup>3</sup>. Consequently, reconfiguration of the standby control system will be needed if the system seeks to limit its electrical consumption levels to those documented for existing water supply systems.

## ACKNOWLEDGEMENTS

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## COMPETING INTERESTS

The authors of this paper conducted this research on an independent basis on behalf of the University of Exeter at the request of the patent holder for the system. A research contract between FlushRain Ltd and University of Exeter Consulting Ltd. was set up to allow the University of Exeter to be remunerated for staff time and laboratory costs associated with the study.

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# Greywater reuse perceptions from students at the University of Reading

Matthew J. Smith<sup>1\*</sup>, Katherine Hyde<sup>1</sup>

<sup>1</sup>The University of Reading, URS Building, Whiteknights, Reading, Berkshire, RG6 6AH

**Aims:** The study aimed to compare and contrast results from surveys taken in 2014 and 2015 from two cohorts of students. The study hoped to further evaluate understanding of student's social perception towards water reuse and in what circumstances would they be prepared to use it.

**Place and Duration of Study:** Two survey questionnaires were conducted in the spring of 2014 and 2015 at the University of Reading.

**Methodology:** A questionnaire was constructed and sent via email communication to all students in the halls of residence at the University of Reading. The questions were developed to obtain data on reuse perspectives and to gauge the students' understanding of recycled greywater. Results were analysed across the two cohorts.

**Results:** Results suggest that 95% of respondents fell into four groups; 1) those in support of greywater for all uses, 2) those in support of greywater for most uses, 3) those in support of greywater for non-drinking uses only; 4) those in support of it "if it is safe to use". Respondents from both 2014 and 2015 showed a lack of distaste towards the use of recycled greywater.

**Conclusion:** Respondents from both 2014 and 2015 showed that they would not be adverse towards to use of recycled greywater.

**Keywords:** Greywater reuse perception, greywater questionnaire.

## 1. INTRODUCTION

Accessibility to clean water in urban areas is increasingly a global issue, with the World Water Organisation predicting by 2025 two thirds of the global population will face water shortages [1]. The average water usage per capita in the United Kingdom is around 150 litres of water per day [2] of which 33% of this water (greywater) is potentially suitable for reuse [3]. However, it could be argued that even though the amount of water that could be reused is high, the perceived health risks and other factors contribute to the reason the reuse of this resource being low.

Following from earlier greywater research conducted at the University of Reading in 2012, 2013 [4] and 2014, this paper tries to expand the knowledge already shared. This paper will compare and contrast customer concerns and expectations from this year's cohort of students (274 replies, 2015) to last year's students (135 replies, 2014) in reply to a greywater questionnaire survey distributed to those living in university halls of residence. Currently no halls of residence at the University of Reading have a greywater recycling system.

### 1.1 GREYWATER – PERCEPTIONS AND MISCONCEPTIONS

The failure of some greywater recycling systems' implementation can be a lack of understanding by the decision makers/benefactors into the impacts and importance of the associated social and economic factors [5]. Once schemes have overcome these initial barriers

\* Tel.: +44 771630948.

E-mail address: cg003180@reading.ac.uk.

towards development the next challenge is to convince people that recycling greywater and reusing it is simple and, in most cases, safe for toilet flushing and irrigation. It is therefore important to learn about the various influencing factors that encourage or discourage people from reusing water.

The concept of greywater reuse has historically been met with distaste and this is evident throughout the literature since the 1970s [6]. This attitude is supported by Kaercher *et al.*, [7] who identified that whilst communities may have recognised the rationale of recycling domestic greywater, they felt uncomfortable using recycled greywater themselves. This indicates that customers can initially recognise the benefits of the reuse rationale, but prompts the question as to the reasons for them having been discouraged from using it. Is this due to the water resource itself, the misinformation or perceived misconceptions surrounding water reuse?

A number of perceived misconceptions identified by Kaercher *et al.*, [6] include; health risks associated with greywater reuse; restricted uses for recycled greywater; unavailable or inadequate information about greywater recycling; unknown or unexplained benefits to the environment; the cost involved when recycling greywater and socio-demographic factors. Misconceptions can also derive from assumptions as to what constitutes greywater. For example, greywater may be confused with 'sewage' i.e. "black water". Therefore, it is important for the successful future application and use of greywater recycling schemes, that a realistic and open-minded perception of this resource is achieved. Ilemobade *et al.*, [8] has suggested that there are four main reasons that people perceive greywater reuse to be risky. "1. The resource is an unnatural source of water. 2. It is sometimes perceived as harmful. 3. The decision to use greywater may be irreversible. 4. The safety and quality of greywater can be associated with a number of easily detectable factors including colour, smell and particulate matter" [8]. Ilemobade *et al.*, [8], found that smell was the most highly used qualitative judgement applied by greywater users, followed by colour.

The risk perception barriers against greywater reuse operate in either or both of the conscious and sub-conscious domains within individuals. To achieve a realistic evolution in the acceptance of greywater for reuse, at least two elements must work together. Firstly, the amendment of perceived negative risks and barriers; secondly, the promotion of the positive effects and benefits. It is therefore suggested that to improve the perception of greywater reuse the following are a minimum requirement: education about the efficiency of greywater recycling; how human health is safeguarded; the benefits of greywater recycling for protection to the environment and for the sustainability of resources. The transfer of knowledge should be delivered in a strategic and organised way to ensure the widest possible communities are reached.

The misconceptions about smell and colour of recycled greywater can often be addressed in practical ways. It may be possible to provide physical proof to users by using a real time monitoring system. Demonstrations can be conducted to show that equipment is working correctly and safely. Another method to further lower the perceived and actual risks associated with greywater reuse, is to reduce the possibility of human contact, such as through specific types of flushing toilets and irrigation systems [8]. Making financial incentives available may also encourage more greywater recycling and reuse, when offered alongside a structured education of greywater and the recycling systems and a better understanding of any potential risks or absence of risks. Financial incentives have been used in many ways to encourage behavioral change for the use of particular products including renewables [9].

## 2. MATERIAL AND METHODS

From March to May 2014 and 2015, an electronic questionnaire was sent to all those living in the halls of residences at the University of Reading. The survey contained questions to elicit a response to whether the students thought or knew about recycled water and its possible reuse onsite. This response would give a better understanding to the university of the impact on students if it was decided to implement a greywater recycling scheme in student halls of residence.

This survey was completed electronically with answers being sent automatically to a secure database. In order to achieve a high number of responses, it was made as simple as possible for the participants to undertake the survey. Respondents could opt out of any question they did not feel comfortable answering. The survey was designed to obtain views and attitudes among participants towards the reuse of recycled water in halls of residence and whether a recycled greywater supply should be installed. The questionnaire wanted to gain an understanding of whether participants knew what greywater was, how it could be reused, what the respondent's perceptions of risk associated with water reuse, and whether they consider water recycling/water saving important for them or the environment. The questionnaire was comprised of single and multiple answer questions.

In 2014 135 questionnaire responses were received and 274 in 2015. The questionnaires were focused on university halls of residence due to the ease of distribution and the comparable nature of equipment and facilities between the individuals. This limited the answer distribution in respect of age and social status and means that answers are limited to a student population which does not reflect views of the general population. As the same questionnaire has been carried out over the same period in consecutive years, a comparison between the 2 cohorts of students can be drawn. This should indicate whether the issues of water reuse or perceptions of greywater are variable between two similar groups of individuals separated by a year in which they have lived in halls. The answers to the questions that have formed this paper are available in the table and figure headings.

### **3. QUESTIONNAIRE SURVEY; OBSERVATIONS AND DISCUSSION**

The survey results from 135 (2014) and 274 (2015) questionnaires have been analysed and the findings are discussed below.

#### **3.1 Gender and Age Distribution.**

Questionnaires were sent to students in halls of residence in March 2014 and 2015. Numbers of respondents to the questionnaire increased from 135 to 274 over the two year period. The reason for the participation increase is unknown as the same distribution procedure was used in both years of the study

**Table 1 Gender distribution of questionnaire participants comparing results from 2014 & 2015**

	<b>Male</b>	<b>Female</b>
<b>2015</b>	82 (30%)	192 (70%)
<b>2014</b>	47 (35%)	87 (65%)

Both Table 1 and Table 2 show the age and gender distribution of questionnaire participants. Results from both years show that two thirds of participants were female compared to the males' one third. The reason for this distribution is unknown but could be due to the ratio of males to females in the halls of residence. The age range of participants was expected as a large number of those using the halls are just beginning their degree and are predominantly 18 to 20 years old. The distribution of ages between the two years has changed little even with the second survey having higher numbers of participants. The results, therefore, cannot be taken as

representative of the UK's general population but are a small sub section of society consisting of students mostly between the ages of 16 to 25.

**Table 2 Age distribution of questionnaire participants comparing results from 2014 & 2015**

Age range	2014	2015	
16-20 years old	80	59%	170
21-25 years old	41	30%	81
26-30 years old	10	7%	16
31-35 years old	3	2%	3
36-40 years old	0	0%	2
Above 40 years old	0	0%	1

### 3.1 Public opinion of recycled and reused water

The questionnaire participants were able to select more than one statement in response to the questions shown in Table 3, 4 and 5 if they felt it was necessary explaining why the number of responses differs from the number that took the questionnaire. Both set of results indicate that a large majority of respondents would use greywater/recycled water in a variety of different circumstances. No information was given to participants with regards to the definition of greywater, what the water quality is or its origins, but crucially how it is treated for reuse.

The highest proportion of participants from both years indicated that they would be happy to use recycled or treated water if it is for non-drinking purposes or if it is safe (table 3). The first set of results in table 3 below, asked participants whether they supported the reuse of recycled water for all uses. The indication is that those who selected this answer have a low understanding of what greywater is and the quality of this water. It could suggest that they thought the treatment processes used to improve the quality of this water were advanced enough to meet drinking water standards. Participants who selected that they were not supportive of the reuse of water (2 participants from 2014 and 2015) were asked to comment on the reasons why. However, in both surveys these participants decided not to give reasons for this choice. In other research, the explanation for participants being unwilling to use recycled greywater, has been attributed to a number of reasons including, religion and health and safety concerns[8]. However, the results are similar to that of Jeffrey and Jefferson[10] who found that the majority of respondents (89%) in their UK study, agreed with the statement 'I have no objection to water recycling as long as safety is guaranteed' showing wide support for safe reuse of recycled water. The results suggest there is a similar level of understanding or lack thereof, due to the comparable results between the two cohorts of students, with regards to general perception of water reuse. This general perception could be of benefit or disbenefit to the implantation of greywater reuse systems.

Other factors that can hinder how greywater reuse is perceived, relate to the recycling systems themselves. These are; the perceived cost of the system; operation regimes and environmental awareness [11]. However, due to a lack of awareness there was probably a range of different levels of conceptual awareness amongst participants. This level of awareness might have varied from question to question, dependent on each specific reuse proposed.

**Table 3 Results from survey question "Which of the following best describes your opinion of recycled or reused water?"**

Which of the following best describes your opinion of recycled or reused water?	2014	2015
I am in support of it for all uses	20	33
I am in support of it for most uses	26	43
I am in support of it for non-drinking uses only	50	80
I am in support of it if it is safe to use	48	93
I don't support it because of the health risks	2	8
I am not aware that there are any health risks in using recycled water, but I do not like to take chances	3	7
I don't support it (please explain below)	2	2

### 3.2 Factors encouraging greywater reuse

**Table 4 Results from survey questionnaire "Which of the following will encourage you to use recycled water?" Numbers presented in brackets represent percentage of survey population.**

Which of the following will encourage you to use recycled water?	2014	2015
If it is colourless	40 (17)	187 (23)
If it is odourless	52 (22)	194 (24)
Easy to access e.g. simply turning on the tap	62 (26)	204 (25)
Being sustainable, helping to conserve the environment	60 (25)	167 (20)
Positive image with peers and friends	12 (5)	56 (7)
Other	10 (4)	15 (2)
<b>Total votes</b>	<b>236</b>	<b>823</b>

Table 4 reports the factors that would encourage participants to use recycled water. This question also allowed participants to choose as many answers as they thought reflected their view point. Response to this question increased due to the number of participants but also the number of answers each participant chose. From the responses, it is evident that whatever waters the participants would use, colour and odour is an important factor when considering use. From literary sources it is evident that the colour and odour of the recycled water is of high importance when people consider using greywater [6], [8]. It could be suggested that participants of other surveys within the literature may have been more informed to what greywater is when compared to participants of this work.

In both years, it is evident that the most important factor in encouraging people to start using recycled water is easy access to the resource. Thus, as suggested earlier, the easiest way of giving easy access and to improve health and safety aspects of the resource is an inbuilt system lowering direct contact with the reuse water [12]. The use of greywater would then be communicated to users by information leaflets, giving specification of pipes and appliances. From both the 2014 and 2015 results presented in table 4 it is evident that a good proportion of students would like the amount of water they conserve to be placed in an environmental context. This could be achieved by reporting how much water is saved once it has been reused. A surprising result from table 4 is that only a small proportion of students suggested that peers and friends would encourage them to use recycled water. The recycling of goods has often been associated with peer encouragement [12], [6] whereby the actions of one encourage another.

### 3.3 Benefits to the reuse of recycled water

**Table 5 Results from survey question "In which of the following circumstances do you consider it beneficial to recycle or reuse water?" Numbers presented in brackets represent percentage of survey population.**

In which of the following circumstances do you consider it beneficial to recycle or reuse water?	2014	2015
When it helps to save money	51 (21)	186 (27)
When it reduces the environmental impact of taking water from the environment	92 (38)	219 (32)
When it is used for everything else but drinking	48 (20)	102 (15)
When it is used for everything including drinking	3 (1)	29 (4)
When everyone understands when and where to use recycled water	41 (17)	148 (22)
Other	4 (2)	3 (0)
<b>Total Votes</b>	<b>239</b>	<b>687</b>

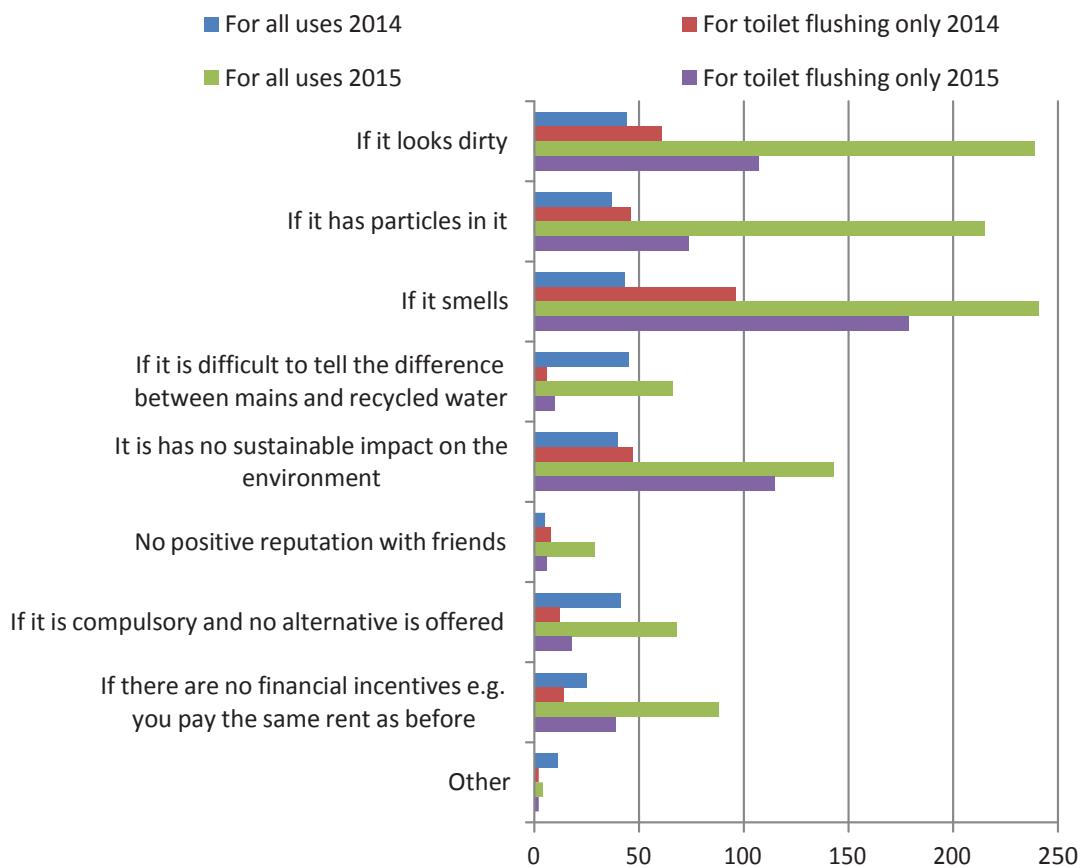
The results presented in Table 5, indicate that the respondents consider the most beneficial circumstance in which to reuse or recycle greywater would be where it reduces the impact on the environment. This may not, however, represent those views of a broader population due to this being a narrow section of society. Similar to the result in 2014, financial incentives involving saving money, rank highly as an encouragement factor in the 2015 survey. Comments left by individuals suggest that they are keen to learn when and where it appropriate to use the recycled water. Participants indicated that all halls of residence should be told about basic sustainability and water saving techniques. Few people suggested that it would encourage them to use the water if it was used for everything including drinking. Again, this could be down to the lack of information given to the participants. These few may have believed that the water could be recycled to a drinking water standard at the reuse site.

### 3.4 Factors discouraging greywater reuse

It is evident from the survey results in **Error! Reference source not found.** that for all uses specified in the survey, a large proportion of the participants would be discouraged from using greywater if: (1) if the greywater were to smell, contain particles or appear dirty (2) if there was no sustainable impact on the environment. Far fewer respondents suggested that if it were difficult to tell the difference between mains and recycled greywater; and it was compulsory and no other alternative was offered would discourage them they would be discouraged from using recycled water. It is also apparent that between the years there is disparity between opinions. The cohort of students answering in 2014 suggested that they were more opposed to greywater that smelled, contained particles and looked dirty that was going to be used for toilet flushing than for all uses, whereas in 2015, the students seemed to show the opposite. Users would be more opposed if the water smelled, looked dirty or contained particles in recycled water, for all uses rather than just for toilet flushing.

From the results in **Error! Reference source not found.** it would seem that around one third of the students in both 2014 and 2015 would be discouraged from using recycled greywater if there was no financial incentive. This may indicate that if students had the choice between halls which used greywater and others that did not this could be a factor in their choice of accommodation. The results indicate the majority of participants would not be discouraged from using greywater even if there was no financial incentive. Participants have also indicated that peer interactions and reputation would not discourage the use of greywater. This gives a very good indication that participants do not think peer pressure or interactions are highly valuable in encouraging or discouraging usage of recycled greywater. This may be due to the nature of the way we use water. Water is only seen at the point of use and is then transported away through the pipe network. Peer pressure can be more prevalent if compared to the case of recycling material goods .With recyclable goods, the individual has to be part of another process

meaning people are more involved with recycling material goods than with water. This may lead to higher levels of peer pressure.



**Figure 1 results from survey question "Actions and properties that would discourage greywater reuse?" survey respondents in 2014 were 135 and 2015 were 274.**

One interesting result is that 2 participants from each year of the survey suggest that they would be discouraged from using recycled water for all uses, if they were not notified that they were using this source and if there was no alternative to greywater available. These participants may have been misled by this question. It was not specified that the recycled water would not be used for personal washing, drinking or cooking. This is also evident by the lower number of people from both cohorts suggesting that the use of recycled water for flushing toilets is much more acceptable. It is therefore recommended that people are notified of greywater use for the purposes of flushing toilets.

The results in Figure 1, suggest that if the recycled water met the criteria that it does not smell, look dirty or contain a large amount of particulate matter, then toilet flushing would be encouraged by participants from both 2014 and 2015. The results support the conclusion that aesthetics and smell of the recycled water are extremely important, and that the quality is very influential upon whether people will be encouraged or discouraged from reusing recycled greywater especially for toilet flushing.

### 3.5 Summary Observations

As suggested earlier, the respondents of the questionnaire were not given guidance with regards to the different applications of the recycled greywater. This is likely to have generated a range of respondent interpretations concerning the circumstances and purposes for which greywater might be reused. It was decided that simply giving more information to users about

the constituents of greywater was not an objective of the survey and may have confused respondents. There was no basis of confidence that could be established prior to the survey being completed to enable participants to understand all the issues they were asked to comment upon. Within both surveys from 2014 and 2015, it is not possible to discern whether the survey participants, who were supportive of greywater systems and reuse, were well informed, moderately informed or poorly informed.

#### **4. CONCLUSION**

The survey was designed to elicit views and attitudes among participants towards the reuse of recycled water in halls of residence and whether a recycled greywater supply should be installed. For both year's surveyed, it was noted that the survey participants' age was selective and between the ages of 16-35 with high proportions of participants being at the lower end of this scale. Reviewing all of the respondents, it was seen that, 95% fell in to four groups; (1) those in support of making domestic greywater available for all uses; (2) those in support of domestic greywater being made available for most uses; (3) those in support of domestic greywater being made available for non-drinking uses only and (4) those in support of it being made available if it is safe to use. Both surveys which were completed by 135 and 274 participants in 2014 and 2015 respectively, demonstrated a number of features which include, a lack of distaste for the use of recycled greywater. This could be interpreted as a reflection on resource and environmental awareness as well as changing attitudes towards water conservation.

These observations need verification by asking similar questions to a population that is connected and has access to a domestic recycled water supply. This would help determine whether or not the lack of preconceived dislike towards greywater or recycled water might be demonstrable in a day to day domestic water consumption amongst a population of the same age. More questions need to be asked with regards to the reuse of water in domestic settings but also the public needs to be further educated further in the benefits of water reuse at the same time that perceived fears of water reuse are allayed.

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# Characterising the Quality of Recycled Greywater in Operational Contexts; Enhancing the Value of Greywater Resources

Katherine Hyde <sup>1\*</sup>, Matthew J Smith<sup>1</sup>

<sup>1</sup>The University of Reading, Engineering Building, Whiteknights, Reading, Berkshire, RG6 6AW

## ABSTRACT

### Aims:

Water efficiency is markedly improved by reusing water of suitable quality (or value) and composition, for appropriate applications. Although greywater reuse might be thought to increase the uncertainty of achieving a specified quality and composition of water supply, robust methods and technologies are available for the local treatment and measurement of greywater.

The aims of this study address the matter of uncertainty by:

- 1) aiming to better define the performance of greywater treatment technologies with reference to specific quality measurements of the recycled greywater, its value, sustainability, and utility;
- 2) appropriately choosing parameters for greywater monitoring that will encourage the taking of more regular measurements and greater diffusion of monitoring equipment, assisting in the minimisation of any risks within greywater implementation systems.

### Study design:

The design involves the treatment of a British Standard greywater as defined in BS 8525-2:2011 [2] by a manufactured system of approximate capacity of 1,200 litres. The first tank in the process (Tank 1) provides oxygen diffusion, aerobic microbiological digestion and nanofiltration combined in a single tank MBR (membrane bioreactor). The second tank, Tank 2, stores the treated water from Tank 1 ready for reuse. This study builds upon earlier research work on technologies, measurement techniques and monitoring for risk reduction in greywater supplies.

**Place and Duration of Study:** The research programme using greywater treatment technologies started in 2012 at the University of Reading, School of Construction Management and Engineering. The programme has been running since then.

**Methodology:** In 2010 and 2011, a single British Standard was published in two parts, BS 8525-1:2010 [1] and BS 8525-2:2011 [2]. The application of these standard greywater system tests proved to be consistently practical and appropriate during the research.

### Results:

Recent greywater test results demonstrated the efficiency of the combined MBR and nanofiltration processes which, in the case of turbidity improvement, achieved approximately 100% process efficiency. The role of turbidity, biochemical oxygen demand and electrical conductivity measurements is discussed, including new thinking about the value of making routine turbidity measurements. Risk reduction and risk avoidance using clear design, careful installation and maintenance procedures, requires greywater manufacturers, installers and users to make regular checks, and to test the quality of the treated greywater. This in turn increases the confidence of users, as well as confidence in the markets for greywater equipment, measurement devices, components and consumables.

**Conclusions:** The take-up and diffusion of greywater technology protects the value of water resources, and contributes to reducing the risks of water scarcity and vulnerability. Locally

\* Tel.: +44 (0) 118 378 8206

E-mail address: Katherine.hyde@reading.ac.uk

monitored greywater ensures that the expectations for safely functioning greywater systems will be met, provided that a number of safety controls are implemented.

## 1. INTRODUCTION

The body of evidence about greywater treatment is slowly gaining momentum and is continuing to demonstrate greater opportunities for greywater utilisation, as well as providing more acuity in assessing and avoiding risks. Social perceptions can influence, for example, the rate of take-up of greywater technology. Social perceptions are a critical influencing factor regarding the acceptability or unacceptability of risks associated with the use of a greywater whose previous uses and users are unknown. The work of Slovic provides a basis for understanding and anticipating public responses to hazards' or risks [3]. Some potential threats are real, others are perceived or imaginary. Health and Safety codes of practice are intended to influence and moderate the social perception of risk both directly and indirectly. However, social perceptions can be elusive and can lead to popular misunderstandings or mis-interpretations of levels of personal threat. [4] described two types of dynamics that may affect social change; firstly, the individuals called 'influentials' who may be disproportionately responsible for social change under certain conditions; and secondly, the other typical circumstance of "easily influenced individuals influencing other easily influenced individuals". Both of these dynamic processes could contribute to the diffusion of social acceptance of the use of treated greywater.

Any historic record of the incidence of contamination or health risks from greywater is, fortunately, weak and not well populated statistically. Contamination that could arise from greywater piped supplies is an outcome that is avoided using carefully designed and engineered systems. The body of evidence about greywater treatment is maturing and continuing to demonstrate greater opportunities for greywater utilisation as well as providing greater acuity concerning risks.

When events have occurred, the specific details of the event are highly localised in causation factors, the progress of the events themselves and outcomes. One of those few events was reported by [5] when following maintenance work in the Netherlands in 2001, the drinking water system was connected to the grey water system carrying untreated greywater. The connection was made in order to use mains water to flush out and clean the renovated pipework. Fail-safe procedures and controls were missing, demonstrating the importance of communicating a clear design, renovation and maintenance process along the design-chain and the supply-chain.

Risk reduction and avoidance using such clear design, and careful renovation and maintenance procedures include; 1) risks to users of mains water arising from potential cross-contamination of mains systems through misconnection or other errors; 2) risks to users of greywater from contamination that could arise from the greywater itself, which might occur if the greywater were not treated appropriately prior to use; 3) other risks to users of greywater described in the literature, for example avoidance of pathogenic aerosols.

All these risks present a challenge to greywater manufacturers, installers and users, to make regular checks and tests of greywater quality, from installation, through daily and weekly operation and final de-commissioning. Evidence of recent greywater test results is presented in this paper, and consideration is given to the programmed and intermittent substitution of turbidity as a monitoring parameter, by other parameters.

Common standards are needed but are only comparable if the data they support are collected according to compatible formats and test conditions. Recent work with British Standard committees [6] has discovered a strong aspiration within one school of thinking concerning water recycling; that is, the rejection of any need for checking or for measurement of the quality of treated greywater in order to determine acceptability. Other schools of thinking have rejected that proposition. More work is required to provide confidence to industry in reporting and sharing of greywater analysis.

## 2. THE NEED FOR MEASUREMENT AND CHECKING OF GREYWATER QUALITY

Many authors have described the concentration and profile of greywater constituent concentrations for example Diaper [7], [8], Dixon [9], [10] and Friedler [11]. According to the BS8525-test procedure, the allowable concentrations of constituents in greywater following treatment are shown in Tables 1 and 2 below, from reference [2], and are determined by laboratory measurement and analytical testing. The results described in this paper were obtained by making up a synthetic greywater according to the British Standard greywater concentration profiles given in Table 3.

In general, the principal approaches to monitoring and measuring water quality fall into two categories;

1. Instantaneous measurements, often potentiometric; these measurements can be automated, hand-held and manually conducted, and sometimes can be made in mid-stream, within the pipe, or in a process vessel or tank;
2. Laboratory analysis usually requires tests to be made on a series of separate aqueous samples stored at specific temperatures, which are measured using both conventional wet-chemistry such as oxidation, and advanced chemistry, such as Mass Spectrometry and Spectrophotometry.

**Table 1: Chemical and physical quality requirements for treated greywater for type test [2]**

Parameter	Spray applications	Non-spray applications			Testing
	Pressure washing, garden sprinkler use and car washing	WC flushing	Garden watering	Washing machine use	
Turbidity NTU	<10	<10	N/A	<10	BS EN ISO 7027
pH	5–9.5	5–9.5	5–9.5	5–9.5	BS 1427
Residual chlorine <sup>A)</sup> mg/L	<2.0	<2.0	<0.5	<2.0	BS EN ISO 7393-2
Residual bromine <sup>A)</sup> mg/L	0.0	<5.0	0.0	<5.0	Blue Book 218, Method E10 [N1]

<sup>A)</sup> Where chlorine or bromine is used in the treatment process.

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**Table 2: Microbiological quality requirements for treated greywater for type tests [2]**

Parameter	Spray applications	Non-spray applications			Testing	
	Pressure washing, garden sprinkler use and car washing	WC flushing	Garden watering	Washing machine use	Spray applications	Non-spray applications
<i>E. coli</i> number/100 mL	Not detected	25	25	Not detected	BS EN ISO 9308-1	BS EN ISO 9308-3
Intestinal enterococci number/100 mL	Not detected	10	10	Not detected	BS EN ISO 7899-2 or BS EN ISO 7899-1	BS EN ISO 7899-1

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The synthetic greywater composition used for testing the greywater equipment to demonstrate performance or compliance is shown in Table 3. The instructions for making the synthetic mix are given in the British Standard [2]. It can be seen that the greywater must include some bacteria derived from treated, final effluents (F.E.) that can be obtained from sewage works. This may sound incongruous in some respects, but to the trained microbiologist, the addition of a small sample of inoculant is essential. The synthetic mix is then able to provide a reasonably realistic greywater for feeding into the inlet to the treatment plant, capable of sustaining bacteria at the beginning of the process. This procedure can then enable the degree of reduction, following treatment, in contaminant concentrations to be calculated and demonstrated, including the absence of pathogenic bacteria. Furthermore, since the research programme commenced in 2013, by applying only relatively small variations in feedstock, any process effects on the concentration of selected contaminants and chemical species can be individually evaluated.

**Table 3: Composition of made-up, laboratory synthetic greywater when mixed to the BS 8525 Part 2 constituent concentrations [2]**

Parameter	Acceptable range	Test method
<i>E. coli</i> (cfu/100 mL)	$10^5$ – $10^6$	BS EN ISO 9308-3
COD (mg/L)	$180 \pm 40$	BS 6068-2.34
BOD (mg/L)	$110 \pm 40$	BS EN 1899-1
NO <sub>3</sub> nitrogen (mg/L)	$7.2 \pm 0.8$	BS EN ISO 13395 or BS EN ISO 10304-1
pH	7.0–8.0	BS 1427
Temperature (°C)	$30 \pm 2.5$	—

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In the case of greywater use within buildings, measurements of quality and composition are required to be accurate and appropriate in order that they can also be meaningful. The greywater quality must be suitable for its intended uses, ie fit for purpose. In contrast, the legally implementable approach for approximately 150 years in the UK has been to treat all piped water to the highest possible standard, to create not only a suitable drinking water, but a water whose quality can be relied on at any moment at any time of day to be suitable for

sustaining human consumption. This results in an important degree of health risk avoidance that the UK population enjoys every day. Greywater fulfills a different use and purpose from treated piped mains water.

Some evidence has been documented about the utility value that is achieved through reusing greywater for toilet flushing and other uses. There is little yet in terms of regulatory mandate for greywater quality and composition, and often the EU European Directive on Bathing Water [12] has been used to exert a legislative or statutory control, at some level, over the general requirements for greywater delivery.

However, this approach whilst useful to the developing market for greywater systems, provides little more than circumstantial reassurance in many cases, reassurance that standards are in place and there is a level of product reliability that consumers can rely upon. The BS tests are performed after manufacture, early in the life of the installation. Certainly, an appropriate British Standard or other international standard, or code of practice still does not deliver the same level of reassurance as a drinking water supply that derives confidence from the support of a judicial legislative system through Acts such as the Water Act UK [13], or the European Water Framework Directive [14].

One of the problems that both users and manufacturers must contend with is that the nature, composition and quality of greywater is likely to vary from location to location, dependent upon the prior uses of the originating mains water. Handwashing water can be some of the most lightly loaded greywater, in terms of organic composition, with less organic matter than shower water, though that would depend upon the predominant uses of the hand basin, and whether used by gardeners or by site workers, for example. There is clearly a wide range of potential users of hand basins and this illustrates one of the important points about greywater quality and composition variability; one hand basin could be used predominantly by one type of user, another by a different type of user and a home hand basin could produce a wider variety of constituent types according to different users. So, how can the variability of greywater quality from one receptacle or faucet to another be expressed, predicted or planned for, and what are the implications?

The greywater treatment unit for this research provided fully oxygenated, nanofiltration in the first stage treatment tank, denoted as "tank 1" in Figure 1, and the treated water then passed into "tank 2", also denoted in Figure 1, for storage and subsequent use. These treatment units are suitable and available for non-domestic, office and institution buildings. They are designed to be able to treat a range of organic loadings, including washing or personal hygiene products and relatively low loadings of 'contaminants' such as soils or fats and greases. Other smaller units may be somewhat less robust, but designed for a more specific type of use, and there may be a potential for smaller greywater treatment units in a number of different locations within a building.

### **3. BS 8525 PROCESS FOR SELECTING PARAMETERS AND CONSTITUENT CONCENTRATIONS**

The greywater quality parameters were selected according to the British Standard Committee System and evaluated by industry experts, Government scientist(s), consultants, academics and has been applied in previously published work [15] [16]. The process lasted approximately from 2009 to 2011 and two parts of the standard were approved and published. Part 1 comprises a Code of Practice and Part 2 provides the specific test arrangements for greywater plant, the concentrations in the test solutions and the allowable constituent concentrations for greywater. Thus, the allowable microbiological parameters were agreed by rigorous comparison with other existing standards that included prior standards of Department of Environment scientists, now Defra, and the Health and Safety Executive (HSE).

#### **4. DETERMINING APPROPRIATE GREYWATER CONSTITUENT CONCENTRATIONS**

The chemical or biochemical constituent concentrations studied at the University of Reading were measured using conventional water analysis, including potentiometric techniques, spectrophotometry and flame photometry, autoanalysis, oxygen depletion measurement for BOD and light scattering measurement for turbidity, amongst others. All of these tests follow either standard, published methodologies such as those of the American Water Works Association, the UK Standing Committee of Analysts, or otherwise ISO/CEN/BS verified methods.

It was assumed at the outset that samples with high turbidity concentrations would also be likely to record high Electrical Conductivity (EC) readings. It has been recognised for many years that those two readings measure slightly different parameters, with electrical conductivity measurements specifically quantifying ions in water that are attracted to electrodes in a potentiometric cell. Some of the colloidal matter that contributes to cloudiness, poor clarity and turbidity will be unlikely to be captured potentiometrically, and therefore, will not be measured using EC measurements alone. The EC measurements need to be considered and understood within the limitations of electrochemical measurement. They had been considered to be of practical benefit in an operational context because of the ease of measurement and the simplicity of the test procedure, which removes some of the barriers to uptake by staff with limited scientific experience. However, the results below question the benefit of routine or over-reliance on the EC test.

Other relationships between parameters include for example, positive turbidity results recorded if many microbiological colloids are present. Then, within an optimised greywater quality control framework, greywater quality can be quickly assessed in terms of the relationship between BOD and turbidity results.

A question has been raised in industry regarding whether turbidity is an essential measurement, as required by BS8525 [2]. The concentration of soap and detergents in the greywater produces turbidity due to chemical bonding and the formation of detergent micelles. It is not ideal to exclude turbidity measurements, and the frequent analysis of EC using potentiometric and hand-held instrumentation, can be seen from these results to provide only limited information in terms of operational and process management. Tests that are performed easily in the field such as turbidity and pH, reinforced by the results from regular BOD and microbiological testing, provide a suitable scientific basis to demonstrate compliance with British Standard BS8525 [2]. This is potentially very important for process monitoring and management of greywater treatment at all sites, and also important for diagnosis should process dynamics change.

Microbiological measurement and scrutiny is an essential element of the evaluation of greywater quality. Its importance must not be relegated to a second tier control parameter, but to include it is beyond the scope of this current paper.

#### **5. OPTIMISING CHARACTERISATION AND OPERATING TO GREYWATER QUALITY REQUIREMENTS**

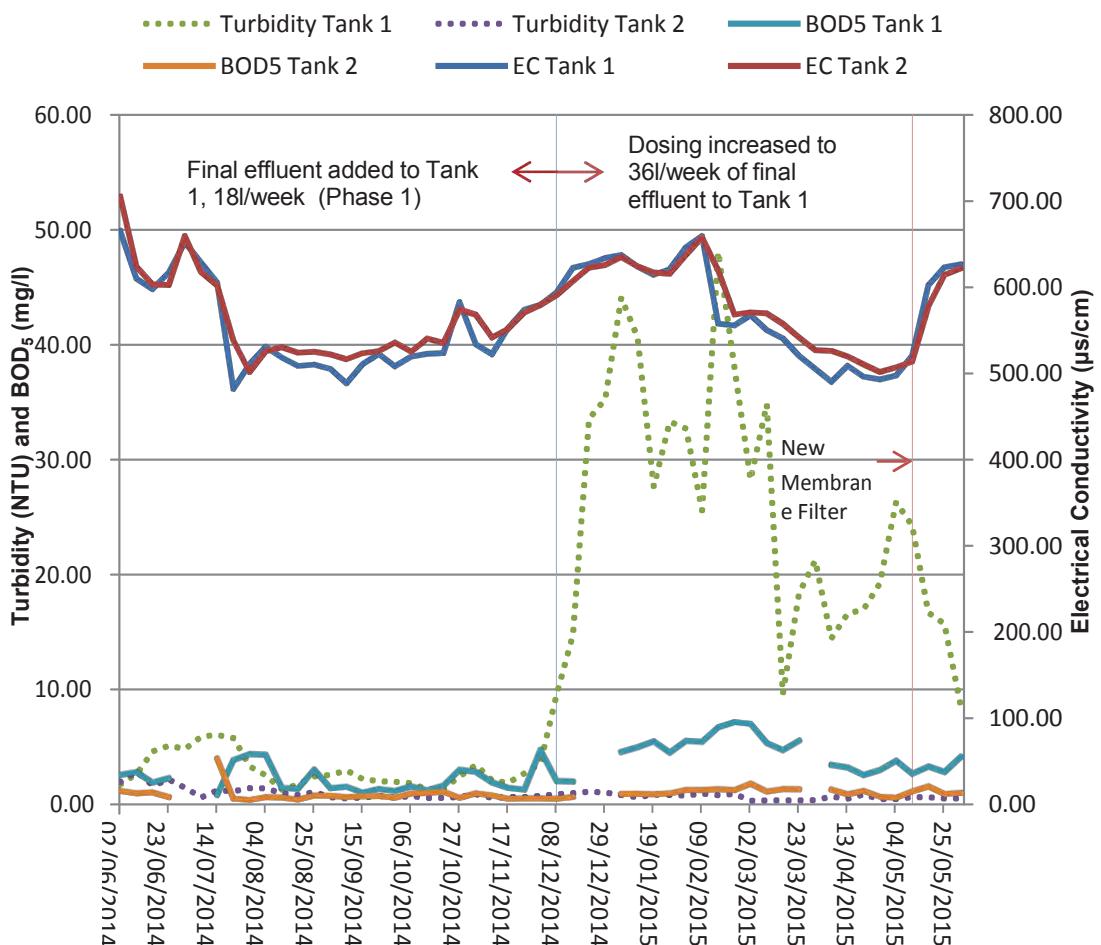
Greywater experimental research at the University of Reading commenced in 2011. Figure 1 shows that the turbidity of the treated greywater has been less than 3 NTU since the start of the testing programme in 2014 (mean 1.5 NTU). Meanwhile in phase 1, the corresponding influent was measured at around 6 NTU, but rose dramatically in phase 2 when the addition of final sewage works effluent (FE) was doubled within the same volume of synthetic greywater make-up. At that time, the turbidity readings peaked at around 40-50 NTU and then decreased as the process stabilised to a new biological 'equilibrium'. Meanwhile, although the EC demonstrated peaks within a similar timescale, the amount of variation around average EC values was much smaller than in the case of the turbidity.

During the same corresponding phases, the measurements of influent BOD were low prior to the doubling of FE make-up, when the concentration of BOD approximately doubled. The

BOD concentration has since remained higher than before the increase to the double quantity of FE, and has now reduced to a concentration lower than the peak.

Although the turbidity seemed to be the most sensitive indicator of the increase in the amount of organic matter, there were reflections of that increase in the accompanying, EC and BOD parameters. In an influent greywater of a relatively consistent composition, over the period of one year's measurements, the relationship between the increases and decreases in the EC and BOD parameters can be compared with those of the turbidity.

The data suggest that turbidity measurements taken at a daily frequency, or at least every other day, and BOD measurements at a preferable frequency of 2-3 times per week may be most appropriate. The turbidity instrumentation is portable and delivers good project value in terms of monitoring and managing greywater quality.



**Figure 1: Twelve month longitudinal study of treatment performance measured by turbidity, BOD<sub>5</sub> and electrical conductivity, showing two influent phases**

Based on the results of the above longitudinal data, the turbidity removal efficiency has been at around 100% since 22 December 2014 and the BOD removal efficiency has achieved 70% over the same period. The importance and significance is emphasised of continuing to measure both turbidity and BOD in greywater.

## 6. CONCLUSION

The quality of recycled greywater and its value are both important criteria against which greywater technologies are judged. The delivered impacts of the technologies are related to the quality, sustainability, value and utility of their outputs, and the financial performance of the technologies can be monitored in this young market. The take-up and diffusion of greywater technology requires a reliance upon and implementation of measurement and monitoring technology. The measurement of turbidity and BOD continues to deliver one important means for achieving these aims. Each of the test parameters in the British Standard plays a role in this respect also.

Risk reduction and avoidance using clear design, careful installation and regular maintenance procedures, requires greywater manufacturers, installers and users, to make regular checks and tests on treated greywater quality. These checks and tests demonstrate how efficiently the greywater process is operating using suitable equipment such as turbidity measurement.

So, suitable equipment for process measurement and control increases the certainty of achieving a specified quality and composition of greywater supply, whilst using robust methods and techniques. In addition, resource strategies for greywater reuse are increasingly contributing to the improvement of water efficiency, value and security. Manufacturers in some respects achieve a reduced exposure to risk in the greywater market through scrutiny of and success in plant performance results. Locally monitoring of greywater can contribute to the partial offsetting of the risk of water scarcity and vulnerability, through safely functioning greywater systems.

## ACKNOWLEDGEMENTS

Aquality Trading & Consulting Ltd.  
British Standards Institution; for Tables 1, 2 and 3

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# The Potential Utilization of Grey Water in Family Houses

Daniela Kaposztasova<sup>2</sup>, Martina Rysulova<sup>1\*</sup>

<sup>2</sup>prof.assistant, Vysokoskolska 4, 04200 Kosice

<sup>1</sup>PhD student, Vysokoskolska 4, 04200 Kosice

## ABSTRACT

**Aims:** Massive use of reused water for non-potable purposes in buildings promotes the conservation of natural resources, water, and thus the overall sustainability in water management. The aim of this article is to point out that grey water system can be also used in family houses with the significant amount of saving potential.

**Study design and methodology:** This study compares two ways of grey water system designs- a calculation and measurements. Both design methods were applied to an existing family house. Firstly, we introduce the calculation for grey water system design in two ways – with or without the use of white water in laundry. Secondly, we present the measurements which were applied to a proposed house where we recorded the amount of consumed water by residents of the house.

**Place and Duration of Study:** Slovakia, Važec, family house, between December 2014 to May 2015.

**Results:** According to this study, we realized the difference between design methods and needs for the establishment of the values used in calculation method to make this process more precise.

**Conclusion:** In Slovakia, the results of questionnaire shows that most of our citizens are pro water saving oriented and open to new water ideas - as in building water cycle. It is clear that for ensuring the exact and well working grey water system we need to engage in grey water system design and to set the standards for it, especially in Slovakia, since there is neither the application of this system nor its standardization.

Keywords: family house, grey water system design, calculation method, measurement)

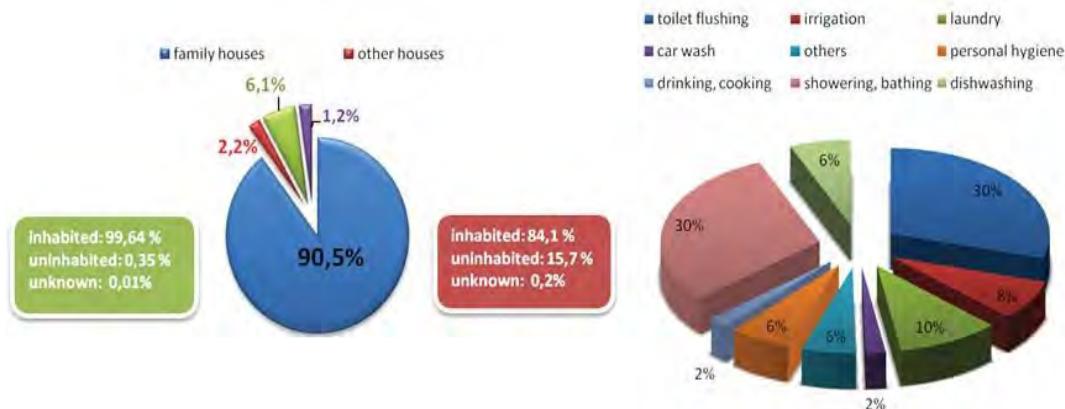
## 1. INTRODUCTION

While the world's population tripled in the 20th century, the use of renewable water resources has grown six-fold. Within the next fifty years, the world population will increase by another 40 to 50 %. This population growth - coupled with industrialization and urbanization - will result in an increasing demand for water and will have serious consequences on the environment [1]. The total volume of water in the world remains constant. What changes is its quality and availability. Water is constantly being recycled, a well known system as the water or hydrological cycle [2]. According to the World Water Assessment Programme [3] about 70 % of water use in the world is used for irrigation, about 22 % for industry and about 8 % for domestic use. In many countries the hydrological cycle is managed in order to provide enough water for industry, agriculture and domestic use. It requires the management of surface and ground water resources, treatment and supply of water, its collection, reusing and returning back to the cycle. These facts lead us to start with the support of the water cycle at the building level. In Slovakia the average consumption is around 145 l/person/day and according to the Population and housing census results 2011 there was an increase of built houses around 3,2 % (Fig. 1). From the 2011 census results with an average of six inhabitants per household average water use per household per day in Slovakia was more than 840 000 000 l/day. And therefore only households are yearly consuming around 308 000

\* Tel.: +421908075057; fax: +421 55 602 4351

E-mail address: martina.rysulova@gmail.com .

000 m<sup>3</sup> / year of potable water. It shows that about 55 % of drinking water may be replaced by alternative water source as rain water, grey water or water from well ...etc. This fact gives credit to reuse of potable water in building water cycle. We need to change the thinking of the society which will be in balance with nature to be more sustainable.



**Fig. 1 Types of houses in Slovakia according the Population and Housing Census 2011 and average consumption of potable water in Slovakia according to the end purpose**

There are many types of water as defined by Kinkade-Levarios [4] for example: atmospheric water – rain and fog, blue water – water from lakes, rivers, green water – soil moisture, storm water – rainwater that has hit the ground, alternate water – water that has been used previously, black water – water from toilets and kitchen sinks, reclaim water – water that has gone through a sewer treatment process and has been filtered and processed for reuse in various ways, sea water – desalination..etc. We would like to concentrate on water types that are the most common and available source in family houses, in this article mainly on grey water potential.

1. Potable water – water from tap, source of water for potable purposes
2. Water from well – could be a source of water for potable and non-potable purposes
3. Rain water – collected water from the roof during precipitation, source of water for non-potable purposes
4. Grey water – waste water from bathtub, shower, basin, source of water for non-potable purposes.

## 2. AIMS AND METHODS

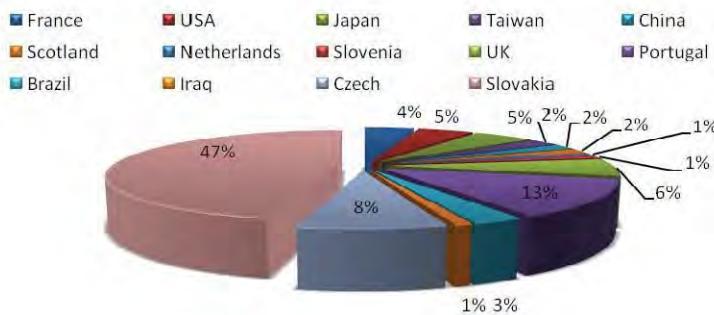
To assess the potential utilization of grey water for non - potable purposes we addressed three specific aims:

1. to identify the water habits of users in the world compared to Slovakia users by questionnaire
2. to investigate the potential of grey water production in family house by estimation method and measurements
3. to show the saving potential (economic and environmental) with or without the grey water system installation

### 2.1 Questionnaire on water use

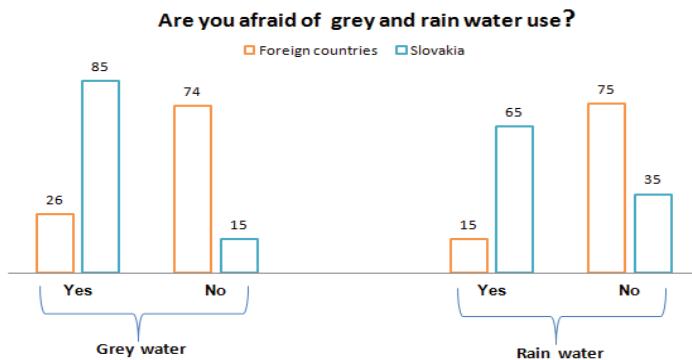
Potable water consumption of the Slovak households isn't above average at all but we use it in inappropriate ways. Questionnaire on Water, as one of data collection methods gives a closer look at water habits of households. In a first step, existing methodologies, standards and guidelines have been analysed. Therefore questionnaire has been sent out to the respondents to identify the water habits in their countries and from all over the world (Fig.2). The questionnaire was completed by the group of 200 people from different spheres of society divided to 85 male and 115 female respondents. The average age is 43 years. The 75% of them live in the family houses. The questionnaire consisted of 10 questions and the last one

was about their opinion on water-energy nexus. A quick overview of final results will show the attitude and differences between the Slovak respondents (SK) and respondents from foreign countries (FC). The whole questionnaire results were presented in [5]. From around 100 respondents from Slovakia no grey water use was identified and some of the houses are not connected to main water supply (reasons are – good quality of the water in the well, no water supply connection).



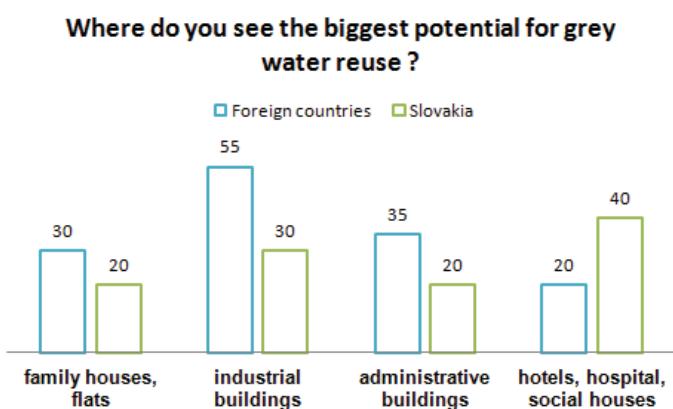
**Fig. 2 Respondents according to the countries of origin**

The important fact is that 80 % of respondents use potable water for all domestic purposes such as flushing toilets and watering the garden or washing their cars.



**Fig. 3 Comparison of grey and rain water use**

Our respondents were asked if they were afraid of grey and rain water use (Fig.3), in fact Slovaks were more afraid of grey water than rain water use, due to the lack of information about such a system of application in Slovakia. Our respondents from abroad see the biggest potential in installing the grey water system in industrial buildings (Fig.4).



**Fig. 4 Biggest potential for grey water reuse**

Respondents from foreign countries were not afraid of reusing grey and rain water. It is interesting that even though Slovaks are afraid of reuse of water around 85 % of them would think about sustainable solutions if they built a new house and 55 % of all respondents would consider installing such a system if the return on investment is between to 6-10 years. The main reasons for water saving was the water bill reduction in 49% of respondents, 41% for sustainability and reservoirs saving only 10%. The questionnaire shows people's willingness to use alternative water source for non-potable purposes rather than potable water. This questionnaire gives us a closer look on people's attitude to alternative water sources and their water consumption habits. The result is that most of our citizens are pro water saving oriented. In Slovakia this area hasn't been so developed yet. It is necessary to define regulation and set standards for designing hybrid systems for example according to foreign national standards and performed experiments in Slovak conditions.

## 2.2 Grey water use at the domestic level

Grey water refers to water sourced from kitchen (depending on national regulation), laundry and bathroom drains, but not from toilets. Grey water may contain urine and faeces from nappy washing and showering, as well as kitchen scraps, soil, hair, detergents, cleaning products, personal-care products, sunscreens, fats and oils [6]. Domestic wastewater (excluding fecal matter and urine) from bathrooms, basins, showers is called ***light grey water***. Contaminated or difficult – to-handle grey water, such as solids-laden kitchen sink water or from laundry is called ***dark grey water***. Grey water systems depend significantly on the behavior of the people using the collection appliances, as well as the quality and volume of water collected. Grey water could be reused – it means that water has not undergone treatment or been recycled – it means when water has undergone at minimum through the filters and disinfection. There are many different methods used to filter/ treat collected grey water, which range in complexity and the level of treatment. Practical grey water systems generally consist of one or more storage tanks, pump, filtration unit, chemical dosing and connecting pipework (Fig. 5). After treatment, we can use this water - called ***white water*** for different purposes as toilet flushing, irrigation, cleaning, and in laundries [7,8,9]. In some cases it seems that application for family houses in terms of their small amount of sanitary devices is not suitable. However, it depends if we asses it form economical or environmental point of view [10,11,12].

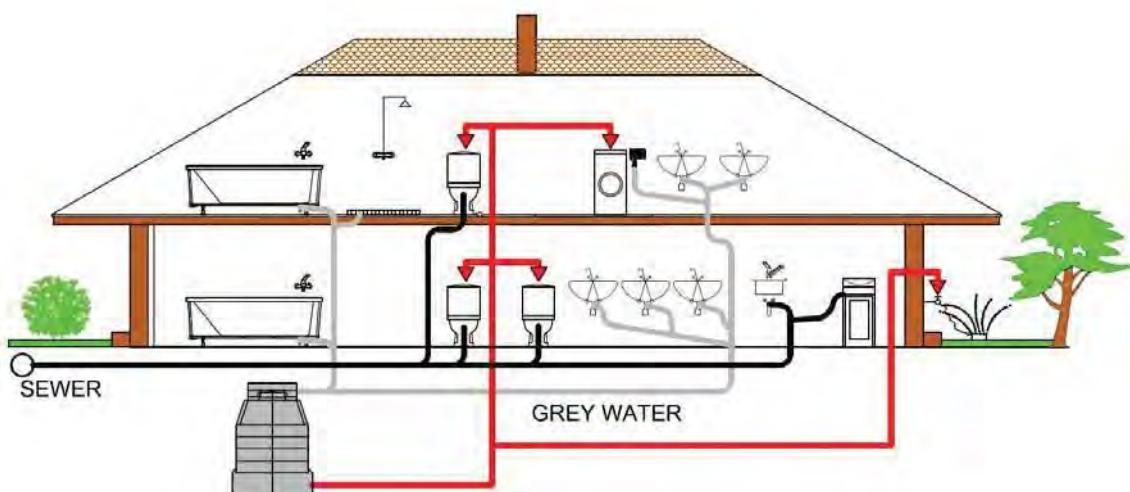


Fig. 5 Grey water in building cycle - scheme [5]

### 3. CALCULATION METHOD VERSUS MESAUREMENTS - CASE STUDY OF GREY WATER POTENTIAL IN THE EXPERIMENTAL HOUSE

If the grey water system is designed for an existing house, there are two ways how to determine suitability of this system. The first step is to assess the use of water in the house. The potential for improving the water efficiency through good housekeeping and other simple conservation measures, as well using rainwater and grey water, needs to be considered. While installing water efficient appliances a 6 month period is needed to see the changes in water pattern. There is a need to consider also seasonal changes of habits in water use (holiday periods, rainfall patterns...etc) [14]. The second way, usually used for a for installation of grey water system in new building design is a calculation method (depending on national regulation).There are a lot of guidelines and regulations developed in many individual countries for the design, operation and maintenance for grey water systems, but in Slovakia we don't have any. This is why we decided to calculate the amount of grey water for our experimental house by estimation method according to British Standard 8525-1:2010 [15].This method helped us to identify the preliminary potential, already in system designing phase, without any structure or water distribution interference, which are undoubtedly advantage for users.

#### 3.1 Grey water yield and demand calculation

For the comparison case study of estimation method results with real measurements we choose a family house in Važec, Slovakia. The house was inhabited by three persons (2 adults, 1 child). The appliances located on the first floor are: three sinks, shower, washing machine, and toilet and there are sanitary appliances (two sinks, bathtub, and toilet) on the second floor. In calculation we used all of the sanitary appliances for grey water production. Treated water will be used for flushing the toilets.

##### 3.1.1 Grey water yield

The following equation were used to determine the greywater yield,  $Y_G$ , in litres (L) and white water demand  $C$ , in litres (L) where the treated greywater is to be distributed for WC flushing:

$$Y_G = n \cdot (L \cdot \{S \cdot U_s\} + \{B \cdot U_b\} + \{(H_{wb} \cdot U_{hw}) + F_{wb}\} + \{\left(\frac{W}{L}\right) \cdot U_{wm}\}) \quad (1)$$

$n$  - is the number of persons

$S$  - is the average flow rate from the shower in litres per minute (L/min)

$U_s$ - is the typical usage factor for the shower

$B$  - is the bath volume to overflow (unoccupied) in litres (L)

$U_b$ - is the typical usage factor for the bath

$H_{wb}$  - is the mean peak flow rate from taps in litres per minute (L/min)

$U_{hw}$  - is the typical usage factor for the hand wash basins

$F_{wb}$  - is the fixed flow from basin taps used for vessel filling

$W$  - is the washing machine water consumption per wash cycle in litres (L)

$L$  - is the maximum dry wash load recommended by manufacturers in kilograms (kg)

$U_{wm}$ - is the typical usage factor for the washing machine

$$Y_G = 3 \cdot (L \cdot \{12 \cdot 4.37\} + \{120 \cdot 0.11\} + \{(10 \cdot 1.58) \cdot 3 + 1.58\} + \{\left(\frac{50}{6}\right) \cdot 2.1\}) \quad (1)$$

$$Y_G = 396.36 \text{ L}$$

*White water demand without laundry*

$$\begin{aligned} C &= 3 \cdot (L \cdot \{6 \cdot 4.42\} \cdot 2) \\ C &= 194.12 \text{ L} \end{aligned} \quad (2)$$

*White water demand with laundry*

$$\begin{aligned}
 C &= n * (V_{wc} * U_{sf}) + \{V_{FWC} * U_{fr} + V_{PWC} * U_{pf}\} + \left\{ \left( \frac{W}{L} * U_{wm} * P_{WM} \right) \right\} \\
 C &= 3 * (L * \{6 * 4.42\} * 2 + (\frac{50}{6} * 2.1 * 1)) \\
 C &= 211.62 \text{ L}
 \end{aligned} \tag{2}$$

### 3.1.2 Grey water system potential

To indicate the potential of grey water system suitability for each building, it is important to meet the following condition:

$$Y_G \geq C \tag{3}$$

$Y_G$  - volume of produced grey water per day (L)

C - volume of white water demand per day (L)

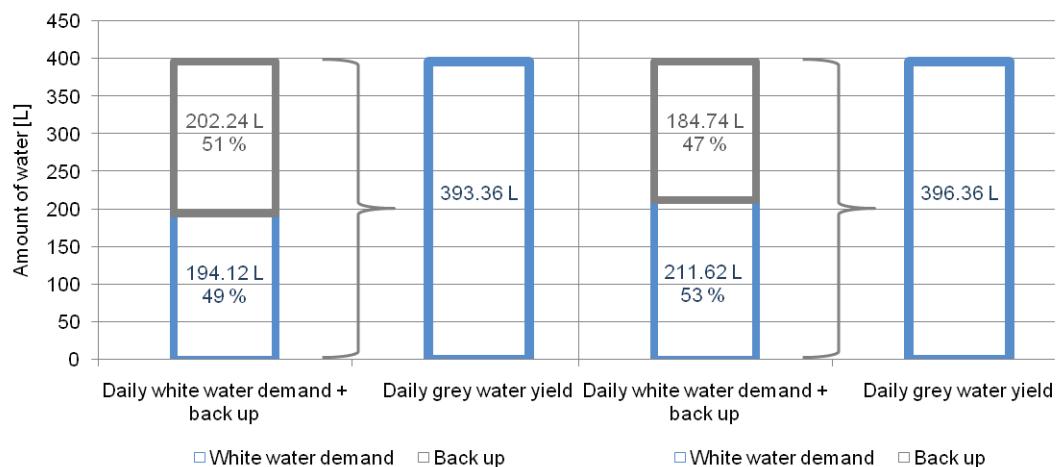
If the condition above is met, and the production of grey water will cover the white water demand, we can consider that the system has the potential for application. In this case study, we can compare grey water production with two variants of water demand - without using white water in laundry or include also water for laundry (Fig.6).

*White water demand without laundry*

$$396.36 \text{ L} ;: 194.12 \text{ L} \tag{3}$$

*White water demand with laundry*

$$396.36 \text{ L} ;: 211.62 \text{ L} \tag{3}$$



**Fig.6 Daily amount of water in grey water system - with and without water use in laundry**

According to the estimated amounts of water the grey water system application could be suitable for a chosen house. Grey water yield also creates the substantial amount of back up, which can supply a house during unexpected water demands. In possibility of no utilization of the backup, water can be safely discharged from the building through safety overflow into the sewerage.

### **3.2 Grey water in - situ measurements**

The in -situ measurements will show us the exact amount of water in the proposed house. According to the user behavior and their water habits, we observed the real production and

demand of grey water. The measurements were recorded for a six-month period and will continue through one year to consider the seasonal changes of habits in water use.

The methodology was based on monitoring of the daily amount of water used for toilet flushing (white water demand) and total water consumption.

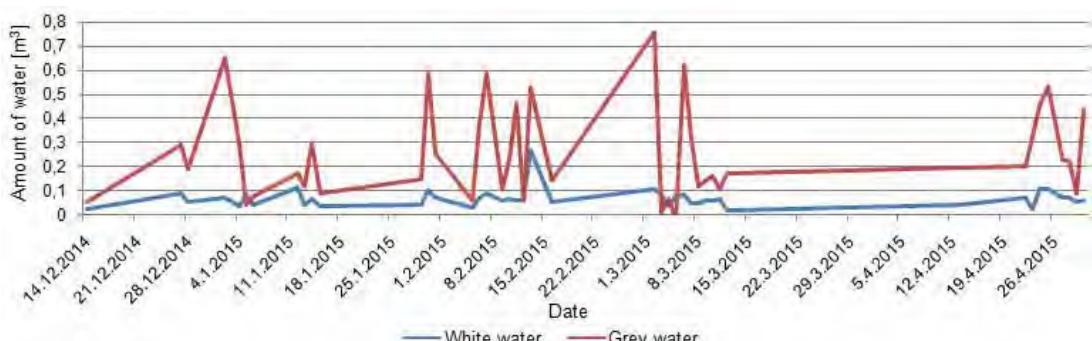
### **3.2.1 Measurement equipment**

The amount of water used for toilets flushing was recorded via water meters, which were set on the water supply pipelines on the sanitary devices. Water meters were installed earlier so we need to set the starting values. The water meter placed on the toilet on the 2<sup>nd</sup> floor, had the starting amount 2.884 m<sup>3</sup> (Fig. 7.), the water meter placed on the toilet on the 1<sup>st</sup> floor had the starting amount 4.696 m<sup>3</sup>. The total amount of water consumption was recorded from the main water meter which is placed in the water meter shaft.



**Fig. 7. Water meters - 1<sup>st</sup> floor and 2<sup>nd</sup> floor**

The values of water were recorded at 6 am daily (Fig.8). Through recorded amounts of persons in house and amounts of water, we could identify the daily water consumption. Also on 4/5/2015 the water consumption only per one person was recorded.



**Fig. 8. Daily water consumption in proposed house by 3 persons**

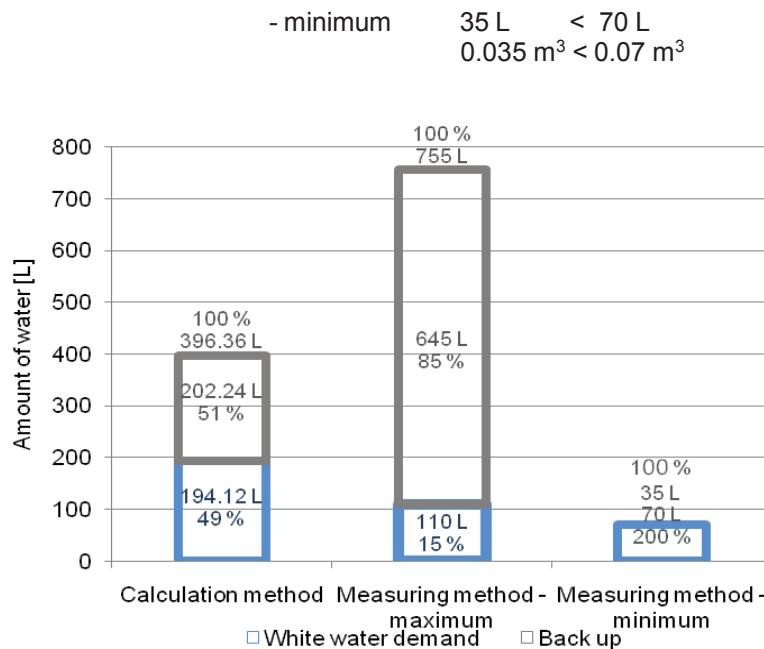
### **3.3 Comparison of the methods**

According to the used method we can compare these amounts with the measured amounts of water with three people in proposed house. The course of the water consumption on figure 8 describes uncertainties in water consumption. Even if the number of persons is immutable, the amount of used water is changing according to their behavior and demands.

By means of the estimation method we compare the white water demand for toilet flushing. From the results of the measurements we have to take into consideration two options - the case of maximal and minimal water consumption.

Calculation	396.36 L :: 194.12 L 0.396 m <sup>3</sup> :: 0.194 m <sup>3</sup>	(3)
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Measurements	- maximum      755 L      > 110 L 0.755 m <sup>3</sup> > 0.11 m <sup>3</sup>	(3)
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**Fig. 10. Comparison of water amount in both cases**

### 3.4 Saving potential (economic and environmental)

It is important to realize what we would like to reach - the environmental or economic savings or both together. The environmental approach gives us the view of other motives as wishing to conserve water, helping the environment and saving the water. The economics include the present worth cost of the capital and operations and maintenance costs and the cost of water per ac-ft. When we consider both capital and annual maintenance and operating costs it is necessary to provide the complete picture of the true cost of the system. The principle of linear regression was used and prediction model created for savings from year 2015 – till 2031. Following table 1 shows the possible water bills reductions per year by replacing the around 55% (all non-potable purposes) of water demand by grey water source. Of course when calculating savings we need to take into account the total installed costs including the water re-use system with all storage, pipework, disinfection, power supply and commissioning requirements. The fact is that for retro-fitted system the costs will be higher.

**Table 1 Potential savings in family house with grey water system with water consumption 211,70 m<sup>3</sup>/ year [5]**

Year	Without grey water			Grey water reuse system							
	Metered water charges [€ VAT]	Σ € + VAT	W cons. (m <sup>3</sup> /Year)	PW price [€/Year]	White water consumption (m <sup>3</sup> /Year)	PW price [€/Year]	White water (m <sup>3</sup> )	PW price [€/Year]	WW price [€/Year]	WP white+gr. [€/Year]	Savings [€/Year]
2015	1.57	1.08	2.85	581.43	492.48	0.41	47.83	540.31	21.12		
2016	1.80	1.28	3.10	673.59	590.84	0.42	49.45	640.29	23.27		
2017	2.00	1.34	3.34	707.73	620.81	0.43	50.56	671.37	26.36		
2018	2.10	1.41	3.50	741.90	650.78	0.44	51.69	702.47	28.42		
2019	2.19	1.47	3.67	776.06	680.75	0.45	52.87	733.62	32.44		
2020	2.29	1.54	3.83	810.23	710.72	0.46	54.08	764.80	35.43		
2021	2.38	1.61	3.99	844.39	740.69	0.47	55.33	796.02	38.37		
2022	2.48	1.67	4.15	878.56	770.66	0.48	56.62	827.28	41.28		
2023	2.58	1.74	4.31	912.72	800.63	0.50	57.96	858.58	44.14		
2024	2.67	1.80	4.47	946.89	830.60	0.51	59.33	889.93	46.96		
2025	2.77	1.87	4.63	981.05	860.57	0.52	60.75	921.31	49.74		
2026	2.86	1.93	4.80	1015.22	890.54	0.53	62.21	952.74	52.48		
2027	2.96	2.00	4.96	1049.39	920.50	0.55	63.72	984.22	55.18		
2028	3.05	2.06	5.12	1083.55	950.47	0.56	65.27	1015.75	57.80		
2029	3.15	2.13	5.28	1117.72	980.44	0.57	66.89	1047.32	60.40		
2030	3.25	2.19	5.44	1151.88	1010.41	0.59	68.53	1078.95	62.94		
2031	3.34	2.26	5.60	1186.05	1040.38	0.60	70.24	1110.62	65.43		

## **4. DISCUSSION**

In Slovakia, the results of the questionnaire show that most of our citizens are pro water saving oriented and open to new water ideas - like installing a grey water system. As grey water systems become more popular, there is a need for standardization to protect the public and to ensure that reliable systems are designed, installed and maintained. The cost benefit of grey water system is sensitive to the assumption made about the system, water availability and water consumption, users' water habits, and changing of the water prices. The main problem with these systems is their reliability. The costs of replacing components can sometimes be higher than potential water savings [15]. The next problem is connected with the life span of materials and payback period. With grey water systems the payback period is about 15-20 years and the life span is just about 15 years, but with new technologies it could be more [6,14]. The total costs of the system can be generally low for those users who are less concerned about money saving and wish to support sustainability from the environmental point of view.

## **5. CONCLUSION**

To achieve sustainability of water resources the approaches taken must be economically, environmentally and socially acceptable and avoid negative impacts on future generation. The aim of this article was to point out the potential utilization of grey water in a family house in real conditions and compare it to the calculated values. It is necessary to define regulation and set standards for designing hybrid systems, for example according to foreign national standards and perform more experiments in Slovak conditions; since the grey water systems are a new concept for Slovak users. According to the several studies and researches, we can improve the design part and introduce the system pointed at its saving potential to users. From this example of grey water application we can consider, that the system is efficient in terms of saving potable water. It is clear that the amount of consumed water is still changing according to the occupation of the house, its behavior and needs.

## **ACKNOWLEDGEMENTS**

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# SURFACE WATER MANAGEMENT

# Renewable energy and sustainable surface runoff management: combining Ground Source Heat and Porous Paving to heat buildings

**Charlesworth\*, S.M., Faraj-Lloyd, A.S., Coupe, S.**

Centre for Agroecology, Water and Resilience, Coventry University, Priory Street, Coventry, CV1 5FB, UK.

## ABSTRACT

### Aims:

1. Assess the feasibility of combining Ground Source Heat Pumps (GSHP) and Porous Paving Systems (PPS) in a domestic setting for heating purposes.
2. Establish the performance of combined PPS/GSHP at the building scale.

### Study design:

Laboratory-scale studies of combined PPS/GSHP established that it does not compromise the PPS' normal benefits. However, it has never been tested at the building scale until now. In the first study of its kind, the combined system was monitored in a detached 3-bedroomed house for 3 years.

### Place and Duration of Study:

Hanson Ecohouse, Building Research Establishment, Watford, UK was monitored from March 2008 - November 2010.

### Methodology:

Temperature at 4 depths in the PPS, at 1300mm above it, and the 4 cardinal points of the house's inside and outside walls was monitored at 10 minute intervals. PPS water depth was checked to determine whether the heat exchangers were adequately covered with harvested water.

### Results:

Analysis of the >1.3 million data points, found that the average Coefficient of Performance (CoP) was 1.8, too low for the 2009 EU Renewable Energy Directive which requires a CoP of 2.875. However, CoP did exceed 2.875 mostly during September, revealing the technology's potential.

### Conclusion:

The combined system's ability to provide heat to a domestic building has been proven through this study. However, improvements in design can improve CoP such as installing the heat exchangers deeper, ensuring no leakage of the geomembrane tanking the PPS, installing it into a "normal" house, rather than a demonstration.

**Keywords:** *Pervious paving; Ground Source Heat Pumps; rainwater harvesting; water quality; Coefficient of Performance;*

\*Tel: +44 2476 888370  
[s.charlesworth@coventry.ac.uk](mailto:s.charlesworth@coventry.ac.uk)

## 1. INTRODUCTION

Sustainable Drainage (SUDs) offers a means of addressing the negative impacts of urbanisation including increased peak flow, time to peak, and volume, as well as decreased time to baseflow [1, 2]. Such a "flashy" response to rainfall leads inevitably to flooding and contamination of the urban environment. SUDs mimic the natural environment by a combination of infiltrating excess surface water through pervious surfaces, detaining it in surface or sub-surface stores and slow conveyance to the receiving water course. This is achieved by individual devices such as Pervious Paving Systems (PPS) which are hard infrastructure (see [3]) or those utilising vegetation in swales, filter strips, green roofs and walls, and wetlands (see [4, 5]). PPS are structures allowing infiltration of surface water which also provide running or parking surfaces for motor vehicles and pavements for pedestrians [6]. They can comprise permeable blocks, porous asphalt, concrete or resin, with a substructure comprising a bedding layer which can be divided from the coarse aggregates beneath by a geotextile (see [3]).

A large proportion of the global energy demand is for electricity [8], and this is likely to increase. Add to this the potential depletion of fossil fuels, which much of the world depends on currently to provide energy, the potential effects of global climate change and contamination of the environment associated with energy production, and alternative sources of energy becomes crucial. Using renewables is encouraged by many governments, for example, in early February 2014, the European Parliament increased the percentage of Member States' provision of energy using renewables from 20%, as it stood previously, to 27% by 2030. Ground Source Heat (GSH) has the potential to provide an abundant and constantly renewable source of energy from the ground, the extraction of which is relatively easy [8]. Whilst the temperature of this heat is relatively low when first extracted, it can be concentrated to provide space heating which is considered to be "environmentally and economically advantageous" [8]. Whilst both SUDs and the harvesting of GSH are not new, their design into a combined structure makes use of surface water which would otherwise be wasted, and provides a relatively new and timely development which [7] have called the "next generation" of PPS.

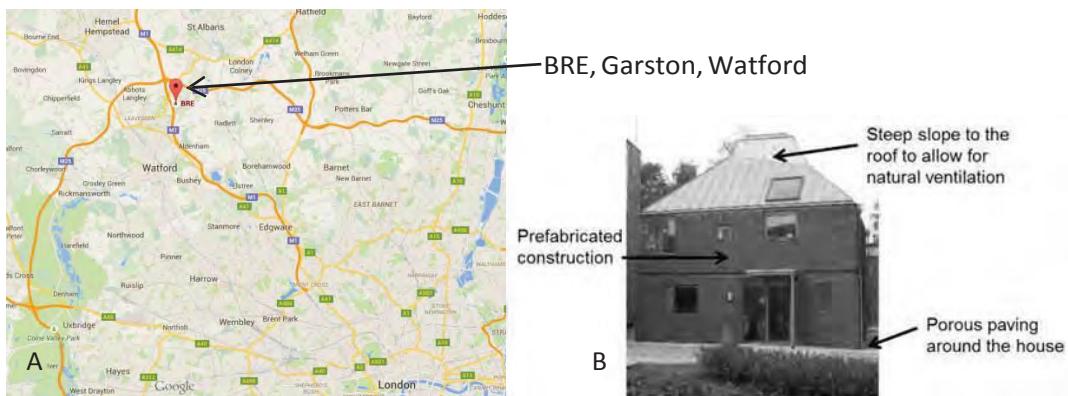
There are some reports of laboratory experiments using small-scale model test rigs of the combined system which have illustrated their potential. Much of the focus has been on establishing whether the inclusion of GSH extractors, or pumps (GSHP), compromise the PPS' ability to improve water quality. The majority of studies found that the PPS performed as usual; for example [9] found removal rates of up to 99% for a variety of pollutants including Biological Oxygen Demand and Ammonia-nitrate and [10] recorded removal rates for turbidity of between 90 and 98%. In terms of microorganisms, removal rates of *E. coli* were over 97% in test rigs [11,12]. However, to date, monitoring of the ability of a combined PPS/GSHP to provide heat at the building scale has not been reported. This paper presents previously unpublished data from combined PPS and GSHP in a domestic setting to address the following two aims:

1. An assessment of the feasibility of combining a PPS and GSHP in a domestic setting for heating purposes.
2. Establishment of the performance of the combined system at the building scale.

## 2. METHODOLOGY

### 2.1 Site description: the Hanson Ecohouse

The Hanson Ecohouse, located on the Innovation Park at the Building Research Establishment, Garston near Watford, UK (Figure 1A) was the first building to have the combined PPS/GSHP installed in order to provide the only means of heating. The Ecohouse was completed in 2007 and is a detached, two-storey, three-bedroomed, fully-furnished domestic dwelling with an internal floor area of 143m<sup>2</sup> (see Figure 1B).



**Figure 1A** Location of BRE, near Watford, UK (Google maps); **1B** Hanson Ecohouse

Table 1 gives the dimensions of the combined system and its structure, with the location of the 50mm x 150m slinky coils which harvested the heat, in the lower sub-base layer. The slinky pipes were laid horizontally in the PPS trench and contained anti-freeze (ethylene glycol) as the heat exchange medium which circulated within them using a heat pump. The heat pump for distributing the under-floor heating in the house was powered by electricity, but this had a performance coefficient of 4:1, which justified its use. The pump had a capacity of 8KW with a performance standard of AHRI/ASHRAE/ISO 13265-2 (manufactured by the Water Furnace Company).

**Table 1** Structure of the combined PPS/GSHP at the Hanson Ecohouse.

	Combined PPS/GSHP
Area	65m <sup>2</sup>
Permeable blocks	80mm
Clean stone	50mm (stone size 2-6mm)
Geotextile	Inbitex composite
Sub-base:	Upper layer 120mm (stone size 5-63mm) Lower layer 100mm (6mm bedding stone): Location of slinky coils
Total excavated depth	- 350mm

The total excavated depth of 350mm is approximately 150mm shallower than is usual for standalone PPS. The reason for this was site-specific since the site had been built on previously and it was not possible to excavate any deeper. Nonetheless, it was thought that it would be possible to produce up to 6 KW of heating or cooling energy from the 65 m<sup>2</sup> collection area with the coil fully covered with harvested rainwater for appropriate heat fluxes and heat exchange through the system. This should have the potential to maintain comfortable temperatures in the house all year round. The PPS was sealed by means of an impermeable 1mm thick impermeable membrane, with the means for excess water to drain into an adjacent swale. Roof water was harvested from 2 adjoining buildings at BRE, and surface water was directed into the PPS/GSHP tank to maximise the volume of collected rainwater.

Assessment of the performance of the combined PPS/GSHP was carried out by monitoring the temperature both inside and outside of the house, specifically the temperature of the exterior

and interior walls as well as the ground temperature at varying depths below the surface of the PPS. It was then possible to calculate the efficiency of the GSHP, or its Coefficient of Performance in the heating cycle or  $\text{CoP}_{\text{heating}}$  using Formula 1.

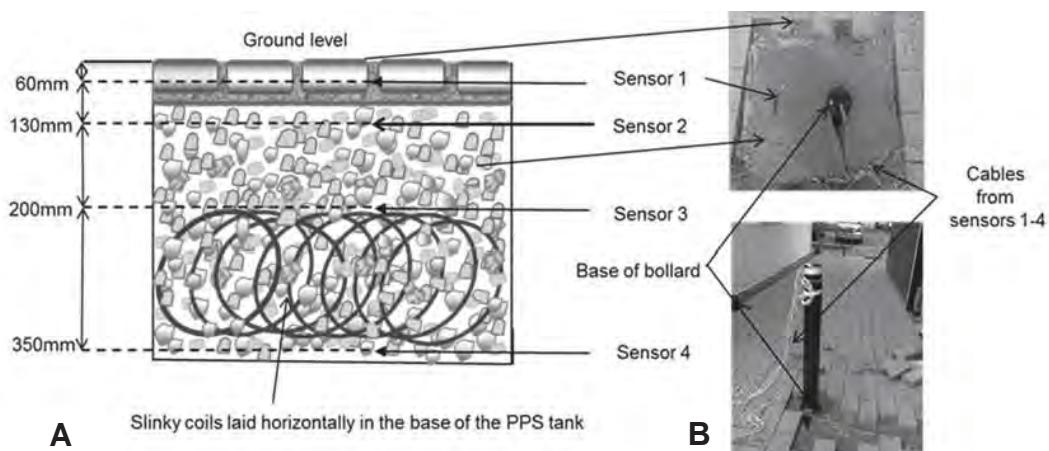
Formula 1

$$\text{CoP}_{\text{heating}} = \frac{T_{\text{supplied}}}{T_{\text{supplied}} - T_{\text{extracted}}}$$

The water depth in the tank was also measured to determine whether enough water was being harvested to keep the slinky coils wet. This was an important consideration since water is a more efficient heat transfer medium due to its relatively high heat capacity.

## 2.2 Temperature measurements and water depth in the PPS/GSHP tank

The temperature of the house as well as the air and subsurface temperatures above and below the surface of the pavement were monitored continuously from March 2008 to November 2010 (15 sensors in total). Figure 2a shows the locations of the sensors in the PPS/GSHP, and their connection through a bollard which itself contained a sensor at 1300mm above the surface of the PPS/GSHP to monitor ambient air temperature (see Fig 2b). The sensors embedded in the PPS/GSHP were within the harvested water at 350 and 200mm, and at depths of 130 and 60mm in the bedding layer and between the blocks respectively.



**Figure 2A** Position of sensors buried in the PPS/GSHP tank and their connection to the bollard

**Figure 2B** Position of sensors in the bollard

Inside the house, constantan (copper/nickel alloy) thermistor sensors (34970A Agilent data acquisition system) monitored temperatures at 10 minute intervals. The sensors were embedded in the wall panels at all four cardinal directions around the house. The >1.3 million data points generated in this way were managed by a Tridium Java Application Control Engine (JACE) 200 logger system sent via ultra-high bandwidth fibre connections to the Community Digital Management Centre located in the BRE Visitors Centre. The resulting data (see Table 2 for a breakdown) was downloaded in PC DOS format.

Water depth in the PPS/GSHP tank was measured via a vertical pipe well installed down to the base of the tank during construction of the combined system and water level measured by means of a ruled stick.

**Table 2** Number of data points collected during the monitoring study.

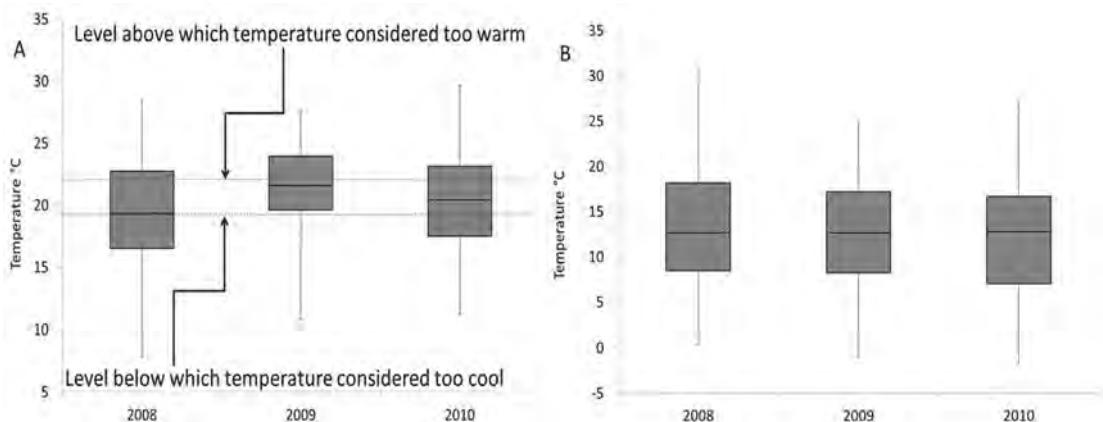
Location of data collection	N =	Number of days data collected
EcoHouse	902,151	718
PPS/GSHP reservoir	255,570	509
Bollard above the reservoir	145,658	509
Total number of observations	1,303,379	

### 3. RESULTS AND DISCUSSION

#### 3.1 Temperature measurements inside and outside of the Ecohouse

The average outdoor temperature over the 3 year monitoring period was 12.6°C, whilst the mean temperature inside the Ecohouse was 20.2°C. [13] would consider this mean indoor temperature "comfortable", the range of which is between  $19.5 \pm 0.5^\circ\text{C}$  in winter and  $21 \pm 1^\circ\text{C}$  in summer. However, figure 3A shows the variation in mean daily temperature inside the house with many readings measured outside of "comfort" levels i.e. where they were either too warm or too cool. It was found that trends for indoor temperature closely followed that of outside, although in general, the temperature indoors was up to 15°C warmer than outside. Winter 2008-2009 was one of the coldest in the UK for many years [14] but these results do show that the PPS/GSHP functioned adequately in spite of the cold conditions.

The variability in the data shown in Figure 3, however, indicates a lack of thermal stability inside the house, mainly due to the fact that it was used to demonstrate various technologies, including the combined system, as part of a national sustainability exhibition. Thus, groups would regularly open and close both the doors and windows during daytime visits, disturbing the distribution of heat in the house. On other occasions, the thermostat had been interfered with, the pump had been switched off or some of the equipment had failed and required resetting.

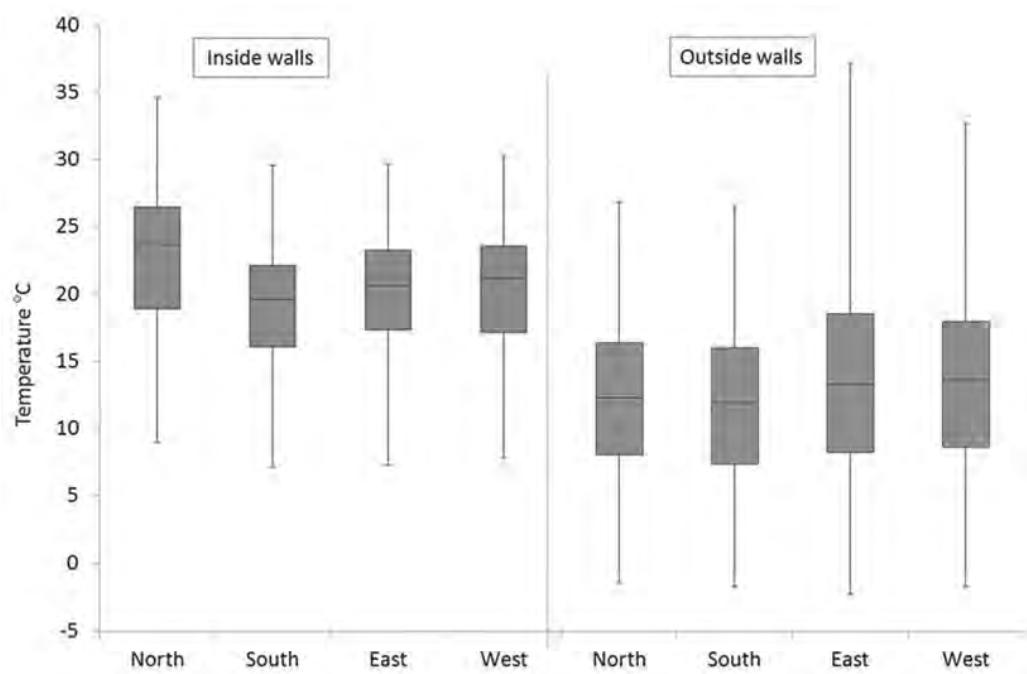


**Figure 3** A. Mean daily indoor temperature compared with [13]'s "comfort" levels shown by dotted lines ( $n=718$ ); and B. outdoor temperature over the 3 years of monitoring, ( $n = 718$ ). The bar in the box represents the median, and the whiskers are maximum and minimum temperatures

Table 3 shows that even when minimum temperatures outside the house were below zero, those inside maintained positive temperatures. This is also illustrated by Figure 4 in which the inside walls recorded higher temperatures, on average by  $8^\circ\text{C}$ , in comparison with the outside walls. Obviously, some of this is due to orientation, with the east and west sides of the house receiving solar radiation in the mornings and afternoons respectively. The house was also shadowed on the south side by other buildings, affecting the thermal capacity of the house walls.

**Table 3** Temperature ( $^{\circ}\text{C}$ ) of overlying air, indoors and at different depths in the PPS/GSHP during the monitoring period (n = 2,449)

Statistical measure	Indoor	Ambient air 1300mm above the tank surface	60mm depth	130mm depth	200mm depth	350mm depth
Minimum	7.8	-3	-4.4	-3.1	-1.9	-1.1
Maximum	29.6	22.5	26.2	24.7	21.2	20.0
Average	20.2	10.0	9.7	9.5	8.8	9.6
Median	19.3	10.8	9.5	9.2	9.1	11.0
Standard Deviation	4.1	6.0	6.9	6.9	6.6	6.7
N =	5,744	509	509	509	509	413



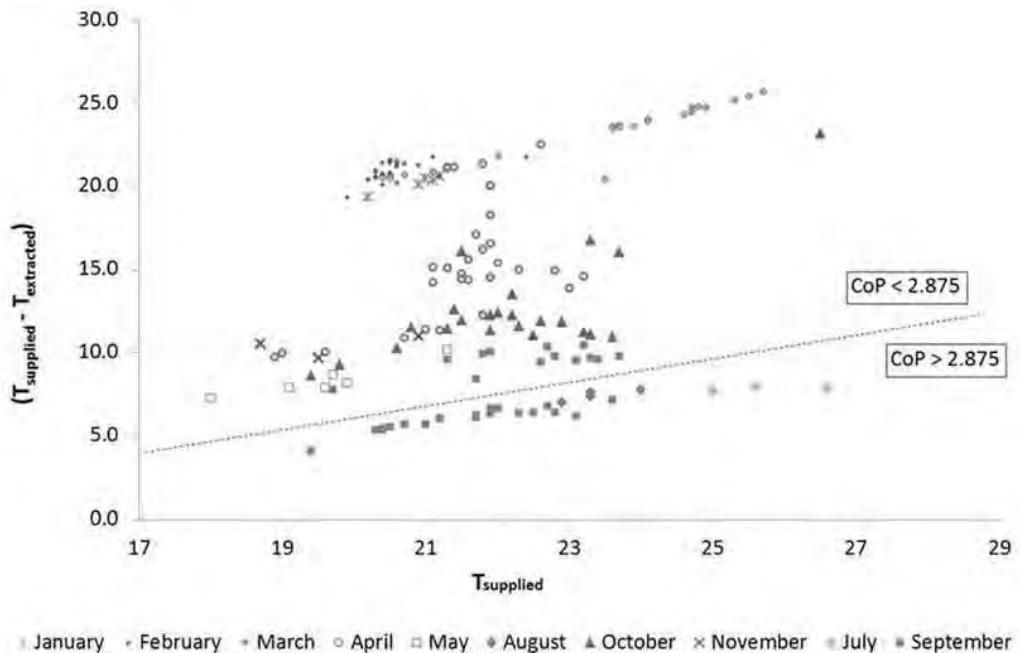
**Figure 4.** Temperatures recorded for inner and outer walls for the 4 cardinal directions (n = 5,744). The bar in the box represents the median, and the whiskers are maximum and minimum temperatures

### 3.2 Coefficient of performance (CoP)

Although the monitoring period was for almost three years, there were only 351 days when the house actually required heating and CoP could therefore be calculated. Of these 351 days, there were times when data were not collected for a variety of reasons and thus this further reduced the dataset to 163 days for which CoP was calculated.

Over the 163 useable days, the CoP value varied between 0.9 and 4.8 with an average of 1.8. With a CoP of 1.8, the system cannot be considered a satisfactory renewable source of energy under the 2009 EU Renewable Energy Directive which requires a CoP of 2.875. However, 27 days did exceed CoP 2.875 (3 in July; 4 in Aug; and the rest (20 days) in Sept) with the highest of 4.8 occurring in September (see Fig 5). For the days on which the ground temperature was less than 1  $^{\circ}\text{C}$  (varying between -1.1 and 0.9), the CoP value was 1.0 or less, indicating that heating was provided to the Ecohouse via the electricity mains without any heat energy being derived from the ground. When the temperature of the ground was greater than 1.9  $^{\circ}\text{C}$  (there

were no recorded ground temperatures between 0.9 and 1.9°C), CoP varied between 1.1 and 3.8, with an exceptional day with a CoP of 4.8, all together totalling 101 days. The CoP of 4.8 was achieved when the indoor and ground temperatures were 19.4°C and 15.3°C respectively; the lower heat load and higher water temperature combining to result in the highest CoP. Lower CoPs occurred when the difference in ground and indoor temperatures were large.



**Figure 5** CoP by month during the monitoring period (n=163). The dotted line represents a CoP of 2.875 (2009 EU Renewable Energy Directive).

Comparing CoP and ground temperature at the depth in the PPS/GSHP at which heat was harvested (ie 350mm; the base of the tank) it was found that CoP increased with increasing ground temperature (see Table 4) since it was strongly influenced by climatic conditions or changing ambient air temperature. This relationship is shown by the correlation between CoP and temperatures outdoors at 0.700\*\*; with CoP and temperature of the ground at 350mm depth in the tank at 0.926\*\*; and with ambient air and ground temperature at 350mm depth at 0.787\*\* (where \*\* signifies correlation is significant at the 0.01 level). The system is likely to be inefficient if the PPS/GSHP is influenced by climate conditions.

**Table 4** Summary of average indoor, ambient and base of tank temperatures (°C), and CoP values throughout the monitored period (n = 163)

	Average ambient air temperature	Temperature at 350mm	Indoor average temperature	CoP
(summer 08) 13 Aug 08 - 29 Sep 08	16.1	15.4	21.5	3.5
(winter 08 - 09) 27 Jan 09 - 29 Mar 09	7.4	-0.1	21.7	1.0
(summer 09) 01 Apr 09 - 30 Sep 09	15.1	10.3	21.8	2.2
(winter 09 - 10) 01 Oct 09 - 30 Mar 10	11.3	8.5	21.8	1.7

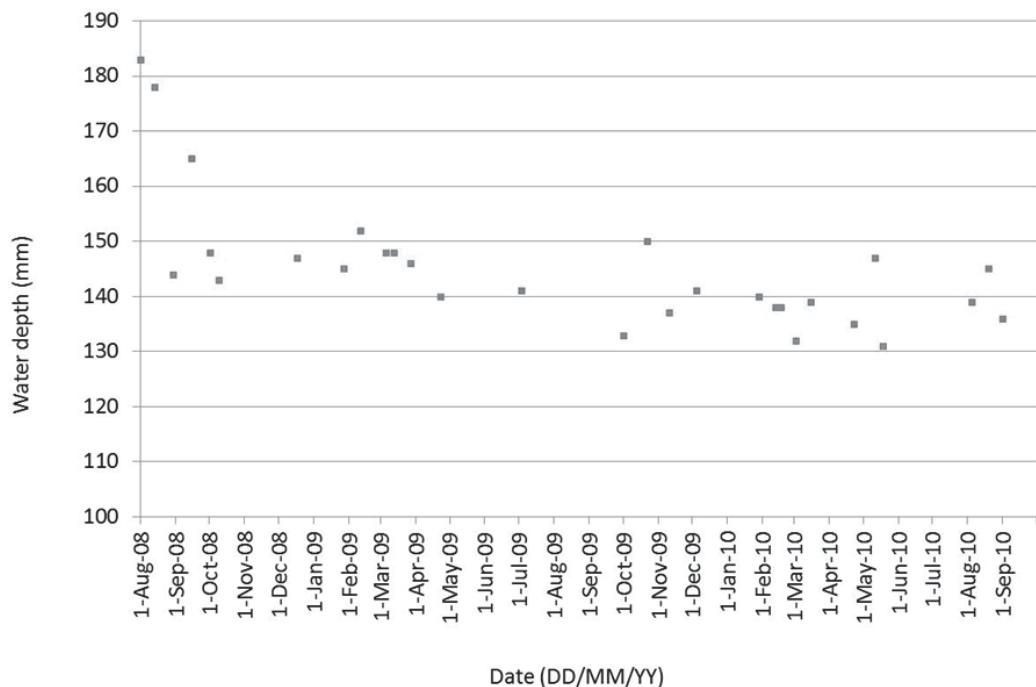
The mean CoP value for days when ground temperature was greater than 1.9°C was 2.3, which is consistent with values reported in a UK study by [15], in which 54 GSH installations

were monitored finding mid-range CoPs of between 2.3 and 2.5, with higher figures over 3.0. CoPs obtained from the combined system provide evidence of its reliability under conditions when the stored rainwater is less influenced by cold conditions.

In studies by [16, 17], where the GSH exchanger units were vertical and buried at 50 and 55m, CoPs were calculated at 1.34 and 2.09 respectively. Despite the heat exchanger pipe in those studies being much deeper than the slinky coils in this study (and thus much less affected by environmental conditions), the CoP obtained from the PPS/GSHP reservoir is higher than that reported in both [16, 17] when comparing Ecohouse ground temperatures  $>1.9^{\circ}\text{C}$ . This can be attributed to the slinky coils being submerged in rainwater, which enhanced heat transfer [18].

### 3.3 Water depth in the water harvesting tank

Figure 6 shows that the depth of rainwater harvested from the PPS/GSHP at the start of the monitoring period was 180.2mm, but from month 4 onwards it averaged about 140mm. The depth at the beginning of the monitoring period reflected a period of heavy rainfall in the first few months, but there may also have been a leak in the PPS/GSHP reservoir. The reason for this may have been due to a gap or gaps in the impermeable SC membrane layer on the sides of the tank or a weakness in the welded membrane joints. Thus, depth measurements do indicate that there was a possibility that the slinky coils were not completely covered which may have led to inefficient harvesting of heat.



**Figure 6** Depths of harvested rainwater in the tank.

It was also found at times during the rainwater level measurements that the stored water was frozen, and it was observed that this took longer to thaw than the ice or snow on the surface of the pavement since heat transfer was relatively insignificant. The slinky coils were therefore occasionally in a frozen environment which would have negatively affected CoP.

## 4. CONCLUSIONS

1. PPS and GSHP combined has the potential to provide cooling/heating at virtually any location and therefore has the potential to reduce electricity bills.
2. The combined PPS/GSHP system proved to be a viable technique that brought multiple benefits associated with SUDs, therefore it is recommended that it can be used wherever is appropriate.

3. The combined system controlled rainwater runoff by allowing infiltration through the gaps between the pavement blocks and provided a secondary use for harvested water from both rainfall and also excess surface water runoff.
4. The combined system was able to provide a 3-bedroom detached house with enough heat, at comfortable internal temperatures at times during the monitoring period.
5. Nonetheless, the daily temperatures inside the house showed little stability and were occasionally uncomfortably cold or warm due to a variety of plumbing, breakdown and electricity supply problems.
6. A PPS/GSHP system with the GSH exchanger installed at a depth of 350mm is highly susceptible to the influence of the ambient air, with significant correlations ( $p<0.01$ ) between CoP, outdoor air temperature and temperature at 350mm.
7. It was found that when the stored rainwater temperature was below 1°C, the CoP was 1 or less; heating provided during such events was completely derived from the electricity mains.
8. The PPS/GSHP had a CoP of 1.8, hence the system cannot be considered a satisfactory renewable source of energy under the 2009 EU Renewable Energy Directive which requires a CoP of 2.875.
9. Measurement of water depth indicated that, possibly due to leakage, levels were lower than ideal, which could have resulted in parts of the coil not being covered with water and hence sub-optimal heat flux and heat exchange.
10. Lessons were learnt from this study, including: the slinky coils need to be located in a deeper structure, probably  $> 500\text{mm}$ ; more care needs to be taken in tanking the PPS to avoid leakage; more research is needed in a "real-life" scenario, rather than a demonstration house; research is needed to monitor water quality in such combined systems to understand better the impacts of harvesting heat in PPS.

## COMPETING INTERESTS

The authors declare no competing interest.

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# Percolation drainage systems

G. Markovic <sup>1\*</sup>, Z. Vranayova <sup>2</sup>

<sup>1</sup> Technical University of Košice, Faculty of Civil Engineering, Institute of Architectural Engineering, Vysokoškolská 4, 042 00 Košice, mail: gabriel.markovic@tuke.sk

<sup>2</sup> Technical University of Košice, Faculty of Civil Engineering, Institute of Architectural Engineering, Vysokoškolská 4, 042 00, Košice, e-mail: zuzana.vranayova@tuke.sk

## ABSTRACT

**Aims:** Storm water management is a relatively new issue in Slovakia. Percolation of rainwater as a part of storm water management is becoming more and more important as a drainage solution in Slovakia. The aim of this article is to point out that with correct planning, design, realization and maintenance of the infiltration facilities, the operation of the device should be fluent and free from complications.

**Study design and methodology:** This study compares two ways of infiltration systems and measurements of infiltration rate in real conditions. Both methods of infiltration were applied to an existing percolation drainage systems. Firstly, we present the measurements of infiltration rate which were measured to infiltration shafts where we recorded the amount of drained rainwater and time required for infiltration. Secondly, we present the measurements of infiltration rate which were measured to infiltration gallery where we recorded the amount of drained rainwater and time required for infiltration too.

**Place and Duration of Study:** First place: Slovakia, Campus of TU Košice, between March 2011 to May 2015.

**Results:** As apparent from the measurements the determination of the infiltration coefficient is the most important parameter for the infiltration facility design. In the first case, the infiltration shaft was tested. Despite the fact that the area for infiltration, respectively the size of the bottom of the shaft is only 0,785 m<sup>2</sup>, the process of infiltration and operation of this facility is fluent and free from complications. Safe disposal of surface runoff is ensured by the infiltration coefficient  $k_f = 1.10^{-3}$  m/s. In the second case, the infiltration gallery (made from plastic units) was tested. The percolation area of the infiltration gallery is 46,08 m<sup>2</sup> which should guarantee a fluent operation according to the theoretical calculation. But with an incorrect determination (without hydrogeological survey) of the infiltration coefficient, the functioning of runoff disposal is too low or in many cases insufficient resulting in the overflow of the infiltration facility.

**Conclusion:** The article presents the experimental measurements and evaluation of the infiltration efficiency in the real conditions and emphasizes the importance of hydrogeological survey. However, the biggest problem is that there is no legal framework as well as no standards or guidelines of sustainable storm water management application techniques, especially in the field of rainwater percolation. Designers may suggest the drainage of rainwater through the infiltration facilities and at this point, the problems arise due to the lack of information and experience in designing along with the shortcomings of legislation. There have already been reported many cases of an inadequate design resulting in poor or insufficient functioning of the systems, many of which have resulted in a damage to the property.

**Keywords:** drainage, infiltration, infiltration units, infiltration shafts

\* Tel.: +421 556024270; fax: +421 556024331.

E-mail address: gabriel.markovic@tuke.sk

## 1. INTRODUCTION

There are several definitions of storm water management available based on different approaches. Water conveyance from the urban areas is performed by the means of drainage systems. Times have changed and so have the approaches in the urban drainage systems, as we have to face different challenges in the urban environment. When natural surfaces are changed to urbanized surfaces, the volume of water that runs off the surface is increased by the addition of new impervious surfaces

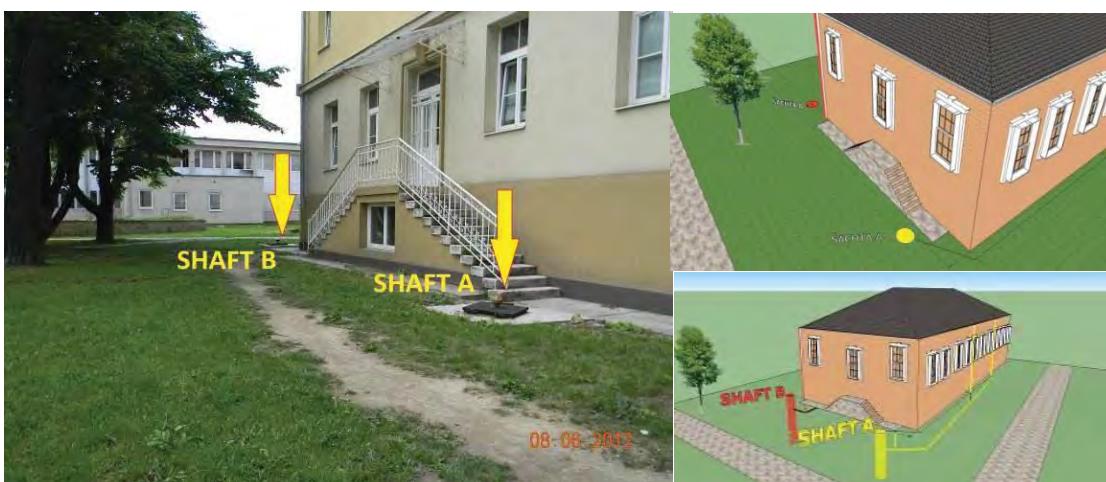
Urban drainage systems can be divided into two most commonly used; a combined sewer system and a separate sewer system. Combined sewer systems convey storm water and waste water away in a single pipe. Where the combined systems are used, the risk of combined sewer overflows appears (CSO) represented by transfers of untreated waste water into receiving waters [9]. On the other hand, separate sewer system carry storm water and waste water in the separate pipes, usually laid side-by-side [10].

## 2. METHODOLOGY

The article describes experimental measurements and evaluation of the infiltration efficiency in the real conditions. The two sites having been tested are located in TUKE (Technical University of Košice) campus and in the city of Prešov.

### 2.1 Experimental research in the campus of TU Košice city

Our research and own measurements in the field of storm water quantity and quality parameters has been started in the campus of Technical University of Košice as a part of the management of storm water project. The objects of our research are two infiltration shafts in TU campus in Košice, already existing prior to our research. These infiltration shafts were designed as a drainage solution for a real school building PK6. Two vertical shafts are located next to the PK6 building. All run-off rainwater collected on the roof flows into the underground pipes (Figure 1) [1].



**Fig.1 The location of drainage shafts near the PK6 building [7]**

The initial measurement started in March 2011 and has continued in the infiltration shaft A so far, followed by the measurement of the inflow of rainwater runoff from the roof of the building PK6.

The headquarters, respectively a control / data unit for the generation of measured data, is a universal data unit M4016 situated in the infiltration shaft A (Figure 3). Infiltration shaft B, respectively devices located inside the shaft, are also connected to the control unit.



**Fig. 2. Data unit M4016 in shaft A**

The registration and control unit M4016 includes a universal data logger, a telemetric station with a built-in GSM module, a programmable control automat and a multiple flow meter in cases when M4016 is connected to an ultrasonic or pressure level sensor (Figure 2) [5].

Under the inflow, respectively rain outlet pipe in the shaft, the measurement flumes for metering of the rainwater inflow from the roof of PK6 building are located in both shafts. The rainwater from the roof of PK6 building is fed through rainwater pipes directly into measurement flumes placed under the ultrasonic level sensor and the sensor then transmits the data about the water level in the measurement flumes to the M4016 unit.

The M4016 unit, into which the signal is transmitted from the ultrasonic level sensor, is preset up to 14 equations or the most used sharp crested weirs. The flow rate is calculated from the relationship between the water level and the flow rate. The purpose of measurement is to calculate the instantaneous and cumulative flow calculated on the basis of water level with the use of a predefined profile - Thomson weir.



**Fig. 3. The measurement flume with an ultrasonic level sensor in the shafts**

Thomson weir consists of two overflow edges with an angle of 90°. The axis of the angle must be vertical. [12] The measurement of inflow rainwater was later extended with other parameters, especially the effectiveness of infiltration shafts when infiltrating the rainwater at the shaft bottom, respectively, the infiltration rate of the inflow water.

The measurement of the inflow of rainwater takes place at the bottom of the infiltration shafts, where the pressure sensors of LMP307 type are located for monitoring of water lever (Figure 4). The sensors are located in a metal container at the bottom of the shafts and used for continuous measurement of water levels and infiltration capabilities of the shafts. The pressure sensor is made of stainless steel with protection IP 68 [1] and is connected with the control unit M4016 by a communication cable where the measured data is sent in a one minute interval while the data about the rainwater inflow is sent directly to the server.



**Fig. 4. The pressure sensor for measuring of the water level at the bottom of infiltration shaft**

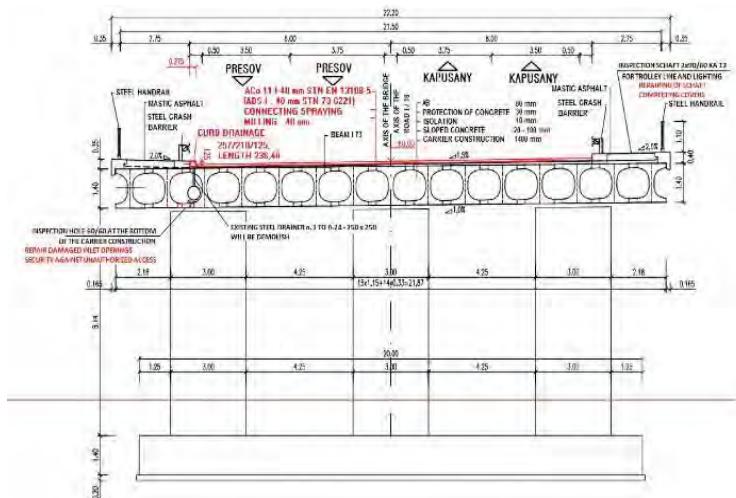
## 2.2 Experimental research in Prešov-city

The second experimental research of infiltration efficiency is located in Šarišské Lúky near Prešov city. The rainwater infiltration as a drainage solution is installed from a bridge road after its reconstruction [4]. The infiltration gallery from the infiltration units was designed in the monitored area by the means of theoretical calculation.

The bridge object (Figure 5) is located on the road 1/8 between Prešov and Kapušany. The approaching two-way road of the bridge contains 4 lanes. It is a bridge road over the railway track, the local road MK Sekcov and the road III/06815. The roadway of the bridge has one-sided slope 1,5% [4].

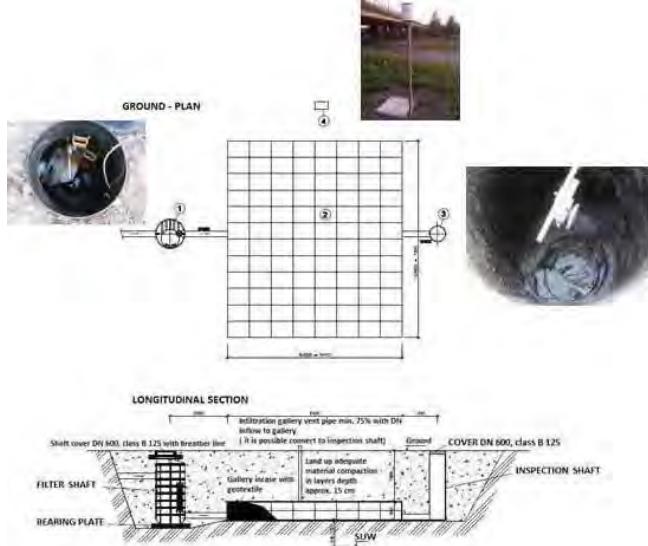
The existing bridge is made of pre stressed concrete units, type I 73 with a cross – section of 115/40, length of 30 and 36 m, 15 pieces per cross section. The per bridge length is 237.80 m, the width between the borders is 18.0 m [4].

The water from the bridge is drained with the use of water separators 250x500 into a chamber which is then emptied into the sewer system. There were 24 units of water separators located on the left side of the bridge and 2 units of water separators located on the right side next to the excessive support structures. During the reconstruction of the bridge, the existing water separators had been removed. The new water separators were embedded into the right side of the original places ending above the ground. The rainwater drainage was built on the left side by the line of the drain canals. There are four lines of drain canals on the bridge object with the outfalls for discharging rainwater pipes, next to the infiltration gallery.



**Fig. 5. Bridge object**

Figure 6 shows the location of measuring equipment and the objects of research. The rainwater from the bridge flows into a filter shaft (1), which captures and sediments coarse and fine impurities. The rainwater then flows into the infiltration gallery (2), where the water is filtered with the use of infiltration into the soil. The measuring devices for the volume of rainwater are the same like in the infiltration shaft in TU campus in Košice. A flow meter is located in the filter shaft and records the entering rainwater in l/s. The water level in the infiltration gallery can be monitored by the means of the float-gauge which is located in the inspection shaft (3). Near the infiltration gallery the rain-gauge (4) is located.



**Fig. 6. Infiltration gallery – situation [4]**

### 3. RESULTS AND DISCUSSION

#### 3.1 Experimental research in the campus of TU Košice-city

As has already been mentioned above, the most important parameter of the design not only for the infiltration shafts but generally for the infiltration facilities is to determine the infiltration coefficient  $k_f$  in the interest area.

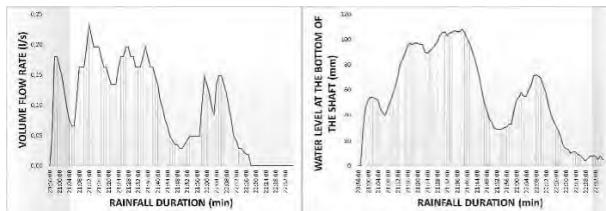
The morphology of the interest area is formed by alluvial plains of Hornád River. The surface of the site is formed of the anthropogenic sediments (fills). Under the layer, the fluvial sediments of Hornád River are located with the sediments of neogene age underneath [8].

The fills of the area of interest consist mostly of gravel clays, building waste and natural gravels. The exploratory bores were used to verify the thickness of these fills from 0.5 to 0.6 meters. Under the fills, the sediments of Hornád River were identified. Right under the backfill the continuous layer of clay with a thickness of 4.0 to 4.5 meters was identified. Under the flood sediments the fluvial gravel sediments of thickness 5.0 to 7.0 meters were identified and the gravels blended with fine-grained soil. The bottom layer consists of clay-gravel with a thickness of 0.7 to 2.7 m [8].

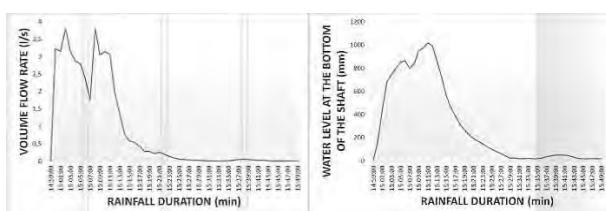
The validation of the hydrogeological survey of the site, respectively verification of the infiltration coefficient  $k_f$  of the soil in studied infiltration shafts near the PK6 building, was performed by taking the samples of soil from the bottom of the infiltration shafts. With the use of laboratory tests, the samples were evaluated as gravel blended with a fine-grained soil and infiltration coefficient set at  $10^{-3}$  m/s which confirms the hydrogeological survey of the site conducted for the object of Technicom in the campus of TU of Košice.

Figures 6-11 represent a typical process of flow rate and subsequent percolation of rainwater during the rainfall events in the percolation shafts [1]. Figures 6-11 show 3 selected rainfall events from the period of 2012 to 2014 with high rainfall intensity. All data from the research show that the total infiltration of runoff inflow into the infiltration shafts from the roof of PK6 building takes place at the same time within the duration of rainfall events, respectively very short-time after. This represents a high infiltration rate of these infiltration shafts determined by the coefficient of infiltration of soil at the bottom of the shaft  $k_f = 1.10^{-3}$  m/s.

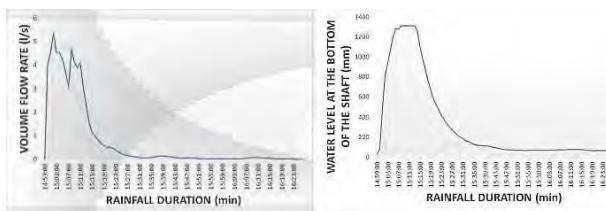
When we compared the size of infiltration area of runoff with other types of infiltration facilities (e.g. infiltration units), the size is several times smaller than other types of infiltration facilities. However, the infiltration coefficient of surveyed infiltration shafts  $k_f = 1.10^{-3}$  m/s ensures the percolation of rainwater in a required time and thus represents a safe disposal of surface runoff for PK6 object [11].



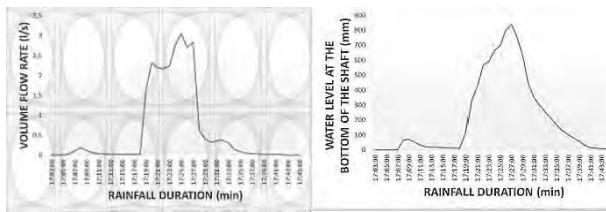
**Fig. 7. Volume flow rate and water level changes at the bottom of the shaft A on a rainfall of 24 April, 2012.**



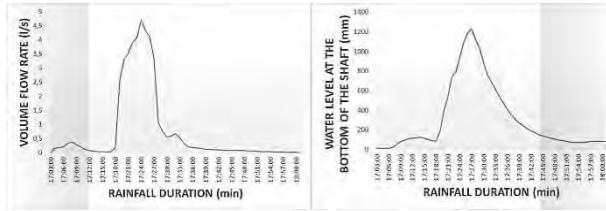
**Fig. 8 Volume flow rate and water level changes at the bottom of the shaft A on a rainfall of 30 July, 2013.**



**Fig. 9. Volume flow rate and water level changes at the bottom of the shaft B on a rainfall of 30 July, 2013.**

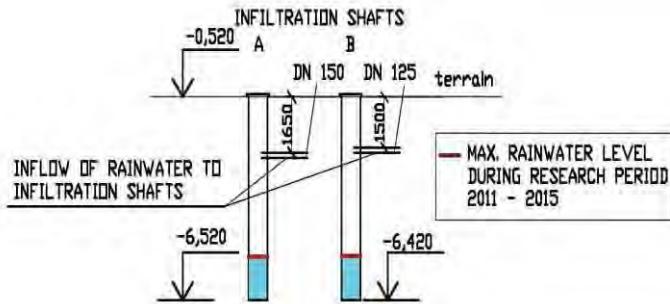


**Fig. 10. Volume flow rate and water level changes at the bottom of the shaft A on a rainfall of 10 June, 2014.**



**Fig. 11. Volume flow rate and water level changes at the bottom of the shaft B on a rainfall of 10 June, 2014.**

The maximum water level in the infiltration shaft A, measured during the research period of 2011-2014, was 1,28 m which is less than 1/3 of the filling depth of the infiltration shaft A. The maximum water level in the infiltration shaft B, measured during the research period was 1,31 m which is less than 1/3 of the filling depth of the infiltration shaft B, too (figure 12) [2].



**Fig. 12. Infiltration shaft and maximum water level during the research**

### 3.2 Experimental research in peripheral part of Prešov-city

The percolation gallery is formed of plastic units. The infiltration block is made from strong polypropylene [4].

The block parameters are  $0,60 \times 0,80 \times 0,33$  m (length x width x height). Each block may be embedded in more layers thus creating an infiltration gallery with a huge capacity on a smaller surface. Depending on a proposed conveyor duty and friction angle of surrounding soil, it is possible to put the modules into the depth of 7,10 m below the ground level. The percolation area of the infiltration gallery is  $46,08$  m $^2$ . Its surface is rectangular. The volume of rainwater draining into the infiltration gallery and the water level changes at its bottom was monitored with the use of devices in the filter shaft.

The design of infiltration facility did not consider the geological survey and the geological data was only estimated. In the design phase of the infiltration gallery, the infiltration coefficient was estimated by a designer as  $8,2 \cdot 10^{-5}$  m/s. The infiltration facility was designed according to the German standard DWA - A 138 [3] and all the parameters of the infiltration gallery were calculated with this infiltration rate which should ensure a sufficient and suitable percolation characteristics for this facility.

However, the results of laboratory test set the infiltration coefficient in the area of interest to  $4,84 \cdot 10^{-7}$  m/s! It means the infiltration efficiency to be about 100 times lower along with the lower accumulation volume of the infiltration gallery in contrast with the one designed for safe disposal of rainwater runoff. This results in the insufficient infiltration rate of the percolation gallery. The infiltration coefficient of  $4,84 \cdot 10^{-7}$  m/s represents practically impermeable type of soil not suitable for the infiltration facilities. Unfortunately, the inaccurate design caused flooding and silting of the infiltration gallery and resulted in the failure of installed devices for research – figure 13.

Table 1 contains measured data of rainwater volume flow rate respectively theoretical calculation of required time for infiltration only one rainfall event. The efficiency of infiltration gallery respectively time required for infiltration of rainwater inflow of one rainfall event in studied infiltration gallery would be ranges of hours respectively in days.

**Tab. 1 Calculated coefficients of hydraulic conductivity in Prešov [6]**

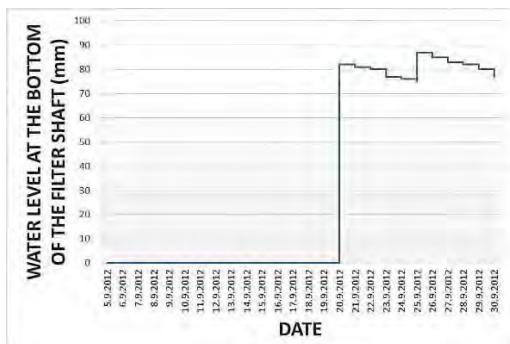
Date	Time from	Time to	Volume of rainwater [m $^3$ ]	Required time for infiltration [hour]
2 April, 2013				
4 April, 2013	22:52	3:46	1,72	28,9

1 February, 2013 28 February, 2013	1:48	22:35	6,99	668,3
30 January, 2013 31 January, 2013	3:00	23:51	1,27	44,8
15 January, 2013 16 January, 2013	11:10	14:51	3,15	27,6
15 December, 2012 19 December, 2012	18:56	16:30	1,4	93,2
1 November, 2012	10:40	23:02	0,12	12,3
19 September, 2012 20 September, 2012	19:49	15:51	3,07	20,03

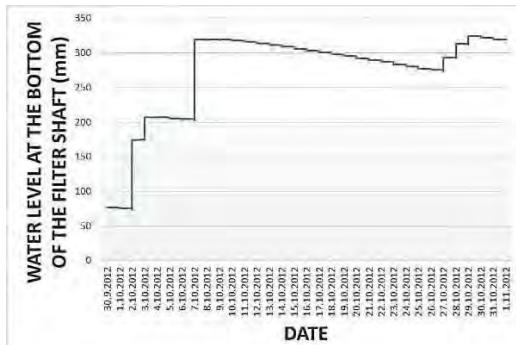


**Fig. 13. Flooded filter shaft with measurement devices**

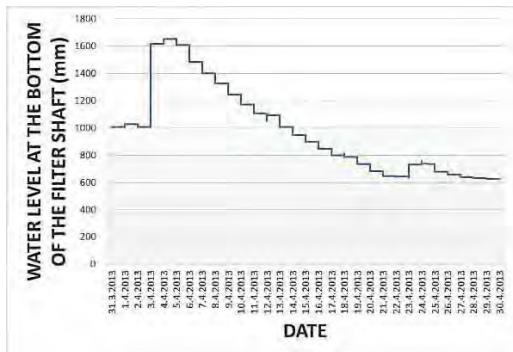
Figures 14-15 represent a starting point of measurements of rainwater percolation in the infiltration gallery, respectively the water level in the infiltration gallery. Figures 16-18 represent a typical process of rainwater percolation in the infiltration gallery, respectively the water level in the gallery during the month. The research data showed that there was a continuously high water level in the percolation gallery. This represents a very low infiltration rate of this infiltration gallery given by the coefficient of the infiltration of soil at the bottom of the gallery given as  $k_f = 4,84 \cdot 10^{-7} \text{ m/s}$  and it also means the overfill of the percolation gallery (figure 16-18).



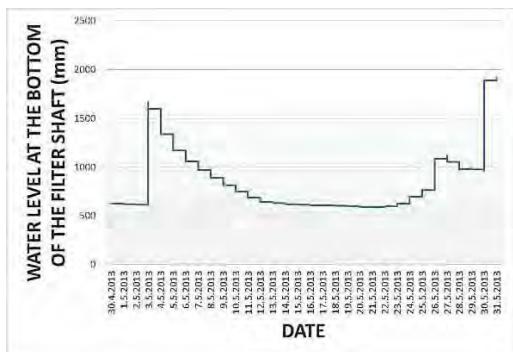
**Fig. 14. Water level changes at the bottom of filter shaft during September 2012**



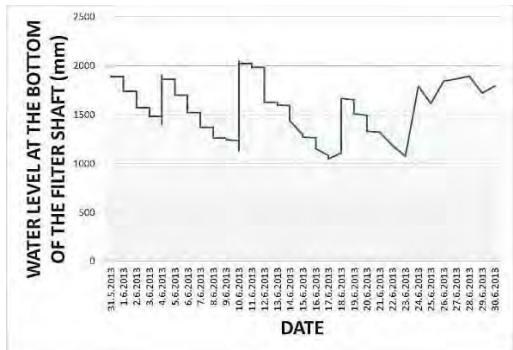
**Fig. 15. Water level changes at the bottom of filter shaft during October 2012**



**Fig. 16. Water level changes at the bottom of filter shaft during April 2013**



**Fig. 17. Water level changes at the bottom of filter shaft during May 2013**



**Fig. 18. Water level changes at the bottom of filter shaft during June 2013**

#### 4. CONCLUSION

The drainage system must ensure a safe disposal of the surface water without endangering the buildings and safety of people. The article presents the experimental measurements and evaluation of the infiltration efficiency in the real conditions and emphasizes the importance of hydrogeological survey. As apparent from the measurements the determination of the infiltration coefficient is the most important parameter for the infiltration facility design. In the first case, the infiltration shaft was tested. Despite the fact that the area for infiltration, respectively the size of the bottom of the shaft is only  $0,785 \text{ m}^2$ , the process of infiltration and operation of this facility is fluent and free from complications. Safe disposal of surface runoff is ensured by the infiltration coefficient  $k_f = 1.10^{-3} \text{ m/s}$ . In the second case, the infiltration gallery (made from plastic units) was tested. The percolation area of the infiltration gallery is  $46,08 \text{ m}^2$  which should guarantee a fluent operation according to the theoretical calculation. But with an incorrect determination (without hydrogeological survey) of the infiltration coefficient, the

functioning of runoff disposal is too low or in many cases insufficient resulting in the overflow of the infiltration facility.

The designers and planners of infiltration facilities need to take into account several aspects while designing. It is necessary to consider the hydrogeological conditions of the site of the design. The result of our research shows that with correct planning, design, realization and maintenance of the infiltration facilities, the operation of the device should be fluent and free from complications.

## ACKNOWLEDGEMENTS

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# How does your garden flow? The impact of domestic front gardens on urban flooding

D.A. Kelly\*

*The Water Academy, Heriot-Watt University, Edinburgh, UK.*

## ABSTRACT

**Aims:** To quantify rainwater runoff from domestic front gardens as a consequence of increased impervious surface area and climate change impacts, thus allowing the runoff contribution from both newly and previously covered front gardens to be assessed in terms of the overall urban flood burden.

**Study design:** Numerical simulation of the runoff from a typical front garden in response to simulated rainfall events for four UK cities (Edinburgh, Manchester, London, and Exeter).

**Methodology:** A typical front garden was simulated with varying areas of impermeable surface area (0%, 10%, 25%, 50%, 75%, and 100%) to represent observed trends in garden paving. Storm events representing current design and projected future rainfall intensities were applied to each of the four cities. The resultant runoff volumes were then quantified.

**Results:** Runoff is shown to be directly proportional to both the impermeable surface area and the rainfall intensity. Areas of impermeable paving can generate substantial volumes of runoff during a storm event which can contribute to localized flooding or add to the urban flood burden. Increased rainfall intensities and frequencies due to climate change are likely to increase runoff further.

**Conclusion:** Domestic front gardens play a vital role in managing surface water runoff in towns and cities. Growing trends of paving over front gardens put this role in jeopardy, while increasing rainfall intensities due to climate change make this role increasingly important. The quantification of domestic front garden runoff provides a mechanism for facilitating the protection, and enhancement, of this important asset in terms of water and urban flood management.

**Keywords:** Climate change, urbanisation, domestic gardens, impermeable surface, flooding

## 1. INTRODUCTION

Domestic gardens make up a significant proportion of our towns and cities. Recent studies in the UK have shown that they can contribute between 22%-36% of the total urban area [1,2] and up to 63% of urban green space [3]. Covering such a large area, domestic gardens play an important role in defining the urban environment: they help support biodiversity by providing food and shelter for wildlife [4]; they help conserve energy by giving shade and shelter to buildings [5]; they improve the urban microclimate by helping to mitigate the urban heat island effect [6]; and they benefit health and wellbeing by providing spaces for exercise and relaxation [7]. Domestic gardens also play an important role in the control of surface water flows by helping to minimize rainwater runoff from properties during storm events [8]. Planting and vegetation in gardens capture and retain rainwater while also helping it to infiltrate naturally into the soil [9].

However, the traditional front garden, characterized by flowerbeds and lawn, is being lost to the growing trend of replacing them with hard paving to provide off-street parking or low-maintenance gardens [10], see Figure 1.

\* Tel.: +44 (0)131 499 5111; fax: +44 (0)131 451 4617.

E-mail address: d.a.kelly@hw.ac.uk.



**Figure 1: Several front gardens completely covered with impermeable surfacing to provide off-street parking in a street in London (Google Street View ©, 2015)**

Whilst this may seem insignificant in terms of the size and scale of a single front garden, collectively this can represent large areas of towns and cities being covered with impermeable surfaces. A study of the London borough of Ealing found that two-thirds of front gardens are at least 50% covered with impermeable surfacing and 25% are completely covered [10]. Across the whole of London, it is estimated that the total area of impermeable surfacing in front gardens totals an area of 32 km<sup>2</sup> [11]. A study of residential areas of Edinburgh found that 56% of front gardens had been completely covered with impermeable surfacing [12]. At the regional level, a study by the Royal Horticultural Society [13] showed that a significant proportion of front gardens are at least three-quarters covered with impermeable surfacing: North East England (47%), Scotland (31%), and South-West England (30%), Eastern England (30%), East Midlands (25%), North-West England (25%), Yorkshire/Hull (24%), South East England (23%), West Midlands (21%), Wales (19%), and London (14%).

Paving over front gardens with impervious surfacing not only adds to the problem of urban densification, it also removes the ability of these gardens to naturally infiltrate rainwater. The consequence is increased runoff volumes, reduced runoff times, increased pollutant loading, and increased peak flows being directed to an already struggling urban drainage system.

Recognizing the implications of this incremental land change on urban flood risk, planning regulations covering garden paving have changed recently in the UK. In England and Wales, planning permission is now required for the installation of paving of more than 5m<sup>2</sup> unless permeable paving is used or the runoff is directed to a permeable area [14,15], while in Scotland, planning permission is required for the installation of any area of impermeable paving [16]. Whilst these changes aim to reduce further loss of front gardens to impermeable cover, they do not address those that have already been lost. Furthermore, given that domestic front gardens constitute such a significant component of the urban environment, and that so many of them have already been covered over, understanding the role of these spaces on the overall urban flood risk is becoming increasingly important, particularly given that rainfall intensities are likely to increase in the future due to the impacts of climate change.

While a growing number of studies have begun to assess flood risk at the urban scale, none have attempted to quantify the runoff from the individual front garden and its contribution to the collective urban drainage burden. It is at this level that information is needed in order to better inform homeowners, developers, policy makers, and legislators about the contribution of these spaces to urban flood risk and to enhance resistance and resilience to future floods. This research aims to investigate the potential impact of paved front gardens on flood risk under both current and future rainfall scenarios. A surface drainage model is used to assess runoff sensitivity to impermeable cover for a typical front garden located in four study cities in the UK (Edinburgh, Manchester, London and Exeter). The impact of climate change is assessed by applying projected change factors derived from future climate scenarios to current design rainfall intensities for each location.

## 2. METHODOLOGY

### 2.1 Study cities

Four cities were selected for the study: Edinburgh, Manchester, London, and Exeter as they are distributed widely across the UK and vary in size, location, and climate, see Table 1. Design rainfall intensities were selected from the relevant British Standard [21] to represent current rainfall conditions for each city based on recommended return periods of 1 in 5 and 1 in 50 year events with a duration of 5 min.

**Table 1: Characteristics of the four study cities**

City	Area (km <sup>2</sup> ) <sup>1</sup>	Domestic garden area (%) <sup>2</sup>	Domestic garden area (km <sup>2</sup> )	Front garden area (km <sup>2</sup> )	Annual rainfall (mm) <sup>3</sup>	Design rainfall intensity (mm/h) <sup>4</sup>	
						1 in 5 year	1 in 50 year
Edinburgh	264	11	29	10	670	58	86
Manchester	116	18	21	7	810	72	130
Greater London	1571	20	314	105	610	86	144
Exeter	48	16	8	3	760	72	130

<sup>1</sup>Administrative boundary of each city [17]

<sup>2</sup>Ratio of domestic gardens to urban area: Edinburgh [18], Manchester [19], London [11]. No data of garden area was available for Exeter, so an average of the other cities was taken.

<sup>3</sup>Annual rainfall statistics for each city [20]

<sup>4</sup>Design rainfall intensities for the 1 in 5 year and 1 in 50 year event [21]

To represent future climate change scenarios, the design rainfall intensities were multiplied by change factors derived by the UK Climate Projections 2009 (UKCP09) which provide estimates of future climate change for the UK across three greenhouse gas emission scenarios (Low, Medium, High) for different decadal time periods [22]. UKCP09 takes account of climate projection uncertainties by presenting the data as probabilistic estimates of future climate based on the strength of current evidence. A 10% probability indicates a change which is very likely to be exceeded, a 50% probability (known as the central estimate) indicates a change which is just as likely to be exceeded as not, and a 90% probability indicates a change which is very unlikely to be exceeded. For this study, the 50% probability was selected for the Low and High emissions scenarios to give a central estimate of change over the range of emissions scenarios. The 90% probability was also used, but for the High emissions scenario only, to represent the upper level of future rainfall change. Analysis was carried out for the 2050s and 2080s to give mid- to long-term comparisons with current conditions. Table 2 shows the rainfall change factors for each of the four cities for the selected climate change scenarios. The projected changes in rainfall, based on that of mean winter precipitation, can be seen to increase from north to south with Edinburgh having the smallest, yet still considerable, changes and Exeter having the largest.

**Table 2: Change in mean winter precipitation for selected time periods, emissions scenarios, and probability levels (adapted from UKCP09)**

Scenario	Change in mean winter precipitation (%)						
	Time Period	Emission scenario	Probability Level	Edinburgh	Manchester	London	Exeter
2050	Low	50%	+6	+8	+12	+12	
	High	50%	+10	+13	+16	+18	
	High	90%	+20	+27	+35	+41	
2080	Low	50%	+11	+15	+16	+19	
	High	50%	+19	+26	+26	+31	
	High	90%	+36	+50	+58	+73	

## 2.2 Typical front garden

Studies of gardens in UK cities have found the average garden size to be between 151-155m<sup>2</sup>, and that front gardens are, generally, half the size of rear gardens [23,24]. In this study, a garden size of 150m<sup>2</sup> is assumed, giving a typical front garden size of 50m<sup>2</sup>. Different areas of impermeable surfacing were applied to the typical front garden based on the extent of garden paving already observed to have occurred in the UK, as discussed in Section 1. The impervious areas studied were: 0%, 10%, 25%, 50%, 75%, and 100%.

## 2.3 Garden runoff model

The runoff generated from the typical front garden was simulated using a previously developed property-level drainage model [25]. The model has capability to simulate the flow conditions of the entire property drainage system (including roof, surface, and local drainage) however, only the surface drainage module was used in this study in order to focus on front garden runoff. The surface drainage module assesses rainwater runoff by using a simple volumetric approach based on the area drained, surface type (permeable/impermeable), and rainfall intensity. The basic effect of permeable surfaces is calculated using the Horton infiltration approach [26], which calculates the quantity of rainwater that infiltrates into the soil rather than running off onto the street, thus:

$$f_t = f_c + (f_o - f_c)e^{-kt} \quad (1)$$

where  $f_t$  is the infiltration rate at time  $t$ ;  $f_o$  is the initial (maximum) infiltration rate;  $f_c$  is the final infiltration rate; and  $k$  is a constant based on soil type. The model was used to simulate the runoff from the typical front garden in each of the four study cities, under current and future rainfall intensities, and for each of the areas of impermeable cover.

## 2.4 Assumptions and limitations

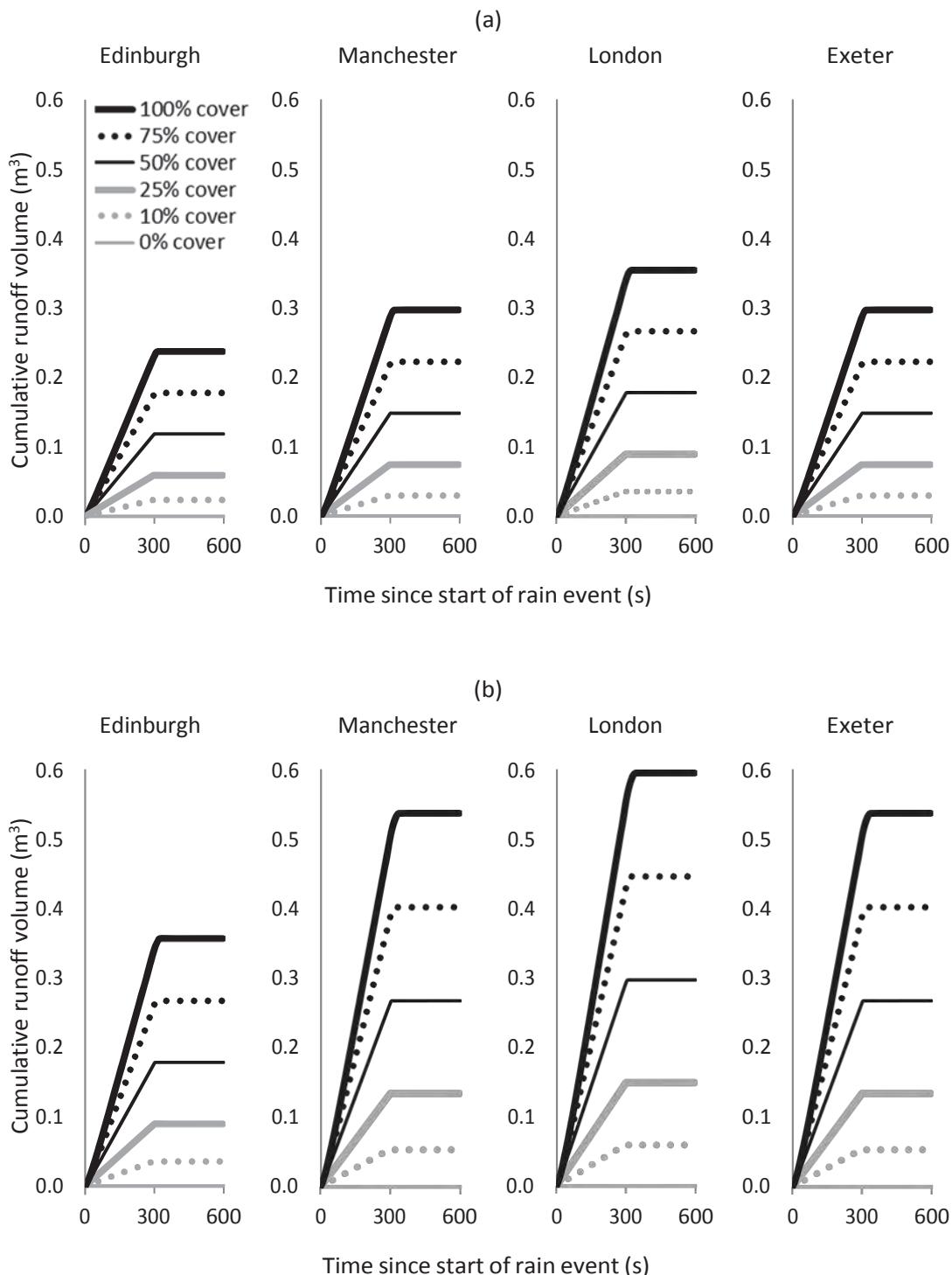
A coarse, well-drained soil with a high infiltration rate was assumed for all permeable surfaces. Areas with finer soils, such clay, could experience higher runoff rates than those discussed in this study due their significantly lower infiltration rates. Antecedent moisture conditions of the soil were not considered in this study. Saturated soils would produce higher runoff rates, as would compacted soils. All runoff was assumed to flow away from the garden and not to any adjacent permeable surface, therefore, assuming maximum runoff conditions.

## 3. RESULTS AND DISCUSSION

### 3.1 Current runoff

In each of the four study cities, the typical front garden with no impermeable paving was found to produce no runoff in response to both the 1 in 5 year and 1 in 50 year events. The addition of even small areas of impermeable paving was found to generate rainfall runoff, see Figure 2. The typical front garden in London generated higher runoff volumes than those in the other three cities due to the higher design rainfall intensities applicable to the south-east (see Table 1). Manchester and Exeter (both located in the west) have the same design rainfall intensities and so typical front gardens in those two cities produce runoff volumes of the same amount. Interestingly, the current 1 in 5 year event in London is equivalent to the 1 in 50 year event in Edinburgh.

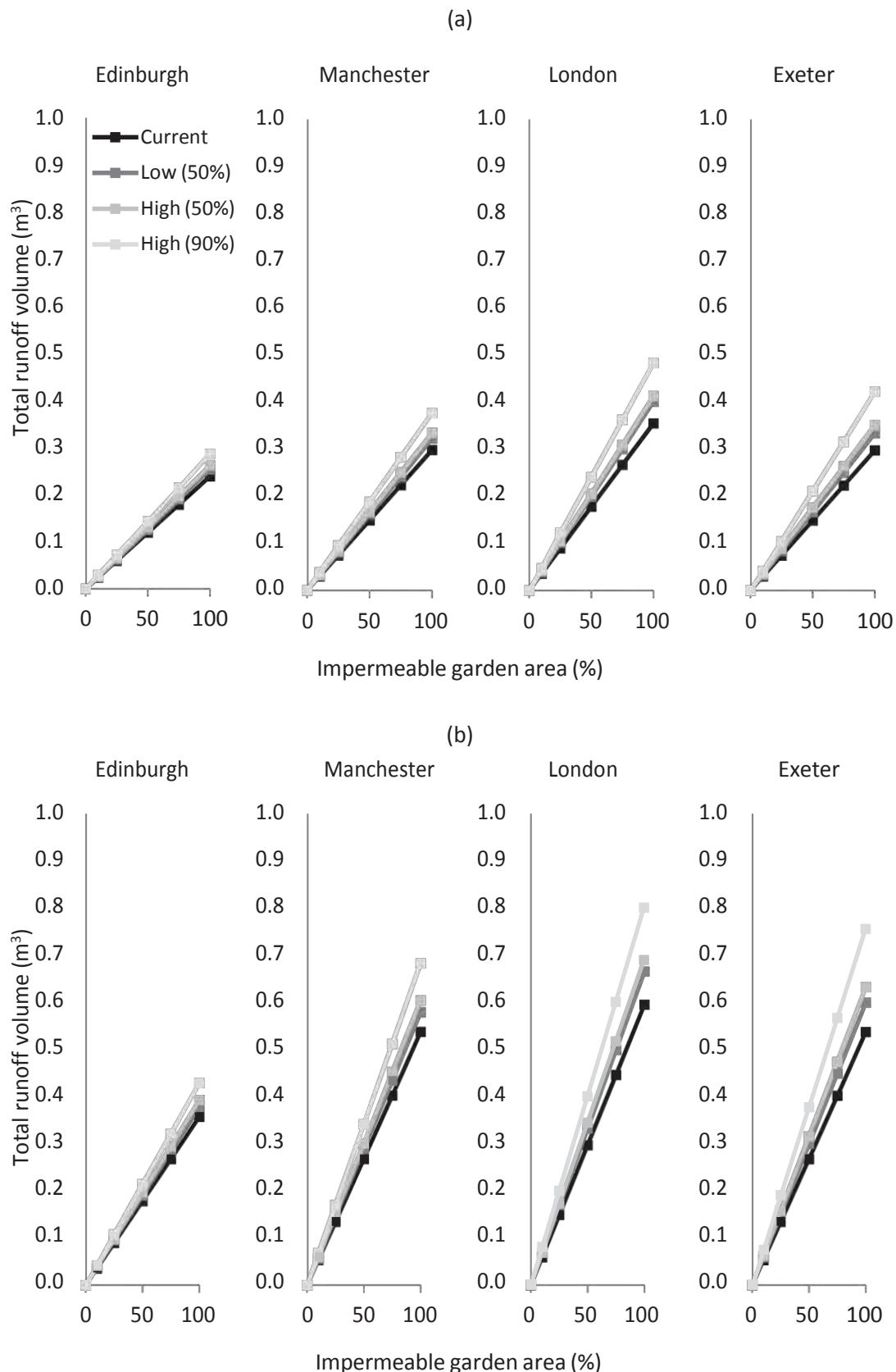
As would be expected, the runoff volume is directly proportional to the area of impermeable cover and rainfall intensity. Taking London as an example, a typical front garden which has 50% impermeable cover generates a runoff volume of 0.297 m<sup>3</sup> (49.5% runoff) during a 1 in 50 year event, while this increases to 0.595 m<sup>3</sup> (99.2% runoff) for a garden with 100% impermeable cover. Across each city, the collective runoff from front gardens can be estimated by extrapolating the runoff volumes in Figure 2 with the cumulative area of front gardens in each city. Accounting for the front gardens with at least three-quarters impermeable cover only [13] (between 75%-100% covered), the total runoff from these gardens is estimated at between: 16-22,000 m<sup>3</sup> in Edinburgh; 14-19,000 m<sup>3</sup> in Manchester; 132-176,000 m<sup>3</sup> in London; and 6-9,000 m<sup>3</sup> in Exeter during the 1 in 50 year design event. While the runoff volume for London is very large due to the size and scale of the city, the contribution to surface runoff from front gardens in each city is substantial.



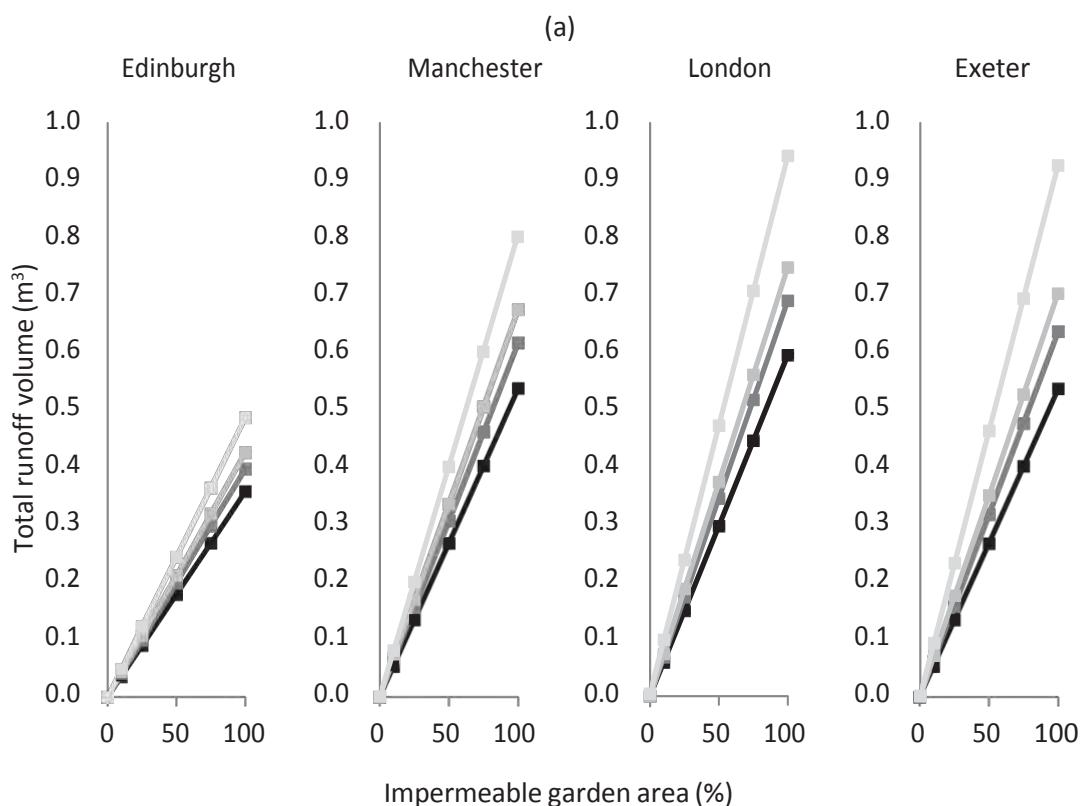
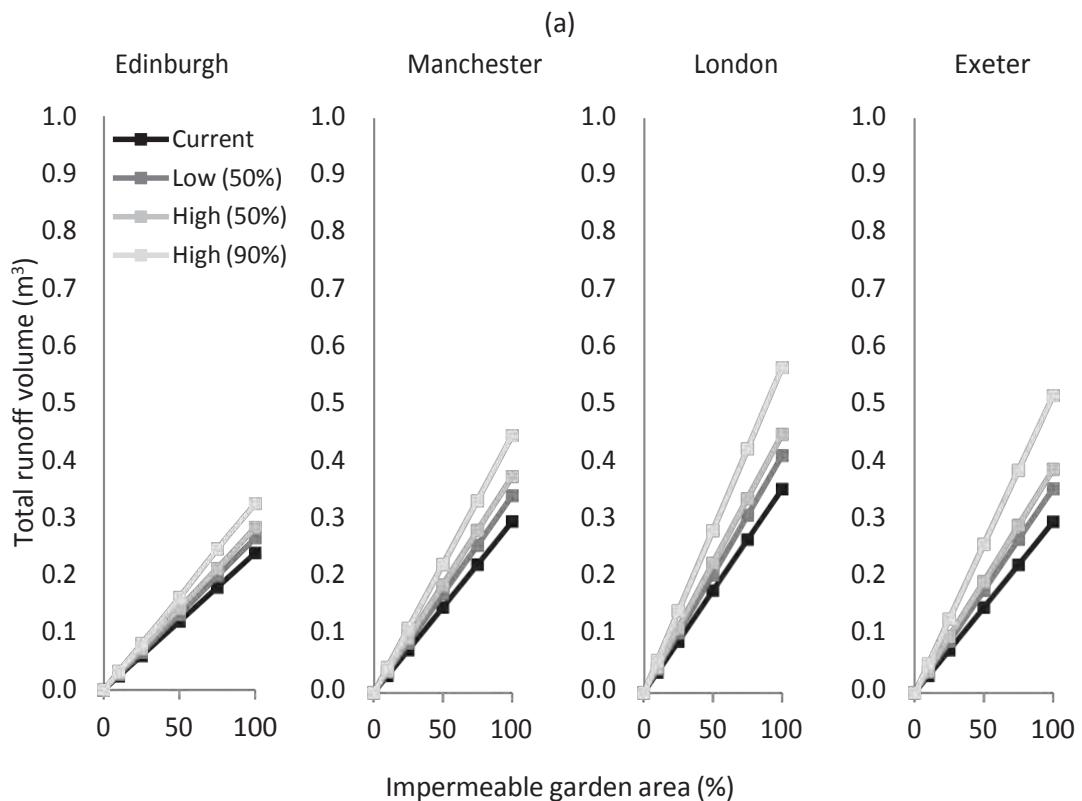
**Figure 2: Variation in cumulative runoff volume with impermeable coverage for rainfall return periods of: (a) 1 in 5 years, and (b) 1 in 50 years**

### 3.2 Future runoff

Figures 3 and 4 show the total runoff modelled for each impermeable garden area for the 2050s and 2080s, respectively, based on the projected rainfall change factors in Table 2. As would be expected, the increased rainfall intensities projected to occur due to climate change have the effect of increasing runoff from the typical front garden in each city.



**Figure 3: Variations in total runoff volume with impermeable garden area and future climate scenario for the 2050s, based on (a) 1 in 5 year return period, and (b) 1 in 50 year return period**



**Figure 4: Variations in total runoff volume with impermeable garden area and future climate scenario for the 2080s, based on (a) 1 in 5 year return period, and (b) 1 in 50 year return period**

Edinburgh is expected to see increased rainfall of up to +20% by the 2050s and +36% by the 2080s. Whilst these are the smallest changes for any of the study cities, they are still significant and could cause the runoff from a typical front garden with 100% impermeable cover to increase from 0.357 m<sup>3</sup> to 0.485 m<sup>3</sup> by the 2080s based on the current 1 in 50 year event. Exeter is projected to experience the largest increase in future rainfall; increasing up to +36% by the 2050s and up to +73% by the 2080s. The modelled runoff from paved front gardens in Exeter, therefore, saw the greatest increase of any of the four study cities: for the 100% impermeable front garden, runoff increased from a current 0.537 m<sup>3</sup> to 0.756 m<sup>3</sup> by the 2050s and further to 0.926 m<sup>3</sup> by the 2080s based on the current 1 in 50 year event. Runoff from the same front garden in London would only be slightly higher at 0.943 m<sup>3</sup> by the 2080s.

Increased future rainfall intensities will see a dramatic increase in the collective contribution of paved front gardens to the overall surface runoff volume across each of the four study cities. Again, considering only those front gardens which are at least three-quarters paved, the collective runoff by the 2080s is estimated to increase by 6-7,000 m<sup>3</sup> in Edinburgh to between 22-29,000 m<sup>3</sup>, by 7-9,000 m<sup>3</sup> in Manchester to 21-28,000 m<sup>3</sup>, by 77-102,000 m<sup>3</sup> in London to 209-278,000 m<sup>3</sup>, and by 5-6,000 m<sup>3</sup> in Exeter to 11-15,000 m<sup>3</sup> based on the 1 in 50 year event. It is highly likely that existing urban drainage systems will be inadequate to cope with this level of increased runoff from paved front gardens. With runoff from all impermeable surfaces, including paved front gardens, likely to increase in future, the risk of urban flooding is bound to increase also unless substantial efforts are made to minimize runoff.

With this in mind, it can be seen from Figures 3 and 4, that each simulated future rainfall event was completely infiltrated by the typical front garden which had no impermeable paving. While this result is based on the garden having coarse and well-drained soil and does not account for antecedent moisture conditions, it clearly emphasizes the role of the domestic garden in helping to control surface water flows in urban areas, which will become increasing important in the future. In light of this, there is a clear argument for encouraging homeowners to "de-pave" front gardens which are already paved over in order to enhance the overall community resilience to both current and future urban flood risk. However, a recent study of properties in Edinburgh found that just 2% of homeowners were considering removing their impermeable driveway and reinstating a garden [12]. The same study suggests that legislation, education, and incentivisation schemes are needed to reclaim the front garden.

While planning regulations have recently changed to minimize further loss of front gardens to impermeable cover, these regulations need to be enforced effectively so that impermeable paving of front gardens is stopped. Furthermore, the regulations in England and Wales should be brought in line with those in Scotland which require planning permission for any area of impermeable paving, rather than for areas over 5 m<sup>2</sup> only. However, no legislation currently exists to target the many gardens across the country that are already covered over.

Educating homeowners about the valuable role that front gardens play in the urban landscape, in terms of biodiversity and environmental enhancement, and providing them with practical advice and guidance on the design and installation of permeable alternatives would help to raise awareness. Some initiatives, such as the Royal Horticultural Society's *Gardens Matter* series [13] and the London Wildlife Trusts' *Living with Rainwater* [26], are already attempting to address this, however, more work is needed. Making homeowners aware of the financial implications of paved gardens could also act as a strong driver for change. There is already evidence that house prices could reduce once the majority of front gardens on a street have been paved over as the streetscape becomes less attractive to prospective buyers [11]. In addition, the increased risk of urban flooding due to additional runoff from paved front gardens, particularly in light of future climate change impacts, could affect household water and sewerage bills.

Incentives for homeowners, such as grants or providing access to free help and advice, could also be used to encourage homeowners to de-pave. Lambeth Council in London provides help in planning de-paving projects as well as tools and compost to carry out the work, however, schemes like this are rare [27]. Financial penalties for paved front gardens, such as increased council tax bills, could also be used as an incentive to de-pave.

## **4. CONCLUSION**

Domestic front gardens make up a significant proportion of the urban environment and as such they play a vital role in the control of surface water by intercepting and infiltrating rainfall. While the importance of domestic front gardens on flood alleviation is already recognized, until now there has been no measure of the contribution of individual front gardens to both the localized and overall urban flood burden. The aim of this research was to provide quantifiable data of front garden runoff volumes so that homeowners, developers, policy makers, and legislators could be better informed about the contribution of these spaces to urban flood risk.

The quantification of runoff from paved front gardens emphasizes the need for them to be considered as a key component in the overall urban water and flood management strategy. This study has shown that while paved gardens pose a significant risk to urban flooding, those that retain the permeable qualities of the traditional garden could provide a positive asset for surface water management, particularly in light of the challenges posed by climate change, by helping to attenuate and manage surface water runoff in urban environments.

Importantly, this study has demonstrated that runoff from front gardens varies greatly with respect to geographical location (due to differences in localised rainfall intensities and projected climate change impacts) and as such, can help to identify areas most at risk both currently and under future climate scenarios. Since future rainfall is projected to increase across the UK, it will be necessary to reduce runoff from every building, new or existing. Homeowners need to be provided with the relevant information and incentives for retaining or reinstating their front garden for the overall societal benefits that this would achieve in terms of flood resistance and resilience.

## **ACKNOWLEDGEMENTS**

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# Financial comparison of the installation costs of retrofit flood alleviation methods that do and do not require power for operation

C J Newton<sup>1,2\*</sup>, F A Memon<sup>1</sup>, D S Jarman<sup>2</sup>, R Y G Andoh<sup>2</sup>, D Butler<sup>1</sup>

<sup>1</sup>Centre for Water Systems, University of Exeter, North Park Road, Exeter. EX4 4QF.

<sup>2</sup>Hydro International, Clevedon Hall Estate, Victoria Road, Clevedon. BS21 7RD.

## ABSTRACT

**Aims:** The aim of this work was to compare the installation costs of multiple flood alleviation methods that do or do not require power for operation. The work also aims to determine whether the installation of passive flow controls into existing sewer systems is more cost efficient than other industry used methods and whether the same flood alleviation method is the most cost effective across the range of flood resistance levels achieved.

**Methodology:** The work compared the costs of flood alleviation methods from two sources (a flow control positioning method and an UK industry report). Four sewer system models were analysed using the flow control positioning method and the four alternative flood alleviation schemes.

**Results:** In all four case studies, the comparison showed that the installation of passive flow controls was a cheaper solution than either of the four methods from the industry report.

**Conclusion:** In conclusion, this work has demonstrated theoretically that passive flow controls are, on average, 60% cheaper to install than more conventional flood alleviation schemes used in the UK water sector. The passive flow control solutions are also cheaper to operate as they do not require electrical energy for operation over their lifespan.

*Keywords:* Cost comparison, flood resistance, retrofit designs, vortex flow controls

## 1. INTRODUCTION

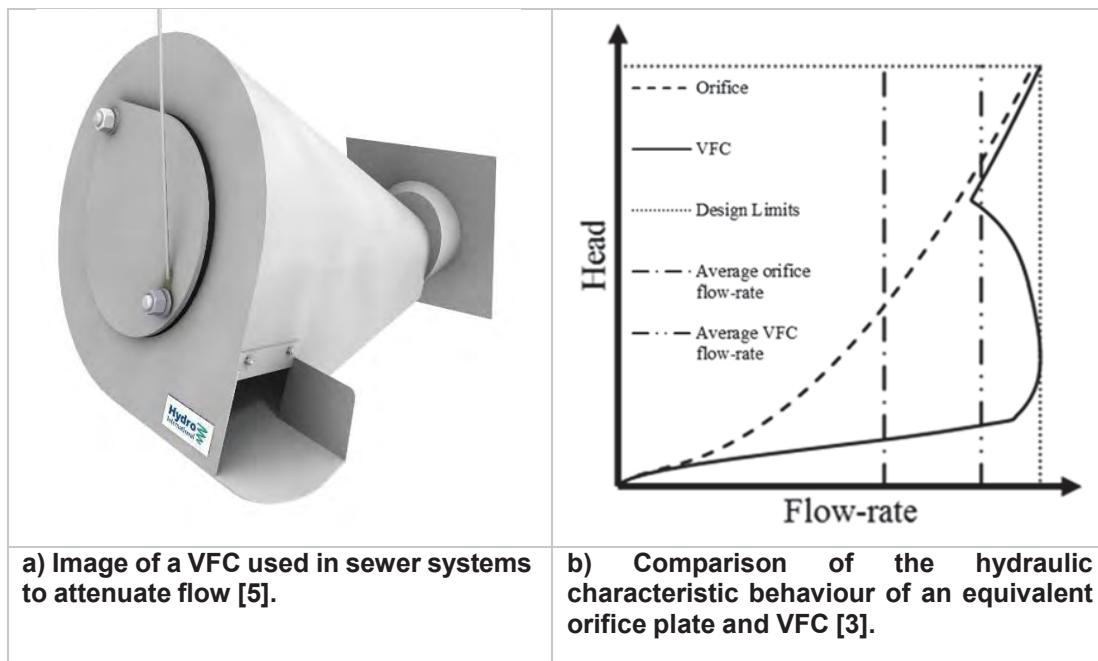
When drainage and sewer systems become stressed, from climate change, population growth and urbanisation, there is a need for retrofit designs to be implemented to prevent undesirable flooding or pollution incidents. There is a wide range of solutions that can be employed [1]. Babtie Ltd & Ofwat investigated the costs of installing retrofit flood alleviation schemes via a data collection and statistical analysis exercise with 10 of the UK sewerage companies. The types of solutions that can be installed, and as categorised in the report, involve: storage; pumping stations; flow diversion; and aboveground flow attenuation, Table 1. These solutions can be expensive to construct (land uptake and excavations) and may require a constant supply of electricity/power to operate.

An alternative solution is to install strategically positioned and designed passive flow controls [2,3]. There are a number of passive flow controls that can be employed (orifice plates and vortex flow controls, VFCs (Fig. 1a), for example). The flow controls attenuate potential flood volumes in the unused capacity of the sewer systems without the need for additional large construction activities as the sewer system is already constructed. As the flow controls are passive, they do not require a constant power supply and, therefore, there are no direct operation costs. VFCs tend to have an improved hydraulic behaviour, as the use of VFCs can

\* Tel.: +00 44 1275 337 928; fax: +00 44 1275 874 979.

E-mail address: cjn202@exeter.ac.uk.

reduce the size of the attenuation storage volume [4]. This is due to VFCs allowing a greater volume of water downstream at lower head levels, Fig. 1b. VFCs also present a reduced risk of blockage compared to orifice plates as VFCs have a larger outlet diameter for the same design flow-rate. The positioning and design of the passive flow controls can be completed using a flow control positioning method [3]. The flow control positioning method provides the user with a range of retrofit sewer system designs with varying costs and changing levels of flood risk. From these outputs, the user can select the most appropriate solution depending on their desired flood risk target and financial constraints.



**Fig. 1. a) Image of a typical VFC and b) a comparison of the hydraulic characteristics of an orifice plate and VFC designed for the same design flow-rate and head level.**

It should be noted that, in the Babtie Ltd & Ofwat report, one of the flood alleviation categories is named 'flow attenuation'. In the flow attenuation category, the flood alleviation solutions considered look at solely adding storage to the sewer system to reduce the risk of flooding. This should not be confused with the flow control positioning method that selects the locations to install flow controls to attenuate potential flood volumes within existing storage capacities.

In this paper, four case studies are discussed in which the theoretical construction costs of flood alleviation schemes have been compared. The comparison aims to deduce whether non powered flood alleviation schemes could also be cheaper to install than other power requiring alternatives, as well as, having cheaper operational costs as no power is required. The final aim is to investigate which flood alleviation method is more cost effective over the achievable range of flood risk levels. Two previous case studies from literature have also been compared to the four new case studies [2]. The novelty of this work is the theoretical comparison of the multiple flood alleviation schemes from the Babtie Ltd and Ofwat report and the positioning of flow controls within the sewer system. Previous literature has discussed cost comparison estimates but only made comparisons to a limited range of alternative solutions [2,6,7]. The literature found that installing passive flow controls into sewer systems, with additional storage where necessary, was a cheaper solution to conventional drainage solutions.

The flood alleviation method entitled 'New pumping station' was not considered in this analysis following the recommendation from the Babtie Ltd & Ofwat report [1]. The author of the report determined there was insufficient data to "give a reliable indication" of the costs (15 schemes from 10 sewerage companies) and that the installation of pumping stations should be re-categorised into other solutions as appropriate.

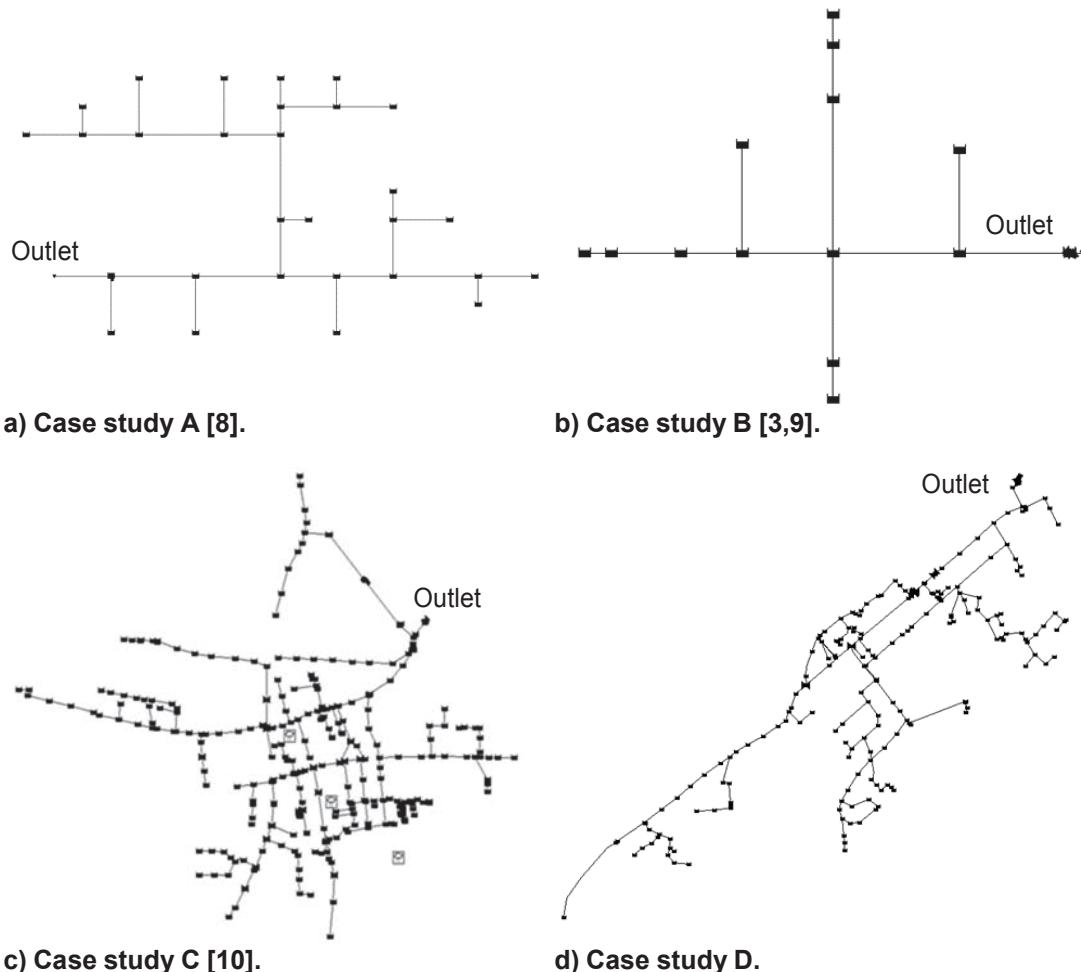
**Table 1. Summary of compared flood alleviation methods and whether the method requires energy to operate [1,3].**

Flood alleviation schemes	Possible solutions.	Power required?
Flow control positioning method	VFCs and orifice plates	No
Flow attenuation by increasing storage	Storage tanks, above ground infiltration, detention ponds and water butts.	No
Sewer Upsizing	Storage, sewer upsizing and possible pumping station.	Possibly
Manage flow	Pumping station or combined sewer overflow.	Possibly
Isolate from the system	Non-return valve or pumping station.	Possibly
New pumping station	Pumping station.	Yes

## 2. CASE STUDIES

In this work, four anonymised case studies are presented, case study A, B, C and D, Fig. 2 and Table 2. The four case studies range in size and complexity. Case studies A [8] and B [3,9] are the simplest of the four case studies with 29 and 14 nodes respectively, Fig. 2a and b. Case studies A and B are both stormwater sewer systems and do not contain a dry weather flow profile. Their respective discharge consents are 200 l/s and 13.2 l/s. Case studies C [10] and D, on the other hand, are combined sewer systems and contain diurnal dry weather flow profiles for an approximate population of 1,300 and 1,850 respectively, Fig. 2c and d. Case study C contains 281 nodes and has a discharge consent of 30 l/s. Case study D contains 211 nodes and has a discharge consent of 22 l/s. All of the four case studies presented are presumed to be located in the UK.

Within Table 2, two additional case studies are described from existing literature, Wadley Road and Evanston [2]. Wadley Road is a case study of a stormwater sewer system located in the Southeast of England. The flooding of four houses occurred annually due to the downstream section of sewer not being able to convey the required volumes of collected surface run-off. Instead of constructing a new bypass sewer, estimated to cost between £90,000 and £100,000, nine VFCs were strategically positioned within the sewer system to attenuate the potential flood volumes in the upstream sections of the system. This solution, positioning VFCs, cost £24,000. The case study of the city of Evanston, Illinois, was regarding a combined sewer system unlike Wadley Road. The residents of Evanston experienced frequent sewer backups caused by over population. Using traditional solutions, it was estimated that the solution would cost \$290 million to increase the capacity of the sewer system to a suitable level requiring construction in 90% of the city. A traditional solution was deemed unviable. An alternative solution of separating the sewer system and using VFCs to control the flow of surface run-off into the combined sewer system was proposed and estimated to cost \$143 million.



**Fig. 2. Schematics of the additional four case study sewer systems analysed**

**Table 2. Descriptions of the four anonymised case studies analysed in this paper and two comparative case studies from literature.**

	Wadley Road*	Evanston*	A	B	C	D
Catchment area (ha)	20	-	14.5	1.5	46.9	15.5
Presumed location	SE (UK)	Illinois (USA)	SW (UK)	SW (UK)	SE (UK)	Scotland (UK)
Approximate population	-	75,000	-	-	1,300	1,850
Number of nodes	-	-	29	14	281	206
Number of pipes	-	-	29	14	285	213
Discharge consent (l/s)	250	-	200	13.2	30	22
Average slope (%)	-	-	0.04	0.02	1.39	2.90

\* Taken from Andoh [2], SW = Southwest, SE = Southeast.

### **3. METHODOLOGY**

In the case studies the estimated costs of implementing a design solution generated from the flow control positioning method [3] and the flood alleviation methods discussed by Babtie Ltd & Ofwat [1] are compared theoretically. Each of the flood alleviation schemes were initially designed to achieve the same flood resistance level as the flow control positioning method solution to which they were compared. The maximum flood resistance level to be achieved in each case study was determined by the outputs from the flow control positioning method (presented in Fig. 3 in the Results section). The term flood resistance refers to the highest return period of rainfall, quantified as 1 in 'x' years, which does not cause the sewer system to behave beyond its design parameters [3]. This includes: physical failure; surface water flooding; and breach of the sewer system's discharge consent.

The four anonymised case studies are also compared to two past case studies that had already been implemented (Wadley Road and Evanston) [2]. In those case studies older generation VFCs were found to provide a more cost beneficial solution to reduce the frequency of flooding. The Wadley Road case study involved positioning nine flow controls into the upstream sections of the existing sewer system to prevent the annual flooding of four dwellings. To the authors' knowledge, the four dwellings have not flooded since the flow controls installation. The Evanston case study involved the installation of flow controls, as inlet restrictors, to prevent the overloading of the combined sewer system from the newly installed separate stormwater system. Excess surface runoff was attenuated within the stormwater sewer system and in aboveground highway gullies.

There are five different flood alleviation methods discussed in this paper, Table 1, and two different methods of estimating the costs of installing the flood alleviation schemes. Section 3.1 discusses the costs calculated from the author's flow control positioning method and Section 3.2 discusses the costs calculated from the Babtie Ltd & Ofwat report. Inflation was not accounted for in either costing method for the comparison of the flood alleviation methods' costs.

All of the flow control positioning method solutions were designed following the specifications in the UK 'Sewers for Adoption' and the minimum flow control outlet diameter was set at 100mm [11].

#### **3.1 Cost calculations from flow control positioning method**

As a requirement of the flow control positioning method, the costs of installing the proposed flow controls is estimated [3]. The costs presented in this paper for the flow control positioning method includes:

1. The cost of the flow controls,
2. Cost of installing the flow controls depending on their physical geometry compared to the geometry of the manhole chamber,
3. Cost of increasing the size of the manhole chamber if required, and
4. An estimated consultancy fee of an additional 20% of the flow control and installation cost, Table 3.

Different costs for installing the flow controls are included depending on the physical geometry of the flow control and whether the flow control can be lowered through the manhole cover. The installation costs of the flow controls, Table 3, were estimated by the author using rates and prices from Spon's *Civil Engineering and Highway Works Price Book* [11]. The costs of the flow controls, orifice plates and VFCs, were supplied by a flow control manufacturer.

#### **3.2 Cost calculations from Babtie Ltd & Ofwat**

The costs for the remaining four flood alleviation methods are presented as the cost per property flooded, Table 4 [1]. For the purposes of this study, the mean average cost per property to install the flood alleviation method was used. As a reminder, the flow attenuation solutions presented in this report only increase the storage capacity of the sewer system and do not

include installing flow controls. To calculate the number of properties that would have been flooded, the following steps were followed for case studies A to D.

1. Determine greatest rainfall return period to use from the outputs of the flow control positioning method.
2. Simulate the sewer system model using a critical input hyetograph [13] with the determined return period.
3. Calculate the flooded area from the simulation assuming the flooded volume has an inverted conical geometry. The slope of the lateral surface of the cone is taken to be equal to the subcatchment slope of the nearest subcatchment in the sewer system model.
4. Estimate the number of properties flooded assuming a property area of 264.5 m<sup>2</sup> [14]. The property area includes an estimated additional 25% for pavement and highway in front of the property.
5. Calculate the cost of installing each flood alleviation scheme for each case study, Table 4.

**Table 3. Summary of costs accounted for in the flow control positioning method. The installation costs were estimated using Spon's Civil Engineering and Highway Works Price Book [12].**

Costs from flow control positioning method	Cost (£)
Costs of flow controls (VFCs and orifice plates)	Provided by the VFC manufacturer
Estimated consultancy fee	+20% of the final cost
Cost of installing flow control through manhole	3,500
Cost of installing flow control by removing chamber lid	13,000
Cost of replacing chamber with a larger chamber.	22,000

**Table 4. Summary of costs per property for each flood alleviation method [1].**

Flood alleviation method	Mean average cost per property (£)
Flow attenuation by increasing storage	58,000
Sewer Upsizing	48,000
Manage flow	32,000
Isolate from the system	18,000

#### 4. RESULTS AND DISCUSSION

The costs of installing the different flood alleviation methods on the four case studies are presented, Table 5. Overall, the table shows that positioning passive flow controls had a cheaper construction cost in all four of the case studies (A, B, C and D).

In case study A, it was found that the installation passive flow controls was cheaper than installing any of the alternative flood alleviation schemes. The solution using VFCs required the

installation of eight flow controls and achieved a maximum flood resistance level of 1 in 28 years. Due to the size of the flow controls, all of the lids of the manhole chambers had to be lifted to install the flow controls. The solution was 56% cheaper compared to the cheapest Babtie Ltd & Ofwat solution named 'isolate from the system', which required the installation of non-return valves and pumping stations, Table 1.

Installing passive flow controls was also more beneficial in case study B, where it was found that installing VFCs was 89% cheaper than the next cheapest solution (isolate from the system solution). In case study B, two VFCs were required to achieve the maximum flood resistance level of 1 in 108 years. Both of the VFCs were able to be installed through the lid of the manhole chamber. VFCs were more beneficial than orifice plates in this case as the flow-rates in the pipes were lower and orifice plates were not able to attenuate the flow without breaching the 100mm flow control outlet limit as set in 'Sewers for Adoption' [11].

In case study C, it was found that installing VFCs in the sewer system would be more cost effective than implementing any of the Babtie Ltd & Ofwat flood alleviation schemes (cheaper by £17,500, 10%). Case study C required the installation of 21 VFCs to achieve the maximum flood resistance level of 1 in 71 years). Six manhole chamber lids required removing to install the flow controls into the sewer system. As in case study B, the positioning of orifice plates within the sewer system did not provide an increase in the flood resistance level as the orifice plates could not attenuate the required volumes of water.

**Table 5. Comparison of flood alleviation scheme costs for the four case study sewer systems each achieving the maximum respective flood resistance level as achieved by the flow control positioning method. The cheapest flood alleviation method overall is highlighted.**

Flood Alleviation Method	Costs to install flood alleviation methods on each case study (£)					
	Wadley Road*	Evanston*	A	B	C	D
Number of properties flooded	-	-	21	7	10	2
Flow control positioning method (VFCs)	24,000	143 M	170,500	13,250	162,500	6,500
Flow attenuation by increasing storage	-	-	1,218,000	406,000	580,000	116,000
Sewer Upsizing	-	290 M	1,008,000	336,000	480,000	96,000
Manage flow	90,000	-	670,000	224,000	320,000	64,000
Isolate from the system	-	-	378,000	126,000	180,000	36,000
Percentage difference to cheapest scheme	-73%	-51%	-56%	-89%	-10%	-82%

\* Taken from Andoh [2] and does not use the flow control positioning method [3] or Babtie Ltd & Ofwat [1] calculations.

Case study D followed a similar pattern to case study B, installing passive flow controls was also the cheapest solution compared to the 'isolate from the system' method by £29,500 (82%). Installing the VFCs into case study D achieved a maximum flood resistance level of 1 in 3 years. One VFC were installed and the manhole chamber lid was not required to be lifted.

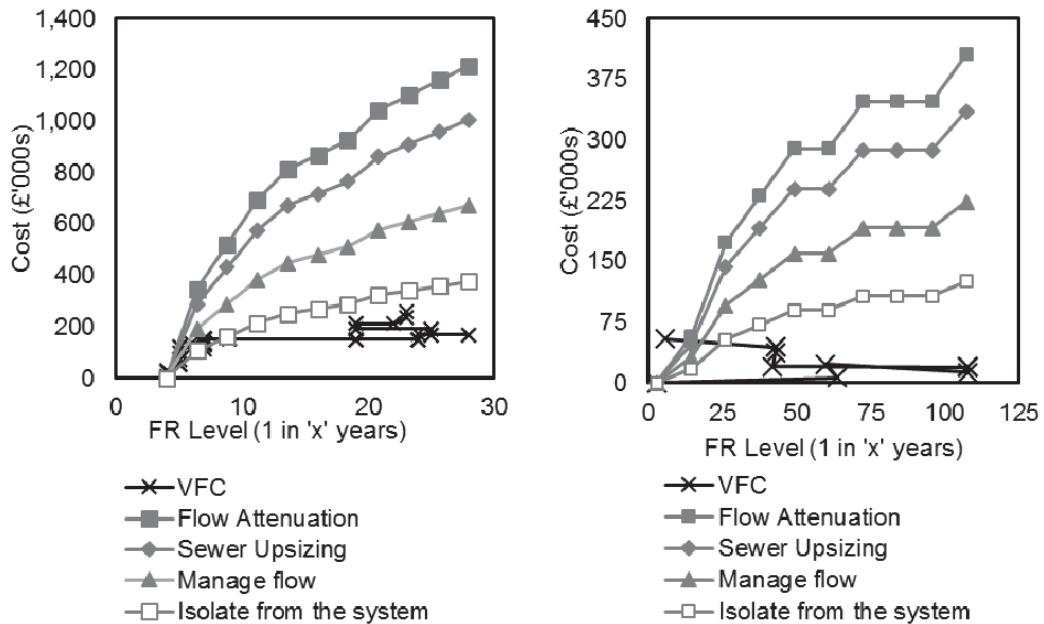
The estimated costs for the flood alleviation schemes in case studies A, B, C and D agree with the costs from the historic Wadley Road and Evanston case studies that installing passive flow controls is a cheaper solution [2]. Over the six case studies presented, installing VFCs into the sewer system were on average 60% cheaper than implementing any of the alternative flood alleviation schemes from the Babtie Ltd and Ofwat report.

The costs of the flood alleviation methods against the flood resistance level is plotted in Fig. 3. The flood resistance levels were found from the application of the flow control positioning method. The maximum cost values for each series in Fig. 3 are presented in Table 5. The aim is to also investigate which flood alleviation method is more cost effective across the range of flood resistance levels achievable.

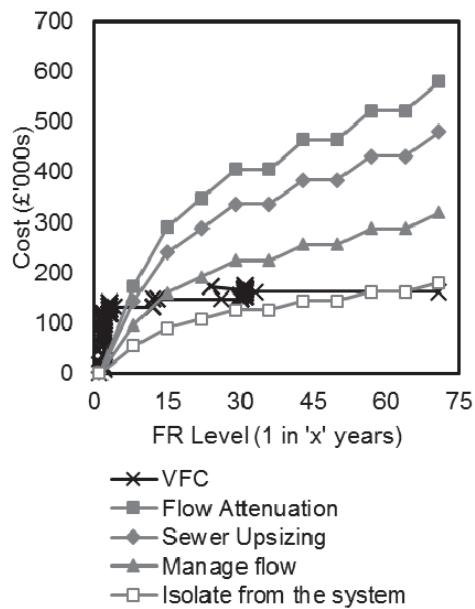
Fig. 3a is the plot presenting the costs of the different flood alleviation schemes for the range of flood resistance levels (1 in 4 years to 1 in 28 years). The plot shows that the solutions provided by the flow control positioning method provide the cheapest solution for the flood resistance levels achieved greater than 1 in 10 years. This is due to there being adequate storage within the sewer system for the quantity of collected surface runoff. The same can be said for case study B where all of the flood resistance levels achieved by the flow control positioning method, up to 1 in 108 years from 1 in 3 years, were a cheaper solution than the other flood alleviation schemes from the Babtie Ltd & Ofwat report, Fig. 3b. After the solution with the greatest flood resistance level was achieved, 1 in 108 years, any additional flow controls positioned reduced the flood resistance level to 1 in 6 years. This was due to the VFCs designed and positioned being too restrictive and attenuating to much flow. The flow control positioning method is unable to remove already positioned flow controls, but can redesign existing controls.

The outputs from case study C also show that installing passive flow controls into the sewer system was the cheaper solution compared to the flood alleviation solutions from the Babtie Ltd & Ofwat report at the maximum achieved flood resistance level of 1 in 71 years, Fig. 3c. The flow control positioning method's proposed solution was £17,500 cheaper than the 'isolate the system' solution (10%). The solution proposing passive flow controls was only cheaper than the Babtie Ltd & Ofwat schemes above a flood resistance level of 1 in 70 years, Fig. 3c. This is most likely due to the flow control positioning method not positioning a flow control in the most optimal location to increase the flood resistance level, but where the greatest spare capacity was first. Fig. 3d shows that, for the whole of the flood resistance level range, the flow control positioning method flood alleviation scheme was the cheapest solution. At the maximum achieved flood resistance level, 1 in 3 years, the flow control positioning method flood alleviation scheme was a cheaper solution than the other four flood alleviation schemes by a minimum £29,500 (82%).

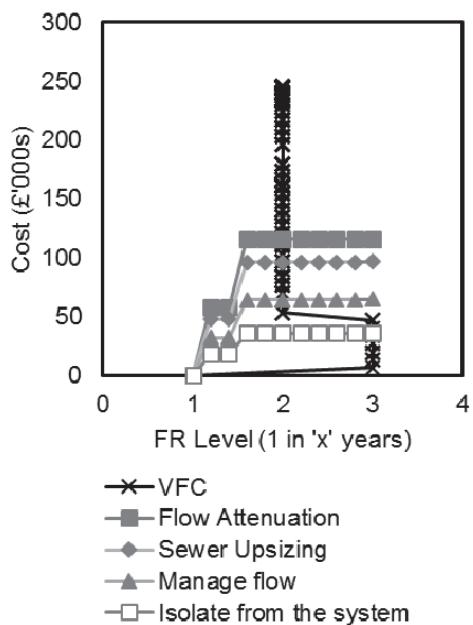
It is observed in all of the plots presented in Fig. 3 that there are not solutions presented for a wide range of the flood resistance levels when VFCs are positioned in the sewer system. This is due to the flow control positioning method [3]. The flood resistance levels achieved are determined by the flow controls designed and positioned within the sewer system. The primary aim of the method is to design a flow control to attenuate the greatest volume of water possible in the sewer system. The measured flood resistance level is used to determine and quantify the change in the flood resistance level of the sewer system and, hence, whether benefit can be achieved. The flow control positioning method does not aim to propose a design for each flood resistance level.



a) Case study A.



c) Case study C.



d) Case study D.

Fig. 3. Cost against flood resistance level plots for the additional four case study sewer systems analysed in this paper

## 5. CONCLUSION

The outputs from the four anonymised case studies presented in this paper show that passive VFCs can be, on average, a 60% cheaper sewer retrofit solution, compared to the other solutions that often require power to operate. This is because VFCs require no electricity supply and no overly major construction projects for installation as the VFCs can be installed within existing sewer system chambers. In contrast, isolating from the sewer system can include the installation of non-return valves and new pumping stations and, even though 'isolate from the system' is on average the cheaper of the four Babtie Ltd & Ofwat schemes used; over the course of the lifetime of the flood alleviation scheme the total cost may increase due to power costs and additional maintenance. The outputs do not show that the installation of passive flow controls is the cheapest solution for all flood resistance levels below the maximum achieved.

The results from case studies A, B, C and D concur with the installed solutions presented by Andoh [2], as well as add additional comparisons to other literature [6,7].

## ACKNOWLEDGEMENTS

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# WATER / WASTEWATER TREATMENT

# Challenges for sustainable wastewater management in the urban sector

Asher Brenner

Unit of Environmental Engineering, Faculty of Engineering Sciences,  
Ben-Gurion University of the Negev, Be'er-Sheva, 8410501 Israel

Water scarcity and environmental pollution are crucial challenges in a warming world with an ever growing population. Addressing them will require the development of careful water resources management that is based on the effective integration of natural water sources, new water supplies, and pollution prevention. Modern water-supply and sanitation systems introduced at the beginning of the 20<sup>th</sup> century are regarded as one of the greatest engineering achievements contributing to human health and sustainability. However, the massive production and use of thousands of anthropogenic chemicals during the last century have resulted in the release of toxic and problematic materials into the environment. Moreover, the ever-increasing urbanization and population density ultimately may cause a long-term concentration build-up of these substances in the closed-loop cycle of water supply and wastewater treatment and reuse. Even the well-established treatments used to treat urban wastewater are considered insufficient today since many emerging contaminants [the so-called organic micro-pollutants (OMPs)], are not completely removed in conventional processes. Among the OMPs are pharmaceuticals and personal care products (PPCPs), some of which are considered endocrine disrupting compounds (EDCs). A variety of methods have been developed to improve wastewater treatment processes including membrane bioreactors (MBRs), and advanced oxidation processes (AOP). However, these improvements and even tight membrane processes such as reverse osmosis (RO) used in effluent desalination, do not function as absolute barriers against OMPs.

Decentralized wastewater management (DWM) has become a new fashion in recent years based on the assumption that it may offer economic, social, and environmental advantages. Decentralized wastewater treatment systems incorporate collection, treatment, reuse, and disposal of wastewater of various types, including domestic, commercial, or industrial wastes. These systems can be applied for local urban neighborhoods and communities, public institutions, touristic sites, etc. It has been claimed that these small-scale systems can assure the same effluent quality and process safety & reliability, as large-scale centralized systems. Another trend related to DWM is the segregation and separate treatment of black-water, grey-water, and yellow-water (urine). The motivation of separate management of grey-water (usually on a small-scale) is the potential to save potable water and to supply reclaimed water for non-potable reuse applications such as gardening or toilet flushing, thus contributing to sustainability. However, even the classic management to obtain conventional effluents quality (based commonly on values of TSS, BOD, and fecal coliforms) requires the application of a complex treatment train, including equalization (due to the extreme fluctuations of grey-water production during the day), solids separation, biological treatment, disinfection, and excess sludge management. This treatment sequence requires high sophistication of daily maintenance and control.

Furthermore, grey-water contains high levels of problematic substances such as preservatives, biocides, softeners, plasticizers, emulsifiers, and more (commonly present in

\* Tel.: +972 8 6479029; fax: +972 8 6479758.

E-mail address: brenner@bgu.ac.il

personal care products). One example is the group of parabens which possess estrogenic potency, and which may form toxic by-products following chlorination. The motivation of yellow-water separation is the high nutrient content and fertilization potential of urine. On the other hand, urine is the human body sink for pharmaceuticals and for illicit drugs such as cannabinoids, cocaine, amphetamine, steroids, and others. Hence, urine is actually a complex liquid that cannot be treated simply just as a nutrient source. It should also be noted that the construction of separate systems (including collection, treatment, and reuse or disposal) for various types of wastewater in a crowded urban area is itself complicated and costly. It may also increase the risk of accidental exposure to pathogens and other toxic chemicals.

Thus it means that DWM and separate management of grey-water or yellow-water is not as simple and sustainable. It is actually a concept of "diffuse solution" that may cause diffuse pollution, in place of a point source control (gained in centralized systems). Therefore, a revolution in the concept of wastewater management is required to realize the goal of sustainability, meaning protection of human health and of other species, preservation of environmental quality & ecological balance, and thoughtful recovery of energy and nutrients. **In this regard, my opinion is that wastewater should be treated to superior quality in order to enable its reuse, or its return back to nature in the same quality that it has been obtained.** This means that added-stringent standards and more sophisticated technologies will have to be implemented. Upgrade of current technologies can be based on integration & hybridization of processes such as AOP, activated carbon adsorption, and tight membrane separation methods, in a quaternary treatment stage (added to existing practices of secondary and tertiary treatment stages). The formula to define the optimal configuration of these progressive technologies has not been developed yet.

In addition to technology upgrade, advanced monitoring tools and methods are required to identify the fate of a variety of raw pollutants and their degradation by-products at the  $\mu\text{g/L}$  and even  $\text{ng/L}$  levels along treatment routs. Since severe water quality standards, secure management canons, and innovative technologies must be equal for all kinds of treatment systems (including all types of wastewater and all magnitudes of treatment processes), several doubts arise regarding decentralization and wastewater segregation.

**Keywords:** *Wastewater management, sustainability, organic micro-pollutants, quaternary treatment, decentralization, grey-water, urine.*

# Hydroponic fertigation with anaerobic membrane bioreactor (AnMBR) permeate - A tool for wastewater nutrient recovery

Calabria, J., Dick, G., Bair, R., Ozcan, O., Yeh, D

## ABSTRACT

**Aims:** Demonstrate the potential use of anaerobic membrane bioreactor (AnMBR) permeate as liquid fertilizer for use in a hydroponics system, evaluate the performance of permeate in comparison to conventional hydroponic fertilizer, identify system inefficiencies and suggest optimal design parameters

**Study design:** The study measured and monitored the growth performance of tomato plants cultured in a hydroponic static solution culture configuration.

**Place and Duration of Study:** Department of Civil and Environmental Engineering, University of South Florida, Tampa, FL, USA, August – September 2013

**Methodology:** Six hydroponic substrates: permeate (P1), 50% dilution of permeate (P0.5), conventional fertilizer (C1), 50% dilution of C1 (C0.5), Tap water serving as the blank (B1) and permeate adjusted to a pH of 6.5 with nitric acid (P1\*). Leaf count, bloom count, and dry weight after 33 days were measured as indicators of plant growth performance.

**Results:** AnMBR permeate yielded an average growth performance of 70% of that of the control plants grown using a commercial nutrient blend. AnMBR permeate that was adjusted to lower pH with nitric acid performed generally better averaging 80% of the control's growth performance parameters. All solutions displayed health and growth performance better than that of the blank solution.

**Conclusion:** AnMBR permeate requires conditioning prior to use in a hydroponics system in order to avoid nutrient deficiencies induced by high ammonia concentrations in permeate. Conditioning includes lowering permeate pH and oxidizing ammonia to increase nitrate concentration in the permeate.

**Keywords:** wastewater recycling, wastewater reuse, anaerobic digestion, membrane filtration, food production, plant nutrient requirements, urban agriculture, *Lycopersicon lycopersicum*, static solution culture

## 1. INTRODUCTION

Global increases in population, rapid urban development, and the unmanaged use of non-renewable resources foreshadow a grim future of food, water, and energy shortages across the globe. As the availability of fresh water diminishes, the cost of agriculture will rise and the price of potable water will become an important factor that will govern how water resources are used. Furthermore, urbanization and the demands for resources that accommodate it, is occurring in the major developing areas of the world at an alarming rate. By 2050, it is estimated that 7-8 billion people will reside in the cities of the world consuming 2800 cubic kilometers of fresh water [1].

Methods for sustainable recovery of resources highlight efforts for sustaining the continued growth and development of the planet's societies. Food security for example, will require the rapidly urbanizing areas of the world to develop efficient crop production strategies, especially in water scarce regions. Hydroponics methods have been growing interest for urban settings as these systems can be designed to optimize grow space and do not require fertile soil. Hydroponics describes the horticultural practice of cultivating plants in a soilless medium and is useful for observing the performance of fertilizers [2]. The roots of the plants are in constant contact with an aqueous nutrient solution, which allows for efficient nutrient acquisition by the plant. Conventional hydroponics systems utilize manufactured nutrient solutions to serve as fertilizer for the plants. Phosphorous, a major component of fertilizer is obtained from the mining of the earth's phosphorous reserves (projected to be depleted by the end of the century) [1]. Thus, there is an apparent need for nutrients derived from renewable sources that can be used for various horticultural applications such as hydroponics.

Adequate performance of permeate as a nutrient source for horticultural applications can boast many advantages for decentralized wastewater treatment that would be achievable through technologies such as the AnMBR. Gikas and Tchobonoglou [3] argue that decentralized and satellite treatment systems will be crucial in order to increase water reuse opportunities in response to water resource management issues. They also show agricultural irrigation and landscape irrigation as major reuse opportunities. Decentralized technologies such as the AnMBR will allow for recovered resources to be utilized onsite or near the point of generation. Permeate generated by an AnMBR can be used in nearby landscaping or horticultural and/or agricultural operations minimizing the impact of both the wastewater treatment process and horticultural operation. Such an integration of the water and food sectors boasts many implications for improving local sustainability in by enhancing food security, preserving potable water, and improving nitrogen use efficiency (NUE) [4; 5].

## 2. MATERIAL AND METHODS / EXPERIMENTAL DETAILS / METHODOLOGY

### 2.1 AnMBR Configuration & Operation

Permeate for this study was produced by a 20.45 liter AnMBR designed for the treatment of domestic wastewater at ambient temperatures. Two sequenced reactors of equal volume (10.23 liters), the first of which operated as an upflow anaerobic sludge blanket (UASB), and the second as a completely stirred tank reactor (CSTR). Two membrane modules provided a total of 0.0423 m<sup>2</sup> of membrane surface area. Tubular ultrafiltration membranes (Pentair, X-flow modules) made of polyvinylidene fluoride (PVDF) and with an average pore size of 0.03µm were used inside the modules. Wastewater was provided by direct extraction from the grinder station of a local elementary school's septic system. Analysis of reactor performance was conducted by (BAIR et al., *in progress*). Reactor performance analysis included analysis of permeate for nutrient content. Ammonia, total nitrogen, and total phosphorus were analyzed using HACH test kits (HACH Loveland, CO).

## 2.2 Laboratory Hydroponics Growth Experiment

A total of 18 tomato plants were grown indoors in a static solution culture<sup>1</sup> configuration using six different liquid nutrient solutions. Tomato plants were grown in a 1 liter liquid volume of solution with continuous aeration; the solution was regenerated every 7 days. The nutrient solutions used included permeate from a pilot scale anaerobic membrane bioreactor (AnMBR) labeled P1, the control solution used was a commercial hydroponic nutrient blend, MaxiGro™ (General Hydroponics, Sebastopol, CA), labeled C1. Tap water was used as a blank solution. Plants were also grown in 50% dilutions of the permeate solution and MaxiGro™ solutions, labeled P0.5 and C0.5, respectively. To match the ideal pH that is recommended in hydroponic applications, the sixth solution consisted of pure AnMBR permeate that was adjusted to a pH of 6.5 using nitric acid and labeled P1\* [6].

### 2.2.1 Growth Conditions

The experiment was conducted indoors in an indoor greenhouse to discourage influence from nearby indoor activities. 30 tomato seeds were started using Ready Gro™ super plugs (Botanicare, LLC. Chandler, AZ). Lighting was supplied by two SS Sun Blaze T5 4' w/ 4 Lamps (Sunlight Supply, Inc., Vancouver, WA) which had a maximum output of 20,000 lumens. During the seed starting phase, seeds were exposed to 14 hours of light followed by 10 hours of darkness. Once transferred to growth reservoirs, light/dark schedules were adjusted to 12 hours of light, 12 hours of darkness.

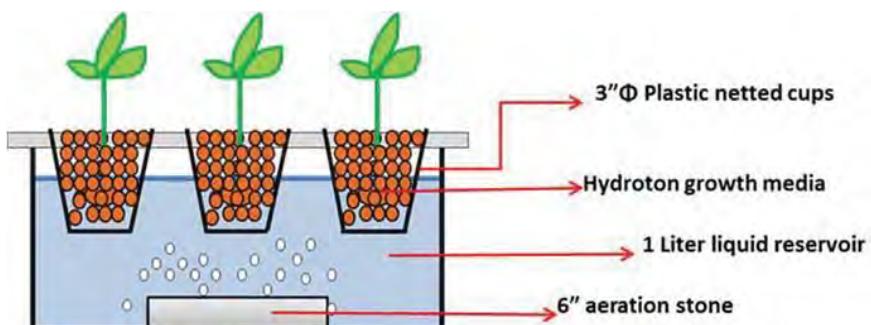


Fig. 1. Diagram of static solution culture growing three plants

After 12 days, 18 healthy plants were transferred to the static solution culture reservoirs. Seedlings were placed in 3-inch plastic net cups (Sunlight Supply, Inc., Vancouver, WA) filled to volume with hydroton (expanded clay pellets) to secure the plug. Three plants were placed in a rectangular Styrofoam container measuring 9 cm x 26 cm x 8 cm comprising one grow cell. 1 litre of aqueous solution was added to the reservoirs weekly. Tap water was added as needed to maintain liquid level. Three net pots were suspended above the solution in each grow cell containing a 6" aeration stone submerged in the aqueous solution that operated continuously.

### 2.2.2 Nutrient Solutions

AnMBR permeate was collected from the permeate reservoir of the AnMBR system. Permeate was used without alteration to determine the effects on plant growth. A 50% dilution of AnMBR permeate was also used. The average permeate pH was above the ideal range used in hydroponics; therefore another test series utilized pure permeate that was adjusted to a pH of 6.5 using nitric acid. Commercially available nutrient solution (MaxiGro™) was used as the control solution. 7.5 grams of MaxiGro™ was added to 4 L of tap water to make the stock commercial fertilizer solution. Additionally, a 50% dilution of stock commercial solution was tested. Tap water was used in the blank grow cell.

<sup>1</sup> Static solution culture describes the hydroponics technique that grows plants in containers filled with solution, with or without aeration. Plant roots are given sufficient headspace in the reservoir to receive oxygen.

### **2.2.3 Growth Measurements**

The height of each plant as well as the number of leaves on each plant was recorded every other day for 33 days. On the final day of the measurement period, final height and leaf count measurements were taken as well as the number of flowers developing and fruits. Wet and dry weights of the root and shoot portion of each plant were also measured. These parameters were chosen as indicators of vegetative growth performance [7].

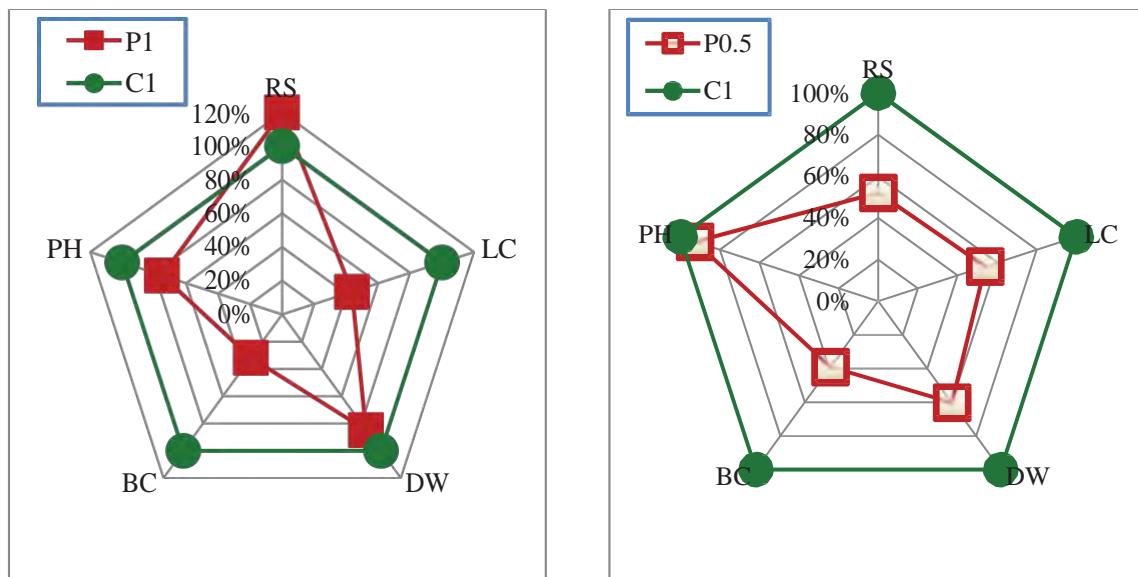
## **3. RESULTS AND DISCUSSION**

### **3.1 Laboratory Growth Results**

The composite indexes displayed in **Figures 2 - 7** illustrate the comparison of growth performance achieved by the various hydroponic solutions in regards to five parameters assumed to be indicative of healthy growth: leaf count (LC), final plant height (PH), final dry weight (DW), final number of blooms (BC), and the weight ratio of root to shoot (RS) [7]. The control solution is assumed to yield baseline performance, thus all solutions were compared to the performance achieved by plants grown in the control solution.

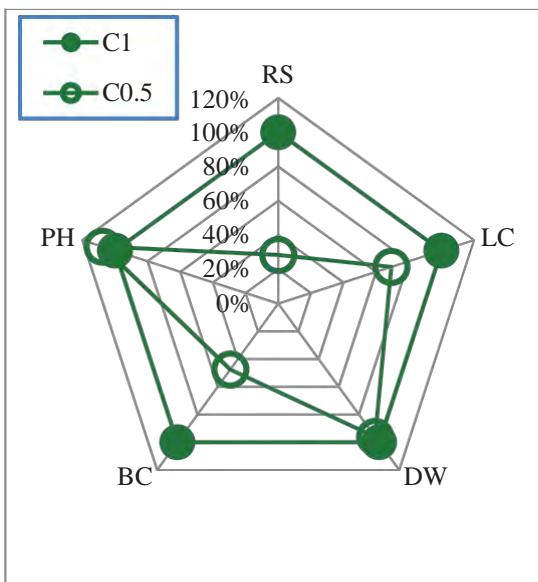
Plants grown in undiluted permeate yielded 84% and 96% of the control dry weight for pure permeate (Figure 2) and pH adjusted permeate respectively (Figure 6). Diluted permeate yielded 60% of the control dry weight (Figure 3) while diluted commercial fertilizer reached 96% of the control dry weight (Figure 4).

The formation of blooms and leaves was lowered greatly in plants grown in pure permeate and the 50% dilution permeate solutions (labeled P1 and P0.5 respectively). Plant height was also stunted. However, the pH adjusted permeate yielded rapid growth with similar values for plant, height, leaf count, bloom count, and dry weight as that of the control (MaxiGro™) solution.

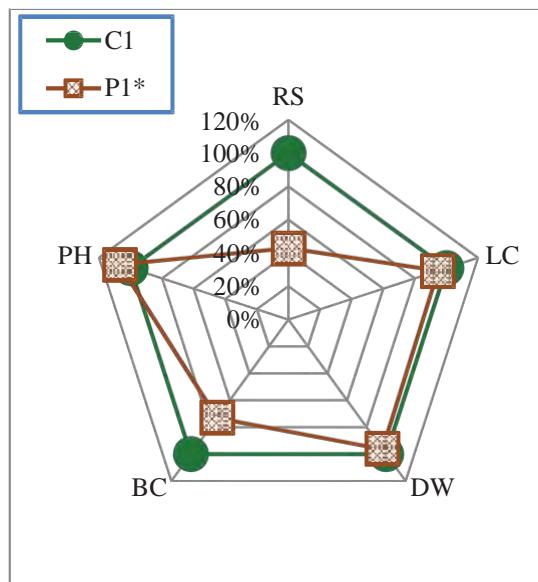


**Fig. 2. Permeate growth performance**

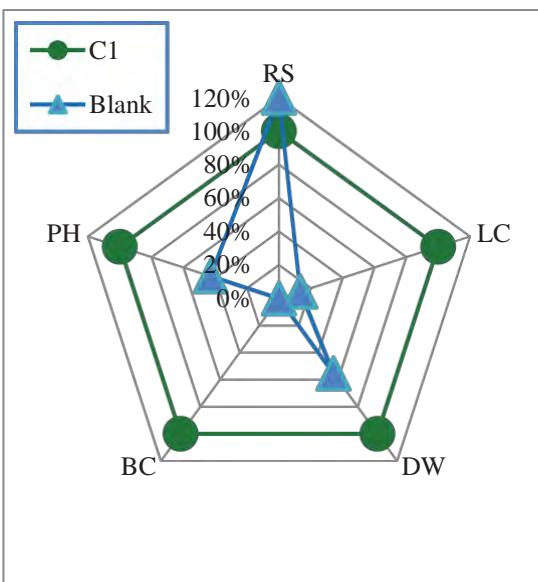
**Fig. 3 Diluted permeate growth performance**



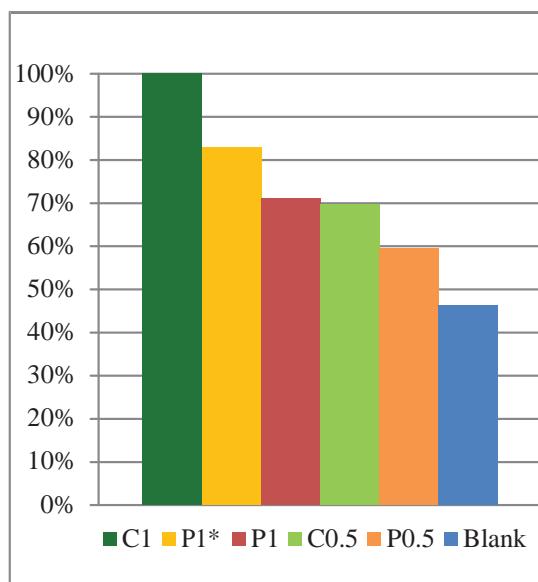
**Fig. 4. Diluted commercial fertilizer growth performance**



**Fig. 6. Permeate (pH adjusted) growth performance**

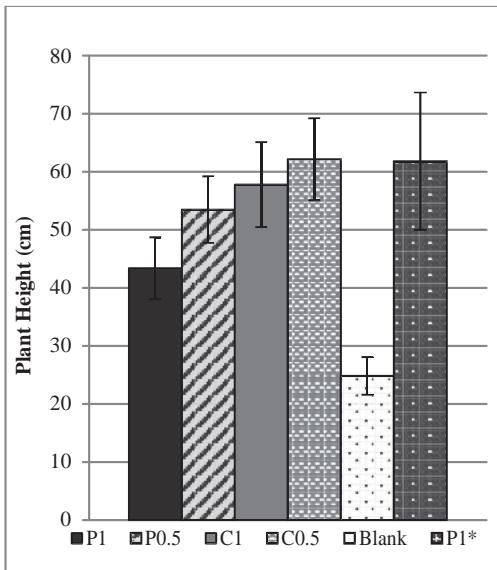
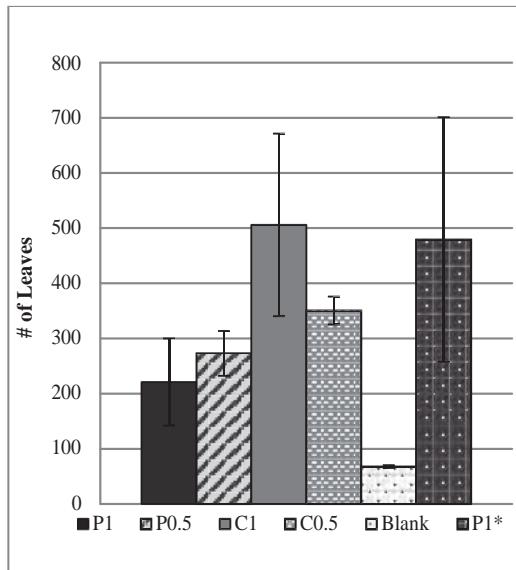


**Fig. 5. Tap water (Blank) growth performance**



**Fig. 7. Normalized Composite Growth Score**

The permeate solution conditioned with nitric acid experienced increased growth performance but also experienced high variability in performance among the three plants grown in the solution.

**Fig. 8. Average final plant heights****Fig. 9. Average final leaf counts**

### 3.2 Discussion

The results indicate that permeate from the AnMBR system can yield viable tomato plants with minor alteration. Tomato plants growing in the pH adjusted permeate solution did not develop extensive root systems like that of the control group, yet the plants displayed good health in regards to leaf count, plant height, bloom count, and color. Another observation to note the only group of plants to experience the setting of fruits were the plants grown in diluted permeate. All plants grown using AnMBR permeate solutions exhibited positive growth with minor signs of stress caused by either a slight nutrient deficiency or toxicity (see figure 10). A characteristic of AnMBR permeate that must first be addressed is the ratio of ammoniacal nitrogen to total nitrogen.

**Fig. 10. Ammonia-induced  $\text{Ca}^{2+}$  toxicity observed in older leaves of tomato plants grown in P1 solution.**

In AnMBR permeate,  $\text{NH}_4^+$  accounts for 70-80% of the total nitrogen whereas in the commercial fertilizer blend,  $\text{NH}_4$  comprised a much lower percentage of 15% of the total nitrogen. Reduction in growth is experienced by plants where  $\text{NH}_4^+$  is the major form of N available for plant uptake as carbohydrate depletion can occur with  $\text{NH}_4$  nutrition. The presence of high  $\text{NH}_4^+$  concentrations can also cause calcium, potassium, and magnesium deficiencies as the ammonium cation competes with other cations for plant absorption [8; 9]. This can explain why the permeate adjusted to a lower pH experienced greater growth as nitric acid was used, thus increasing the concentration of nitrate ions within the solution. Adding a nitrification stage to the process of permeate utilization could serve as a solution to the issue of high  $\text{NH}_4/\text{TN}$  ratios exhibited by AnMBR Permeate. Such is seen in aquaponics systems where fish-waste rich in  $\text{NH}_4^+$  is nitrified in plant beds filled with porous inert media [10].

Aquaponics systems operate in a fashion similar to the practice proposed by this experiment. Waste from one process within a system serve as an input to another process within the system. The practice of aquaponics has experienced a lot of exposure recently as it conveys a more sustainable method of cultivating fish and crops for consumption. However, aquaponics systems still require inputs of a food source for the fish as well as make up water and energy to move water within the system [10]. Similar systems that combine the AnMBR technology for wastewater treatment with hydroponics systems can eliminate or replace the inputs fish feed and makeup water. The AnMBR makes possible the safe extraction of nutrients from wastewater streams, effectively converting the outputs of human practices into inputs for the AnMBR-hydroponics system. Such integration represents a more sustainable option producing food crops.

Further investigation is necessary to legitimize the use of this form of treated effluent for household and commercial growing operations. Information regarding the presence of heavy metals and nutrient composition for instance would prove beneficial. Also, if treated waste streams such as the AnMBR permeate used in this experiment are to be considered for fertilizer usage, a longer study is warranted to assess the yield capabilities and nutrient profile of food crops produced.

The integrated system in operation at Learning Gate Elementary School in Lutz, FL demonstrates a successful integration of small-scale resource recovery and utilization. The purpose of the system is to serve as a learning tool for students which demonstrates how the utilization of biorecycling principles can transform materials in waste streams into usable resources. Although operation and maintenance of the system was minimal, the greenhouse was able to produce viable plants with marked yields. The performance of the integrated system has implications of possible small-scale horticultural operations in areas previously deemed inadequate for crop production. Additionally, the major inputs to these operations are organic waste materials, recovered greywater or rainwater, and electricity to power a recirculation pump.

#### 4.1 Safety Concerns

The direct use of treated waste water to produce edible crops carries inherent risk of transmission of pathogens. However, membranes have been proven to effectively remove pathogenic materials [11]. The EPA suggests that microfiltration and ultrafiltration membranes demonstrate the ability to achieve 7-log removal of pathogens and particles. Removal efficiency depends upon a number of factors, one being the state of the cake layer on the membrane surface which supplies additional filtration capability, blocking sub-pore sized particles. The EPA (2001) reported on the removal efficiency of membranes when tested for the removal protozoa, bacteria, and viruses, turbidity, and particles. Protozoan cysts of major concern, *cryptosporidium* and *giardia*, are removed via sieving as the diameters are on average, 2 to 3.5 times larger than UF nominal pore diameters. Bacteria removal performance is similar as the diameter of most bacterial cells tend to be at least one order of magnitude greater than UF nominal pore size. Virus removal efficiency depends primarily on the state of the dynamic cake layer which serves to remove sub-pore sized viruses via

adsorption into the cake layer or larger particles and constricting pore diameter. Thus, influent streams with high turbidity increase the removal efficiency of UF membranes as more material is present to induce fouling. A pilot UF system treating tertiary wastewater effluent achieved greater than 6.9 log removal of MS2 Bacteriophage [12]. However, in almost all cases some level of chemical disinfection was warranted for MF/UF filtrate to ensure reliable safety.

This work proposes that AnMBR permeate can be made suitable for hydroponics applications where edible crops are produced. Regulatory frameworks such as the World Health Organization's Guidelines for Safe Water Reuse and the California Department of Public Health Title 22 Code of Regulations have set forth regulations regarding the safety of recycled waters for application as irrigation water of edible crops. Title 22 mandates that recycled water used for irrigation must meet the definition requirements of disinfected "tertiary recycled water" as described in section §60301.230 of the Title 22 regulations. The addition of a disinfection process such as chlorination or ozone treatment to a membrane bioreactor system should achieve the mandated 5-log removal for disinfected tertiary recycled water. Moreover, the World Health Organization (WHO) guidelines for safe water reuse requires 4-log removal of pathogens for drip-irrigation of low-growing crops [13]. Drip-irrigation closely resembles hydroponic fertigation as liquid fertilizer is applied directly to the plant root zone, thus minimizing contact of the above-ground portion of the plant. Future experiments should measure pathogen removal to ensure that AnMBR permeate can be deemed suitable for the hydroponic production of edible crops by various frameworks such as the World Health Organization's Guidelines for Safe Water Reuse and the California Department of Public Health's Title 22 Code of Regulations.

#### **4. CONCLUSION**

The use of AnMBR permeate as a source of nutrients for hydroponics operations does not prove to be ideal when in the post-AnMBR process state. Modification of AnMBR permeate is necessary to yield more favorable plant growth performance. Modification includes pH adjustment, transformation of the nitrogen species, and possible micronutrient addition. Future work should include complete analysis of AnMBR permeate to determine the presence and concentration of any beneficial micronutrients as well as heavy metals, salinity, and other materials deleterious to plant growth.

Future laboratory hydroponics experiments should include plant tissue analysis to better determine the mass flow of materials from permeate to plant to quantify possible material losses from volatilization. Future greenhouse experiments should measure the amount of external inputs to the integrated system in order to make such an integration a possible option.

#### **ACKNOWLEDGEMENTS**

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# Low Energy Forward Osmosis Desalination Process and a Comparison with Conventional Reverse Osmosis

Ali Al-Taee and Adel. O. Sharif

Qatar Environment and Energy Research Institute, Qatar Foundation, Qatar

## **Abstract:**

**Aim:** The current study proposes to evaluate the performance of FO-RO system through investigating the impact of operating parameters on system power consumption and product water quality.

**Methodology:** Conventional RO performance has been evaluated under constant pressure and constant recovery rate using a number of seawater feed salinities. Pressure-Assisted FO (PAFO) and FO processes have been evaluated using different feed pressure and feed and draw solution flow rates. Pre-developed FO computational program and Reverse Osmosis System Analysis (ROSA) software have been used to estimate the performance of FO-RO and RO processes.

**Findings:** The outcomes of current study can be considered to improve the performance of FO-RO system.

Keywords: Desalination, Reverse Osmosis, Water Scarcity

## **1. INTRODUCTION**

Water scarcity problem has affected many countries world wide and become a growing problem which has been aggravated by contamination of water resources, publication increase and global warming. As a result, many countries used desalination as a measure for water supply to cities and towns in arid and semi-arid areas. The main desalination technologies for freshwater supply are Multi Stage Flash (MSF) and Multi Effect Distillation (MED) in thermal technologies and Reverse Osmosis (RO) in the membrane technologies; besides of other techniques which have limited capacity such as Membrane Distillation (MD) and Electrodialysis (ED) [1-5]. There are advantages and disadvantages in each desalination technique, however, RO technology has been recognized as more cost-effective than MSF and MED [7, 8].

Currently, RO is the desalination technology with largest number of installations worldwide. There are different types of RO membranes which are applicable for brackish and seawater desalination. The mechanism by which RO membranes operate is the physical separation of ionic species from the saline feed. Typically, seawater is pretreated to remove impurities in colloidal size then pressurized up to 80 bar and fed into the RO membrane. Most of ionic species are rejected by the membrane selective layer while freshwater crosses the membrane and collected in the permeate channel. Commercial RO membranes rejection rate to monovalent ions is about 99.75%. Despite all advantages of RO technology, it suffers from several draw back such as the intensive feed pretreatment [1]. Furthermore, the performance of RO membrane degrades over the time due to scaling and biofouling [9, 10]. This results in an increase of the desalination power consumption and degradation in the

\* E-mail address: [asharif@qf.org.qa](mailto:asharif@qf.org.qa)

permeate water quality. The TDS of permeate increases over time as a result of losing the selectivity of RO membrane. Several studies have been carried out to reduce the fouling and power consumption of the RO membrane system [11, 12-14].

Unlike conventional RO process, FO operates by natural osmosis as a driving force for freshwater extraction from the feed seawater. A concentrated solution, the draw solution, of osmotic pressure higher than the feed solution is provided at one side of the FO membrane for freshwater extraction from the seawater on the opposite side. Freshwater crosses the FO membrane and diluting the draw solution which requires further treatment for recycling and reuse [15]. RO and NF membranes have been suggested for the regeneration of draw solution. Therefore, the most expensive step in FO-RO system is the RO treatment due to the high hydraulic pressure required for freshwater separation from the draw solution [14, 15, 16]. FO pretreatment has a several advantages including reducing RO fouling propensity, increasing RO recovery rate, and minimizing chemicals use [14]. Unfortunately, experimental permeate flow in FO process is much lower than theoretical permeate flow due to the phenomenon of Concentration Polarization (CP) [15, 17]. Dilutive and concentrative CP at the draw and feed side of the FO membrane, respectively, reduce permeation flow. Water permeation across dilutes the draw solution, lowering the concentration at the boundary layer and reducing the Net Driving Pressure (NDP) across the FO membrane. Same time, permeation drag force increases solute accumulation in the support layer on the feed side of the FO membrane hence increasing the osmotic pressure of feed solution. There are several means to enhance water permeation in the FO process including i) reducing the effect of concentration polarization and ii) using Pressure Assisted FO (PAFO) process. Increasing the concentration of draw solution is not only increasing the NDP across the FO membrane but also the concentration of feed solution to the subsequent RO regeneration process, hence the cost of desalination process will be more expensive [14]. Membrane flux can be increased through reducing the effect of concentration polarization. For a given FO membrane, this can be achieved by increasing the flow rate of feed or draw solution [18-21].

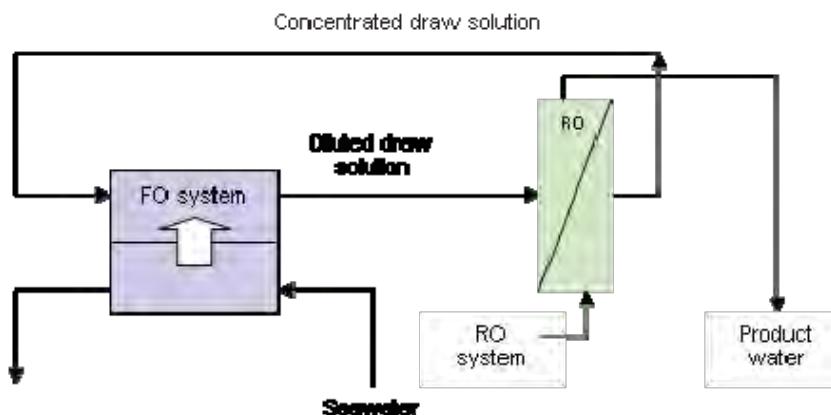


Figure 1: FO-RO system for seawater desalination

In traditional FO-RO system, the osmotic pressure of draw solution is the main mechanism for water transports across the FO membrane. Although increasing the concentration of draw solution increases the osmotic pressure and water permeation, it also increases the cost of RO regeneration process. However, there is no study investigated the effect of these parameters on the performance of FO-RO system. Furthermore, there is no data about the performance of PAFO-RO system and the enhanced feed flow FO-RO system. In PAFO-RO system, membrane flux is promoted by increasing the NDP across the FO membrane whereas membrane flux

is promoted by reducing the effect of CP in the enhanced flow FO-RO system. The current study investigates the performance of PAFO-RO system and enhanced flow FO-RO system under different feed pressures and flow rates.

## 2. METHODOLOGY

Enhanced permeation flow is highly desirable in the FO process to reduce the concentration of draw solution to be treated in the RO process. PAFO and enhanced flow FO processes were proposed to promote water flux; this was achieved without increasing the concentration of draw solution. Draw and feed solution entered the FO membrane for freshwater extraction and draw solution dilution. In the PAFO process, membrane flux was evaluated under different feed pressures while different feed flow rates were tested to evaluate water flux in the enhanced flow rate FO process.

### 2.1 Pressure Assisted FO (PAFO)

Feed pressures between 2 bar and 6 bar were evaluated to enhance water flux across the FO membrane. The hydraulic pressure was applied on the feed side of the FO membrane using constant concentration of draw solution. Two different operating modes were investigated in the FO process; draw solution facing the membrane active layer (DS-AL) or the FO mode and feed solution facing the membrane active layer (FS-AL) or the PRO mode. Water flux in the FO PRO operating mode was estimated from the following equation: [22]

$$J_w = A_w \left( \frac{\frac{Db}{Fb} \frac{e^{(-J_w)}}{e^{(J_w K)}} + P_f}{1 + \frac{B}{J_w} (e^{(J_w K)} - e^{\frac{(-J_w)}{k}})} \right) \quad [1]$$

where,  $J_w$  is the water flux (in  $\text{L/m}^2/\text{h}$ ),  $\frac{Db}{Fb}$  and  $\frac{e^{(-J_w)}}{e^{(J_w K)}}$  are the osmotic pressures associated with the bulk draw and feed solutions, respectively,  $k$  is the bulk mass transfer coefficient (in  $\text{m/s}$ ),  $B$  is the solute permeability coefficient (in  $\text{kg/m}^2/\text{h}$ ),  $K$  is the solute resistivity for diffusion within the porous support layer ( $\text{s/m}$ ), and  $P_f$  is the feed pressure (in bar). For FO operating mode, membrane flux was calculated from the following equation:

$$J_w = A_w \left( \frac{\frac{Db}{Fb} \frac{e^{(-J_w K)}}{e^{\frac{J_w}{k}}} + P_f}{1 + \frac{B}{J_w} (e^{(J_w K)} - e^{\frac{(-J_w)}{k}})} \right) \quad [2]$$

Typically, specific power consumption of the FO process is about 4% to 6% of that of the RO process. However, specific power consumption of FO process increases when a positive hydraulic pressure is applied on the feed solution; i.e. PAFO process. The expression used to estimate specific power consumption in the FO process is [14]:

$$E_{s-FO} = \frac{(P_{fs}Q_{fs} + P_{ds}Q_{ds})}{\lambda \lambda * Q_p} \quad [3]$$

In equation 2,  $P_{fs}$  and  $P_{ds}$  are the pressure of the feed and draw solutions (in bar), respectively,  $Q_{fs}$  and  $Q_{ds}$  are the flow rate of the feed and draw solutions (in  $\text{L/h}$ ),

respectively,  $Q_p$  is the permeate flow rate (in L/h), and  $fJ = 0.8$  is the pump efficiency. Total power consumption of FO-RO system is equal to the sum of RO power consumption plus FO power consumption:

$$E_{s-t} = E_{s-RO} + E_{s-FO} \quad [4]$$

Where  $E_{s-t}$  is the total power consumption in FO-RO system (in kWh/m<sup>3</sup>),  $E_{s-RO}$  is the power consumption in the RO process (in kWh/m<sup>3</sup>), and  $E_{s-FO}$  is the power consumption in the FO system (in kWh/m<sup>3</sup>).

## 2.2 Flow enhanced FO

Using high feed flow rates demonstrated the capability of reducing the effect of CP and increasing the membrane flux. This will lower the concentration of draw solution going to the RO membrane system; hence the cost of regeneration process is decreased. Feed flow rate to draw solution flow rate ratios ( $Q_{f-in}/Q_{ds-in}$ ) between 4 and 8 was tested in the FO model and the resultant membrane flux was calculated. Membrane flux was calculated in the PRO and FO modes. For PRO mode, membrane flux was calculated from the following equation [23]:

$$J_w = A_w \left( \frac{\frac{V}{Db} e^{-\frac{L_w}{k}} - e^{(J_w K)}}{1 + \frac{B}{J_w} (e^{(J_w K)} - e^{-\frac{L_w}{k}})} \right) \quad [5]$$

where,  $J_w$  is the water flux (in L/m<sup>2</sup>/h),  $V$  and  $V$  are the osmotic pressures associated with the bulk draw and feed solutions, respectively,  $k$  is the bulk mass transfer coefficient (in m/s),  $B$  is the solute permeability coefficient (in kg/m<sup>2</sup>/h), and  $K$  is the solute resistivity for diffusion within the porous support layer (s/m). For FO mode, membrane flux was calculated from the following equation [23]:

$$J_w = A_w \left( \frac{\frac{V}{Db} V - e^{\left(\frac{L_w}{k}\right)}}{1 + \frac{B}{J_w} (e^{(J_w K)} - e^{-\frac{L_w}{k}})} \right) \quad [6]$$

## 2.3 RO modelling

RO membranes require high feed pressure for ions separation from freshwater in the conventional RO process and for draw solution regeneration in the RO step of the FO-RO system. Therefore, it is recognized as the most energy intensive step in the RO-FO system. Practically, RO system requires higher feed pressure for operation over the time due to the membrane fouling [25, 26]. This is an evitable problem especially in the RO for seawater desalination and it is accelerated by the presence of impurities in seawater such as colloidal particles and organic matters. The seawater feed for conventional RO membranes comes from an open intake system with Silt Density Index (SDI) less than 5. In contrast, the feed for RO membranes in the FO-RO system is a pure ionic solution with SDI less than 1; as such the fouling propensity of RO membrane in the FO-RO system is insignificant [27, 28]. Membrane fouling results in an annual flux decline about 7% as in the following equation:

$$J_n = J_o - (0.07nJ_o) \quad [7]$$

where  $J_n$  is the permeate flux in year  $n$  (in L/m<sup>2</sup>/h),  $J_0$  is the initial permeate flux, and  $n$  is number of years. Equation 7 was applied to estimate the RO membrane flux over the expected lifetime of five years. Based on 7% flux decline, the specific power consumption of conventional RO system can be estimated from the following equation:

$$\frac{E_{S_n}}{Q_n} = \frac{P_f * Q_f}{\lambda \lambda * r_i} \quad [8]$$

where  $E_{S_n}$  is the specific power consumption in year  $n$  (in kW h/m<sup>3</sup>),  $P_f$  is the feed pressure (in bar),  $Q_f$  is the feed flow rate (in m<sup>3</sup>/h),  $r_i$  is the pump efficiency (assumed to be constant at  $r_i = 0.8$ ), and  $Q_{pn}$  is the permeate flow rate in year  $n$  (in m<sup>3</sup>/h). It should be noted that  $Q_f / Q_{pn}$  term in equation represents the inverse of recovery rate (%Re). The average recovery rate at year  $n$  was calculated as [29]:

$$Re_{n-ave} = 1 - \left(1 - Re_n\right)^{\frac{1}{x}} \quad [9]$$

where  $x$  is the number of elements in the pressure vessel. Equation 8 is valid for 8 inch Dow Filmtec RO membrane such as SW30HRLE-400i module which has been used in the simulation of current study. Concentration polarization,  $CP$ , factor in the 8" Dow FILMTEC module was estimated as the following [30]:

$$CP_n = \exp(0.7 * Re_{n-ave}) \quad [10]$$

where  $CP_n$  is the concentration polarization factor in year  $n$ . There are a number of assumptions have been made in the current study to simulate the performance of PAFO-RO system and RO system:

- i) There is 7% annual decline in the membrane flux,  $J_w$ , due to membrane fouling and scaling. This assumption holds on the conventional RO system whereas the fouling and scaling of RO membrane in the FO-RO system assumed insignificant due to the high purity of the feed solution.
- ii) RO membrane replacement is every five year due to the performance degradation. However, based on assumption one, the lifetime of RO membrane in FO-RO system may exceed five years.

Table 1: Seawaters composition

SW TDS (mg/L)	Ions Concentration mg/L							
	K	Na	Mg	Ca	HCO <sub>3</sub>	Cl	SO <sub>4</sub>	SiO <sub>2</sub>
40000	441	12278	1473	480	162	22105	3086	1.1
45000	496	13812	1657	539	182	24868	3472	1.2
50000	551	15347	1841	599	202	27633	3858	1.4

Finally, the recovery rate of conventional RO system should not exceed 40% for seawater TDS over 40 g/L to avoid accelerated membrane fouling and scaling problems [31]. For the RO membrane in the FO-RO system, the recovery rate could exceed 40% because of the high feed quality. However, an optimal recovery rate, which is defined as the recovery rate that minimizes the specific energy consumption, can be achieved in the RO step of the FO-RO system. Three seawater salinities were studied for the feed of the conventional RO and FO-RO systems. The concentrations and compositions of seawater feeds are shown in table 1. High seawater concentrations, usually, is a challenge for the conventional RO system whereas it is

less problematic for the FO-RO system. 1 M NaCl was used as the draw solution of the FO process. Due to the relatively low osmotic pressure gradient across the FO membrane, hydraulic pressures between 2 bar and 6 bar were applied on the feed side of the PAFO process.

### 3. RESULTS AND DISCUSSIONS

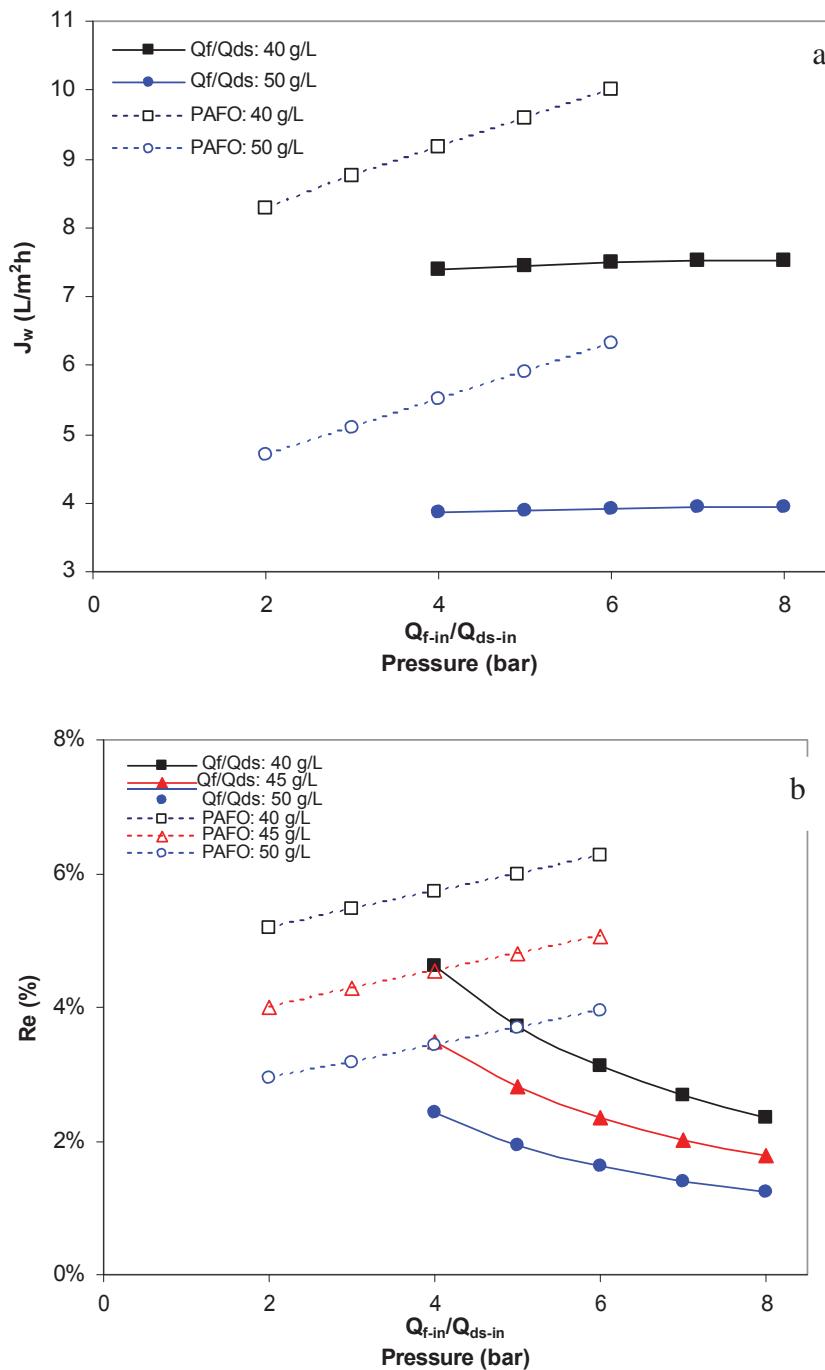
#### 3.1 Performance of PAFO and enhanced flow FO

Two techniques were evaluated for the enhancement of membrane flux in the FO process. Firstly, PAFO process was evaluated under feed pressures between 2 bar and 6 bar to improve water permeation across the FO membrane. Secondly, the flow rate of feed solution was increased to reduce the effect of CP and increasing water permeation towards the draw solution side. Draw solution to feed solution flow rate ratios ( $Q_{f-in}/Q_{ds-in}$ ) between 4 and 8 were applied in the FO process. The main advantage of using high feed flow rate over the draw solution flow rate is that increasing draw solution flow rates increase the concentration of diluted draw solution to be regenerated by the RO process in the FO-RO system [18, 20]. This will increase power consumption and cost of seawater treatment. Whereas increasing the feed flow rate promotes water permeation across the membrane, hence the concentration of draw solution is reduced.

Figure 2 shows the impact of feed pressure and flow rate on the performance of the FO process. Membrane flux,  $J_w$ , increased with increasing feed pressure and flow rate in the PAFO and enhanced flow FO processes respectively (figure 2a). For any given feed salinity, increasing the feed pressure resulted in a higher membrane flux than increasing the flow rate of feed solution. At 40 g/L feed salinity, membrane flux increased by 1.8% and 21% when the  $Q_{f-in}/Q_{ds-in}$  and feed pressure increased from 4 to 8 and 2 bar to 6 bar respectively. The impact of PAFO and feed flow rate on water flux was higher at 50 g/L seawater salinity; membrane flux increased by 2.3% and 34% when the  $Q_{f-in}/Q_{ds-in}$  and feed pressure increased from 4 to 8 and 2 bar to 6 bar respectively. This demonstrated the stronger effect of PAFO and enhanced flow FO process in reducing the severe CP in FO membrane at 50 g/L seawater salinity. Furthermore, membrane flux decreased with increasing seawater water TDS from 4 g/L to 50 g/L due to the lower NDP across the FO membrane and more severe CP effect.

The impact of feed pressure and flow rate of the recovery rate of the FO process is shown in figure 2b. Simulation results show that FO recovery rate decreased with increasing the salinity of seawater from 40 g/L to 50 g/L; this was due to the higher osmotic pressure of feed solution and CP effect at 50 g/L. Increasing the feed pressure of the PAFO resulted in an increase of permeation flow and the recovery rate of RO membrane. In contrast, the recovery rate of the FO membrane decreased with increasing the ratio of  $Q_{f-in}/Q_{ds-in}$  in the enhance flow FO process. This was mainly due to the lower feed conversion ratio at higher  $Q_{f-in}/Q_{ds-in}$  ratios. For example, the feed flow rate doubled when the  $Q_{f-in}/Q_{ds-in}$  ratio increased from 4 to 8 whereas the NDP kept constant. However,  $Q_{f-in}/Q_{ds-in}$  ratio of 8 was required to alleviate the effect of CP on the feed side especially at high seawater salinities. Using high feed flow rates also increased power consumption of the FO process. Thus, the performance of PAFO and enhance flow FO processes was evaluated in terms of the power consumption. In general, specific power consumption,  $E_s$ , was higher at 50 g/L seawater salinity because of the higher feed osmotic pressure and lower NDP across the FO membrane (figure 2c). For PAFO process,  $E_s$  was 1.15 kWh/m<sup>3</sup> and 0.73 kWh/m<sup>3</sup>, respectively, at 50 g/L and 40 g/L seawater salinity and 6 bar feed pressure. At 8  $Q_{f-in}/Q_{ds-in}$  ratio,  $E_s$  was 1.58 kWh/m<sup>3</sup> and 0.83 kWh/m<sup>3</sup>, respectively, at

50 g/L and 40 g/L seawater salinity. However, results show that PAFO approach is more economic than enhanced flow FO approach (figure 2c). For the seawater salinities investigated in this study,  $E_s$  in the enhance flow FO approach was between 12% and 27% higher than that in the PAFO approach ( $Q_{f-in}/Q_{ds-in}$  ratio = 8).



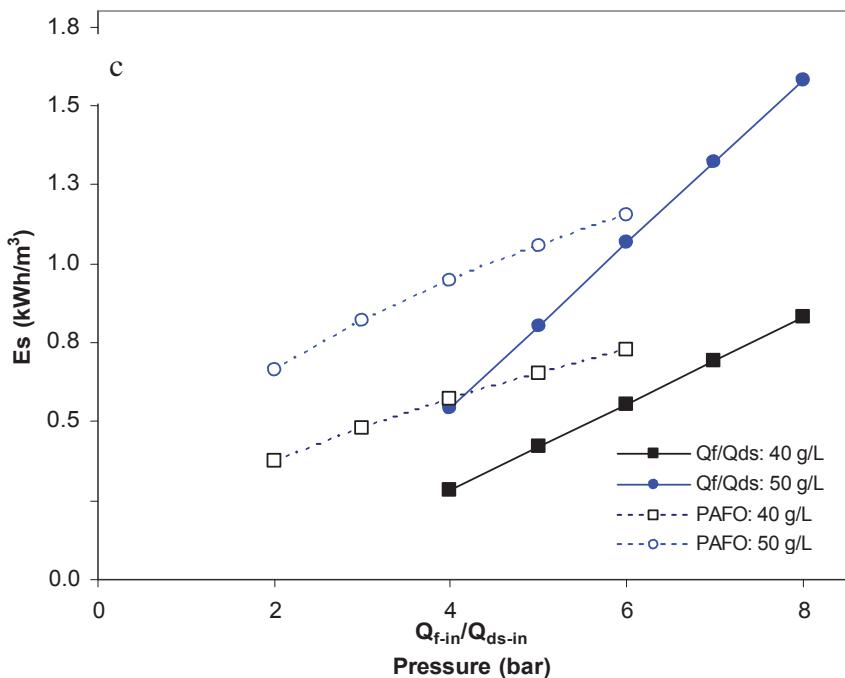


Figure 2: Impact of increasing feed pressure and flow rate on the FO performance a) membrane flux b) recovery rate c) specific power consumption

One of the important parameters in the PAFO-RO and enhanced flow FO approaches. Higher dilution of the draw solution means the lower energy requirements for regeneration of draw solution in the RO process. Figure 3 shows the concentration of diluted draw solution from the PAFO-RO and enhanced flow FO. The impact of increasing the feed flow rate on the TDS of diluted draw solution,  $C_{ds-o}$ , was insignificantly low, e.g. between 0.28% and 0.2%. However, the impact of the increasing feed pressure in the PAFO-RO on the  $C_{ds-o}$  was more obvious. This shows that PAFO-RO approach was more efficient in diluting the draw solution than the enhanced flow FO approach. This in turn will effect the cost of RO regeneration process which is the most energy intensive step in the FO-RO system.

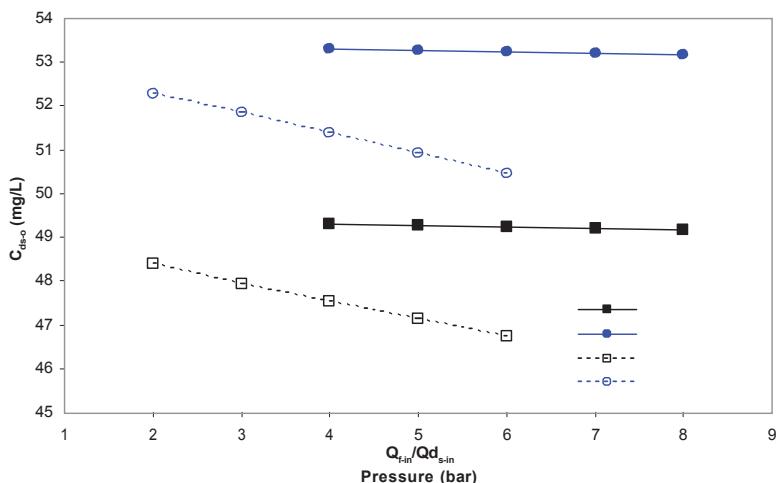


Figure 3: Concentration of diluted draw solution in the PAFO-RO and conventional RO systems

### 3.2 Impact of membrane orientation

The effect of membrane orientation on the performance of the PAFO-RO system was investigated for 40 g/L and 50 g/L seawater salinities. The results in figure 4 show the impact of membrane orientation on the membrane flux. Concentration polarization results in a lower membrane flux due to i) decreasing the osmotic pressure gradient across the membrane by the dilution of draw solution, Dilutive Concentration Polarization (DCP) ii) accumulation of solute in the porous support layer, Concentrative Concentration Polarization (CCP). Simulation results indicate that water flux was slightly higher when the membrane was operating in the PRO mode (draw solution was facing the active layer). These results are in agreement with previous studies which demonstrated that higher membrane flux can be achieved when the FO membrane operates in PRO mode [23, 32]. This was because the effect of DCP can be reduced when the membrane was operating in PRO mode by making the active layer smoother and denser to improve the shear stress at the membrane surface. The results showed that at 50 g/L and 6 bar feed pressure,  $J_w$  was 6.27 L/m<sup>2</sup>h and 6.31 L/m<sup>2</sup>h for the operating modes FO and PRO respectively. At 40 g/L  $J_w$  value was slightly higher; 9.7 L/m<sup>2</sup>h and 10.02 L/m<sup>2</sup>h for the operating modes FO and PRO respectively.

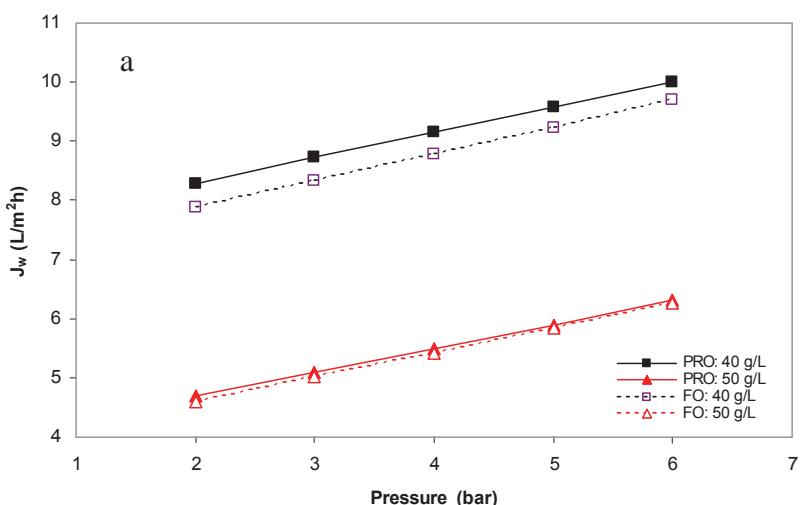


Figure 4: Impact of membrane orientation on the performance FO process

### 3.3 Performance of RO and FO-RO systems

The performance of PAFO-RO and RO systems was investigated for a number of feed salinities between 40 g/L and 50 g/L. It is assumed that conventional RO system performance would be affected by fouling while the performance of RO membrane in the PAFO-RO system is relatively constant over the membrane life (figure 5a). Due to the membrane fouling, water flux in the conventional RO system decreased with time. This was due to membrane permeability loss due to fouling and scaling problems. Membrane permeability during five years of the membrane life is shown in figure 5b. The membrane permeability,  $A_w$ , was 0.98 L/m<sup>2</sup>h.bar in year one and decreased to 0.69 L/m<sup>2</sup>h.bar after five years; this shows 30% decline in the  $A_w$  of the RO membrane. The figure also shows that membrane irreversible resistivity,  $R_{irr}$ , increased every year due to the fouling and scaling problems.

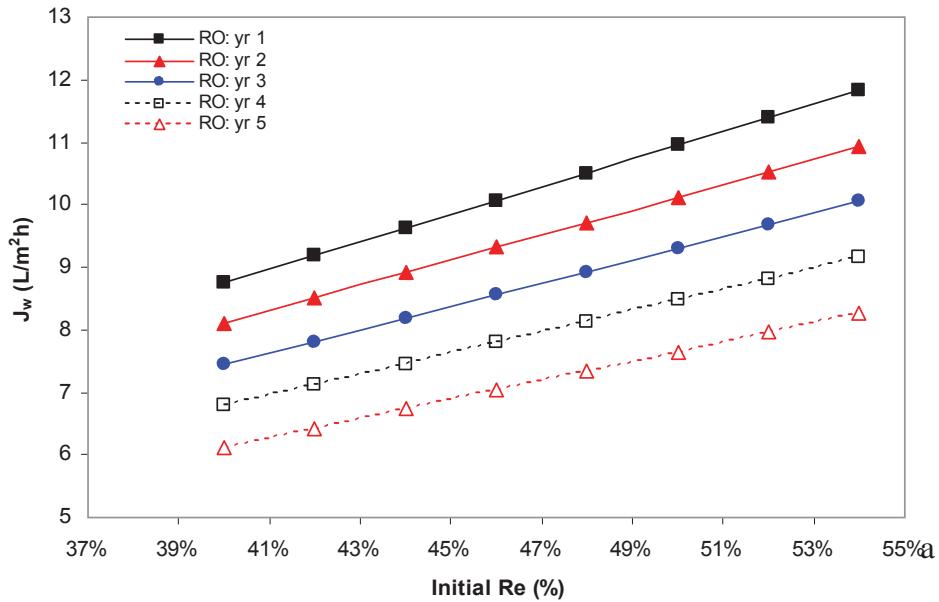
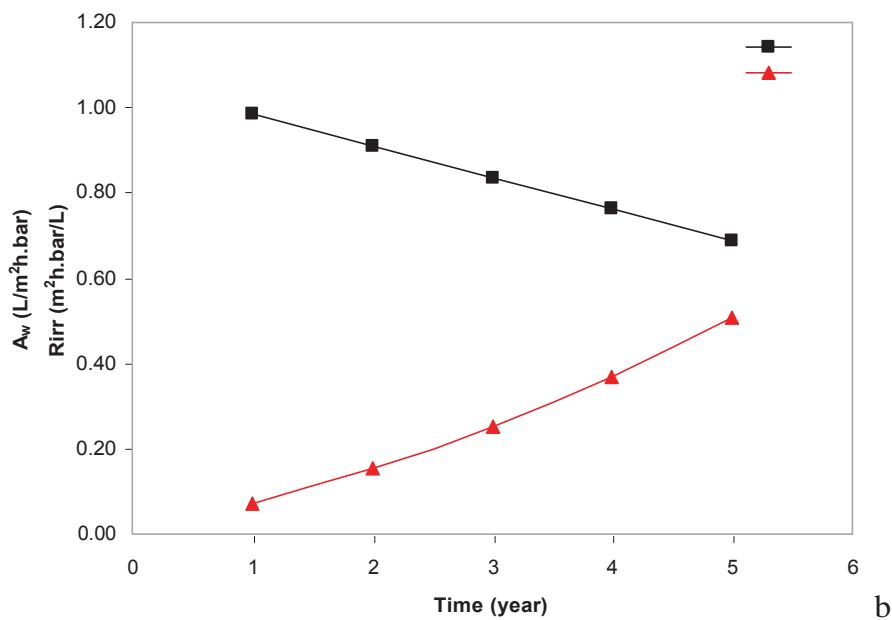


Figure 5c shows the Es and Est in the conventional RO and PAFO-RO systems, respectively. It should be mentioned here that optimum recovery rate in the conventional RO system shouldn't exceed 38% for 50 g/L seawater salinity and 40% for 40 g/L and 45 g/L seawater salinities to avoid accelerated and severe membrane fouling [31]. As such, PAFO-RO system was more energy efficient than the conventional RO system at 45 g/L and 50 g/L seawater salinities where as the conventional RO system was more efficient than PAFO-RO system at 40 g/L seawater salinity. Table 3 shows the specific power consumptions and recovery rates of PAFO-RO and conventional RO systems.



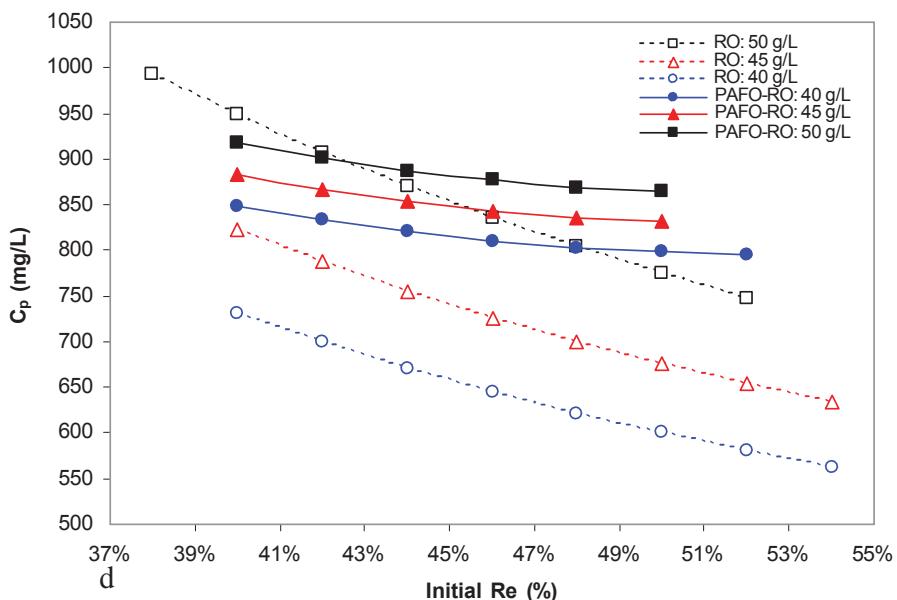
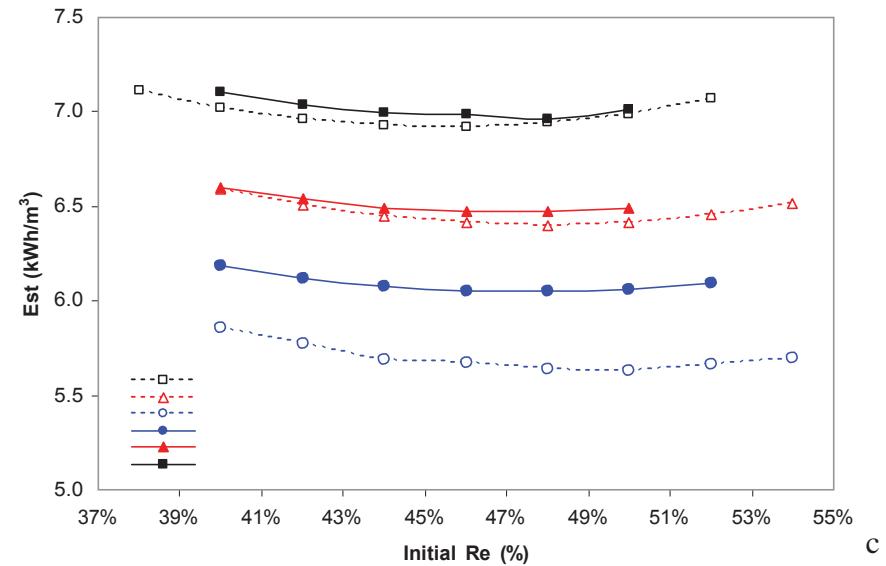


Figure 5: Performance of FO-RO and RO systems a) membrane flux b) conventional RO membrane permeability over time c) specific power consumption d) permeate concentration

Table 3: Power and recovery rates of the PAFO-RO and RO systems at different recovery rates

Process type	Seawater Salinity					
	40 g/L		45 g/L		50 g/L	
	%Re	Es	%Re	Es	%Re	Es
PAFO-RO	48	6.05	48	6.4	48	6.98
RO	40	5.86	40	6.6	38	7.11

Finally, the PAFO-RO and conventional RO systems were evaluated in terms of the permeate quality (figure 5d). The results show that permeate TDS,  $C_p$ , optimum

recovery rates was lower in the conventional RO than in the PAFO-RO system at 40 g/L while  $C_p$  was close in the conventional RO system and PAFO-RO systems was very close at 45 g/L; 823 mg/L and 836 mg/L respectively. At 50 g/L,  $C_p$  was 869 mg/L and 993 mg/L, respectively, for PAFO-RO system and conventional RO system.

#### 4. CONCLUSION

PAFO-RO system was proposed for the desalination of high salinity seawater. The performance of PAFO-RO system was compared with the conventional RO system to select the most cost-effective system for seawater desalination. PAFO and enhance flow FO approaches were investigated to enhance the performance of FO membrane and increases membrane flux. Simulation results showed that membrane flux and specific power consumption of the PAFO approach was better than of the flow enhanced FO approach. Furthermore, PAFO produced more diluted draw solution which required lower energy for regeneration by the RO process. The impact of membrane orientation was also investigated and found that PRO mode is more efficient than FO mode because of the higher water flux. The simulation results also showed that PAFO-RO system is more efficient and cost-effective than the conventional RO system especially at seawater salinities higher than 40 g/L meanwhile the conventional RO system was more energy efficient than PAFO-RO system at 40 g/L seawater salinity.

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# Comparison of Many-Objective Optimisation and Multi-Criteria Analysis for Improved Water-Energy Efficient Design of Water Treatment Works for India

Andrew P Duncan<sup>1\*</sup>, Seyed MK Sadr<sup>1</sup>, Fayyaz Ali Memon<sup>1</sup>,  
Dragan A Savic<sup>1</sup>

<sup>1</sup>University of Exeter Centre for Water Systems, Harrison Building, North Park Road, Exeter, EX4 4QF, UK

## ABSTRACT

**Aims:** This study aims to provide a Decision Support Software (DSS) tool for the water and energy-efficient design of water treatment works (WTWs) in India and to compare two alternative methods of optimisation of the treatment options for all unit processes and stages in the WTW. This applies to both potable water and wastewater treatment solution selection.

**Study Design:** The study involves a literature review of existing approaches to water treatment solution optimisation; stakeholder workshops (in India) to capture requirements of potential end users of the software; DSS tool design, coding, testing and implementation. Results are to be collected from a number of pilot site users as well as from lab studies. Analysis of results is to include comparative sensitivity analysis and for the 2 optimisation methods.

**Place and Duration of the Study:** The stakeholder workshops took place in India 5-7 May 2015. The software design, coding, implementation and analysis of results are being carried out at University of Exeter, UK, from September 2014 – August 2016 inclusive. Roll-out to pilot users in India will take place commencing Autumn 2015.

**Methodology:** Water and/or wastewater treatment is a complex process involving the simultaneous optimisation of a number of criteria, which can be grouped into the four categories of financial, technical, social and environmental objectives. Water and energy efficiency are assigned as technical objectives; since they can be measured directly, despite influencing all other categories of objective too. Design factors to be decided include choices of unit process at each of a number of stages in the treatment train. In turn, these are constrained by factors such as influent water quality, available footprint, budget and availability of skills and materials. Existing Decision Support Systems (DSS) software tools for water treatment optimisation have used a number of approaches. Using the novel WETSUiT (WatEr Treatment decision SUpport software Tool), we plan to investigate the performance of Many-Objective Optimisation (MOO) and compare it with Multi-Criteria Analysis (MCA). The former is a many-dimensional approach in which each objective is treated as equally important and facilitates the ultimate design selection by a human Decision Maker (DM); the latter is a single dimensional approach in which the performance criteria are pre-assigned weightings so that the final decision is automatic. Strengths and limitations of each optimisation approach, as applied to water treatment are delineated. Pilot case studies will be in collaboration with our Indian project partners and stakeholders.

**Results:** The results of the initial stakeholder workshops are summarised in this paper and will inform the final design of the WETSUiT tool for deployment in India, both for potable water treatment (Water4India Project) and wastewater treatment and re-use (Project Saraswati).

**Conclusions:** Water-energy efficient treatment plant designs for India will thus be facilitated for the future.

**Keywords:** [decision maker, decision support, many-objective optimisation, multi-criteria analysis, treatment train, water-energy efficiency, water treatment]

\* Tel: +44 1392 724075; E-mail address: [a.p.duncan@exeter.ac.uk](mailto:a.p.duncan@exeter.ac.uk).

## 1. INTRODUCTION

India faces multiple challenges regarding its scarce water resources. A history of poor water management has led to opportunities to improve treatment of water, both for potable use and of wastewater for industrial and/or agricultural re-use. Ongoing urbanisation and national government initiatives like the *Swachh Bharat* (Healthy India) mission (mainly directed towards rural India) are creating unprecedented demand for water and wastewater treatment [1], [2]. Consequently, the potential for water re-use also presents an opportunity to improve both water and energy efficiency.

The selection of potable water or wastewater treatment train solutions are complex processes involving multiple criteria of fitness, multiple choices of technology and multiple constraints. This makes unaided manual selection a challenging task and one that, whilst it may produce acceptable solutions, is relatively unlikely to achieve the global optimum as measured by the criteria of fitness chosen. To simplify the manual task, criteria may in practice be omitted.

Joint EU-Indian Government funded projects such as Water4India [3] and Saraswati [4] address some of the above challenges through collaboration of a number of Indian and European partners. As part of these projects decision support software (DSS) tools are being provided to stakeholders. These aim to aid the above complex decision making processes involved in selection of optimal water treatment technology solutions. The flexible design of such software tools allows for water and energy efficiency to be prioritised as performance criteria, when evaluating alternative solutions.

## 2. LITERATURE REVIEW OF DECISION SUPPORT SOFTWARE

Historically, DSS tools have taken different approaches and key examples are now reviewed. The process of synthesis of treatment trains for municipal wastewater treatment was first explored by Rossman [5], [6] during the course of which the EXEC/OP model was developed. This is aimed at generating a set of attractive design alternatives for wastewater treatment. Eight conventional wastewater treatment processes, ranging from influent pumping to chlorination, and thirteen sludge treatment processes were included in the model. The rules according to which the various treatment processes might be combined were specified by a relatively simple flow diagram.

Process	Cost		Net Energy	
	(\$/1000m <sup>3</sup> )	(% of Total)	(kWh/1000m <sup>3</sup> )	(% of Total)
<b>Least-cost system:</b>				
Pumping	8.5	11.6	37.0	10.8
Preliminary treatment	4.2	5.8	1.0	0.3
Primary sedimentation	7.1	9.8	2.0	0.6
Activated sludge	22.2	30.4	166.0	48.3
Chlorination	6.6	9.1	32.0	9.3
Anaerobic digestion	5.8	8.0	79.0	23.0
Gravity thickening	1.1	1.4	0.3	0.1
Sand drying beds	8.2	11.2	0.3	0.1
Incineration	9.2	12.7	26.0	7.6
<b>Least-energy system:</b>				
Pumping	8.5	10.0	37.0	13.9
Preliminary treatment	4.2	5.0	1.0	0.4
Primary sedimentation	7.1	8.5	2.0	0.8
Activated sludge	22.2	26.3	169.0	63.7
Chlorination	6.6	7.8	32.0	12.1
Lime stabilization	2.4	2.8	16.0	6.0
Sand drying beds	18.8	22.3	0.5	0.2
Truck transport / landfilling	14.5	17.2	8.0	3.0

**Fig 1. Example of unit process cost and energy consumption for least-cost and least-energy system scenarios (after Rossman) [6]**

The indicators used were total financial costs or net energy consumption (without energy recovery), either of which required minimisation using a single-objective optimisation approach. Fig 1 is reproduced from Rossman [6] and details unit financial costs and net energy consumption for the two optimisation scenarios. Rossman later developed a hybrid approach to generate alternatives [7], which included a structured knowledge base containing: List of unit processes and indicators for estimating their performance, Rules for excluding a unit process based on acceptable configurations and area limitations, Unit process pre-treatment requirements and Procedures for estimating real and pseudo-costs. A branch-and-bound algorithm based on state space search guided by knowledge-based heuristics was then used to determine treatment trains that meet the treatment goals by sequentially adding unit processes, and using a bounding condition to stop the addition of processes if the pseudo-costs exceeded a user-specified value.

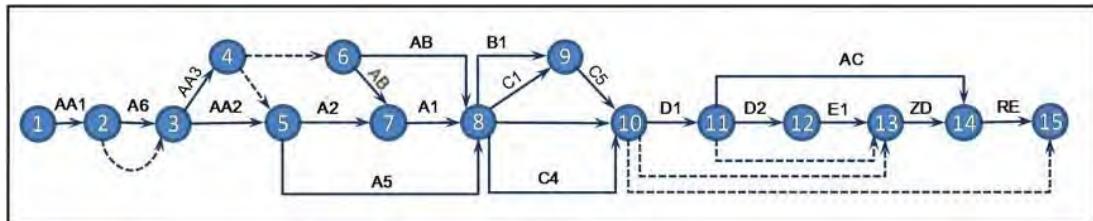
Chen and Beck [8] took the more computationally intensive but more exhaustive approach of Monte Carlo simulation [9] to synthesise treatment trains and identify more sustainable urban wastewater treatment options. The authors considered 22 liquid and 11 solids treatment technologies and specified rules that ensure that the treatment trains included conventional treatment as well as emerging novel techniques. They then generated randomly 50,000 feasible treatment trains (that met all the rules), and analysed the results to identify the unit process technologies most suitable to be used. The indicators used were grouped into two sets both of which had an emphasis on sustainability; the first of which focused on biochemical constituents of the effluent stream: C, N & P concentrations, heavy metals, biologically recalcitrant and toxic organic chemicals, pathogenic bacteria and viruses, suspended solids in the liquid treatment train and water content in the sludge treatment train. The second group of indicators focused on other factors: land area, capital and O&M costs, odour emissions, desirability (environmental global impact), robustness with respect to influent stream fluctuations, volume and water content of solid products, amounts of C, N and P recovered in the solids product. Where quantification of criteria was difficult, a grading scheme (1 .. 5) was used.

Krovvidy et al. [10] took the approach of developing treatment trains according to rules based on unit process performance data and external rules specifying the interactions between these technologies. Decision trees (ID3 algorithm) and data contained in the treatability database developed by the Hazardous Waste Treatment Research Division of the United States Environmental Protection Agency (USEPA) were used to generate about 230 rules that described the removal properties of a particular technology on a given compound at a given concentration [11]. This determined constraints for the processes. In the synthesis phase, the method uses an A\*-based heuristic search [12], [13] approach to generate viable alternative treatment trains that reduced the pollutant concentration to required levels. This was assessed using fuzzy possibility curves. The indicator criterion used was financial cost alone for solutions that met effluent quality constraints for a specified influent stream. The solutions were then ranked in increasing order of cost.

Yang and Kao [14] employed a similar approach that incorporated fuzzy preference rules specified by the user in the selection process. The application (and therefore the treatability database used) was for industrial wastewater treatment. Typically, the number of potential contaminants of concern is greater than that found for domestic/municipal wastewater treatment. Also, specific processes are often used for removal of specific pollutants, which makes the selection of treatment processes for industrial wastewater treatment significantly different from those for municipal wastewater treatment. Indicators were set for each process in terms of its treatment efficiency (for given chemicals) and financial cost.

The approach taken by Elimam and Kohler [15] in the sequencing of industrial wastewater treatment processes considered 22 unit processes, ranging from preliminary to tertiary treatment. Like Yang and Kao [14], the cost and pollutant removal efficiencies were provided for each process. Their sequencing rules were specified using an acyclic directed network, an example of which is shown in Fig 2. Here, each unit process was represented by a single labelled arc. The unlabelled 'dummy' arcs were used to encapsulate the precedence relationships between the processes. Fig 3 illustrates the approach taken by Elimam and Kohler [15], who constructed a table showing alternative processes for preliminary, primary,

secondary and tertiary treatment together with their estimated annual costs for an assumed nominal inflow level and percentages of pollutant removed for the indicators listed in Fig 3.



**Fig 2. Wastewater Treatment Network Directed Graph (after [15] [16]) Codes: see Fig 3.**

Characteristics of the treatment processes		Treatment classification	Process description	Code	Percentage of pollutant removed							
Cost (\$)	COD	TSS	TKN	TN	NH3	OIL	H2S	CR				
1. Preliminary treatment	Screening and grit removal	AA1	30.00	0	0	0	0	0	0	80	0	
	Balancing and cooling (lagoon)	AA2	155.00	0	0	0	0	0	0	0	0	
	Emergency storage (tank)	AA3	228.00	0	0	0	0	0	0	80	0	
2. Primary treatment	Dissolved air flotation	A1	105.00	20	50	0	0	0	75	50	50	
	Lime flocculation (flash mix)	A2	96.00	0	0	0	0	0	0	0	0	
	Alum flocculation (flash mix)	AB	58.00	0	0	0	0	0	0	0	0	
	Filtration for primary treatment	A5	241.00	0	80	0	0	0	75	0	0	
	Primary sedimentation (API)	A6	23.00	0	25	0	0	0	0	0	0	
	Primary sedimentation (chemical)	A7	34.00	20	67	0	0	0	67	0	50	
	Induced air flotation (IAF)	A8	60.00	0	60	0	0	0	67	50	0	
	Reverse osmosis	AC	68.00	80	95	90	90	90	90	90	90	
	Trickling filter	Bi	0.00	67	0	65	15	70	50	99.2	50	
3. Secondary treatment	Rotating biological contractor (RBC)	C1	0.00	67	0	65	15	70	50	99.2	50	
	Activated sludge: Conventional I	C3	251.00	75	0	90	20	90	60	99.2	50	
	Activated sludge: Conventional II	C4	296.00	75	0	95	85	95	60	99.2	50	
	Final tanks	C5	28.00	0	0	0	0	0	0	0	0	
4. Tertiary treatment	Filtration for secondary treatment	D1	241.00	40	40	0	0	0	50	0	0	
	Ozonation	D2	91.00	45	0	0	0	0	0	95	0	
	Activated carbon	E1	385.00	50	20	10	5	0	50	0	50	
	Chlorination	ZD	30.00	0	0	0	0	0	0	0	0	
	pH control	TK	43.00	0	0	0	0	0	0	0	0	
	Storage	RE	15.00	0	0	0	0	0	0	0	0	

**Fig 3. Characteristics of the treatment processes (after [15])**

This informs the many-objective optimisation (MOO) process for the design of WWTPs. Similar such data is a requirement for all the existing and proposed wastewater treatment technologies involved in the SARASWATI project, based on the parameters from the Indian Guidelines for Wastewater Treatment [17], [18].

Another approach taken by some researchers was to consider pre-determined combinations of unit processes forming treatment trains. This is appropriate for considering decentralised treatment packages gaining popularity in developing countries. For example, Tang et al. [19] include 46 and 94 combinations (decision variables) for wastewater and sludge treatment, respectively, and used the Analytical Hierarchy Process (AHP) to select the best treatment alternatives, using a matrix-mathematical technique with weights assigned for each process alternative.

The focus of the expert system developed by Economopoulou and Economopoulos [20] was on finding the least-cost treatment alternatives for small and medium communities of up to 5000 PE. The paper focused on the use of natural (sustainable) treatment processes. It also catered for seasonal variation, which, in Greece, can play a significant role due to climate (e.g. seasonal irrigation) and tourism. The methodology dealt simultaneously with treatment, reuse and/or disposal and was used to develop a rational management scheme that satisfied all relevant treatment requirements and receiving water quality standards. The expert system software developed was based on a conventional flow-chart style design.

Addou et al. [21] as well as Bick and Oron [22] also used AHP for the selection of the most appropriate wastewater treatment option. Five different treatment trains were used in their evaluation in each of the papers. The focus of these researchers was on a large number of

technical, environmental, social and economic factors considered in the selection process rather than the large number of possible treatment alternatives. These could be regarded variously as indicators (in terms of the objectives for the plant design) or constraints, where the factors set limits on the range or combination of decision variables in the design.

Dinesh [23], [24], in his PhD thesis, developed a knowledge base containing design and costing information for 39 wastewater treatment processes and six processes for sludge treatment and disposal. This was included in MOSTWATAR, a software package for optimum selection of technologies for wastewater reclamation and reuse. The knowledge base also contained a series of rules used in the generation of treatment trains, covering viable process configurations, site-specific considerations, and maximum allowable process influent pollutant levels. The generation of treatment trains was performed by a genetic algorithm (GA). Fitness criteria were based on qualitative scores [0-3] for each process to cater for intangible factors, such as ease of construction, plus financial cost.

The WAWTTAR decision support tool developed by Finney and Gerheart [25] was based on comprehensive information covering 200 different water and wastewater treatment processes. The information contained in the knowledge base on each unit process was classified under five categories (general, construction, O&M (operation and maintenance), siting, impacts, and on-site miscellaneous) covering a wide range of information ranging from costs to specifics of resources required for each unit process. In order to design appropriate solutions for the location, users could specify which treatment chemicals, media and what construction materials (from comprehensive lists) were available locally. The generation of treatment trains, however, was not guided and the tool required users' experience and familiarity with treatment processes in generation of treatment trains. The indicators used were selected from Capital Cost and O&M Cost or Total Cost, plus 6 standard water quality parameters, which were tracked through each process in the treatment trains: BOD, settleable solids, suspended solids, pH, oil and grease and faecal/total coliforms. An additional 5 constituents were critical for advanced secondary, tertiary, reuse and industrial treatment systems: nitrogen forms, phosphorus forms, metals, oocysts and COD.

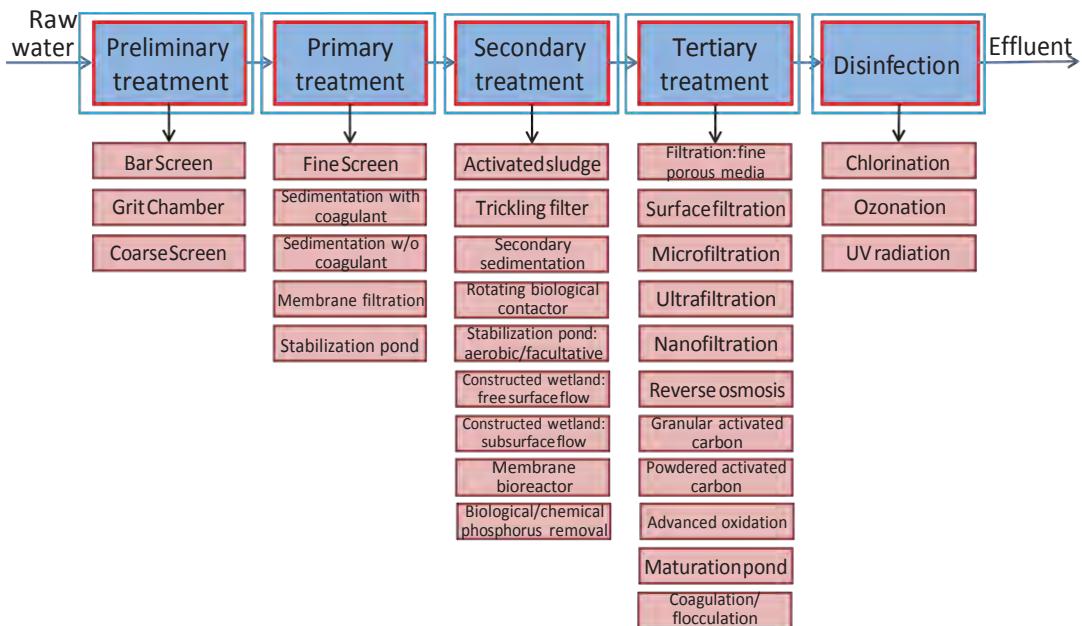
### **3. METHODOLOGY**

Building upon the work of the above researchers, this study proposes the WETSUIT (WatEr Treatment decision SUpport software Tool) and uses it to provide a means to evaluate the relative merits of Many Objective Optimisation (MOO) and Multi Criteria Analysis (MCA) approaches to selection of optimal potable water and wastewater treatment solutions. WETSUIT, therefore, combines a pre-selection process with an optimisation process (either MOO or MCA).

#### **3.1 Pre-selection process**

The pre-selection process is to be based on directed acyclic graphs to filter out non-feasible treatment trains - given the constraints: influent stream quality and quantity, available footprint, proposed use of effluent stream and solid by-products, allowable technologies (user-defined), process compatibility (matrix), availability of energy, financial budgets, materials and skills. Potentially feasible solutions then become candidates for the optimisation process, which mix-and-match treatment technologies at each required stage in the treatment train.

Fig 4 illustrates the variety of unit processes potentially available for selection at each of 5 stages of wastewater treatment in a train. Starting with the influent/raw water, a directed graph exists in which the nodes are the unit processes and the edges are the connections between processes at successive stages in the train. The graph represents a combinatorial explosion of potential treatment train configurations due to making successive choices of unit process at each of the 5 stages. However, some processes are mutually incompatible and these are disallowed by removal of the appropriate edges in the directed graph.



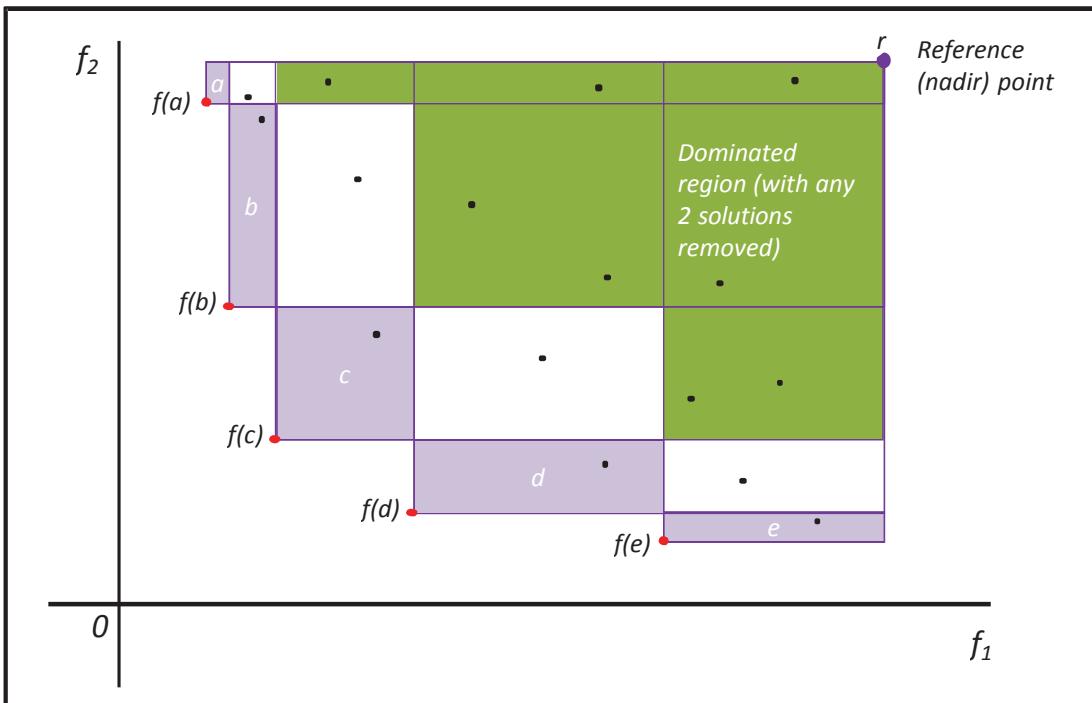
**Fig 4. Wastewater treatment unit process options at 5 stages in the treatment train**

### 3.2 Many Objective Optimisation

For the Many Objective Optimisation (MOO) approach, the M objective criteria are treated as orthogonal objectives in a (normalised) unit M-dimensional hypercube, of which water efficiency and energy efficiency are represented by two of the dimensions. Recent advances in Evolutionary Algorithms (EAs) allow the possibility of optimisation based on many objectives simultaneously; so it becomes feasible to optimise a number of criteria under the 4 groups headings: financial, technical, social and environmental, simultaneously. Hypervolume-based EAs, such as the Hyp-E algorithm [26], evaluate the fitness of each solution in relation to an entire population of candidate solutions. A fixed "nadir" point (guaranteed to be less fit than the solutions in the population in all of the objective dimensions) is taken as a reference point for the calculation of a hypervolume measure for the entire population of solutions [27]. Fig 5 illustrates the concept of hypervolume fitness in a 2D example with 5 candidate solutions ( $f(a)$ - $f(e)$ ) shown as well as the reference point ( $r$ ). The fitness of each solution is calculated by estimating the reduction in total hypervolume that would be caused by removal of that solution from the population. In Fig 5, these are represented by the light (mauve) shaded areas labelled "a" to "e" for each of the 5 solutions  $f(a)$ - $f(e)$ . Dominated solutions (represented by the black points) have a zero effect on total hypervolume, so can be removed from the population for the next generation (depending on elitist strategy adopted). The least fit non-dominated solution is that which would cause the smallest non-zero reduction in hypervolume (in the illustration  $f(a)$ ). This can also be removed from the population for the next generation; thus maintaining selection pressure. The HypE algorithm also considers multiple solution removal and the darker (green) shaded area in Fig 5 shows the hypervolume (in this 2D case, area) that is still dominated if any 2 of the solutions are removed from the population, as an example of the fitness evaluation strategy used.

At each generation, selection, crossover and mutation operators are applied as standard; except that the pre-selection process checks the feasibility of the offspring solutions prior to their inclusion in the new generation's population.

On completion of optimisation, the hypervolume measure can also be used to rank the candidate solutions, to facilitate the human Decision Maker (DM) in making the final selection of solution(s) to be implemented or investigated further. Results from the many-objective optimisation can be presented to the DM in the form of star diagrams with the same number of rays as objective criteria. In a cost minimisation approach, the DM would be looking for a star-polygon with a minimum area, for example.



**Fig 5. Hypervolume population fitness - 2D example with 5 non-dominated solutions ( $f(a)$ - $f(e)$ ) and many dominated ones (after [26])**

### 3.2 Multi-Criteria Analysis

For the Multi-Criteria Analysis (MCA) approach, the integrated AHP-PROMETHEE method is chosen as this combines advantages from the earlier, simple, Analytic Hierarchy Process (AHP) [28] with the Preference Ranking Organisation MeTHod for Enrichment Evaluations (PROMETHEE) [29], [30]. The combined method allows possibilities for group decision making through the use of a fuzzy-logic approach to the weighting scheme for the performance criteria. Again, candidate solutions will require checking using the pre-selection process to ensure compliance with all constraints.

### 3.3 Stakeholder Requirements Capture Workshops

Between 5 and 7 May 2015, Project Saraswati stakeholder workshops were held in Chennai, Mumbai and New Delhi, India to discuss the water quality guidelines and decision support tool and gather feedback on the requirements of potential users and stakeholders. Key messages from these workshops are summarised in section 4.1.

### 3.4 Evaluation Approach

The trial of the WETSUiT decision support tool is to be carried out using case studies from both potable water and wastewater treatment scenarios. The MOO and MCA approaches will be tested separately to evaluate their effectiveness in ensuring feasible solutions are produced in every case, using a variety of individual and aggregated criteria and a range of numbers of criteria. A sensitivity analysis of MCA with respect to changes in values of criteria weights will be made.

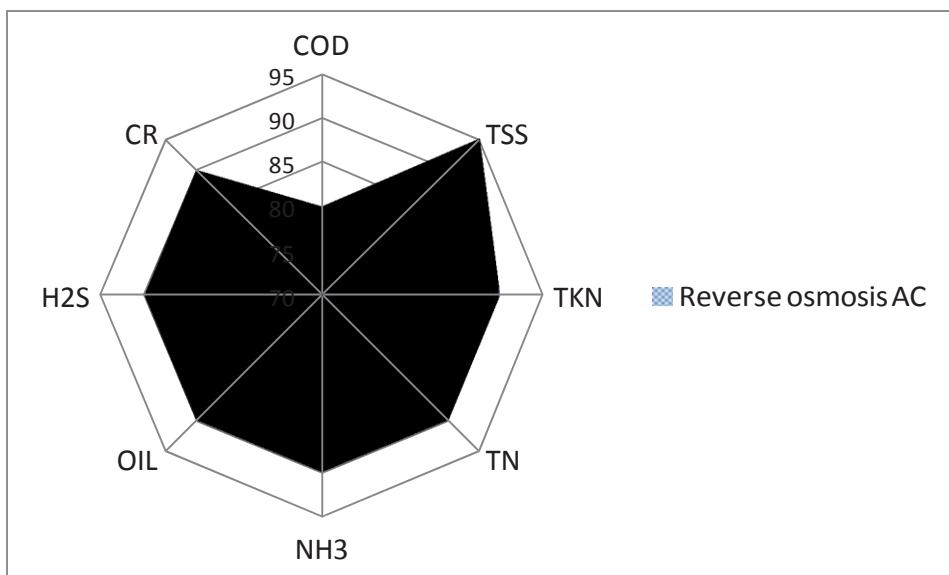
Additionally a comparative trial will be conducted to quantify: 1) Execution times (mean and spread); 2) Correlation between the MOO's and MCA's rankings of candidate solutions. 3) Euclidean norm of criteria performance of the rank 1 solution proposed in each case.

A trial focusing on relative effectiveness of the two approaches to optimise both energy and water efficiency specifically will also be carried out.

## 4. RESULTS AND DISCUSSION

This conference paper describes current work being undertaken, the software for which is currently at the coding stage. The contribution of the study is intended to be to test the effectiveness of the use of recent developments in optimisation algorithms in their application to water treatment decision support, when larger numbers of performance criteria are used than previously. It is also intended to compare the MOO approach with the MCA approach and conduct case studies to allow users to feedback their experiences and preferences for the uses of these 2 approaches. Therefore it is intended for WETSUIT to present results to the users by employing star diagrams (see Fig 6) and stacked bar charts, which can be used for both of these optimisation methodologies.

In order to assess the requirements of the DSS tool, three stakeholder workshops were held in India from 5-7 May 2015. Stakeholders were largely drawn from water professionals from Indian local government, utilities, consultants and academics and were approximately 100 in number total, over the 3 workshops held in Chennai, Mumbai and New Delhi.



**Fig 6. Star diagram showing example of pollutant removal percentage efficiency for a reverse osmosis unit process against 8 independent criteria (pollutants) as the rays of the chart**

### 4.1 Key Messages from Stakeholder Workshops

#### **Potential end users**

A question was asked regarding who might potentially use the DS tool software and the responses from all 6 breakout groups at the 3 workshops are briefly summarised as follows:

- Housing colonies; Drainage boards; Engineers (e.g. from watchdogs; environmental regulators); Municipalities / Urban Local Bodies; Panchayats; Apartment complex managers; Construction industry (civil engineers / architects); O&M companies; NGO's; Consultants; Academic institutions.

#### **Proposals from stakeholders for improving uptake of the DSS tool**

The points below represent a collection of the most often repeated responses regarding how to improve potential uptake of the DSS software tool. These were from 2 breakout groups held at each of the 3 workshops:

- The software needs to be freely downloadable and accessible in the long term (after the end of the project)
- A programme of capacity building, awareness and user training as well as publicity and promotion is required. This should be included in curriculum of educational institutions (e.g. Environmental Engineering).

- Dissemination should also be online and through social media.
- A self-learning feature should be incorporated; based on comparison of ranked best solutions with that finally chosen by the DM for each scenario
- A list of strengths and weaknesses for each technology in the library should be provided
- Localized software versions in a number of Indian languages would be preferred
- Support from policy makers should be sought
- The trial of the WETSUIT decision support tool is to be carried out using pilot case studies in conjunction with key stakeholders.
- A water credit scheme could be adopted
- A multi-platform application will allow use on tablets and smart-phones as well as PCs.

**Required / desired DSS software features**

The points below represent a collection of the most often repeated responses regarding features required for the DSS software tool. These were from the breakout groups held at all 3 workshops:

- A clear-cut ranking of solutions is preferred in order to aid the final decision
- Social acceptability is an important group of criteria to include
- Other important criteria include: techno-economic indices; environmental impact; possible water credits;
- The software should be flexible and adaptable to new technologies
- Needs to comply with water directives, standards and guidelines
- Printable output is required
- Users must be able to define local rates, technology preferences, budget constraints etc.
- The software should provide risk, uncertainty and sensitivity analyses
- The software needs to operate for a range of scales of water treatment solution (decentralised / centralised)
- A 2-stage process should be adopted: 1) Constraints handling 2) Optimisation
- An alarm for inconsistent data should be provided.

The coding work for the WETSUIT DSS tool is currently ongoing and results of the case studies using it will be presented at future conferences and through journal papers. A study focusing specifically on water-energy efficiency is also planned.

## 5. CONCLUSION

In conclusion, this paper has reviewed historical and existing decision support software (DSS) tools for water treatment applications. The ongoing study itself aims to build on this as well as to exploit recent advances in MOO and MCA algorithms to demonstrate and compare achievable performance in DSS tools for selection of technology solutions for both potable water and wastewater treatment. The results are to be reported in future journal publications.

## ACKNOWLEDGEMENTS

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## COMPETING INTERESTS

None.

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# Cultivation of microalgae with membrane-filtered wastewater: implications for energy and nutrient recovery from wastewater

Pickett, M.<sup>1</sup>, Ozcan, O.<sup>1</sup>, Jean, H.<sup>1</sup>, Quinones, A.<sup>1</sup>, Moore, K.<sup>2</sup>, Love, J.<sup>2</sup>,  
Yeh, D.<sup>1\*</sup>

<sup>1</sup> Department of Civil & Environmental Engineering, University of South Florida, 4202 E.  
Fowler Ave, ENB11B, Tampa, FL 33620, USA

<sup>2</sup> Biosciences, College of Life and Environmental Sciences, University of Exeter, Stocker  
Road, Exeter, EX4 4QD, UK

## ABSTRACT

The incorporation of algal cultivation at the wastewater treatment plant (WWTP) setting provides a steady source of water and nutrients for algal growth, and uses photosynthetic energy to remove nutrients, reducing WWTP energy and chemical demands. Furthermore, this advantageous relationship generates a biofuel crop for additional energy production. The diverse microbial fauna, as found naturally occurring in wastewater streams, has the potential to affect algal growth, either negatively (through grazing or competition) or positively (through symbiosis). This specific research is aimed at investigating the direct relationship between the cultivated microalgae *Chlorella sorokiniana* and naturally occurring wastewater microorganisms under realistic growth conditions. Clarified wastewater effluent (Clarified effluent- CE raw) was collected from the Exeter WWTP and membrane-filtered to remove microorganisms at two size cutoffs: microfiltration (MF- 0.1μm nominal pore size) and ultrafiltration (UF- 40kDa molecular weight cutoff). Overall, nutrient removal and growth rates remained efficient with all growth mediums. Diurnal growth curve fluctuations show a distinction between the three wastewater streams, with the microfiltered clarified effluent stream (CE MF) having the largest changes in curve amplitude. The implications of these variations in growth patterns are not well understood, though the interactions amongst naturally occurring microorganisms in the wastewater do affect the growth of the algal cells. Overall, wastewater can be a suitable medium to cultivate algal biomass product and has the potential to result in energy savings in a scaled-up system.

*Keywords:* algae, wastewater treatment, biofuel, *Chlorella sorokiniana*, membrane, ultrafiltration, microfiltration

\* Tel.: +1 (813) 974-4746; fax: +1 (813) 974-2957.

E-mail address: dhyeh@usf.edu.

## 1. INTRODUCTION

Whether or not “peak oil” is an actuality [1], there appears to be a strong scientific consensus on the anthropogenic nature of climate change and a significant correlation between climate change effects and increasing atmospheric greenhouse gas concentrations [2,3]. Between the years 1751 and 2012, an estimated 356 billion metric tons of carbon have been released to Earth’s atmosphere through anthropogenic fossil fuel consumption and cement production [4], in contrast with approximately 2 trillion metric tons of carbon that existed in the atmosphere in 1750s. One strategy to slow down carbon accumulation in the atmosphere is to switch from fossil fuels to renewable biofuels in an attempt to create a direct recycle loop between carbon dioxide assimilation to biomass via photosynthesis and the subsequent oxidation of the biomass back to carbon dioxide via combustion.

A variety of biofuel crops, including corn, switch grass and canola, have been researched for their potential to adequately replace some proportion of the global fossil fuel demand. Theoretically, algal cultivation for biofuel requires less water and results in higher biomass and energy yields compared to other biofuel crops due to much faster growthrates. Alga is more desirable than other proposed biofuel crops due to its lack of competition with food crops, compared to corn for example. Terrestrial biofuel crops require large areas of land, fresh water and fertilizers for growth. Comparatively, algae do not require much land use, can be cultivated in both fresh and saline water, and can obtain nutrients from prevalent sources of nutrients such as wastewater streams. [5]

The incorporation of algae cultivation at the wastewater treatment plan setting creates a mutually beneficial relationship. Wastewater treatment plants are required to meet discharge standard limits, often times including restrictions on nutrient levels. Nutrient removal contributes significantly to the overall energy demands of a plant and can be reduced with the inclusion of algae cultivation. [5, 6] Algae are also benefitting plant operations via CO<sub>2</sub> sequestration; plants utilizing aeration basins produce high quantities of CO<sub>2</sub> (via respiration of aerobic heterotrophs) and algae consume CO<sub>2</sub> during photosynthesis.

## 2. MATERIAL AND METHODS

### 2.1 Stock Culture

Stock cultures of *Chlorella sorokiniana* were obtained from the Scottish Association for Marine Science (Oban, Scotland) and were cultivated in Chu 13 Medium [7] over several weeks to provide inocula for continuous experimental trials.

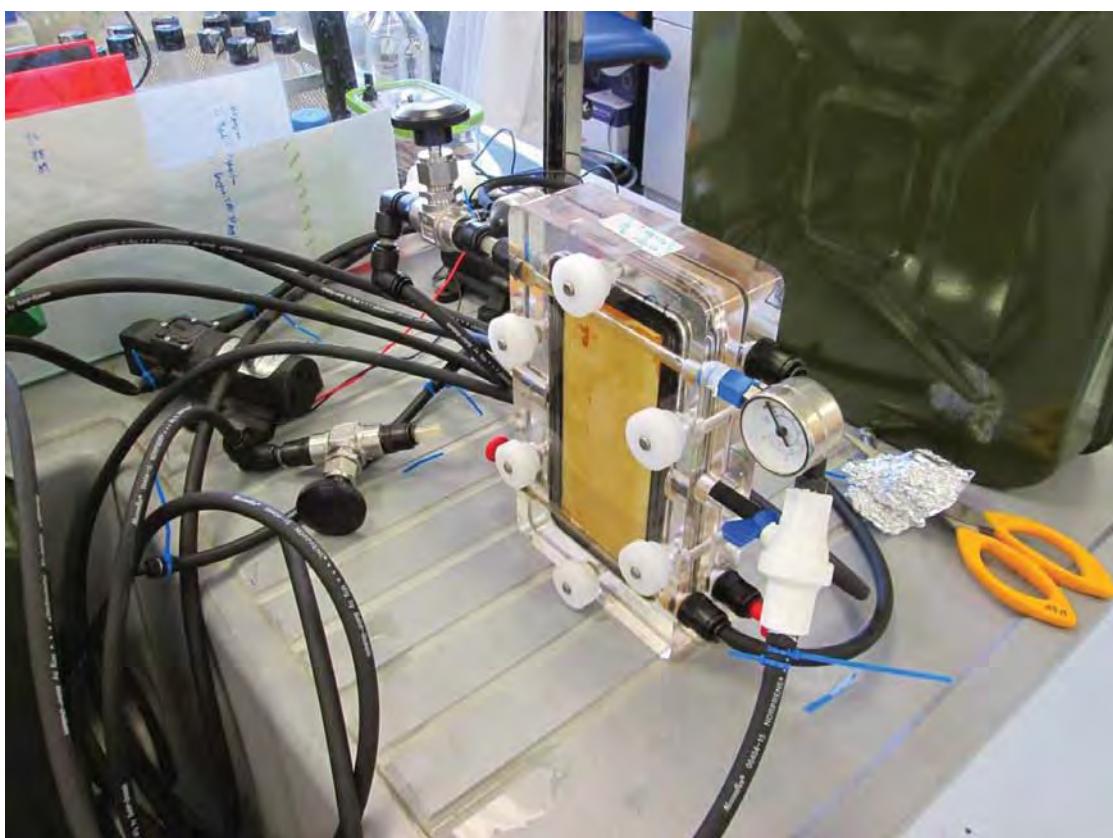
### 2.2 Feedstocks

Post nitrification clarifier effluent stream from Exeter Municipal WWTP, henceforth referred to as clarified effluent (CE), was used as one of the feedstocks, and it was further filtered using Rayflow crossflow filtration modules by Orelis Environment (Salindres, France) (Fig. 1) through 0.1 µm nominal pore size microfiltration (MF) and 40 kDa molecular weight cut off (MWCO) ultrafiltration (UF) polyvinylidene fluoride (PVDF) membranes, yielding two additional feedstock types for experimentation. A total of four feedstock types were therefore used for the experimental trials: Chu 13 Medium (Reference Media), the unfiltered CE stream (CE Raw), the MF filtrate of CE (CE MF), and the UF filtrate of CE (CE UF).

### 2.3 Cultivation

All experiments were conducted as batch cultivated systems using 1 L Erlenmeyer flasks, which were filled up to 0.6 L line per batch with a mixture of feed and algal inocula for every trial, excluding blanks, which did not contain any inoculum. Cultivation was done within Algem incubators by Algenuity (Stewartby, UK) (Fig. 2). Air was supplied to the cultures at approximately 50 cm<sup>3</sup>/min. The incubators were programmed to mimic average local (Exeter, UK) climate for the month of June in terms of temperature and dynamic light intensity for day and night cycles using global coordinates. This was done to ensure a better fit for the experimental conditions to a real life application scenario involving the cultivation of *Chlorella sorokiniana* on-site using Exeter WWTP’s clarified effluent stream. Batch cultivation was

performed for the duration of 7 days per experimental run, and four samples were taken from each reactor over this time period. At the start of each run, reactors were inoculated with the stock culture of *Chlorella sorokiniana* to an optical density of 0.2 at 600 nm wavelength, an accepted starting point for algal cultures, with the exception of blanks. To do this and to ensure no background interference from the varying growth mediums, the volume of stock algae needed was determined based Chu media as background, i.e., no interference at 600 nm. The same volume of stock algae culture was added to each of the flasks, independent of growth medium. Optical density was the only method of measuring culture growth used.



**Fig. 1. Rayflow membrane modules used for wastewater filtration**

#### **2.4 Randomization**

In order to ensure random distribution of errors, temporal and spatial distributions of reactors were randomized. A total of 27 trial runs were performed, which were randomly distributed over 6 weeks with 4 to 7 replicates per feed type within 6 incubators that were operational at any given time.

#### **2.5 Filtration of samples**

All samples taken were filtered through 1 µm nominal pore size Whatman Nuclepore Track-Etch Membrane filters (GE Healthcare Bio-Sciences, Pittsburgh, USA) in order to differentiate between associated and non-associated fractions of the microbial communities within the reactors for further genomic analysis which is not included in this study. All nutrient testing was done on the non-associated (filtrate) stream generated by this process, yielding information on the soluble fractions of the available nutrients.

#### **2.6 Analytical nutrient methods**

Culture density was monitored in real time using Algem incubators' built-in optical density sensors at a set wavelength of 740 nm. Total Nitrogen (TN), Ammonium Nitrogen ( $\text{NH}_4\text{-N}$ ), Nitrate Nitrogen ( $\text{NO}_3\text{-N}$ ), and Total Phosphorus (TP) were analyzed using Hach Methods 8000, 10072, 10031, 10020, 10127, respectively (Hach Lange Company: Salford, UK). TN and TP analyses were conducted only on soluble fractions of processed samples. Therefore these two parameters will be referred to as Soluble Nitrogen (SN) and Soluble Phosphorus (SP), respectively.

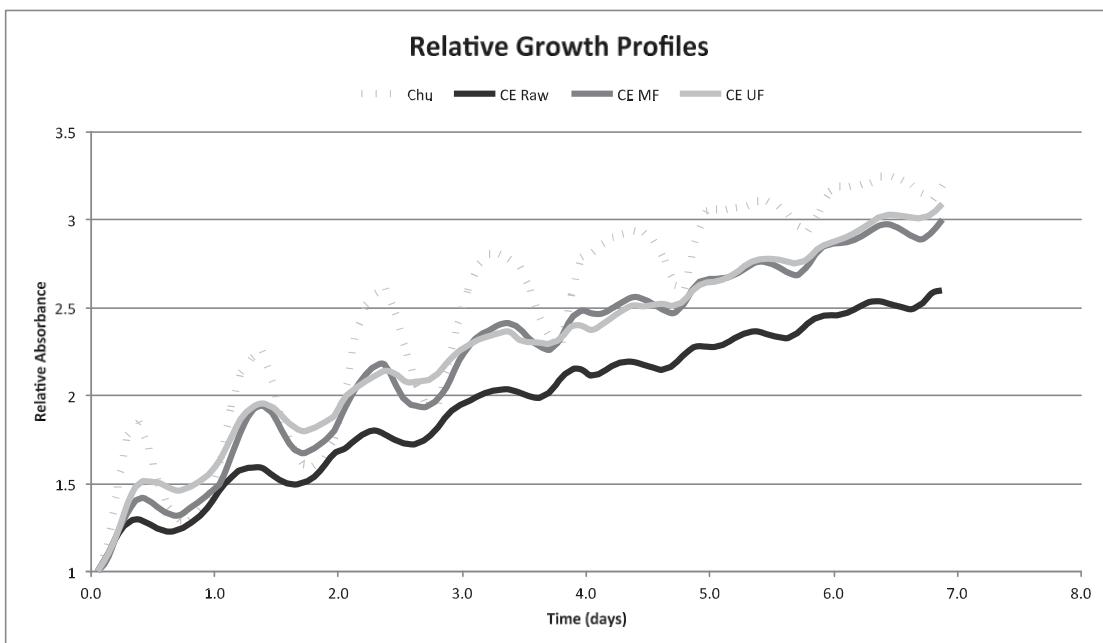


**Fig. 2. Algem photobioreactor systems used for algae cultivation in this study**

### 3. RESULTS AND DISCUSSION

#### 3.1 Growth curves

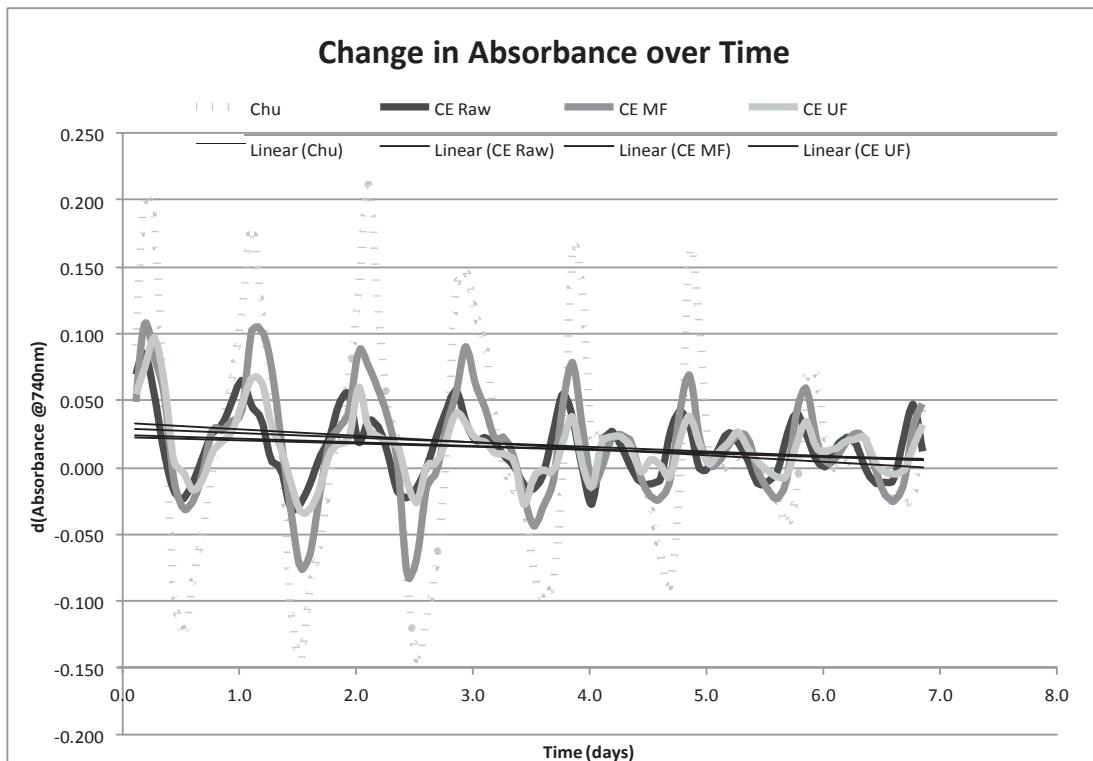
Based on optical density readings, all series exhibited diurnally fluctuating trends (Fig. 3), which has not been previously observed in the literature to the best of our knowledge. The diurnal pattern was most pronounced in the Chu series. Growth rates ranked in the order of Chu media > CE UF = CE MF > CE raw (unfiltered), based on overall growth normalized over the seven day growth period. Overall, successful algal growth was achieved within each medium. It is possible that significant microbial diversity within the CE Raw medium resulted in more competition and therefore a slightly lower algal growth. However, the CE MF and CE UF overall growth is quite comparable to that of the growth media, Chu. This confirms that clarified effluent wastewater is a suitable medium for algal growth, with some limitations including possible competition or predation from autochthonous wastewater biota.



**Fig. 3. Growth profiles for *Chlorella sorokiniana* cultures grown in different feeds over 7 days, quantified by real time absorbance measurements at 740 nm. Chu, CE Raw, CE MF and CE UF represent the four feedstocks used in the experiment.**

#### 3.2 Nutrient removal

Nutrient removal efficiencies remained high for each of the growth mediums analyzed. Over the 7-day growth period, soluble phosphorus was consistently completely removed. Because nutrient analysis was done only at the end of the growth period, it is unclear when phosphorus in the system was depleted; phosphorus-limited conditions could have been the result of decline in growth rates. Figure 4 shows the change in growth over time. The negative slopes of the linear trendlines on the figure implicate declining cultures at the time of harvest, seven days, i.e., no longer in exponential phase possibly due to nutrient-limited conditions. Similar to phosphorus removal, significant portions of soluble nitrogen, ammonia and nitrate, were removed over the growth of the cultures.



**Fig. 4. Change in Absorbance at 740nm over time with linear trendlines for each growth medium: Chu media, CE Raw, CE MF, CE UF.**

Both influent and effluent nutrient results are provided for further analysis in Table 1. Unprocessed post nitrification clarified effluent (CE Raw) SN, NH<sub>4</sub>-N, NO<sub>3</sub>-N, and SP were 47.0 ±3.9, 6.8 ±0.6, 35.4 ±6.1, and 2.5 ±0.6 mg/L, respectively. To note, Chu medium did not contain any ammonia to start. The decreasing influent SP concentrations may have occurred through the initial medium filtration process; as the membrane pore size decreases, the SP concentration decreases.

**Table 1. Initial (i) and final (f) concentrations (in mg/L) of each nutrient parameter for *Chlorella sorokiniana* cultures batch cultivated over 7 days in feedstock types Chu, CE Raw, CE MF, and CE UF. Initial values represent post-inoculation soluble nutrient concentrations. Error figures to the right represent one standard deviation. The corresponding percent removal is reported for each nutrient parameter.**

	SN <sub>i</sub>	SN <sub>f</sub>	%♦	NH <sub>4</sub> -N <sub>i</sub>	NH <sub>4</sub> -N <sub>f</sub>	%♦	NO <sub>3</sub> -N <sub>i</sub>	NO <sub>3</sub> -N <sub>f</sub>	%♦	SP <sub>i</sub>	SP <sub>f</sub>	%♦
Chu	46.0 ±4.6	31.2 ±3.4	31%	0.0 ±0.0	0.2 ±0.4	0% 99%	45.9 ±3.9	15.9 ±2.9	65% 48%	63.4 ±2.6	1.6 ±0.7	97%
CE Raw	46.6 ±3.7	21.4 ±2.8	54%	4.8 ±0.4	0.1 ±0.2	99% 99%	34.1 ±4.4	17.2 ±3.0	48% 53%	15.5 ±3.5	0.0 ±0.0	100%
CE MF	44.0 ±2.9	21.3 ±1.9	52%	6.0 ±0.6	0.1 ±0.3	99% 100%	37.6 ±2.6	17.7 ±1.7	53% 48%	12.5 ±3.8	0.0 ±0.0	100%
CE UF	43.7 ±3.6	22.6 ±3.2	48%	5.8 ±1.7	0.0 ±0.0	100% 99%	36.0 ±3.4	18.8 ±2.7	48% 53%	9.5 ±2.9	0.0 ±0.0	100%

#### 4. CONCLUSION

Exponential growth was observed for *Chlorella sorokiniana* within all feedstocks tested in 7 days of batch cultivation under realistic conditions for Exeter UK. Complete removal of

ammonium nitrogen and phosphorus were observed, which may be both due to microbial uptake and precipitation-stripping mechanisms of ammonium and phosphate at elevated pH levels. Since all systems became phosphorus limited during the 7-day trial runs, the absolute potential for nitrate, and consequently, soluble nitrogen removal is currently unknown under the specified conditions. No significant difference was observed between cultivation using filtered and unfiltered versions of the post nitrification clarified effluent in terms of growth or nutrient removal potential. Wastewater has been shown to provide adequate nutrients, freshwater and energy for algal growth, which can efficiently convert wastewater into potentially valuable resources [6]. Results from the study will inform engineers and scientists regarding engineering design, process kinetics and microbial ecologies of the growing field of integrated algae cultivation and wastewater treatment.

## ACKNOWLEDGEMENTS

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# Estimation of the costs of energy for commercially available dewatering technologies in aggregate industry

Ezatollah Mozaffari\*, Bijan Maleki, Amin Zargaran, Sara Jalili

Imam Khomeini International University, Qazvin Iran, P. O. Box 2BB

## ABSTRACT

**Aims:** To estimate the costs of energy used for three commercially available dewatering technologies in aggregate industry.

**Study design:** To technically analysis the three dewatering systems to highlight the most energy consuming aspects associated with these systems.

**Place and Duration of Study:** Imam Khomeini International University, Qazvin Iran, July 2014 to Sep. 2014.

**Methodology:** Replacing a new dewatering system with that of the old one is a challenge. It should be more cost-effective and bring about more enviro-economic benefits. The three technologies are compared in terms of their mechanical and hydrodynamic parts. An energy-wise comparative study would assist us to assess their performance. Conducting preliminary energy balance and cost estimation would also be shown to be theoretically useful.

**Results:** Tests were specifically conducted with the Jameson cell to find out its capability in dewatering sludge for the aggregate industry. The results demonstrated that the estimated costs are lower for the Jameson cell.

**Conclusion:** The Jameson cell is found to be an energy saving dewatering alternative for the aggregate industry when compared with the dissolved air flotation and thickener technologies.

**Keywords:** *sludge dewatering, Jameson cell, dissolved air flotation, thickeners, energy costs, aggregate industry*

## 1. INTRODUCTION

The aggregate and ready mix concrete industries in Iran use a great deal of water and the rate is increasing by about 5% per year [1]. With the increase in production of these industries, an additional volume of water is required. Dewatering of sludge from sand and gravel washing is therefore a major concern to aggregate and construction materials production industry. Often, the clarification systems they use need reviewing, because of being old fashion and less effective. For example, there are hundreds of aggregate production plants in Tehran urban areas and surroundings. Many of these plants do not have effective systems for clarifying water and recycling. The aggregate industry uses water primarily to wash out the silts, clays and foreign materials from the raw material and to separate out the excess fines in the classification of the salable product. The amount of water needed per tone is dependent upon the amount of contaminants that need to be scrubbed off or washed from the product and the amount of fines that may have to be separated out. The process of washing is done using a number of equipments including washing screens and classifiers. The more fines are created the higher amount of water and energy is needed for removal. Use of water varies from 10 l/t to 500 l/t depending on the materials processed. The discharged water from the plant also varies from a light to heavy concentration of suspended particles ranging from fine sand to silts and clays to colored pigments [2].

\* Tel.: +9828 33901133

E-mail address: eazem101@yahoo.co.uk

The conventional method of clarifying this waste water is comprised of some hydro cyclones followed by a series of settling ponds. The settling ponds are inefficient and impose a great deal of energy losses. A new survey in Iran shows that only around 50% of the water could be recycled [3]. This figure should change because the crisis of water scarcity in dry areas such as Qom is becoming worse [2]. The use of chemicals such as coagulants and flocculants to help particles and contaminants sediment in the ponds is vital, but there need to be a change in the conventional settling systems. This paper investigates the energy efficiency of three commercially available technologies to improve the settling time and water recycling. The replacement is compromised by making a comparison between the newly introduced system and those already in use in the industrial sludge dewatering. These technologies will be demonstrated in terms of their mechanical and hydrodynamic parts. An energy-wise comparative study will follow to assess their performance. It will be demonstrated how the replacement model could be more energy saving and cost effective taking a theoretical energy balance and cost estimation approach. More importantly is the energy consumption which is the issue of our discussion in this paper. We investigate the likelihood of replacing the existing sludge ponds in aggregate industry with any of the three introduced technologies for energy saving comparison.

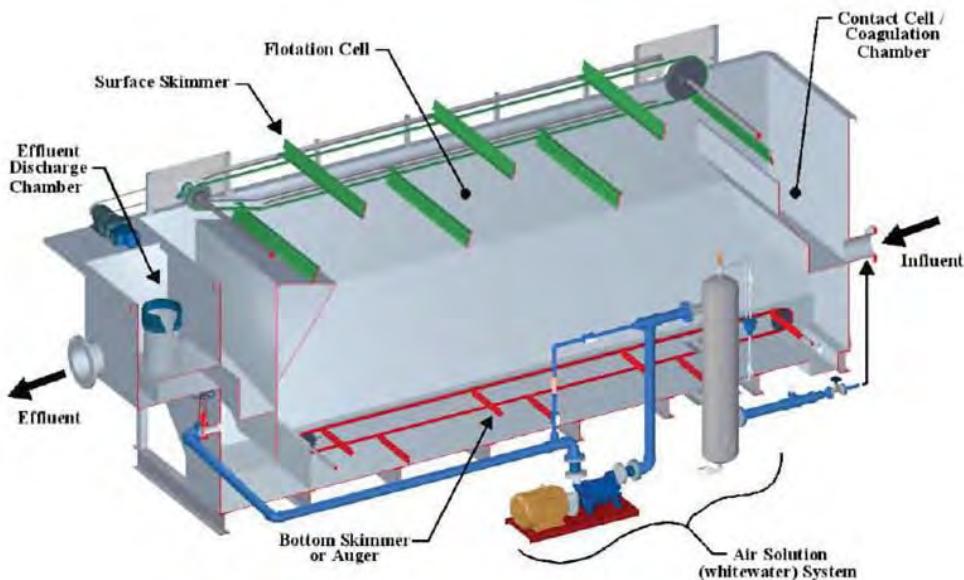
## **2. COAGULATION/FLOCCULATION/FLOTATION, A COMBINED TECHNOLOGY**

Conventional coagulation-flocculation practices are essential pretreatments prior to sedimentation processes. These process agglomerate suspended solids together into larger bodies so that they can more easily settle. A chemical coagulant, such as iron salts, aluminum salts, or polymers, is added to source water to facilitate bonding among particulates. Coagulants work by creating a chemical reaction and eliminating the negative charges that cause particles to repel each other. The process requires chemical knowledge of source water characteristics to ensure that an effective coagulant mix is employed. Improper coagulants make these treatment methods ineffective.

However, it has been observed that the settling time is too long giving rise to an incomplete dewatering process. Not only is the old method time consuming but also is energy consuming [4]. Thus, the method should be accompanied or combined with other methods to improve the dewatering efficiency. The two well established methods are the thickening and the flotation methods. Flotation is a method of generating bubbles and making them available for particles to attach to bubbles. It is a separation method based on particles surface chemistry as well as system hydrodynamics. Thickening is also a solid liquid separation method in which provisions are made for the generated flocs to be recovered while the clear water is recycled.

### **2.1 Dissolved Air Flotation**

A conventional combined method incorporates coagulation/flocculation/flotation in one package called dissolved air flotation system [5]. The removal is achieved by dissolving air in the water or wastewater under pressure and then releasing the air at atmospheric pressure in a flotation tank or basin. The released air forms tiny bubbles which adhere to the suspended matter causing the suspended matter to float to the surface of the water where it may then be removed by a skimming device [6] (Figure 1).



**Fig. 1. Schematic view of the DAF system [6]**

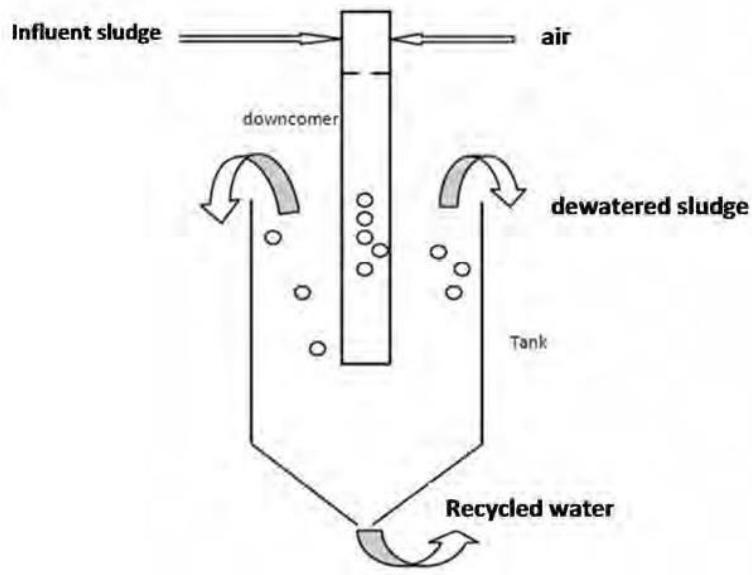
A portion of the clarified effluent water is pumped into a small pressure vessel into which compressed air is also introduced. In order to release the tiny air bubbles into the tank, first the effluent water is pressurized with air. The air-saturated water flows through a pressure reduction valve just as it enters the front of the float tank. Moreover, a pump is needed for conveying the clarified effluent water, also a raking skimmer is mounted at the bottom of the tank to prevent flocs from being settled. The system particularly well-suited for the removal of algae, unwanted coloring and lighter particles that resist settling out of treated source water [16].

## 2.2 The Jameson Cell flotation technology

The Jameson cell originally was invented by Professor Graeme Jameson from the University of Newcastle, NSW, Australia the late 1980s, and since then been used extensively in the mineral processing and industrial wastewater treatment fields [7, 8].

The prime features of the Jameson cell have been introduced elsewhere [9, 10], but its innovative potential for effective dewatering will be discussed here. That the Jameson cell possesses hydrodynamic characteristics that bring about energy saving is of more interest in this research. The Jameson cell is an innovative flotation process driven by fluid mechanics. The principle of using air bubbles to recover particles is the basis of the technology. The advantages of modern Jameson cells are generating small bubble size. The air is self-induced and an external compressor or blower is not required. It also occupies small footprint and offers operator-friendly designs. Figure 1 shows a schematic view of Jameson cell. As can be seen there is no mechanical part fixed for agitation, which is an unavoidable part in conventional flotation devices. The fine bubbles are consistently generated through imparting intense mixing which brings about rapid flotation and high capacity. It is simple operation and is extremely energy efficient. The way air bubbles are generated and their interaction with particles in the Jameson cell is the key for achieving high efficiency. The energy for flotation is delivered by conventional pump power consumption, and is therefore significantly lower than the equivalent mechanical flotation cell [11].

The downcomer, the middle column shown in Figure 2, is the heart of the Jameson cell where intense contact between air bubbles and particles occurs. Feed is pumped into the downcomer through the slurry lens orifice creating a high-pressure jet. The jet of liquid shears and entrains air from the atmosphere. Removal of air inside the downcomer creates a vacuum, causing a liquid column to be drawn up inside the downcomer.



**Fig. 2. Schematic view of the Jameson cell [8]**

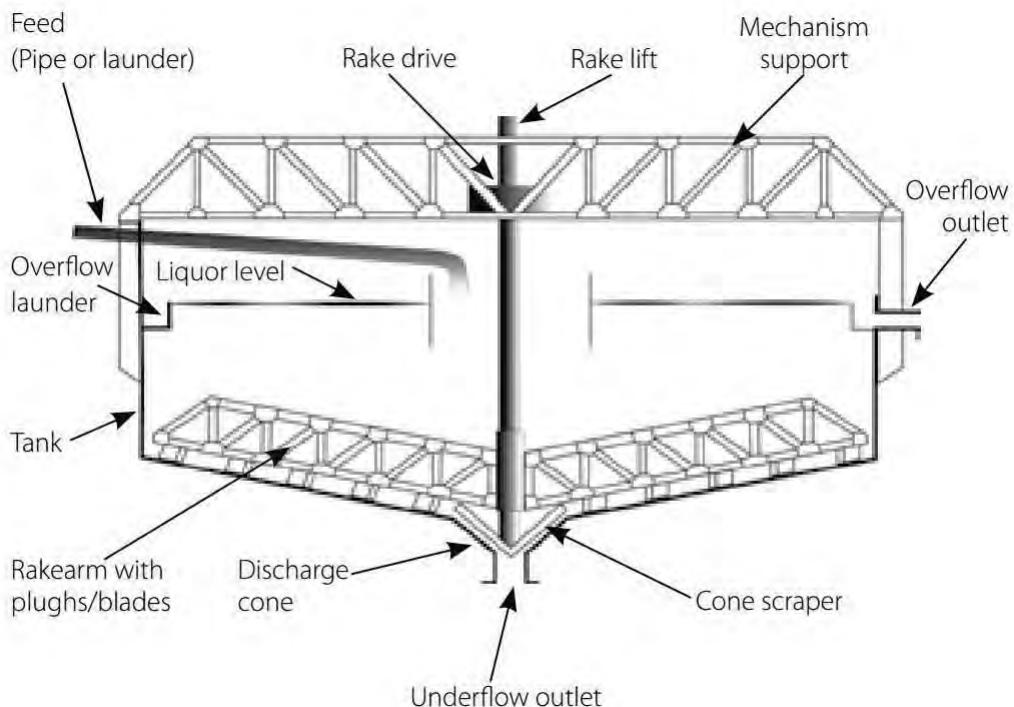
The jet plunges into the liquid column where the kinetic energy of impact breaks the air into fine bubbles which collide with clay and silt particles. The very high interfacial surface area and intense mixing result in rapid particle attachment to the air bubbles, and high cell carrying capacities. The downcomer is where bubble-particle collision, attachment and collection occur. The different hydrodynamic regions of the downcomer are the free jet, induction trumpet, plunging jet, mixing zone and pipe flow zone. The tank pulp zone, external column shown in Figure 1, is where clay and silt-laden bubbles are disengaged from the downcomer. The tank, also known as separation cell, is designed to ensure an efficient, quiescent zone for separation of clay and silt-laden bubbles from the cleaned pulp [12]. Such a design maximizes safe removal of particle-bubble aggregates into the froth zone at the top of the tank and a clean clay-free and silt-free water discharged from the bottom of the tank.

It can be shown that how the input energy by the feed pump dissipated all through hydrodynamic system, as explained above and resulted in effective and fast dewatering of sludge.

### 2.3 The gravity thickeners

Gravity thickeners are vastly used in mining and mineral processing industries [13]. They are normally low in height but long in diameter to provide enough retention time to the incoming sludge to settle. The way the influent enter the thickener is important. Arrangements must be made to dampen the turbulence of the incoming feed so that the entry into the thickener will be as laminar as possible and will not interfere with the solids that are already settling inside the tank. This is done by feed well as shown in Figure 3. In order to convey the settled solids from the entire area to the discharge cone the raking arms are designed. The drive head, together with the raking arms, are the heart of the thickening system. The drive head may be driven by up to 4 electric motors. The torque may be calculated using the following formula:

$$T = 1 \dots \quad (1)$$



**Fig. 3. Schematic view of an industrial scale thickener [14]**

Besides, there is a need for a lifting device and torque control. The lifting device is the element that raises and lowers the raking arms during operation so that the blades follow the interface of the settled solids by monitoring the torque. Pumping of dense underflows is always a problem on thickeners, because the position of the pumps in relation to the discharge cone can be very critical.

In addition to the above, sometimes a mixing tank is needed to accomplish the flocculation prior to thickening. Some newly designed thickeners may have this mixing system inside them, which in turn makes the system even more complicated.

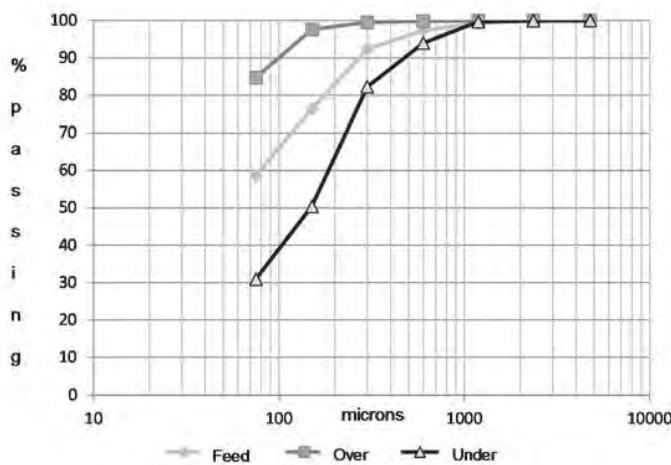
### 3. EXPERIMENTAL PROCEDURE

In order to study the dewatering efficiency of the Jameson cell in aggregate industry, one of the plants, the Alvand aggregate plant located in Qom province in Central Iran was selected for sampling. The plant uses conventional flocculation-sedimentation method with very inefficient settling ponds. The discharge to the ponds is the overflow of the two hydro cyclones. Samples, 50 lit each, were collected and sent to the lab. For testing with the Jameson cell. Full scale experiments were run adding the flocculent solution on line to the system at a point just below the air inlet entrance. The flocculent solution was prepared in desired dilution. The feed tank was filled with sludge and the Jameson cell was run while the flocculent solution being added at the injection point. This way, the two processes (flocculation and flotation) could be combined in single stage.

### 4. RESULTS AND DISCUSSION

#### 4.1 Size analysis of samples

Figure 4 shows the size distribution of hydro cyclone feed, underflow and overflow (the testing sludge).



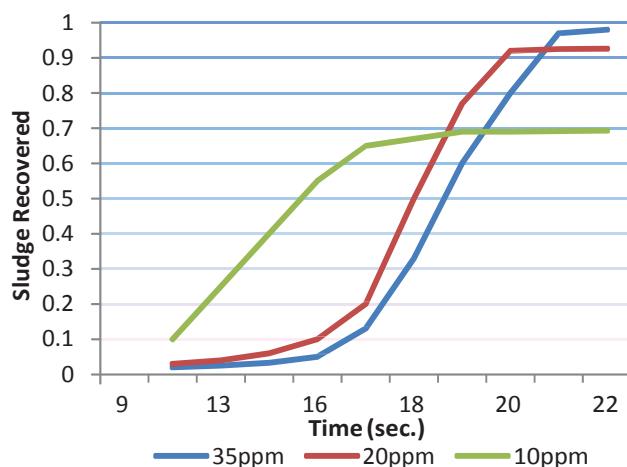
**Fig. 4. Size distribution of hydro cyclone feed, underflow and overflow (sludge)**

#### 4.2 Flocculation test results

The results of the sludge conditioning with flocculent shows that the rate of sedimentation was improved considerably using commercial Magnafloc flocculent. Settling rate was approximately 16 time faster in the case of using Magnafloc flocculent. With this improvement it can be concluded that a residence time of minimum 6mins. Will be required for the thickener to let the flocs settle.

#### 4.3 The Jameson cell test results

The results of the full scale experiments are shown in Figure 5. It can be seen that over 97% of the suspended solid in the sludge was recovered to the froth. This is in agreement with other researchers who recover minerals and coal in the Jameson cell [12]. Figure 5 also shows that the system is capable of removing the suspended solid in less than 22sec.



**Fig. 5. Sludge removal in the Jameson cell at different doses (ppm) MIBC frother**

The recovered froth is low in volume and thick enough for easy handling and removal. The water recovery also indicates over 80% that is comparable to that of conventional settling pond method (50%).

#### 4.4 Reporting on the performance of DAF and thickeners

The DAF performance data may be collected for making comparison with that of the Jameson cell [15, 16]. When working at a desired condition that is to fill the flotation tank with numerated number of tiny bubbles, the system can produce recoveries as high as 97% similar to that of the Jameson cell. However, the process does not work well with highly turbid waters because heavier particles, like silt and clay, are not as easily floated to the water surface. This figure is reported for suspended matter such as oil and organic particles [16].

The thickeners' performance data collected from the mine sites in Iran reveals that large thickeners could hardly produce thickened sludge. Reports from iron ore mines in central Iran indicate that the solid content of the final tailings is between 45% to 55% [16]. However, some worldwide mining equipment manufactures claim that they have improved their thickeners' performance by incorporating sophisticated mechanical parts [14].

## 5. THE CHALLENGES OF WATER-ENERGY FOR AGGREGATE INDUSTRY

Water and energy are intertwined. As the energy is required for water treatment, the water also is required for energy production. Therefore, reusing wastewater and closing water and energy cycles is one way to address reducing resources. We look at the range of energy required to convey and treat water to acceptable levels. This range may vary from 0.2 to 1.4-1.5 kWh/m<sup>3</sup> depending on the pumping head, level of treatment and plant capacity [14].

It can be demonstrated that by introducing and replacing a new dewatering system to the existing sedimentation ponds in the aggregate plants energy could be saved in the followings: Recycling more water (80% instead of 50%), and producing thicker residue with potential reuse. In the next discussion section a comparing energy prices for the three dewatering systems will be introduced. Tables 1 to 3 show the scale and operating conditions of DAF, thickeners and the Jameson cell.

**Table 1. The Jameson cell system**

Scale	Total Influent flow (gpm)	Total Air flow rate (gpm)
Full Scale	330	33

**Table 2. DAF system [6]**

Scale	Influent flow (gpm)	Recycle rate (gpm)	Recycle pressure in the vessel, (psig)	Air injection rate (cfh)
Full Scale	330	90	80	65

**Table 3. Thickeners system [13, 14]**

Scale	Influent flow (gpm)	Diameter (m)	Driver Motor	Driver Motor Torque (Nm)
Full Scale	330	8	Some (4 or more) electric motors	11680

### 5.1 The pumping costs

It should be noted that in this case study the influent rate is 75 m<sup>3</sup>/h which is equivalent to 330 gpm. It has also been assumed that the influent flow should be pumped up to 4m (14 feet) high to reach the systems. Therefore, the pumping cost of inlet flow could be calculated by the following equation [17]:

$$C_{\text{Pumping}} = 0.7 \cdot Qhc / (390 \mu_p \mu_m) \quad (2)$$

where, C is cost per hour, Q is volume flow (gpm), H is head (ft), c is cost rate per kWh,  $\mu_p$  and  $\mu_m$  are the pump and motor efficiency, respectively.

Substituting the head equals to 10 feet for the thickener and DAF systems, and 25 feet for the Jameson cell as well as the cost rate per kWh in order of £0.1, the pumping cost may be calculated to be approximately £0.086044 and £0.21511 for thickener and Jameson systems, respectively. These values are the pumping costs per hour valid for the Jameson and for the thickener systems. But, for the DAF system, an extra pumping cost will be needed for recycling a portion of the clarified effluent. Thus, an additional 40% of the cost of the main pump may be considered making the total pumping cost for the DAF system in order of £0.1204616 per hour.

## 5.2 The Air Compressing and the Driver Motor costs

Theoretically, the power required for the adiabatic compression of air can be expressed as [18]:

$$P_{\text{Compressor}} = [1 - N P_1 V k / 33000 (k - 1)] [(P_2 / P_1)^{(k-1)/Nk} - 1] \quad (3)$$

Where  $P$  is compressor power,  $N$  is number of compression stages,  $K$  is adiabatic expansion coefficient,  $V$  is volume of compressed air at atmospheric pressure, also  $P_1$  and  $P_2$  are absolute initial and final pressure, respectively. So compressor power equals to 0.15 hp.

Therefore, the cost of compressing the air for the DAF system will be [18]:

$$C_{\text{Compressor}} = (0.7 \cdot P_{\text{Compressor}} \cdot c) / \mu_c \quad (4)$$

Where  $\mu_c$  is efficiency of the compressor. So, cost of compressing the air for the DAF system will become £0.0131647 per hour.

As for the thickeners energy cost estimation, there also exists the driver motor cost. The required power is calculated using equation (1), where the value 8 is given for the coefficient  $K$ . The driver motor cost of a thickener with 10m diameter and with a torque of 11680 Nm will be [13, 18]:

$$P_{\text{Driver}} = wT \quad (5)$$

Using a driver motor with 11680 N.m torque and angular velocity of 20 (rpm), the associated power could be worked out as 24.457 kW.

which, will yield the associated cost as:

$$C = P_c \quad (6)$$

Therefore, the cost of this driver motor will be £2.4457 per hour.

As for the DAF system, there are two driver motors which support both the top and float skimmers. The skimmer system consists of non-metallic glass reinforced nylon chain with a maximum recommended working load of 1740 lbs., or average ultimate strength of 2800 lbs. In a double pitch roller chain [19]. So, energy costs for 2 skimmers of DAF system are:

For the top skimmers:

$$P_{\text{Skimmer}} = FV \quad (7)$$

Thus, the power for the top skimmer is 7.7399 kW and also for the bottom skimmer it will be 12.455 kW. The associated costs therefore will be £0.774 and £1.2455 per hour for the top and bottom skimmers, respectively.

## 5.3 The comparing energy costs

Finally, the energy cost comparison for the three dewatering systems may be worked out as in Table 4:

**Table 4. Energy cost comparison for the three dewatering systems**

System	Pumping Cost	Air Compressing Cost	Driver Motor Cost	Total Cost
DAF	£0.1205	£0.0132	£0.774+£1.2455	£2.1532
Thickeners	£0.0860	-----	£2.4457	£2.5317
Jameson cell	£0.2151	-----	-----	£0.2151

The Jameson cell offers a short retention time (~20sec., Figure 5) with no extra energy consuming sections. However, in the thickeners and DAF systems the motor driver exerts extra energy. They also require much larger volumes because the sludge must reside longer (~20mins) in these systems. In order to lower the risk of overestimation/underestimation it has been attempted to avoid being close to the cut-off values. For example, thickeners come with diameters much larger than 10m [14]. The cost of compressing the air for the DAF system is also estimated taking an air volumetric rate that is analogous to the rate of influent flow [18]. It can be argued that one of the most energy consuming design factor in thickeners is handling the thickened sludge in large volumes. Likewise, the way the tiny air bubbles are introduced to the DAF system demands extra energy both for the bubble generation and for the skimming stage [15]. It can, therefore be concluded that the shorter the sludge resides in the system (as in the Jameson cell) the less energy required for displacing the thickened sludge.

It must be born in mind that some factor such as using the pumps in high pressure conditions might incur further cost. This might be the case in DAF, where pumping a portion of the clarified effluent water would further increase the air compressing cost. Moreover, the use of mechanical and moving parts that is inevitable in the thickeners and DAF systems imparts further maintenance costs to these systems giving rise to more energy demands and losses [20].

## 6. CONCLUDING REMARK

The water cycle in aggregate production plants contribute significantly to the amount of energy consumed. Particularly, in a dry area like Qom which suffers from shortage of water, and they must bring water in trucks from long distances. The Jameson cell can be a competent solution to replace the old fashion settling pond sludge dewatering. It is expected that the device will be capable of treating sludge with higher yields and clay and silt removals. This will have a profound effect when reviewing the energy efficiency in comparison to DAF and thickeners. This high collection efficiency is because of higher probability of floc-bubble collision / attachment prevails in the downcomer. Shorter residence time brings about higher capacity making it capable of treating more sludge in shorter time.

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## COMPETING INTERESTS

The authors have no financial relations to other projects in regard to this research.

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# INTEGRATED WATER MANAGEMENT

## Future-proofing Integrated Water Resources Management: Taking an iterative approach to developing resilience frameworks

Dr Mary Gearey\*

School of Environment and Technology, University of Brighton,  
Cockcroft Building, Lewes Road, Brighton, BN2 4GJ, UK

### ABSTRACT

**Aims:** The aim of this paper is to contribute to a discussion around the potential role of resilience theory in adaptive Integrated Water Resources Management (IWRM) strategies.

**Study design:** Resilience theory offers water resource managers, practitioners and communities of interest the opportunity to imagine a much more porous boundary between those who govern water resources and those who consume water resources in light of changing water conditions. Yet resilience is a contested term, with most examples of resilience identified after a disruptive event has caused resilient actions, processes or responses to surface. As a result, practitioners and citizens are exposed to a multiplicity of case studies of resilience-in-action resulting from natural hazards or calamitous social events, but with scant guidance as to how to recognise ex-ante resilience and nurture it within the organisations, processes and communities they work with.

**Methodology:** Three different resilience matrices are critiqued, taken from the fields of humanitarian relief, urban contingency planning and social-ecological systems, to isolate which components may be of use to IWRM practitioners when preparing resilient planning strategies.

**Results:** Resilience appears to be iteratively developed through action, social learning, within representative institutions and through shared goals. The type of resilience sought, be it system maintenance or system transformation, seems secondary to the need for a negotiated consensus on 'what happens next'.

**Conclusion:** Rather than a static, prescriptive tool for IWRM, it is hoped that envisioning innovative resilience framework(s) will initiate conversations between water resource practitioners and communities of interest, with future-proofing, in its widest sense, at its heart.

Keywords: *resilience, resilience frameworks, future-proofing, Integrated Water Resource Management (IWRM)*

### 1. INTRODUCTION

Water environments in England and other developed economies, will face a range of challenges over the next twenty five years. These dynamic changing water conditions are produced by a complex range of drivers including water resource competition due to population rises and urban clustering, different, sometimes conflicting, use of catchments by a variety of stakeholders, together with factors associated with climate change perturbations (IPCC 2012). These changes are multifarious, multi-scalar and multi-temporal, and create unknown future pathways which require a re-evaluation both of natural resource management techniques and a shift in the way we as a society use and value water (Dovers and Handmer 1992). The dominant paradigm has been universal potable water supply, based on principles such as public health and equitable access to resources. Thinking ahead, water stress, in all its myriad

forms, may lead to a regime shift in which universal provision cannot be guaranteed. Further, an inability to pay rising water charges will be the hallmark of the coming decade. The effects of austerity on the ability of 'delinquent' consumers to pay for water services have already taken hold. Residents in Detroit, USA, falling behind on their water service accounts by only \$150 have had their domestic water supply turned off by the local water municipality ahead of privatisation (Independent, June 23rd 2014). The situation in Detroit is not unique in the USA. Baltimore City's Department of Public Works began issuing 'shut off' notices to residents owing \$250 or more in April 2005. (Baltimore Sun, 18<sup>th</sup> May 2015). We begin to see the nested issues of social and personal 'well-being' linked intimately with a natural resource and the pressing need to ensure both reliability of supply and equitable access of supply.

Initially developed out of the work of complex systems theorists in the 1970s as a way of understanding dynamic open ecological systems, the term 'resilience' has been popularised in a range of literatures to include other system types, including social, material, financial and psychological. What links these diverse fields of inquiry is the notion of resilience as central to system recovery; that whilst the form of the system may alter in the event of a shock, its essence and functionality is retained. The IPCC's (2012:563) definition of resilience is emblematic of this: 'The ability of a system and its component parts to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner, including through ensuring the preservation, restoration or improvement of its essential basic structures and functions'.

Those involved with operationalising IWRM approaches are increasingly sensitive to the need to embed resilience within their practice, particularly in response to 'nexus' thinking around protecting critical infrastructure through collaborative planning (Benson, 2014). Yet resilience is a term which is not value neutral. We must be sensitive to the fact that resilience will mean different things to different practitioners. As Weichselgartner and Kelman state (Weichselgartner and Kelman 2014), resilience resides in a plethora of disciplines with no unifying definition, and moves from a descriptor of a system to a normative tool which is used to justify a range of approaches and responses without considering issues of power, equity and social capital (2014:252). The Resilience Alliance defines a resilience approach as assuming 'an uncertain and complex natural-resource context and aims to achieve sustainable long-term delivery of environmental benefits linked to human well-being' (ResilienceAlliance 2010). We begin to see a different role for resilience theory – moving from one which maintains a system's operating practice, for good or for bad, to one which encompasses approaches which support a vision of long-term social-environmental well-being, rather than extant system integrity, at its heart. Further, as most examples of resilience are identified ex-post – after a disruptive event which has caused resilient actions, processes or responses to surface -practitioners and citizens are exposed to a multiplicity of examples of resilience resulting from natural hazards, calamitous social events or environmental shifts, but with scant guidance as to how to recognise ex-ante resilience and nurture it within the organisations, processes and communities within which they work with and reside. The aim of this paper is to contribute to a discussion around the potential role of resilience as an agent provocateur, which tasks water resource managers and practitioners to imagine a much more porous boundary between those who govern water resources and those who consume them. This paper critiques three different resilience matrices, taken from the fields of humanitarian relief, corporate reorganisation, urban contingency planning and social-ecological systems, in order to begin to identify components of

resilience which could contribute to adaptive IWRM strategies in respect to changing water environments. Rather than a static, prescriptive tool for IWRM, it is hoped that envisioning resilience will begin a conversation amongst water resource practitioners and communities of interest, with resource future-proofing, in its widest sense, at its heart.

## 2. METHODOLOGY

Ambiguity surrounds the articulation of resilience: what are the attributes we are looking for to denote the presence of resilience in responses, actions, policies or processes? There is not space in this paper to dissect the multiple presentations of resilience which are pertinent to IWRM. These would include the dialectical relationship between resilience and vulnerability(Aguirre 2007), the power relationships that underpin the question of resilience for who and for what purpose ((Gaillard 2007) (Nelson, Adger et al. 2007)), and the interplay between resilience that supports the human world and that which supports ecological life; or, as Evans and Reid (Evans and Reid 2014) would have it, less interplay than endgame. Rather, this paper would seek to position itself as a pragmatic enquiry. If we accept that resilience offers the potential to re-imagine a rejuvenated IWRM, one in which practitioners and communities work towards a common goal of resource integrity, then what types of conditionality, what types of social-ecological hallmarks are we looking for? Within this approach is a recognition that resilience is often presented as an endpoint; yet it is more useful to view it as a self-reflexive endeavour that must renew itself and change as conditions change, self-aware of the normative values that underlie it at different temporalities. Given resilience's current championing by state policy, in the UK at least, it has been argued that rather than a liberating articulation of self-empowerment and community actualisation (Edwards 2009), resilience can also be presented as a neo-liberal device which divests the state of risk and so passes the costs of climate change inequitably onto its citizens (O'Malley 2013). We must be sensitive to perspectives that see resilience as positioned within wider macro spatialities, as a tool to sustain capitalist social relations (Harvey 2011). As a crude literature reveals over 295,000 peer-reviewed articles and books since 2005, with 61,000 relating to water management the term seems unlikely to fade away anytime soon.

As water resources lie at the heart of critical infrastructure which supports social-economic continuity, yet is itself an ecological entity, the resilience literature within the field of social-ecological systems (as opposed to the application of resilience in other disciplines such as engineering, genetics, psychology or agronomy ) is our primary focus. It details the dynamic relationship between the social world, the world of people, policies and processes, and its interaction with the environment, often encapsulated in a period of change, crisis or transformation. Change or crisis of significant magnitude can lead to a threshold moment when a stable state transforms, leading to reorganisation or renewal, as outlined by Holling and Gunderson's seminal work *Panarchy* (Holling and Gunderson 2002). Social-ecological resilience is a system's ability to broker that change or crisis either successfully, stability is resumed, or transformatively, a new stable state is created. By necessity, thinking about social-ecological resilience involves multi-disciplinary and cross-disciplinary approaches.

Social-ecological resilience thinking has much to offer IWRM as it moves towards sculpting governance strategies within the context of unknown futures. Social-ecological resilience has been depicted as a resource which can be harnessed to

enable adaptive or transformative responses to these unknown futures (Nelson, Adger et al. 2007, Pelling 2011) as a way of ensuring the integrity of water resources and hence 'future-proofing' IWRM strategies. There seems to be a role then, at least theoretically, for social-ecological resilience thinking to help support IWRM's quest for good governance, as defined by the Global Water Partnership (GWP) as "the range of political, social, economic and administrative systems that are in place to develop and manage water resources, and the delivery of water services, at different levels of society" (GWP 2003). The two aims, the GWP to ensure global water delivery and the Resilience Alliance's commitment to ensure human and ecological well-being, marry together.

## 2.1 Resilience in action: Key signifiers

If IWRM good governance goals and social-ecological resilient approaches are contiguous, then how will an IWRM practitioner recognise resilience in the field? The resilient systems approach as synthesised by Bahadur (Bahadur, Ibrahim et al. 2010) (Table 1, below) has 10 characteristics.

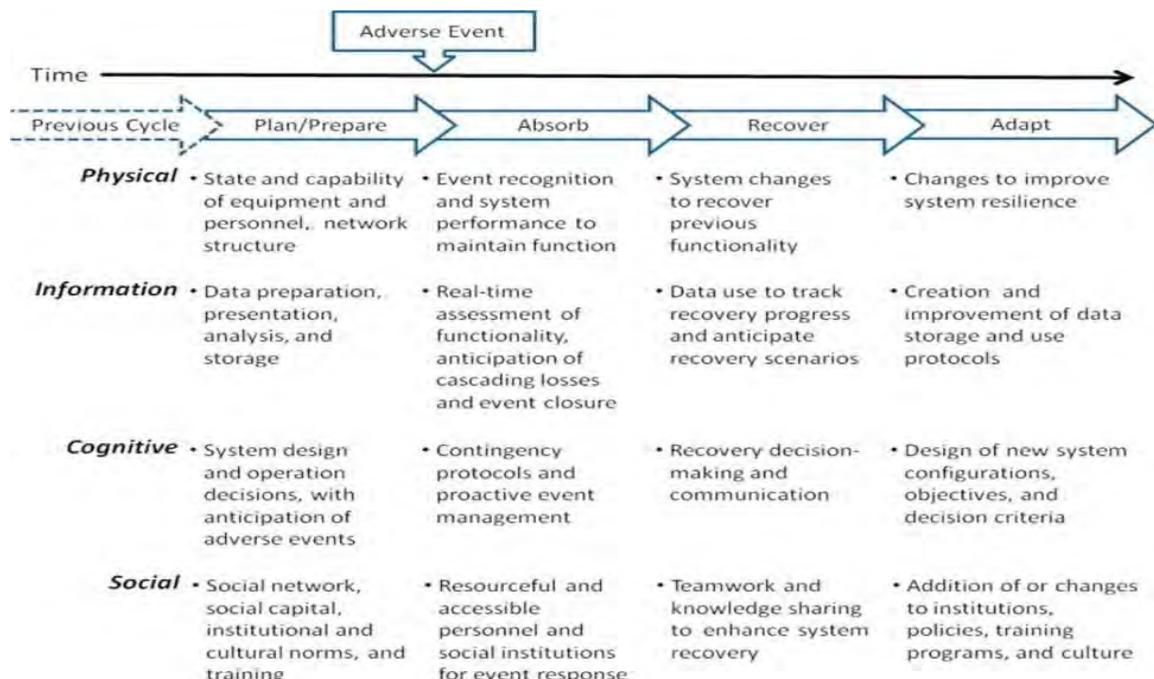
<b>Ten main characteristics of a resilient system</b>	
<b>1</b>	A high level of diversity in groups performing different functions in an ecosystem; in the availability of economic opportunities; in the voices included in a resilience-building policy process; in partnerships within a community; in the natural resources on which communities may rely; and in planning, response and recovery activities.
<b>2</b>	Effective governance and institutions which may enhance community cohesion. These should be decentralised, flexible and in touch with local realities; should facilitate system-wide learning; and perform other specialised functions such as translating scientific data on climate change into actionable guidance for policymakers.
<b>3</b>	The inevitable existence of uncertainty and change is accepted. The non-linearity or randomness of events in a system is acknowledged, which shifts policy from an attempt to control change and create stability to managing the capacity of systems to cope with, adapt to and shape change.
<b>4</b>	There is community involvement and the appropriation of local knowledge in any resilience-building projects; communities enjoy ownership of natural resources; communities have a voice in relevant policy processes.
<b>5</b>	Preparedness activities aim not at resisting change but preparing to live with it; this could be by building in redundancy within systems (when partial failure does not lead to the system collapsing) or by incorporating failure scenarios in Disaster Management (DM) plans.
<b>6</b>	A high degree of social and economic equity exists in systems; resilience programmes consider issues of justice and equity when distributing risks within communities.
<b>7</b>	The importance of social values and structures is acknowledged because association between individuals can have a positive impact on cooperation in a community which may lead to more equal access to natural resources and greater resilience; it may also bring down transaction costs as agreements between community members would be honoured.
<b>8</b>	The non-equilibrium dynamics of a system are acknowledged. Any approach to building resilience should not work with an idea of restoring equilibrium because systems do not

	have a stable state to which they should return after a disturbance.
9	Continual and effective learning is important. This may take the form of iterative policy/institutional processes, organisational learning, reflective practice, adaptive management and may merge with the concept of adaptive capacity.
10	Resilient systems take a cross-scalar perspective of events and occurrences. Resilience is built through social, political, economic and cultural networks that reach from the local to the global scale.

**Table 1:** Ten main characteristics of a resilient system. Bahadur et al (2010,2-3).

Bahadur's characteristics provide us with the tenets for assessing a social-ecological system's resilience, but they do not provide the tools for developing a resilience framework to enable practitioners to embed resilience as part of a good governance strategy. How is it possible to determine if an IWRM system has resilience? As a way of thinking widely about approaches, three resilience frameworks from the disciplines of humanitarian response, contingency planning, and ecology are reviewed. The aim then is to try to imagine what elements of a methodological toolbox would be useful for supporting a form, or forms, of resilience, with respect to changing water environments, which would support a 'future-proof' IWRM approach. Inherent in this re-imagining is a presupposition that IWRM cannot sit outside of broader socio-economic or political economy discussions but is part of the fabric of resilient futures in symphony with more inclusive governance models (Gearey and Jeffrey 2010).

### 2.1.1 An Humanitarian/Post-Disaster Relief Resilience Matrix



**Figure 1:** The Resilience Matrix as taken from Linkov et al (2013).

Linkov et al's model , Figure 1, was first developed by the US Army as a framework for assessing responses to disasters. At first glance its limits can be clearly seen: the pathways are linear, depicting the system experiencing the event as insular and heterogeneous. There is no scope for multiple pathways or experiences and therefore is too rigid to adopt in its current form as a tool for adaptive planning. Its form is very much that of a command-control vertical structure and takes no account of contingency building to include the utility of other knowledges in the system. Its utility in this paper is an exemplar of planning that removes the complexity of human

interaction, power and agency from the model. It presumes shared information and shared access and presents a system as bounded and enclosed, with contagion, the 'shock', as an unusual event rather than an ongoing influence. Thinking widely about IWRM adaptivity, an approach which presumes linearity, of event or process, fails to address the complexity of social-ecological interactions. Resilience, from this perspective, is concerned with 'bouncability' – returning to a desired previous state. Linkov's (Linkov, Eisenberg et al. 2013) model does however recognise that system longevity depends upon adaptation. Walsh-Dilley et al's (Walsh-Dilley, Wolford et al. 2013) research paper for Oxfam America entitled 'Rights for resilience: Bringing power, rights and agency into the resilience framework' helps illuminate the absence of other viewpoints in Linkov's model. For Walsh-Dilley, resilience must move beyond command-control to embrace the needs of the disempowered, the voiceless, in society. Power rights and agency are encapsulated in the term 'social justice'. Although not developed into a model per se, the authors set out building blocks or components which reflect the capacity of a system to enact resilient approaches which support effective governance and build political resources through acknowledging civic capacity, natural resources, economic resources and, finally, resources that support learning and knowledge sharing, the 'deep changes' (Science Europe Scientific Committee for the Humanities 2014) that support behavioural adaptation to novel futures.

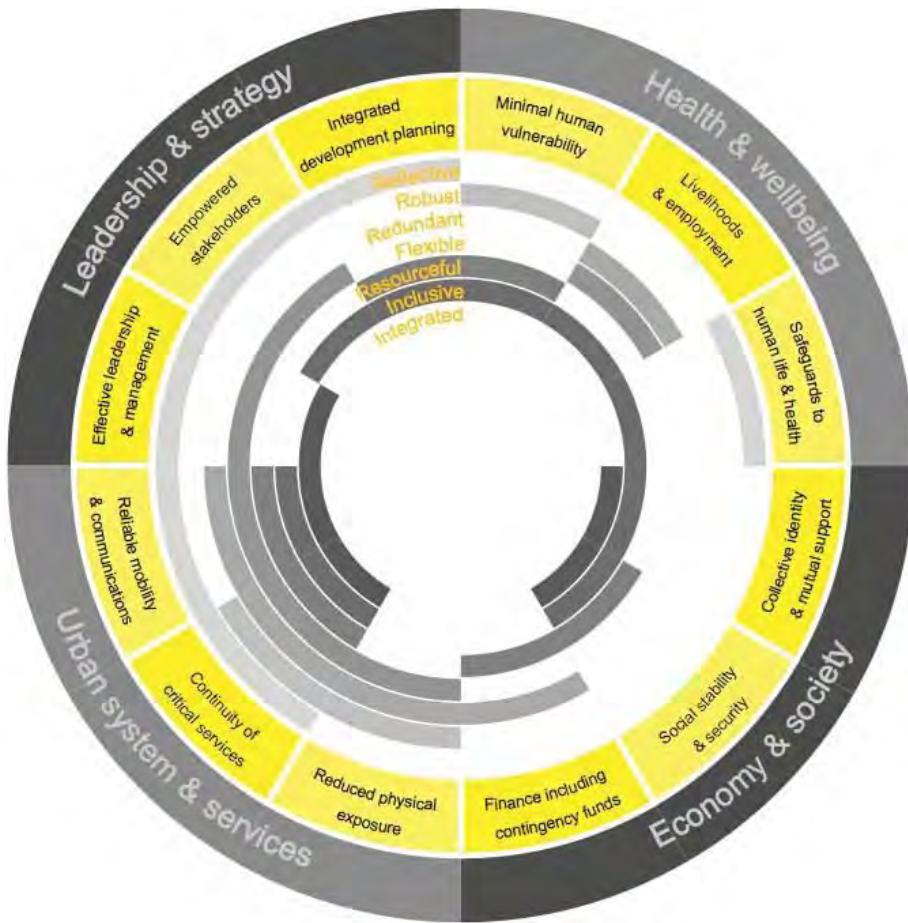
Walsh-Dilley's key conclusions are (2013, p33-34):

- Resilience is a contested process, both in terms of how it is defined and how it is generated in particular locations.
- Equity is central to a responsible, social-justice approach to resilience.
- A social justice approach to resilience supports the empowerment of local actors and recognises that access to rights and resources are necessary to generate resilience.
- Building resilience is not only about moving forward to build adaptive capacity but also about understanding the structures that facilitate or inhibit resilience.

This more nuanced approach adds subtlety to Linkov's matrix. The two combined enhance the utility of each's perspective. The concept of contested processes is key when thinking about IWRM and resilience. Climate change perturbations may require quite drastic revaluations of how we use and value water. Resilience thinking may play a part in embedding social justice aspects within IWRM as long as the concept of equity lies at the heart of provision.

We see in the above framework an unwillingness to synthesise a strategic vision and a tendency towards insularity. Given IWRM's strategic role in a functional developed economy the framework would need to build in the complexity inherent in dynamic systems. The approach developed by Arup International and the Rockefeller Foundation (Arup International and The Rockefeller Foundation 2014), predicated on the idea of the resilient city, as depicted in Figure 2, goes some way to bridging this conceptual impasse.

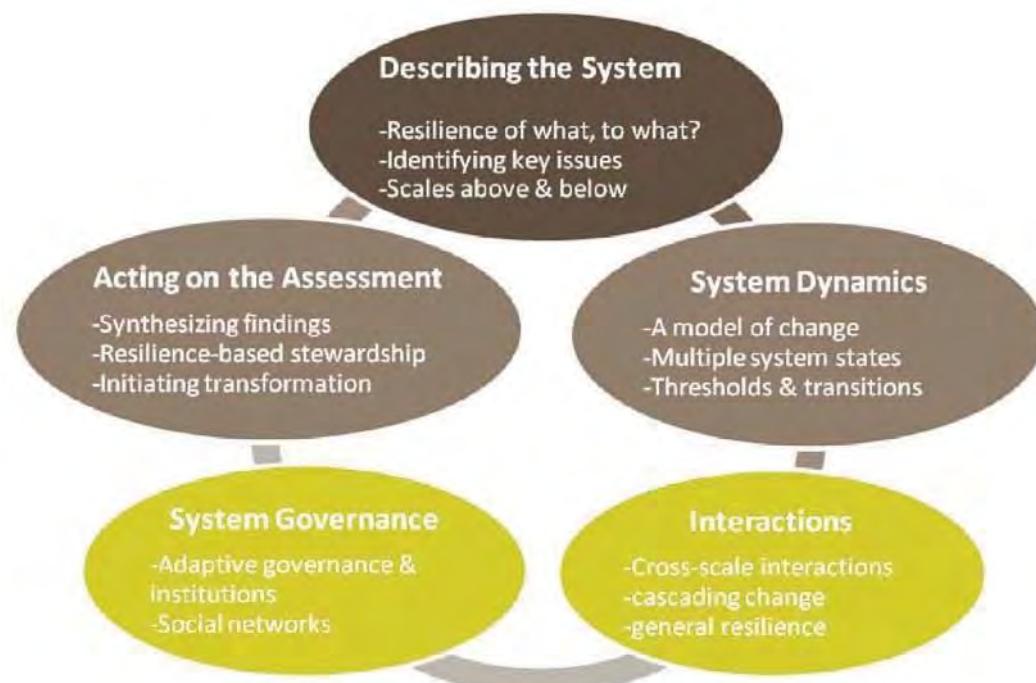
### **2.1.2 The City Resilience Framework**



**Figure 2:** Arup International/Rockefeller Foundation – city resilience framework (2014).

Figure 2's framework is currently being used to build an index of resilient cities, using all the above components to determine where strengths and weaknesses lie. The 'system' in this instance is a city – though its boundaries are necessarily fluid. The utility of this model is its comprehensive approach. It would be straightforward to plot the strengths and weaknesses of a city's IWRM system using this framework. What remains unspoken, and is to a large extent the result of the reductionist nature of the 'wheel' is the question of 'resilience for whom or for what?' The glaring omission in the model is, as ever, the environment. The focus on 'urban resilience' precludes the need to ensure 'rural resilience' and so it remains obscured. The model is inherently 'human centred', with the needs of the non-vocal environment entirely absent. Again, revisiting the frameworks examined so far reveals that human life presides over the approaches – how will this sit with the essentially water centred world view of IWRM (Benson, Gain et al. 2014) which encapsulates both the human and non-human aspects of water resources? The social-ecological systems approach outlined below in Figure 3 might go some way to providing a more appropriate fit.

#### 2.1.3 An Integrated Social-Ecological Systems Resilience Model



There are five main stages of the assessment framework. The actual process is iterative and reflexive at each stage and requires referring back to earlier steps and revising as necessary.

**Figure 3:** Resilience assessment model taken from the Resilience Alliance handbook (2010).

Given the complexity of IWRM spatial and temporal applications Figure 3's stripped back model may reduce the 'noise' from competing sectors. 'Describing the system' offers each IWRM practitioner the opportunity to depict the boundary of their professional world. By cross-referencing these worlds it may be possible to cross identify and understand the limitations that each practitioner type faces when thinking widely about resilience, particularly when confronted with unknown possible futures. There is no movement towards constructing a normative framework, but rather an acceptance than multiple frameworks, potentially thought about in terms of scale or theme, may broaden out the focus of conversations between IWRM practitioners and the communities of interest they work alongside. It is this pedagogic learning aspect which offers the opportunity to enrich these conversations and prioritise resilience within the ambit of societal 'well being' rather than IWRM 'business as usual'.

### 3. RESULTS AND DISCUSSION

Returning to Bahadur's 'characteristics of a resilient system' (Table 1) and trying to think widely around the resilience model's presented above, we begin to see that not only are structural elements at play, which will be pertinent to each IWRM context, but also far more subtle qualities that support the invisible mesh of the social contract (Estlund 2012). Issues of trust, legitimacy, values and aspirations hold societies in fragile networks of correspondence with each other. Bahadur's index reveals through closer scrutiny that resilience is iteratively developed through action, social learning, within representative institutions and through shared goals. The type of resilience sought, be it an existing goal and system longevity such as 'economic growth' or a new system goal but using the same system framework, such as 'well-being', seems immaterial – as long as there is uniform consensus on 'what happens next'.

Given the 'unknown futures' that IWRM practitioners work within, it seems that this almost intangible question 'what is it that we want?' is at the heart of resilience framework(s) and at the heart of future proofing IWRM. This would then help address a crucial question regarding; resilience for what and for whom? Given the disjuncture

between the challenges facing water resources and the desire for universal potable water supply provision (United Nations 2000). It could be suggested that IWRM needs to move beyond the platform of community outreach that it currently utilises and work towards a more radical scope. Education programmes do not lead to attendant behavioural changes when we look at water consumption (Syme, Nancarrow et al. 2000). The Science Europe Scientific Committee for the Humanities have suggested the need to support projects which create 'deep change' with regards to long-standing convictions and motivations to societal challenges (Science Europe Scientific Committee for the Humanities 2014). Arguably this involves IWRM practitioners being receptive and working more closely with a wider range of communities of interest to enable co-produced and co-designed resilient approaches.

Combined with Linkov et al, Arup/Rockefeller and the ResilienceAlliance, a synthesis of all three resilience models could begin to take an approach to iteratively build a more complex picture of the operational, political, cultural and environmental landscapes pertinent to each IWRM system. The task of developing resilience frameworks which support IWRM endeavours may benefit from embracing uncertainties of approach and scale, and adopting an adaptive learning approach, but with the end result, security of water resources, as their primary focus. Taking resilience as a target, albeit one with caveats regarding resilience for whom and at what cost, this porous approach might well provide a useful discussion point when thinking widely about how to future-proof IWRM.

#### **4. CONCLUSION**

- As IWRM is a systemic 'process' rather than a set of protocols, there can be no one singular resilience framework which can be deployed. Instead, it may be of greater utility for IWRM practitioners and stakeholders to work together within and along catchments to develop localised approaches to supporting whatever vision of resilience they determine to be appropriate.
- Building relationships of trust between water resource managers and water users will be crucial in enabling the 'deep change' that will need to evolve regarding people and water resources. Incorporating the principles of resilience frameworks at an operational level before crises events will strengthen vertical and horizontal relationships of co-operation amongst a variety of user groups.
- IWRM practitioners cannot direct macro policy change in support of resilient approaches, but by demonstrating their utility through operational practise with consumers and communities it is hoped that over time the opportunity spaces for more creative policy options widens.
- As a governance objective, resilience is placed within a powerful socio-technological position. Careful application of resilience focused policy options is needed to ensure that policy instruments that could be viewed as neo-liberal attempts to inequitably pass on the cost of environmental liabilities are deployed and communicated in such a way as to demonstrate the overall utility and necessity of developing resource focused approaches.

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# Every Drop Counts : A Whole Town Approach to Delivering Water Efficiency Initiatives

Kerri Russell

*Essex & Suffolk Water, Canon Barns Road, East Hanningfield, Essex, CM3 8BD*

## ABSTRACT

**Aims:** With Essex & Suffolk Water's (ESW) acknowledged reputation for trialing new approaches to achieve genuine water savings, ESW piloted a whole town approach, Every Drop Counts to delivering water efficiency during the summer of 2014. With the support of a huge marketing campaign the aim was to increase participation and achieve higher water savings.

**Place and Duration of Study:** 'Every Drop Counts' launched in the summer of 2014 in the town of Billericay, Essex.

**Methodology:** Every Drop Counts brought together all of ESW's leading water saving programs to one place at one time. Billericay received projects including the multi-award winning H<sub>2</sub>eco project, school education programmes, retrofit audits for high street shops and much more. To take it beyond simply delivering many projects in one place at one time, ESW utilised various communication channels including community radio, newspaper, billboards, promotional stands, social media and community talks to engage different cohorts. What's more Every Drop Counts provided a unique opportunity to conduct behavioral economics research alongside micro-component analysis.

**Results:** Over 15,000 customers engaged with Every Drop Counts. Twenty percent of households received a free water audit and are now saving over six million litres a year while 30 commercial premises are benefitting from a 15% reduction in consumption.

**Conclusion:** Analysis of results indicates that a concerted focus in one area can result in synergistic water savings. Moreover, the social demographics must be a pre-requisite of a target area must be considered while scoping a potential area. Lessons learnt from delivering a project of this scale will undoubtedly improve the evidence base and determine future best practice.

**Keywords:** *Water conservation, water efficiency, saving water, retrofit, whole town approach, domestic water use, marketing and communications.*

## 1. INTRODUCTION

Although the UK's climate is often considered to be wet, the truth is rather different. Parts of England receive less than 700mm of rainfall each year (Met Office, 2014) which is even lower than many Arabic countries, for example Oman (Yu et al, 2010). Water deficiency is particularly acute in the South and East of England where large numbers of people are living

\* Tel.:01268 664934

E-mail address: kerri.russell@nwl.co.uk.

and working and sustaining an excessively high demand. This, together with the higher per capita consumption compared to the rest of the country, means that managing water resources is a real challenge for the South East. Furthermore, the unprecedented challenges associated with global warming also pose a real threat to the availability and quality of potable water (see IPCC, 2013). It is widely acknowledged the UK will experience warming temperatures and changes in seasonal precipitation patterns, while extreme weather events will be more common and more intense (UKCP, 2009). Hotter weather will likely lead to more evaporation from reservoirs and rivers, while aquifers will not recharge as efficiently with intense rainfall leading to rapid surface run off (DEFRA, 2011).

These issues surrounding supply and demand are becoming progressively more important for water companies, creating greater challenges to balancing supply and demand. Two approaches to address this are to expand water resource capacity, a highly capital intensive option or invest in demand management techniques including metering, leakage reduction and water efficiency activity. ESW prides itself on its demand management techniques, which incorporate all three of the techniques mentioned above. This paper focuses on one in particular, its water efficiency and water conservation practices.

ESW is widely regarded as the leading water company in the field of water efficiency, and since 1997 has developed a strong and robust strategy to deliver long term sustainable water savings. Its strategy for delivering water efficiency during AMP5 has focused on delivering an effective mix of installing water saving products and engaging customers in order to change their water using behaviours. Defras Statement of Obligations for PR14 and the expectation that water companies will deliver overall demand reductions via demand management measures, including water efficiency poses a real challenge for water companies. Nevertheless, ESW's firm grounding and wealth of experience in delivering successful campaigns provides it with an advantage to achieve real and quantifiable water savings.

To achieve real demand reductions, ESW adopted an entirely different approach to water efficiency in 2014. During the summer, ESW launched its first whole town approach, 'Every Drop Counts' in the town of Billericay, Essex. The project, delivered by ESW's Water Efficiency Team, brought together all of ESW's leading water saving programs to one place at one time.

ESW currently undertake a wide range of projects on an annual basis throughout the supply area at different times of the year. In order to trial the effectiveness of a 'whole town approach', each individual annual project was carried out at the same time in the same town.

The Water Efficiency Team sought assistance from its in-house Marketing Team to develop a brand that would take the campaign beyond simply delivering many different projects in the same place at the same time. Generating a community feel was the target – the people living in Billericay needed to know they were part of something special. It was hoped the marketing

and engagement would result in greater participation in each individual project and therefore deliver higher water savings.

Billericay received projects such as ESW's multi award winning H<sub>2</sub>eco project, school education programs including Little Green Riding Hood and retrofit audits for high street shops.

By adopting an innovative whole town approach to water efficiency, ESW aimed to engage and communicate with all social demographic groups across Billericay and in doing so encourage their participation in the numerous water saving projects on offer.

This paper aims to detail the individual projects undertaken as part of EDC and will then present the results of the individual campaigns.

## 2. METHODOLOGY

The following section aims to detail how each of the individual projects, which contributed to EDC, were undertaken.

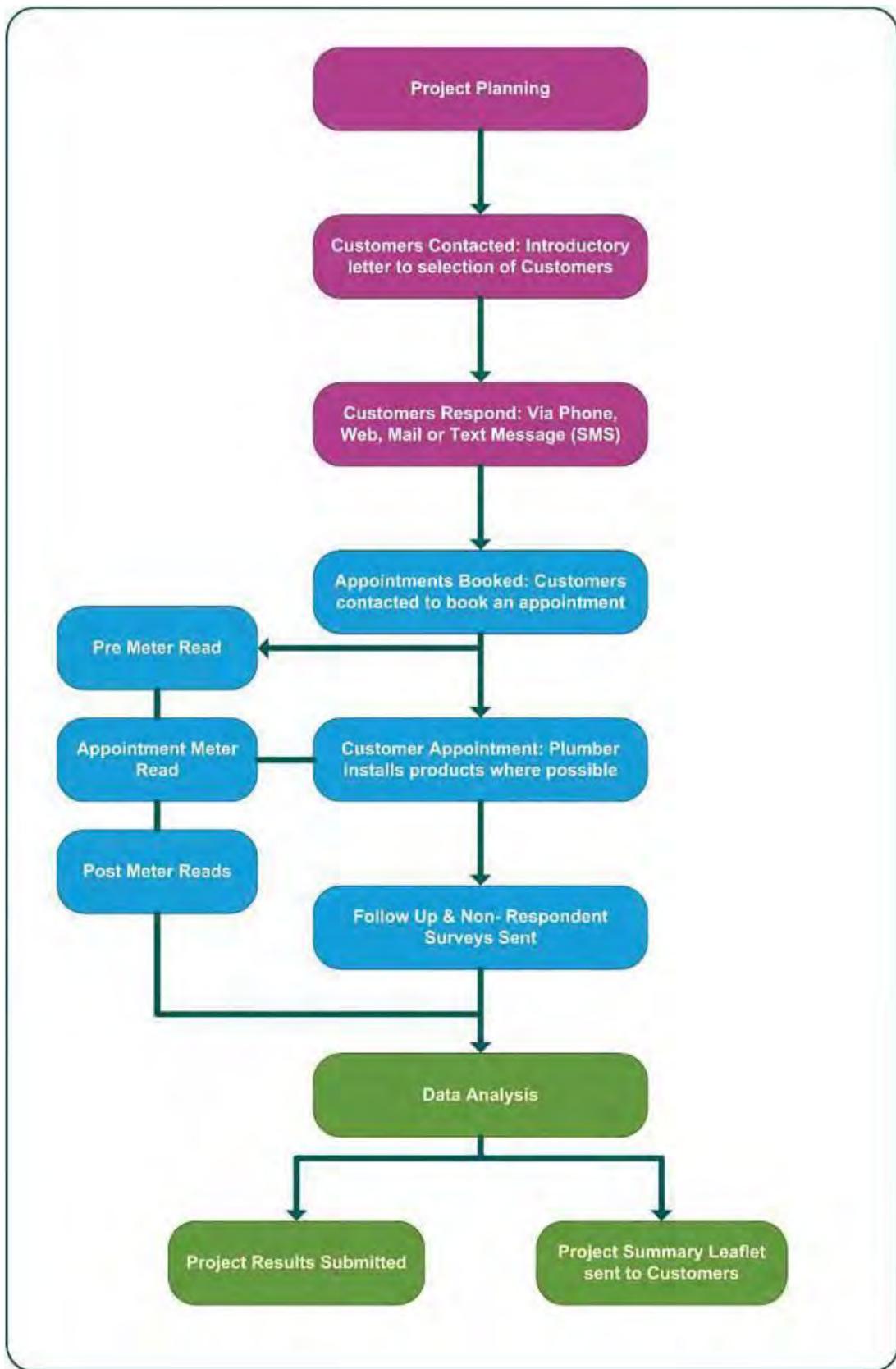
### 2.1 H<sub>2</sub>eco Home Retrofit Audits

H<sub>2</sub>eco is ESW's multi-award winning home retrofit project which since its inception has delivered 19,503 water audits to metered and un-metered customers. Since starting in 2007, the project has been a culmination of developments, feedback and lessons learnt.

H<sub>2</sub>eco's key objective is to leave the property of each participant as water efficient as possible. A plumber is provided, free of charge, to fit and deliver of a wide range of retrofit water saving products. The project aims to effectively engage with the customer, by explaining the purpose of each product as it is fitted while moving around the home and garden. To supplement the installation of water saving products, the plumber also provides advice and literature to educate the customer further on how to save water in their home and garden. This approach has delivered proven long term and sustainable behaviour change.

An area of 15,000 customers was targeted in Billericay, the key project stages are illustrated in Figure 1.

**Figure 1.** H<sub>2</sub>eco project stages



Furthermore, ESW utilised the delivery of H<sub>2</sub>eco and the Every Drop Counts campaign as a platform to undertake a unique piece of behaviour economics research which assessed the

affect of monetary incentives on levels of participation. The research was undertaken in partnership with the University of Chicago and Oxford University. To deliver the research effectively, the customer base was split into seven equal groups and each tested the effect of a differing value of financial incentive.

In an attempt to explore and understand the impact H<sub>2</sub>eco has on water consumption, in recent years ESW has commissioned several research projects. Continuing in this vein, H<sub>2</sub>eco offered an opportunity to trial a new micro-component logger called Siloette. The trial designed to establish the proof of concept and demonstrate the potential of using the Siloette product and analysing pre and post micro-components.

26 properties enrolled onto the H<sub>2</sub>eco project were successfully logged using Siloette. The 26 properties were screened upon application and identified as having a wide scope to install water saving products. Upon application the customer would be asked a series of pre-determined questions relating to the number and type of toilets and showers in the property, number of dripping taps and occupancy. Those properties highlighted as having a number of suitable fitments for water saving products were then selected for the Siloette product. The aim was to maximise the volume of micro component data available for analysis. The 26 properties were then logged for at least three weeks prior to the H<sub>2</sub>eco visit and 3 weeks post visit.

## **2.2. Spring Gardening Campaign ‘Save a bucket load’**

The ‘Save a Bucket Load’ Spring Gardening Campaign aimed to promote sustainable and efficient water use in the garden and generate long-term behavioral change among customers. The message of ‘Save a Bucket Load’ in the garden was communicated to residents in Billericay using variety of formats including a promotional stand, advertising in the Essex Enquirer newspaper, numerous radio adverts on a local radio station ‘Pheonix’ FM and social media including Twitter.

The intense media campaign supported the using water wisely message and helped promote the efficient use of water in the garden while also encouraging the distribution of 4,000 garden kits.

## **2.3 Commercial Audits**

ESW did not limit their engagement to domestic customers but also engaged with commercial water users along Billericay High Street and in the Radford Industrial Estate. Similarly to H<sub>2</sub>eco’s offering to domestic residents, the aim of engaging with businesses was to offer the opportunity to receive a free water saving audit.

Billericay High Street has a wealth of public houses, restaurants, shops and bars together with privately owned independent units. The premises were contacted in three ways; firstly a letter introducing what was on offer was sent to each commercial unit. This letter was addressed generically to the management of the particular retailer to ensure the correct person within the building read the letter. The letter also included an information leaflet detailing the specifics of the water saving program. A “high street run” was the second line of engagement whereby two ESW employees physically visited each retailer to promote the program encouraging them to sign up to an appointment. Following the “high street run”, if the commercial unit had not made contact to book a water saving audit, an email and/or phone contact was made to explore whether they were interested in having an appointment. The email addresses and telephone numbers were collected during the “high street run”.

A similar approach was adopted when trying to engage with business owners in Radford Industrial Estate. A visit was made to each of the 30 or so units and this was then followed up with an email and a phone call.

#### **2.4 General Awareness Promotional Stands**

ESW delivered a series of promotional stands across Billericay. Their purpose was to promote and encourage participation and support in three campaigns; the ‘Save a Bucket Load’ Spring Gardening campaign, H<sub>2</sub>eco and general water saving awareness.

#### **2.5 Education**

As part of Every Drop Counts, ESW was keen to engage with the younger generations. Therefore, all primary schools in Billericay were offered Little Green Riding Hood (LGRH) pantomime play. For a number of years, ESW has worked with a local theatre company to offer a school performance play which is based on the fairy tale Little Red Riding Hood. LGRH is a fun and energetic play that teaches the children about the importance of being ‘green’ and not wasting water. The performance, which also includes a workshop reinforcing what children learnt, is aimed at Key Stages 1 and 2.

ESW recognises the value of engaging with younger generations, therefore explored additional opportunities to engage with this age range. As a result, contact was made with the two local Brownie packs in Billericay. The aim was to offer the Brownie’s a fun-filled evening of water related games and activities to help raise awareness of saving water. It was hoped then that the children would head home and ‘pester’ their parents to save water and ultimately join up to H<sub>2</sub>eco.

ESW's new secondary school program, Aqua Innovation, was launched as part of the Every Drop Counts. The programme encourages secondary school students (Year 7 and 8) to think about water using habits and ways water consumption can be reduced. As part of the programme, students are challenged to come up with an innovative way to influence other people's water using behaviour. They are then tasked to implement their idea.

## **2.6 Communication and Engagement**

As introduced earlier, the Every Drop Counts campaign involved delivering a suite of water efficiency initiatives to one place at one time. The individual projects remained unchanged and were delivered in a similar, if not the same format as previous years. However, the single element taking the Every Drop Counts campaign beyond simply delivering many different projects in the same place and the same time was the level of communication, advertising and engagement undertaken. Consequently, ESW's Marketing Team delivered a suite of marketing activities in order to develop a buzz, hype and community feel within Billericay. It was hoped that support from a wider marketing campaign would result in greater participation and therefore deliver higher water savings.

In order to engage with a diverse range of cohorts across Billericay, ESW utilised different media outlets. The four main media areas utilised to reach the largest range of customers within Billericay was radio, newspaper, bill boards and external communications.

In particular, ESW worked in partnership an advertising company, to look at potential opportunities to engage with billboard advertising together with electronic rolling boards. Every Drop Counts was publicised on billboards at Billericay Train Station and on an electronic rolling board outside Waitrose supermarket.

To support the visible project brand, several radio communications were organised. Two members of ESW's Senior Management Team appeared on two credible radio stations; BBC Essex and Phoenix FM. ESW's Supply Demand Strategy Manager, Martin Lunn and Essex Operations Manager David Aland, were informed about the Every Drop Counts campaign details prior to their radio interviews. Their task was to promote the campaign and detail the projects on offer to the residents of Billericay. Martin Lunn also featured on BBC Essex's question time which allowed customer's, across the entire supply area, the opportunity to call in and ask water related questions.

The Water Efficiency Team also promoted Every Drop Counts internally through its internal communications newsletter 'H<sub>2</sub>Info' and local intranet, 'Cascade'. The purpose of this was twofold; firstly the Water Efficiency Team wished to engage with all employees particularly those residing in Billericay, potential custodians for the project. And secondly, should

employees receive any customer contact enquiring about the campaign; the employee would be suitably equipped to direct the customer accordingly.

Furthermore, Every Drop Counts was publicised in two separate newspapers/magazines; The Essex Enquirer and the About Town Today magazine.

### **3. RESULTS AND DISCUSSION**

This section of the paper aims to detail and discuss the results of each individual project undertaken during the campaign.

#### **3.1 H<sub>2</sub>eco Home Retrofit Audits**

Of the 14,813 customers invited to take part H<sub>2</sub>eco, 3,009 (20.3%) full home retrofit audits were completed, surpassing the target of 3,000. The project achieved an average OFWAT assumed water saving of 44.8litres/prop/day and an average measured saving of 6.1litres per property per day which equates to an average 2% reduction in household consumption. The water savings achieved by each household is equivalent to an average financial saving of £6.67 a year. These savings are a result of installing and / or distributing 19,327 water saving products and services. This includes; 784 ecoBETA dual flush devices, 1,407 shower attachments and 3,392 tap devices.

While it was anticipated the behavioral economics research incentives and the general EDC communication and marketing would help boost customer participation in the project, the number of applications received for H<sub>2</sub>eco largely followed the trends that had been noted in previous phases. It is believed this finding is indicative of the ACORN (A Classification of Residential Neighbourhoods) classification across the Billericay area. Of those households targeted in H<sub>2</sub>eco, over 50% fell into the 'Affluent Achievers' category. It can be argued that this social demographic group is less engaged in water efficiency initiatives due to the modest financial incentive on offer and the fact they are rarely at home to receive an audit.

Furthermore, the measured water saving achieved during this phase was generally lower than previous phases. Historically, households who have participated in H<sub>2</sub>eco save on average 23 litres per day. This finding could be attributed to the reduction in the overall fit rates of the key water saving products such as the ecoBETA dual flush retrofit device and multiple tap aerators. When comparing phase 8 fit rates with phase 9, dual flush conversions fell from 43% to 21% and multiple tap aerator installations fell from 53% to 36%. During the delivery of phase 9, it was recognised that the quality and general maintenance of the average property visited was exceptional, with many new, up to date and expensive fixtures in place. Thus, many of the fixtures and fittings audited had been upgraded with modern kitchen and bathroom suite fitments which meant many of the water saving products were unsuitable.

Both the reduction in toilet and tap installations could be in part attributable to the overall affluence of the participants.

Although the participation levels and measured savings during EDCs were not evidently enhanced by the additional marketing and communications, ESW believes the same approach, with the addition of learning and improvements, in a different area will deliver very different results.

### **3.1.1 Behavioural economic research**

As mentioned in section 2.1, ESW together with the University of Chicago and University of Oxford, utilised this phase of H<sub>2</sub>eco as a platform to explore cost effective ways of increasing the level of participation. Early analysis of the results suggests that while the cost per audit increases, paying an individual £15 to participate in H<sub>2</sub>eco encourages 15% more customers to participate than the control group with no incentive. This research is continuing into the subsequent phase of H<sub>2</sub>eco in 2015 where we are exploring ways to increase the number of customers who take up the audit while lowering the overall cost per audit. Current propositions include varying the amount paid for referring various numbers of friends.

### **3.1.2 Siloette logger trial**

A Siloette logger was installed on the inlet flow meter to each of the 26 properties. All of the data was captured for the whole period of logging (100% success with no data loss). Statistical analysis has been undertaken on the pre and post periods for toilets and showers and using the Siloette loggers it has been possible to log the flow and disaggregate the micro-component flows.

While the number of properties and hence the number of devices installed was very small the results provide a good indication of the impact of pre and post intervention. It is however, very difficult to present a more formal statistical output. Nevertheless, of the 26 properties logged 7 properties had a dual flush device installed and post analysis indicates an average saving from a dual flush device is 16.7 per device per day. Furthermore, the analysis indicates the installation of either a Save-a-flush bag or an aerated shower head can achieve a water saving of 3.8 litres per day. For the aerated shower head saving in particular, it is difficult to understand how indicative these results are since it's based on a small number of installations and a small number of showering events.

## **3.2 Spring Gardening Campaign ‘Save a Bucket Load’**

The community radio, Phoenix FM launched the ‘Save a Bucket Load’ campaign to listeners in Billericay. The campaign remained live for 28 days with 6 individual adverts played each

day. The advert, which was design and produced by Hot Rocking Radio encouraged residents living in Billericay to visit a dedicated page on ESW's web site to request free water saving products and a free SowPot. Alongside this call to action, the advert promoted a series of key using water wisely in the garden messages providing customers with helpful hints and tips.

Upon request of the free garden water saving products, the customer was asked to enter a promotional code. In total, 13 garden kits were requested using the promotional code ESWPhoenix.

A promotional stand was also set up and delivered within Billericay. The aim was to increase the campaigns visibility in and around Billericay offering residents the opportunity to pick up a SowPot and free water saving pack. The promotional stand, which was managed and coordinated by Groundwork Essex Suffolk Norfolk, was one of many promotional stands used to promote the 'Save a Bucket Load' campaign. After spending one day at Lake Meadows, Groundwork Essex Suffolk and Norfolk distributed 237 SowPots and Garden Using Water Wisely leaflets.

Furthermore, ESW's Communication Team supported the campaign and helped promote key messages via social media. Between April and July 2014, 108 tweets themed around different aspects of saving water, general advice and calls to action to get a Spring Gardening kit were circulated and shared with ESW's followers. As a result, during the first two weeks of the campaign ESW saw a 17% increase in followers from 291 to 714. Twitter provided a fashionable and fun way to present helpful hints and tips.

### **3.3 Commercial audits**

For the first time, ESW trialled a "high street run" as a method of recruitment. In a single day 166 high street shops were visited. Of the 166 high street shops contacted, 20 (12.04%) retailers took up the offer straight away and were keen to have a water audit, while 53 (31.9%) retailers advised that the 'decision maker' was not in. A further 30 (18%) retailers referred all contact to their head office. Physically visiting each retailer benefitted the program since the ESW representative was able to converse with the retailer and 'sell' the benefits of the campaign.

The Water Efficiency Team also approached Radford Industrial Estate which hosts approximately 30 businesses offering services ranging from plastic manufacturers to bathroom and kitchen suites. All 30 units were invited, 10 (33%) units actually went ahead with a water saving audit.

In order to understand how successful the commercial audits were in saving water, a series of three sequential meter reads were obtained for each premise (for both the high street shops and Radford Industrial Park). A set of three meter reads were successfully obtained for 27 of

the units. Following analysis of the meter reads, on average each commercial premise is saving 91.97litres per day which equals a total annual water saving of 772,109litres. This is equivalent to 15% reduction in consumption.

### **3.4 General awareness promotional stands**

In total, Groundwork Essex Suffolk and Norfolk managed and delivered 9 promotional stands designed to; advertise the Spring Gardening Campaign, publicise and recruit customers onto the H<sub>2</sub>eco project and disseminate general water saving. In doing so, they successfully distributed 237 Sowpots (as discussed in section 3.2), secured 166 H<sub>2</sub>eco applications and engaged with over 700 customers.

### **3.5 Education**

Three performances of LGRH were delivered to two schools in Billericay. The pantomime was enjoyed by 683 children. Since delivering the performances at the two schools it is assumed that 0.011MI of water is being saved each day.

In addition, two Brownie packs benefitted from an evening of water saving related games and activities

Every Drop Counts saw the launch of ESW's new Aqua Innovation programme targeted at secondary schools. It was open to six schools in Billericay, and one Secondary School, St John's School took part. A group of 15 students took on the challenge to come up with an innovative way of raising awareness in both their school and community about the importance of saving water. Over the course of the project, the group discovered the main water wasting issue in their school was not turning off the tap when brushing teeth. Through innovative ideas, presentations and workshops the group reached out to over 260 Year 2 and 3 children and 50 adults.

### **3.6 Communications and Engagement**

The Water Efficiency Team hoped that support from a wider marketing and communications would help raise awareness and visibility of the EDC campaign thereby increasing participation in projects and subsequently increasing the amount of water saved. However, as with most advertising it is very challenging to measure the direct impact and success of each individual media route.

On initial reflection, it appears the wider marketing campaign had little impact in encouraging participation in the water saving projects in particular H<sub>2</sub>eco, since the number of applications received largely followed trends that had been noted in previous phases. ESW recognises this eventuality could simply be down to the target project area, time of year and social demographics. Taking this into consideration, ESW will perform similar marketing activities in

the 2015 Every Drop Counts campaign, supplemented with additional measurement techniques, to measure the true impact of such marketing.

#### **4. CONCLUSION**

Continuing to strive for real and quantifiable water savings, ESW plan to continue their focus on the delivery of a whole town approach. This approach to delivering water efficiency has a notable capacity to achieve a long lasting legacy in the local community. The scale of Every Drop Counts goes far beyond similar initiatives currently carried out by other water companies and although the participation levels followed trends of previous years, ESW is confident a concerted focus in one area can result in synergistic saving of water. ESW believe the same approach, with the addition of learning and improvements, in a different area will deliver very different results. Therefore, work is underway to deliver Every Drop Counts in the Grays area of Thurrock during the summer of 2015. Of course, the learning and experiences gained from trialling Every Drop Counts in Billericay will assist ESW in continuing to improve and develop their water efficiency offering to its customers.

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# The Metabolic City and the Alternative Water-Services design methods

Fernanda Garcia-Alba Garciadiego\*

Civil, Environmental and Geomatic Engineering, University College London

## ABSTRACT

**Aims:** This paper's purpose is to critically review the literature and describe a methodology that will identify new values in relation to Water Sensitive Urban Design (WSUD) in order to encourage the implementation of sustainable water management.

**Study design:** Case study of an experiment of stakeholders' decision-making.

**Place and Duration of Study:** This research will be in an informal urban neighbourhood near the southwest boundary of Mexico City, over what was previously an Ecological Conservation area. The study is planned to take place in 2016 and 2017.

**Methodology:** This research is based on the *metabolic city* approach as a theoretical framework and is comprised by two phases: site analysis to produce a Fuzzy Cognitive Map, using information gathered by interviews and surveys. The second phase is scenario design with the participation of three groups of stakeholders, integrating spaces for water to explore opportunities for Water Sensitive Urban Design (WSUD).

**Results:** The final result will be a Fuzzy Cognitive Map representing the Problem Definition and a final comprehensive design scenario developed by all the stakeholders in order to discover the feasible values that are achievable through a WSUD.

**Conclusions:** This paper aims to promote thoughts and reflections of what is essential to implement the methodology, as the values and principles that are needed to create the right outputs to integrate WSUD into the urban realm.

**Keywords:** Urbanisation, Water Sensitive Urban Design, Stakeholders participation, Green Infrastructure, Water Consumption, Fuzzy Cognitive Maps, Urban Planning, Mexico City.

## 1. INTRODUCTION

Excessive consumption of natural resources is jeopardizing the sustainability of cities. In consuming resources and producing waste, cities can be thought of as undertaking a series of socio-ecological transformation processes, influencing each other and producing social and physical environments [1]. From a *metabolic* point of view the city is as production-consumption system, where the resources that enter into the city are inputs transformed into goods, energy or stock, and where the losses go back to the environment [2]. The problem is that this consume-dispose system comprises an unbalanced relationship between the city and its surroundings, compromising the availability of the natural resources, within and beyond the urban boundary [3].

Today, more than half of the world's population live in cities and is likely to increase in the future [4]. Most of the urban sprawl happens rapidly in developing countries, with construction of housing racing ahead of formal planning and infrastructure provision for new urban settlements [5]. This rapid urban growth causes environmental harm when rural and natural surroundings are modified to provide space for new urban settlements.

\* Tel.: +44 7539516503.

E-mail address: fernanda.garciadiego.14@ucl.ac.uk.

Water resources are highly constrained in many cities. According to OECD by 2030 half of the world population will be living in severe water stress condition because of water over-exploitation and water pollution [6]. Conventional sanitation systems, particularly those based on combined sewers, compromise water quality as they mix rainwater with domestic or industrial waste [7]. Fortunately, new drivers are pushing alternative solutions to incorporate water supply and disposal services in a sustainable manner [7]. Integrated Urban Water Management (IUWM) refers to techniques and concepts that aims to operate water services more sustainably, reducing economical cost and ecological impacts of conventional water services [8]. Even though IUWM approaches reduce pressure on water resource consumption these have not been widely adopted in developing countries [9] where it is a priority to provide universal access to drinking water and sanitation [10].

The purpose of this paper is to outline a research method to identify options to incorporate an Integrated Urban Water Management (IUWM) in an informal peri-urban neighbourhood in Mexico City. This research conceives of the city as a complex metabolic socio-environmental system, where a single input such as rain, became a natural-social hybrid<sup>1</sup>, interacting with other urban networks. The *metabolic approach* is used in this research because it provides a sustainability framework for the city, relating socio-economic links and technology drivers to biophysical flows [2], delivering a better understanding of the connection between water and the city. This research aims to find additional values of IUWM in order to create an incentive to adopt sustainable technologies in the urban area. The paper begins with a critical literature review to define the current situation in Mexico City and introduces a methodology that incorporates stakeholders and community in an experiment that may achieve transition towards water sustainability.

## 2. INTEGRATED URBAN WATER MANAGEMENT

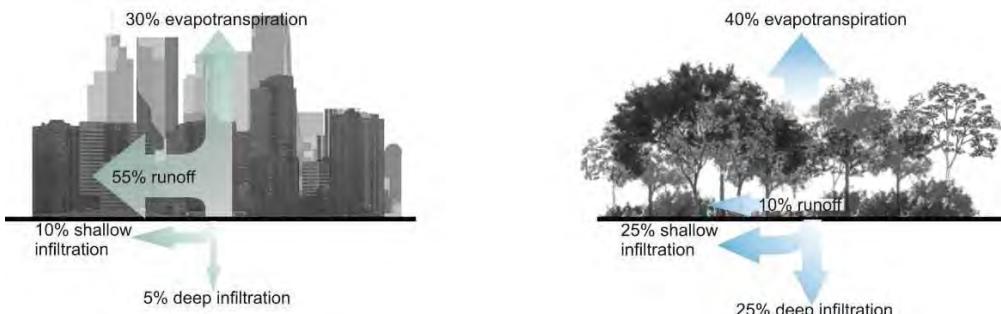
Urbanisation is the consequence of multiple physical, social and economic interactions, such as market forces and dynamic processes [11]. Urban settlements concentrate political and administrative functions, infrastructure and the means of production [12]. In developing countries, urban centres attract people from rural areas. Economic development encourages people to move close to opportunity centres, often settling where the land is available in peri-urban [13], [14].

In developing countries, the extremely fast growth of peri-urban areas reflects the inability of the authorities to satisfy housing demand [15]. Eventually, authorities tend to legalise new irregular settlements to mitigate housing deficit. However, it is extremely expensive to supply these areas with conventional services through upgrade approaches, particularly when they require demolishing houses to provide space for roads and service trenches [16]. Some authors explain that this kind of intervention is a form of violence because it involves evictions and relocations [17] and neglects dwellings' character and vernacular activities [18], [19]. For these reasons many upgrade programmes fail. Abbott [20] proposes that infrastructure shapes the urban area, but traditional upgrading ignores the informal urban character, and the use of alternative service methods can be a good approach to work within informal settlements.

Urbanisation impacts ecosystems and the hydrological cycle, because it transforms natural connections to the environment [21]. Rain-water is unable to filter into the underground due impermeable paving in urban areas, which increases water runoff and pollution. In that way, in a natural setting 50% of rain is infiltrated into the subsoil whereas in urban setting it is just 15 %, and the water runoff becomes 45% higher in impervious areas [22], see Fig. 1.

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1. Some authors see the urban system as a complicated network of resources, where natural resources become interwoven with natural-social hybrids [63] at the moment they enter into the city, affecting several urban systems [61], [64].



**Fig. 1. Diagram of urban and natural water runoff, based on Pazwash [22].**

Every day urban activities produce most of the common water runoff pollutants, like household products (thinners, solvents, cleaning agents, among others); oil and grease; de-icing substances, dust from tyres, pavements and construction sites; and chemicals for lawns; as well as illicit disposals and septic systems [22]. Water pollution diminishes water quality but the main problem is when rainwater is mixed with domestic and industrial waste, making its treatment more difficult [23].

## 2.1 Surface water management

A range of approaches have emerged in order to manage water in a sustainable manner, while producing environmental, social and economic benefits. Surface water runoff is a key feature of urban water systems and integrated approaches to managing runoff differ in name depending on the region where they are from and the range of benefits and principles that are being pursued [8].

*Sustainable Urban Drain System (SUDS)* is an approach formed by a series of technologies and techniques that reduce and retain water runoff, enhancing water quantity and quality [8]. Runoff is managed at source [24], reducing the overall load on conventional drains and removing diffused pollution [25]. Systems include the use of filter strips, swales and infiltration basins among other techniques to enhance water infiltration while reducing water pollutants through physical and biological processes [24]. Water Sensitive Urban Design (WSUD) is a broader approach to the same issues and involves a philosophical attitude towards urban design. The goal of this approach is to reduce the hydrological impacts of urban development on the environment, using the landscape to integrate surface and storm water management [8] and incorporate strategies to reduce water consumption such as water recycling and rainwater harvesting [26]. In that way, WSUD aims to restore the local watercourses and reduce demand for water by mimicking the natural hydrological cycle [27].

Finally, Green Infrastructure (GI) is the most comprehensive approach because it encourages the construction of natural networks to enhance ecosystem services, like clean air and water [28], and protection against natural hazards (floods and landslides) [29]; while providing urban amenities, human health and social equity [8]. In summary, GI through interconnected green areas adds resiliency to a city, because it relies on biodiversity conservation, ecosystem services and climate change adaptation [30].

There are several barriers to the incorporation of IUWM into cities and urban design. Khoo [31] explains that the main problem starts with conceptualising this term ‘sustainability’, because it is contested and evolves over time and space. This is compounded by difficulties associated with measuring sustainability, due to the lack of appropriate knowledge and methods. In addition, sustainability indicators such as *Material and Energy flow Analysis and Ecological Footprint* presented a poor understanding of social sustainability [2]. Some authors point out the lack of positive institutional attitudes as the main restriction towards IUWM in urban planning [32]. In summary, it is necessary to bridge the gap between sustainability research and its real development [2], [33]. Bos et al. [34] point out that this problem is caused by a lack of knowledge and can be reduced with experiments that help to develop knowledge to support change at different levels of governance.

## 2.2 Case Study: Mexico City

Rapid population and urban growth from the 1940's to the 1980's created what today is the Mexico City Metropolitan Area (MCMA) [35]. A megacity of over 20 million inhabitants, the MCMA covers an area of 7.866 km<sup>2</sup> over the Federal District and the neighbouring State of Mexico [36]. Urban sprawl was the result of policies and subsidies that promoted massive self-constructed housing for the poor. Consequently, settlements in risk-prone areas with no infrastructure services have been formalised [37], [38]. In addition, Mexico City's urban growth has been produced by intense economic-political pressures. The peri-urban area is where several social groups' interests clash. Housing lots in conservation areas are highly valued by top income groups, which has increased developers' interest in some areas of the urban ring [39].

This capital city was originally settled on a lagoon system [40]; but urban development policies of drying the lakes with massive deforestation has created a dry valley with periodical intervals of tougher flash floods and droughts [41]. Water consumption in Mexico City is higher than in any other developing country, at an average of 360 litres of water daily per person, while UN suggest that this amount should be 150 litres [42]. However, 60% of piped fresh water is supplied to only 3% of the population [43], while more than 1 million people received water for just a few hours per day and 180,000 people do not have access to this service [42]. Water supply deficiencies affect primarily peri-urban low-income inhabitants, who receive water from trunk-pipes, a more expensive service [43]. This is worrying because water service operation costs are elevated and the water service is heavily subsidised [44]. Investment in water supply and sanitation in Mexico City was about 1.7 billion dollars in the year 2002<sup>2</sup>, while water pumping operations — clean water, collected waste water and rainwater — expenditure was 2.436 petajoules, about 20% of the electric consumption of the Mexico City Metropolitan area [45], [46].

Urban sprawl has reduced the natural assets of the area. About 59% of the Federal District is considered *conservation land* [47]; however, 8,842ha of conservation area has been lost due to urbanisation processes [48]. This loss compromises the area's ecosystem services, because this land infiltrates the water into the subsoil, helping to recharge the city's underground aquifer [45]. Now, it is estimated that more than 60 million litres of water is lost because water that previously infiltrated into the aquifer is disposed as polluted water [49]. This problem is serious because 49% of Mexico City's fresh water comes from groundwater [42]. The aquifer's over exploitation is causing drawdowns of the groundwater level, and consequently, subsidence in the city [44], [50]. On the other hand, during the rainy season water disposal can be 210 m<sup>3</sup>/s and 80% of it is storm water [51].

Existing literature mainly describes the hydrological problems through history but does not propose anything new to mitigate Mexico City's problems [52]. Some authors suggest that the lack of procedures and policies encouraging sustainable approaches is because the Metropolitan Area is politically divided by the Federal District and the State of Mexico, which undermines any institutional coherence [37], [47].

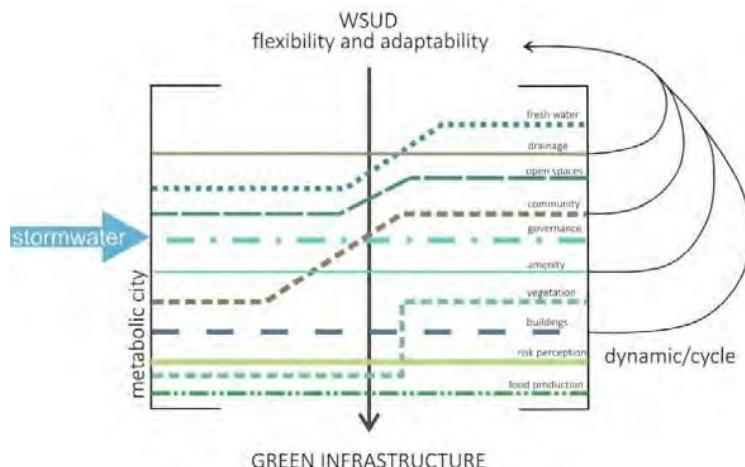
## 3. METHODOLOGY

This research aims to study the possible outcomes of introducing a Water Sensitive Urban Design (WSUD) in an irregular settlement in the southwest boundary of Mexico City, where the rain is more intense and the soil is adequate for water re-infiltration into the aquifer [50]. This design will take the SUDS principle of working with water locally and the WSUD understanding of rainwater as an asset not a hazard, while producing social and ecological benefits for neglected areas.

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*2. Mexico City expended about 600 million of dollars per year -from 2000 to 2005- just to pump fresh water [46]. In that way, water that comes from the Cutzamala River (2B.3 % for the total amount) is conveyed from 126 km away and pumped over 1,200m high. Each water cubic meter from that source required an initial inversion of 23 million dollars [52].*

The main concept is to incorporate rainwater in a new urban production-consumption process. Through the *metabolic approach*, it is assumed that rainwater is a flow that will influence other systems or networks. The whole neighbourhood system will change when WSUD is introduced to the urban pattern, so it is important to plan the outputs that will modify the WSUD and deliver functioning Green Infrastructure (**Fig. 2**). But, will the metabolic city framework help to understand the interaction among the rain's inputs-outcomes and the urban settlement?



**Fig. 2. Schematic water cycle diagram which emphasises the rainwater as an input in the metabolic city.**

WSUD aims to reuse water, modifying people's habits and behaviours towards water [53]. Behavioural changes can be achieved by the incorporation of new benefits inside an urban area. But how is it possible to find the benefits that can trigger this consumption behaviour?

*Isla Urbana* is an NGO that builds fresh water systems for individual dwellings in neglected areas of the south west boundary of Mexico City [54]. This is a viable solution for basic service provision. However, it is important to create a more comprehensive method that goes beyond just a water provision approach. It is also vital to incorporate public space within the WSUD approach. This task is difficult because peri-urban areas are characterized by a blurred distribution of authorities' responsibilities [11]. History has proven that with time irregular settlements tend to be regularised with traditional infrastructure, even though they are not always guaranteed good services [12], [39]. So, how is it possible to incorporate WSUD in an already constructed informal sites?

### 3.1 Methods

This research will analyse a case study of introducing Water Sensitive Urban Design (WSUD) in an irregular settlement. A comprehensive analysis of a site will be developed through Fuzzy Cognitive Maps (FCM) and Context Maps, to understand human perception and the physical characteristics of an area. Then, a WSUD proposal will be developed within three groups of stakeholders related to the area. In this way, the stakeholders' perceptions can be understood and possible actions to adopt WSUD can be discovered.

#### 3.1.1 Fuzzy Cognitive Maps

Cognitive maps are graphical representations of organised knowledge [55] that are used to illustrate dynamic networks [56]. These are often used in participatory planning and decision-making contexts because they create a framework of stakeholders' understanding and a structure for a particular interest [55]. The main benefit of this kind of map is that it analyses complex social-ecological systems through variables and relations [57]. The relations (edges) receive numerical values, ranging from -1 to 1, representing values of positive or negative influences among elements [57], [58]. Concepts are represented by nodes (variables), linked

with each other through edges, expressing causal relationships between the concepts [59]. The edges values are represented in a matrix list, in order to understand the whole system structure.

In this way, a Fuzzy Cognitive Map (FCM) integrate stakeholders' perspectives. The basic information will come from semi-structured interviews with stakeholders, who are experts or have a deeper knowledge of the area and its social-environmental relationships. The interviews will target the following three main topics and the relationship among them:

- Water issues (environmental and social impacts)
- Urban growth
- Environmental loss

The interviews will generate the main concepts (variables), while the relationships (weight edges) will be the result of surveys, answered by participants. A comprehensive FCM will be developed contrasting the perceptions of different stakeholders and assessing priorities within a site.

### **3.1.2Context Maps**

In order to produce a Water Sensitive Urban Design (WSUD) for an urban area, it is important to understand the physical character of the studied area and its physical conditions. This part of the research will describe the area, through observation, graphical information (maps, drawings and photographs) and statistical data; and analysing the physical urban configuration and its components (infrastructure, constructions, roads, services, and open spaces, among others). Context maps will integrate the data, showing the most important characteristics of this place, to later apply the FCM analysis and distribute opportunities and constraints within a physical area; that means, to allocate the results of the FCM in the real world.

### **3.1.3Stakeholders participation to project WSUD scenarios**

This research phase is about creating WSUD scenarios, incorporating future goals and the pathway to a sustainable urban pattern. In that way, three design scenarios will be developed with the collaboration of three main actors: planners-authority, professionals-institutions (universities) and the local community. In addition, the information gathered from the previous phase, comprised in a FCM and drawings, will be used to create a *Control Scenario*, called "*business as usual*". The analysis of the existing problems with a simple calculation of the water runoff will be developed to help the stakeholders to understand what is happening. Existing WSUD projects will be used to explain the main elements or techniques that can be used to integrate water within the existing urban pattern, see **Fig. 3**.



**Fig. 3. Scenarios development by stakeholders, control scenario and WSUD examples will lead the design of the stakeholder's scenarios.**

It is important to show stakeholders that the rain (input) is an asset and that they will have to design spaces or techniques to realise the outputs they want to get from it, creating benefits instead of waste. The scenario construction phase will be done in one or two sessions with each stakeholder group, disclosing desired visions and achievable goals. Each group will work independently to achieve equal participation. In that way, this phase will follow Mahmoud's [60] Scenario Development Plan comprising the next four phases:

1. Scenario Definition: identifying main problems, goals and key variables, while recognising predictability and uncertainty.

2. Scenario Construction: defining techniques, behaviours and desirable outcomes towards a sustainable use of water.
3. Scenario Analysis: recognising consequences, driving flows and system components.
4. Scenario Assessment: diagnosing opportunities and trade-offs and visioning future panoramas.

Finally, a Comprehensive Scenario will be developed with the three stakeholders. This scenario will pursue the participants' reflection about the most valuable and invaluable elements. The idea is to study, within a final discussion, the benefits that can be achieved and the concepts that can produce a real transition towards a water sensitive design.

#### **4. DISCUSSION**

It is important to be cautious while intervening in urban systems and places. Traditional upgrading programmes in informal areas tend to fail, because they do not understand the social-natural interactions within the settlement and they are expensive [19]. Similar experiences happen in public spaces when they turn into unpredicted areas, such as when public parks become rubbish dumps and dangerous areas [61]. For that reason, this research ask:

- Does the metabolic city approach contribute towards creating the right framework for understanding relationships between society and water?
- Can FCM help to understand the dynamics within an irregular settlement, considering it as a socio-environmental system which evolves with time?
- Has Water Sensitive Urban Design [WSUD] the necessary flexibility to deal with socio-environmental dynamics (flows) in an informal settlement?
- Can WSUD encourage a better water metabolism of a local area (increasing water supply —input— while decreasing the volume of water disposal —output—) without compromising other areas of the city?

Pressure over water resources is extremely high in Mexico City [62]. In order to achieve sustainability it is necessary to ensure the equitable distribution of resources among current and future generations, both in quantitative and qualitative terms [2]; so, it is vital to reduce existing consumption and to improve resources distribution. For that reason, it is important to think differently and see what alternatives can help to achieve sustainability. Integrated Urban Water Management (IUWM) provides a framework to achieve sustainability, but the reason why these approaches have not been adopted are not well known.

This proposed research methodology aims to understand the stakeholders' perceptions about an informal area and the benefits that can be achievable through WSUD, which can only be accomplished through experimentation. One of the constraints to achieving for sustainability is the insufficient data in social, economic and ecological aspects [31]. This project aims to unravel the knowledge of local processes that are necessary as a prerequisite for successful designing, in order to discover which values can activate the use of WSUD as the design driver.

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# A review of urban water-energy linkages in end-use: a call for joint demand studies

Simon De Stercke<sup>1\*</sup>, Ana Mijic<sup>1</sup>, James Keirstead<sup>1</sup>

<sup>1</sup>Department of Civil and Environmental Engineering, Imperial College London, London, UK

## ABSTRACT

**Aims:** a review to show the importance of combined water and energy demand end-use studies and to illustrate techniques which can be used for this.

**Study design:** review of energy-related water end-use and water-related energy end-use studies.

**Place and Duration of Study:** cited studies on urban water/energy use are mainly based on the UK, Australia or the US; over the course of the past decades but mainly recent years.

**Methodology:** a search was done for studies about the different energy and water end-uses in cities, their quantification, and methods to estimate those end-uses from aggregate indicators such as total energy or water use. Particular focus was given to the estimation of water-related energy and energy-related water.

**Results:** research has focussed on the disaggregation by actual end-use for energy and for water separately, estimating the corresponding water/energy use. There is considerable uncertainty on the joint end-use of water and energy.

**Conclusion:** combined water/energy end-use is an important end-use component. Water and energy end-uses have separately been studied elaborately empirically in relative to combined water/energy end-uses. Empirical studies of the latter can reduce uncertainties which benefit both utilities and end-users.

**Keywords:** urban water, water-energy nexus, end use, end-use disaggregation, micro-component analysis

## 1. INTRODUCTION

Cities are centres of human capital, where the demand for services is highly concentrated. An important part of these services, crucial to modern urban living, requires energy and (clean) water. Mobility, illumination, hygiene, comfort, hydration, information are some examples. Vast infrastructure exists within the city and far beyond its borders to enable the provision of those services, and the area from which resources are drawn is much greater than that of the city.

With increasing population and urbanisation, the demand for services is on the rise. This is putting freshwater resources under pressure in many parts of the world. On the other hand, we ourselves are putting pressure on the energy system, as it is widely recognized that limits need to be imposed on the amount of fossil fuels that are burnt or converted in order to avert dangerous levels of climate change (with a high probability) [1].

In this context, water and energy resources are linked in many ways. Thermoelectric and hydroelectric power generation reduce the availability of water for other uses: e.g. in the United States, cooling water alone represents 5% of all consumptive uses, and a quarter if agriculture is excluded [2, 3]. Urban water systems require energy to pump water and in wastewater

\* Tel.: +44 (0)20 75946018; fax: +44 (0)20 75945934.

E-mail address: s.de-stercke14@imperial.ac.uk

treatment and distribution, as well as for supply expansion through e.g. imports or desalination. Global warming is changing the hydrological cycle, increasing the intensity of both droughts and floods. In turn, these changes can decrease electricity generation potential [4].

The linkages between water and energy on the supply side of each are significant and can be vast for a single unit such as a nuclear power plant or a pump in the ring main system of London. At the end-use level, the linkages for a typical unit (such as a residential boiler) are orders of magnitude smaller in absolute terms. However, when the end-use services are aggregated, the linkages turn out to be far greater than those at the supply stage. Several studies have found this on the water side, with end-use being responsible for 86% of water-related energy for all sectors in Australian cities [5] and 96% in UK homes [6]. The same holds on the energy side: the water used at the end-use in conjunction with energy is larger in aggregated volume than the water consumed in the energy supply chain from primary to final energy. A simple example illustrates this: bringing a liter of water to boil from 20°C requires about  $(100-20)*4.186 \text{ kJ} = 335 \text{ kJ} = 0.093 \text{ kWh}$ . Assuming an end-use efficiency of the water kettle of 85%, a (consumptive) water intensity of wholesale electricity of 1.02 L/kWh [7], and transmission and distribution losses equal to 20%, the cooling water consumed to boil the liter of water in the UK would on average be 0.14 L. Cooling water consumption is the greatest component in the water consumption of the electrical energy supply chain (making up over 80% of it) [8]. As most energy-related water in end-use requires less energy per unit volume, and as the water intensity of fuel (such as natural gas) supply chains is generally lower than electricity's, this illustrates how end-use is the biggest component of energy-related water.

Several studies have estimated the magnitude of the supply-side linkages, both for the water intensity of energy supply [9,10,11] as well as for the energy intensity of (municipal) water supply [12,13,11]. Although there is considerable variation among the estimates for different locations, these can be largely quantified and explained by local circumstances. The (especially residential) end-use however is much more granular, and even though the technological characteristics are likely less site-specific than for the upstream linkages, the differences in behavior and modes of operation create variation and uncertainty of a different nature, and therefore make the end-use linkages less quantifiable and explicable.

There is a disconnect between the importance of water-energy linkages at the end-use and the knowledge about them. This disconnect is also apparent when energy or water are regarded separately: end-use is the main leverage point for systemic efficiency in each of those systems, yet is the most difficult to measure because of its granularity. However, when looking at the two systems in isolation at the end-use stage, the essence of end-use is ignored: water and energy are in demand because of the services they enable. Many of those services are neither a purely water nor purely energy service, but combined services with crucial cross effects. Knowledge of only water consumption by service or only energy use by service is not sufficient to understand the demand for all water and energy services. The aim of this paper is to review the current understanding of water and energy at the end-use, as well as their linkages, and to highlight the importance of linking both research streams.

The scope of this paper is limited to the residential sector, for the reasons that it represents the largest demand category in urban settings, that the services demanded are similar to those in the commercial sector, on which less has been published, and that there has been little comprehensive research on end-use linkages in the industrial sector [5]. The industrial sector is also much more heterogeneous in terms of users and therefore does not lend itself to a general approach. The context of a developed country, with full access to piped water, is implicit.

Section 2 reviews the understanding about energy end-use and the methods involved. Section 3 discusses this for water demand. Finally, section 4 shows what has been done to understand water-energy end-use linkages, and demonstrates the importance of this area.

## 2. ENERGY DEMAND

Commercial energy is used for a broad swath of applications in the modern urban household. Natural gas is used for cooking, for space heating and to heat water for consumption. Oil is also

used sometimes for the latter two. Electricity is a highly versatile energy carrier and apart from straightforward heating applications, is used to power electronics and provide information, to illuminate, and to provide mechanical power for several tools and appliances.

However, to both end-users and the utility companies it is quite unclear what fraction of energy consumption is used for which service, and when the energy consumption for this service occurs. Fuels are used mainly for heating, but how much for heating food, for heating shower or tap water, and for heating the space is a guess in most cases. The attribution of electric energy to end-use services is even more problematic because of the myriad of uses.

With the traditional system of monthly billing based on monthly or annual readouts of meters, information about energy consumption is highly aggregated, over time, uses and users: there is little or no more precise information on when energy was used, what for and by whom. Therefore, the potential of this information to inform end-use efficiency decisions is very limited. Estimates are possible but they require additional information about the appliance stock, environment and behaviour.

The importance of having more resolved, disaggregated information on energy end-use, particularly in the residential and commercial sectors, is widely recognised [14]. There are benefits to all actors involved: utility companies can target efficiency programs better, end-users are more aware of how their behaviour affects their energy use through appliance use or thermostat settings [14], and the energy modelling community has better data for calibration [15].

At the level of a single end-user entity such as a household, three main techniques exist to infer the energy consumption by end-use [14]:

- Surveys of the appliance stock and usage patterns by end-users. Combining this information with that from other households allows rough estimates of consumption by end-use.
- Distributed direct sensing: appliances are individually monitored for their consumption. This method is costly but highly accurate.
- Single-point sensing: the total consumption over time is measured, and additional attributes inform the break-down by appliance.

With increasing computational capacity and high-resolution measurement devices, the last method has gained a lot of traction most recently, with data from the first two methods informing the algorithms. Single-point sensing is also referred to as Non-Intrusive Load Monitoring (NILM), inspired by George Hart for electricity consumption [16]. NILM for electricity is the deduction of which appliances are drawing or not drawing current, from the aggregate electric power signal. By extension, NILM is used to derive energy consumption over time of different appliances, and can thus be used to attribute energy to the different uses.

NILM has received most attention with respect to electricity as electric smart meters are diffusing into more households and are allowing electricity use to be monitored at high temporal resolution. Several algorithms exist that differ in the quantities measured (potential, current, active/reactive power), the sampling frequency and the method to identify active appliances [14]. A toolkit called NILMTK (NILM Toolkit) has been developed to compare the different approaches on accuracy [17]. Classification accuracies for single-point sensing upward of 80-90% have been achieved [14].

In the residential sector, (natural) gas is the other major energy carrier. Natural gas is mainly used for heating, but through several methods (such as an open flame for cooking, a fireplace for space heating, or enclosed in a boiler system), the relative consumption of which cannot be derived from monthly or annual readings. Apart from directly measuring each fixture, NILM methods also exist for gas consumption, e.g. based on sound waves with a reported accuracy of over 90% [18].

These energy disaggregation methods can be used to obtain information on how much energy is related to water use at the single household level. Water-related end-use energy is a considerable fraction of the total household consumption, with estimates ranging from 14% to

50% for water heating alone (excluding pumping in dishwashers and washing machines) [19]. However, the energy use in itself does not provide complete information on water-energy services. Without knowledge of the volume of water in each service, it is not possible to gauge service efficiency and gain a proper understanding of the effect on energy consumption of water efficiency or conservation measures.

### **3. WATER DEMAND**

Similar to energy end-use disaggregation, there is a lot of interest in water use disaggregation. Like electricity and natural gas consumption, water use is metered with monthly or yearly intervals (although in some cases not at all e.g. only about a quarter of customers of Thames Water, the main water provider for London, are individually metered [20]).

In the water sector, end-use disaggregation is better known as micro-component analysis [21]. Over the past decades several studies have been performed on consumption by micro-components in samples of households, based on surveys and diaries, measurement of water consumption over time, and recognition of the consumption signatures of the different micro-components [22,23,24]. Micro-component studies are becoming more important as water companies are encouraged to perform them in order to have a proper understanding of what water is used for [22]. New methods for NILM of water consumption are being developed, e.g. based on pattern recognition in pressure waves [25] or in vibrations of the piping [26]. For the average UK household, a main water use is toilet flushing, comprising almost a third of domestic consumption [21]. About half was reported to be linked to energy use through showers, baths, dishwashers, washing machines, and cooking or washing (kitchen sink) [21]. A similar breakdown was found for Australian households in East Queensland, where the share of toilet flushing is however about half that in the UK study [23]. In a California study, indoor water use breaks down roughly the same but with a larger share of perceived leakages (including part of swimming pool filling water) at almost one-fifth; and general outdoor water use (with which little or no end-use energy is associated) is much larger, on the same order of magnitude as indoor use [24], although this result is for the entire residential sector and outdoor use will be smaller for the more central areas of cities.

The water-energy linkages at the end-use are clearly very important from both the water perspective as well as the energy perspective (section 2). There is no lack of useful indicative reference values for energy intensities of different water uses, especially for the residential sector, as shown by several studies and reviews [13,27,28]. However, exact energy consumption does not appear to be empirically determined in studies based on empirical micro-component analysis [23,29,30]. The energy for hot water is estimated using relatively straightforward formulae based on water volume; inlet, outlet and air temperatures; system type; and estimated losses. Mechanical energy uses for water are not considered in many studies. Although the energy models applied to the water end-use data will yield an energy consumption with some accuracy, household-specific and behavioural variables are expected to have significant influence on actual energy consumption through e.g. thermostat settings, heat losses or faulty operation such as a circulation pump which is constantly on instead of being thermostat-controlled [14]. These factors add to the variation and uncertainty on the energy intensity of different water uses due to modelled technical specifications alone, estimated at between 20% and 50% in an Australian study [23].

### **4. JOINT ENERGY-WATER DEMAND**

The lack of actual water end-use data in energy end-use studies, and conversely of actual energy end-use data in water micro-component studies, contrasts with the importance of the end-use linkages between energy and water. This uncertainty has adverse effects for planning, e.g. efficiency measures in new developments might not materialise as expected so that jurisdictions may miss climate change mitigation goals [23]. As water use is a determinant of energy use and vice versa through these linkages, it is also logical that both be combined in end-use studies. This section discusses the benefits of having more linked end-use data on water and energy consumption, instead of separate data for energy and water. Obviously, disaggregated water or energy use information in itself already has great value.

Detailed linked data avail both end-users as well as utilities. For residential customers, the benefits are an increase in awareness of the effect of their behaviour on water and energy use, and more accurate operational cost prediction. One study shows that feedback on shower use leads to a statistically significant reduction in water consumption only when the energy consumption is also reported, not without [31]. Linked end-use data also allow customers to obtain total operational cost data not just by energy end-use or by water end-use, but by actual service. It can put a precise price on the service of hygiene through showers, just as most end-users know the cost of individual mobility by petrol station costs, thus incentivizing them to save on mobility. Finally, it can highlight abnormally high energy or water consumption for a particular water/energy service, such as a thermostat set too high or a faulty one, which may not have been noticed from the end-use energy breakdown itself.

For utilities, reducing uncertainty on the end-use linkages enhances the existing benefits of integrating water and energy demand side management. Successful programmes exist in the United States that integrate water and energy management through collaboration between energy and water utilities, by pooling the costs (e.g. one in-person visit for water and energy readouts or installation) as well as the savings (from direct and indirect water and energy savings) [32, 33]. Empirical water-energy end-use data reduce the uncertainty on estimated savings, and therefore the risk and total cost of the project. This is also very important with respect to planning to meet future demand, as costs from headroom and excess capacity can be reduced.

## 5. CONCLUSION

This paper presented the current understanding of water and energy consumption in end-use for the urban residential sector, and the important linkages between them. So-called smart metering of both systems is slowly becoming more commonplace, allowing for real-time estimation of individual uses through non-intrusive load monitoring (NILM). Research in NILM focusses mainly on electricity, but spills over into gas and water consumption. Though energy and water use disaggregation by themselves have merits, combining them can reveal the actual linkages and can inform energy-for-water models. Household-level water-energy information can raise awareness and induce savings in end-users. For utilities, it highlights where savings are possible, and reduces risk in planning.

Key messages from this review are:

- Innovative ways are being developed for non-intrusive load monitoring for both water and energy consumption.
- There is a need for simultaneous studies of water and energy end-use to reveal the actual linkages.
- Water and energy demand side management is more cost-effective when utilities collaborate.
- Empirical data on end-use water-energy linkages reduces uncertainty for planning and investment in efficiency or demand side management.

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## COMPETING INTERESTS

None.

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*Water Efficiency Conference 2015*

## **Integrated Urban Water Management (IUWM) in a Small Coastal City on the Gulf of Mexico**

**Pacia Diaz<sup>1</sup>, Paul Stanek<sup>2</sup>, Daniel Yeh<sup>1\*</sup>**

<sup>1</sup>*Department of Civil and Environmental Engineering, University of South Florida,  
4202 E. Fowler Avenue, ENB11B, Tampa, FL 33620, USA*

<sup>2</sup>*Public Works and Utilities Department, Water Division, City of Dunedin,  
1401 CR #1, Dunedin, FL 3469B, USA*

### **ABSTRACT**

Water managers tasked with providing reliable water supply to urban areas face challenges related to growing demands, source water protection, environmental preservation and uncertainties of climate change. Water smart cities must look to shift away from the traditional urban water management paradigm characterized by a fragmented approach and adopt a new paradigm; one that manages the urban water cycle in a more integrated way, satisfying contemporary issues and adapting to future needs. This presentation advocates Integrated Urban Water Management (IUWM) as the next water management paradigm and presents Dunedin, FL a highly urbanized coastal city of the Gulf of Mexico, as a case study which takes into consideration contemporary issues and future needs of urban water supply. Where most IUWM case studies focus on greywater and wastewater reuse, this project presents resource efficient water and wastewater management, sustainable and innovative strategies, by exploring the entire urban water cycle and provides an optimistic case for the IUWM paradigm. Innovative strategies in augmenting wastewater reuse and improving groundwater management, and aggressive conservation have contributed toward greater sustainability and resilience. This presentation addresses the nexus of water, climate, energy and land.

*Keywords:* adaptation, AMR, sustainable water management, closing loops, reclaimed water, urban water cycle, urban wellfield, water reuse

## 1. INTRODUCTION

Reliable water supply is essential for communities to function and thrive. It is needed for more than mere human consumption and well-being; it is critical for nearly every segment of urban life. Without it, food production, waste management, power generation, air conditioning, and a myriad of other necessary urban functions would come to a screeching halt. Although modern cities boast from centralized water treatment and distribution, pressures from urbanization and climate change are affecting the reliability of water supply.

These contemporary issues that water utilities face are of particular concern to coastal cities. First, the majority of the US population lives in coastal counties. Extensive development has a direct impact on the hydrologic cycle causing water scarcity, flooding and changes to water quality [1, 2, 3, 4]. Urbanized coasts bring demands for fresh water, most of which depend on groundwater for at least part of their drinking water supply. Overpumping of groundwater as a result of satisfying high water demands is the primary cause of salt water intrusion (SWI) in coastal locations [5, 6]. Dense populations also generate large volumes of waste, which must be treated and discharged, directly impacting water bodies, threatening water quality, negatively affecting recreational waters and natural systems. Especially in the United States, water infrastructure is aged and performs poorly due to leaking distribution pipes and water main breaks [7]. Last, highly urbanized coastal cities rely on tourism, ports and other water-centric industries to sustain their economic base; protecting and preserving their coastal resources is imperative to ensure economic survival [8].

As if water supply reliability and the conservation of water resources was not enough, there is the added issue of energy efficiency in the treatment and distribution of water. Energy consumption is directly linked to water through the water-energy nexus. Highly efficient recycling schemes are sometimes implemented to preserve precious natural water resources at the expense of energy intensive processes, causing higher emissions, also detrimental to the environment [9].

Considering the projected urban growth, subsequent environmental issues, and related issues of water and energy efficiency, there is an urgent need for a shift towards an appropriate urban water management paradigm. Paradigms are the overarching set of ideas, principles and approaches that serve as examples of significant design practice [10]. They typically manifest themselves as the result of similar large scale design responses to the needs of the time. Contemporary issues as well as the anticipated pressures of future climate are precipitating shifts in management although traditional water infrastructure remains in place [11]. At present, the urban water cycle is managed in a fragmented manner through three separate infrastructure systems: drinking water, wastewater and stormwater. This represents a traditional engineering management approach that manages the water cycle as a fragmented and linear type system where water is extracted from the environment, used, polluted and disposed of [12, 10]. Natural systems, on the other hand, use a process where resources are constantly recycled, producing an extremely efficient cycle and minimizing consumption of precious water resources. Following this rationale, integrated urban water management (IUWM) is a paradigm that manages water as a single resource and requires that individual components of the urban water cycle to be managed together rather than separately [13]. IUWM seeks total system solutions through these primary principles: (1) minimizing the amount of pollution generated and discharged, (2) using/reusing water as close to its point of origination as possible, and (3) closely matching the required water quality for its intended use [14]. Collectively, these key principles enable IUWM to establish a water management paradigm where water is managed more efficiently, meeting the needs for contemporary and future challenges in the urban setting. In this paper, we present the case of Dunedin which emulates IUWM. It explores the total urban water cycle, from extraction to discharge, its water management strategies and relevant site specific context, while highlighting IUWM's role in facilitating the sustainable operation of traditional water utilities.

Examining the Dunedin case is beneficial to cities globally. It highlights a micropolitan city with circumstances that exemplify factors which most significantly impact the water sector and how its urban water cycle operates. As a completely built-out city, this case study provides a glimpse of future challenges of fully developed cities. This case study illustrates how a

paradigm shift occurs although traditional water infrastructure remains in place. Observing this transformation temporally and in practice provides useful lessons to utility managers, urban planners and water policy makers, shedding light on the efforts required and the synergistic benefits reaped.

## 2. PRESENTATION OF CASE

This small coastal city in west central Florida on the Gulf of Mexico is approximately 10 mi<sup>2</sup> (26 km<sup>2</sup>) in size and highly urbanized. It has a permanent population of approximately 35,000, which translates into a fairly high population density compared to many coastal cities.

The approach for this study began with the collection of qualitative data in order to characterize the city's water infrastructure and management practices. A literature review of the City's documents relevant to water management background data and challenges was conducted. A general survey of key water infrastructure included site visits to become familiar with its critical functions and supporting infrastructure. Then, quantitative data from the smart water grid system (AMR - Automated Meter Reading) and other data tracking systems was reviewed. Anecdotal information was obtained through informal interviews and meetings with city water managers and operators, as well as sustainability coordinators and urban planners. These observations were then compiled to describe the site specific context for this city, contextual challenges, resource efficient and operational strategies employed for sustainability.

### 2.1. The Dunedin Water Cycle

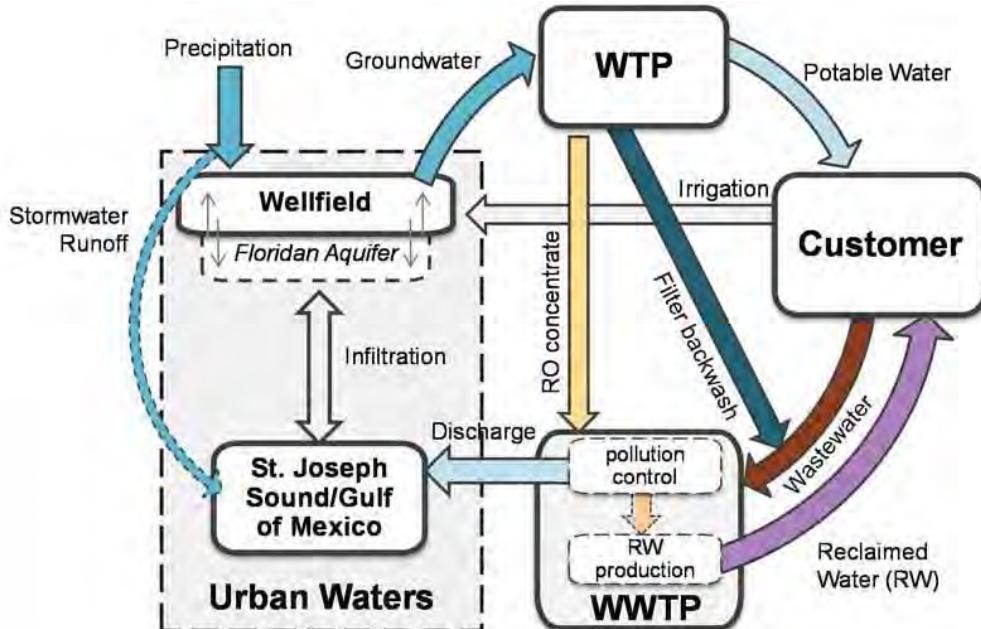
Dunedin's water and wastewater infrastructure is part of a nearly closed loop water cycle (Figure 1). It is composed of a fit-for-purpose dual distribution system for its water supply, consisting of blue pipe (potable) and purple pipe (reclaimed). The cycle begins when raw groundwater is extracted from the urban wellfield and is pumped through a network of pipes to the water treatment plant (WTP). Treated groundwater is then sent through the drinking water distribution system to customers for potable and fire-fighting purposes (blue pipes). Once used by its customers, the wastewater is conveyed by the sewer collection system to the wastewater treatment plant (WWTP) for treatment and recycling. The reclaimed water is redelivered to individual households through the reclaimed water distribution network and used for irrigation. The urban water cycle would not be closed without this important step. Since most of the freshwater recharge is due to precipitation, using reclaimed water for landscape irrigation possibly provides the route for recharging the Floridan Aquifer (the source of the urban wellfield) to some degree. Any surplus treated effluent is discharged into the nearest surface water: St. Joseph Sound on the Gulf of Mexico.

#### 2.1.1. Urban waters

The urban water bodies vital to the Dunedin's community are St. Joseph Sound and the urban wellfield. St. Joseph Sound is the body of water immediately to the west of Dunedin, and lies between its barrier islands and the mainland. It is the City's recreational waters and part of Pinellas County's Aquatic Preserve. The wellfield, uniquely situated beneath the city, is directly linked to the health of its surrounding urban waters. It is the City's only source of drinking water and is vulnerable to urban pollution within the watershed (above it) as well as the condition of the coastal waters (adjacent to it). Groundwater is extracted through its 28 production wells; 1.7 billion gallons (- 6.4 million m<sup>3</sup>) of groundwater was extracted in 2008.

#### 2.1.2. Water infrastructure

The water treatment plant is a reverse osmosis (RO) membrane water treatment facility permitted to treat 9.5 MGD (million gallons per day) (- 36,000 m<sup>3</sup>/day), but averages 3.7 MGD (-14,000 m<sup>3</sup>/day). It provides high quality softening (removal of calcium and magnesium) of raw groundwater from its urban well field. The facility is the largest in the United States to use greensand filtration for pretreatment to remove iron, manganese and hydrogen sulfide. The combination of greensand filtration and RO provides high quality water to its customers, allowing for flexibility in the treatment of a range of water quality types, now and in the future. The treatment process creates two byproduct streams: RO concentrate and greensand filter backwash. Both of these streams are sent to the WWTP.

**ABBREVIATIONS**

WTP	Water Treatment Plant
WWTP	Wastewater Treatment Plant

**Figure 1 – Dunedin’s Urban Water Cycle**

The wastewater treatment plant is an advanced biological nutrient removal (A<sup>2</sup>O) facility and performs a very important role in the urban water cycle at Dunedin: it reduces pollution and it provides a high quality effluent (alternative water source) for irrigation or is discharged during the wet season (Figure 1). The treatment plant has a capacity of treating 6 MGD (-22,700 m<sup>3</sup>/ day), but only receives an average of 4.6 MGD (-17,400 m<sup>3</sup>/day). From this amount of wastewater, it produces nearly 3 MGD (-11,400 m<sup>3</sup>/day) of reclaimed water.

The City's stormwater collection system consists mostly of traditional drainage methods. Stormwater is moved by gravity using either roadside gutters, swales, or routed through an underground piping system. The stormwater is then directed towards retention ponds or water bodies within its respective drainage basin. The stormwater system is not connected to the wastewater collection system.

## 2.2. Contextual Challenges

### 2.2.1. Development

Dunedin lies within Pinellas County, the most densely populated county in Florida [15]. Dunedin's white sandy beaches and subtropical climate also attracts temporary visitors: approximately 5,200 are seasonal residents; tourists visit during the warmer months. This fluctuation can cause large peaks in water demand, especially during high season.

The City is nearly built-out with watersheds at 98% to 100% developed, indicating no significant development in the foreseeable future. Dense urban areas have extensive areas of impervious surface which contribute toward generating a significant amount of stormwater runoff which results in urban flooding. In addition, wellfield expansion to increase groundwater supply severely restricted because of the lack of available land.

### 2.2.2. Coastal location

Urbanized coasts bring high demands for fresh water, most of which depend on groundwater for at least part of their drinking water supply. Unchecked, groundwater withdrawals can lead to well contamination through SWI and permanent damage to the groundwater supply; Dunedin is susceptible to this issue.

Dunedin's coastal location gives rise to drainage issues which impacts water quality in their coastal waters. The steep topography along Gulf shoreline is such that stormwater drains by sheet flow directly into St. Joseph Sound without the possibility of being intercepted for water treatment prior to reaching this water body. St. Joseph's Sound receives all the stormwater runoff from the coastal basin, bringing with it common urban water quality issues, caused by the transport of sediments and nutrients. For 2008, Dunedin saw about 42 inches of rain, which translates into over 4 billion gallons (over 15 million m<sup>3</sup>) of runoff for that year alone. The drainage systems in the southern portion of the City suffer from deterioration, as evidenced by runoff overload, causing clogged pipes and blocked outfalls, and requires significant improvements.

#### **2.2.3. Limited and sensitive water source**

The average precipitation in west central Florida is approximately 54 inches annually (1372 mm), most of which comes during the summer months in the form of thunderstorms. Coastal locations like Dunedin tend to receive less rainfall than inland areas because of a lack of convectional heating. Up to two-thirds of the water received returns to the atmosphere by evaporation or transpiration [16].

Few communities in Pinellas County supply their own drinking water; Dunedin is one of them. Most other cities in the region rely on Tampa Bay Water, the region's wholesale water supplier, for drinking water with an extensive alternative water supply portfolio. Except for a tie-in to the Pinellas County water system as an emergency backup measure, it is water independent, relying on groundwater as its source for drinking water. However, if mismanaged, there is a potential for undesirable impacts. Overpumping has been known to cause land subsidence and, in extreme cases, sinkholes. Karst, a type of geological formation common in West Central Florida, has a tendency for a high incidence of sinkholes [17]. Overpumping can also lead to the draw-down of groundwater levels, causing salt water intrusion by lowering the hydraulic head.

#### **2.2.4. Water quality**

Treatment of the groundwater requires removal of hardness (Ca, Mg) iron, sulfide, manganese, and bacteria. Furthermore, chloride levels in the freshwater wells have been increasing in recent years, indicating a gradual shift in diminishing water quality. Surface waters are also susceptible to diminishing water quality, due to the pollutants and nutrients carried forth from pavement and landscaped areas to receiving waters, degrading the quality of the receiving waters [18]. Effluent discharge from wastewater treatment plants and stormwater runoff can also contribute to the diminished water quality.

#### **2.2.5. Aging infrastructure**

Aging infrastructure requires maintenance and replacement, such as corroded or leaking water lines. At present, drinking water transmission lines in the US transport water under pressure and lose between 6% and 25% of their finished water through leaks and breaks [19, 20]. In Dunedin, 15,000 feet (4,572 m) of water pipe is slated for replacement. Sewer lines suffer a similar ailment as water mains. Wet weather flows leak through inflow and infiltration (I&I). The City estimates that 24.5% of the wastewater flows are attributed to I&I. This volume does not cause the level of service per capita allotment to be exceeded, but it does translate into a greater amount of added chemicals, energy, labor and cost that must be invested to treat the diluted wastewater to be in compliance with State regulations.

### **3. DISCUSSION**

Dunedin's situational context steered them to take steps to reduce existing or elude potentially detrimental issues related to water supply in their community. Although bound to a segregated water infrastructure already in ground, a paradigm shift towards a more holistic management of the urban water cycle was observed in both water managers as well as water consumers. The adopted resource efficient strategies and observed outcomes are summarized by category, four of which are based on sustainability criteria. Though definitions of sustainability may vary from place to place, the basic principles of protecting the environment from the depletion of resources is a common themes [21, 22, 23].

### **3.1. Protect (prevent impairment)**

Protection of the drinking water source is of vital importance for communities and of primary concern for water managers. As a result, a two-step strategy was conceived and implemented to protect the urban wellfield. Step one was to increase the number of wells although no significant population growth was anticipated, allowing for well locations to be more evenly dispersed throughout the City and extraction at a lower rate (restricting extraction). The second step involved reducing the depth of the wells. A significant improvement in water quality has been detected at shallower depths thus reducing wasteful abstraction and treatment. A program for backfilling the deeper wells, some of which were as deep as 300 feet (91 m), was put into effect. This two-step approach, carefully crafted to sustainably manage their water supply, has been affectionately dubbed as the *Sippy Straw Approach*. A sippy cup is an infant's drinking cup, specifically designed to restrict flow through the built-in straw and to prevent spillage if the cup is tipped. Similarly, the *Sippy Straw Approach* mimics these two qualities, with the ultimate goal of judiciously restricting withdrawals and preventing waste. Extracting consistent amounts of high quality groundwater is not the only benefit obtained from this approach. It minimizes drawdown, making groundwater supply more resilient against SWI. A resulting co-benefit is that the number of sinkhole formations was significantly reduced from thirty to just over ten in one year.

### **3.2. Reduce (conserve)**

Water use reduction through conservation and efficiency are what helps communities make the best use of existing water supplies and reduce demand from treatment facilities. Dunedin has attempted to create a shift in practice by strategically guiding users to be more responsible with water use. One such strategy was to work in collaboration with the South West Florida Water Management District (SWFWMD) to distribute a free Water Saver Kit which contained water saving devices that could easily retrofit indoor fixtures to conserve water. The observed outcome was an overall 15.6% reduction in residential water savings.

Another strategy was to create opportunities to guide its residents towards water conservation practices. Many residents in Florida own homes with relatively large grassed lawns which are often planted with St. Augustine turf, a grass variety which requires significant maintenance and watering in order to persist. To reduce water consumption in the irrigation of their lawns and gardens, a landscape ordinance was adopted that calls for drought tolerant (Florida Friendly) landscaping to be planted in new developments. Low volume irrigation systems are mandatory and an inverted rate structure is in force to discourage extensive irrigation of lawns. Finally, watering restrictions have been implemented to allow for residents to water their gardens and landscapes only one predetermined day per week, which is actively enforced.

Dunedin's efforts for conservation paid off. In 2005, their per capita water use was about one third below the State's average of 158 gpcd (589 L/inhabitant/day). However, their efforts did not stop there. Although reclaimed water is treated to a different quality than potable water, it does not mean that it is not an equally valuable resource. During the dry season (February through June), a special effort is made to restrict reclaimed water use through a weekly water volume allotment of 0.8 inch (20mm) over the area of green space. The City works very closely with their customers in providing them necessary information so they are well informed of their reclaimed water allotment during these months. Prior to the start of the dry season, individual tallies are prepared, containing programmed water allotment and the previous year's use and then delivered to every customer's door in the form of a door tag, helping customers avoid being penalized with a surcharge for overuse. As a result, the number of chronic over-users has been reduced and an overall reduction of approximately 60% in consumption, shown by the steadily decreasing gpd/customer trend (Figure 2).

Figure 2 illustrates the result of both potable and reclaimed water conservation efforts. Individual water consumption dropped from 131 gpcd (496 L/inhabitant/day) to its current rate of 62 gpcd (235 L/inhabitant/day); a reduction of approximately 50% since 1993. The availability of reclaimed water has also made an impact on per capita use. Although potable water consumption rates may differ in Europe or in other locations, this significant reduction shows the effectiveness of efforts to increase awareness and change consumption habits. In 1997, only one thousand or so reclaimed water customers were receiving service. As the

planned phases of the system were installed, the customer base grew, with service to many residential communities and golf courses. The figure also illustrates the impact that implemented strategies have had on the reduction of water consumption.

### 3.3. Reuse

Opportunities for reuse increase through IUWM. Closing the loop on waste streams create synergistic opportunities by simultaneously providing an alternative water source and protecting the environment. There are two examples of this within Dunedin's urban water cycle. One instance occurs between the water and wastewater treatment facilities. The waste streams from the RO water production process totals approximately 1.0 MGD (3,785 m<sup>3</sup>/day). Instead of discharging this waste to the nearby urban waters, it is reused to augmenting the volume of reclaimed water. In doing so, it minimizes the amount of point source discharges into coastal waters, reuses water close to its point of origin (within the City limits), and closely matches the quality of water required for irrigation (its intended use) [20]. Another opportunity for reuse occurs at the development located at Honeymoon Island (one of Dunedin's two barrier islands) which was at one time slated for high density development. Water infrastructure was designed and in place prior to the completion of the final phase which never came to fruition. As a result, utility managers were faced with the issue of an oversized water main without the designed demands and a lift station with less than the designed flows. Utility managers, with an IUWM perspective in mind, realized that the excess potable water could augment the much needed flow at the nearby lift station. A valve and discharge pipe were retrofitted to discharge directly into the lift station, synergistically resolving both issues and closing the loop on water loss. Although capturing this waste stream averages about 200,000 gallons (757 m<sup>3</sup>) per day, the annual savings is nearly 50 million gallons (190,000 m<sup>3</sup>). Altogether, approximately 400 million gallons (1.5 million m<sup>3</sup>) are saved annually due capturing waste streams at these two points in the urban water cycle.

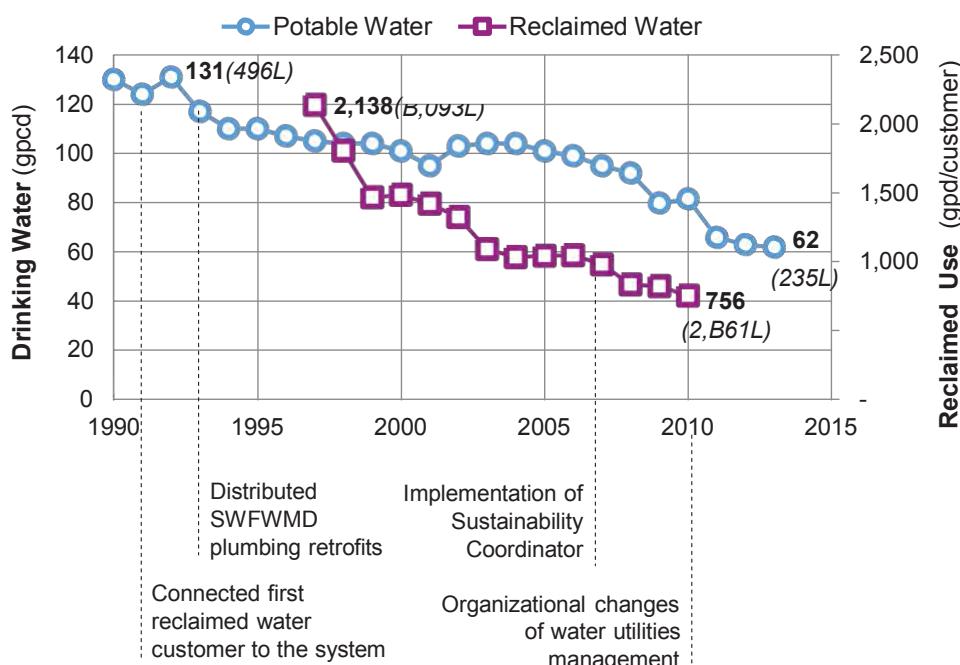


Figure 2 – Historical Potable and Reclaimed Water Demand

### 3.4. Recycle

Wastewater is consistently available in the urban setting. Yet, in 2008, only 2.5% of the treated wastewater from publicly owned wastewater treatment facilities in the US is being recycled [24]. Recycled wastewater is a drought-proof alternative water source that can be used for non-potable applications in an urban setting and is consistently available regardless of seasonal fluctuations [25] and since nearly 50% of residential water use is non-potable in nature, it is ideal as potable water offset. Monthly wastewater flows to Dunedin's WWTP are fairly consistent, receiving an average of 4.6 MGD (17,413 m<sup>3</sup>/day). During the dry season

when irrigation demand is high, 100% of the recycled wastewater is used for reclaimed water, resulting in zero discharge at the WWTP; an amazing feat. Extensive recycling of wastewater into reclaimed water for irrigation significantly reduces nitrogen loading to St. Joseph Sound. Because the demand for reclaimed water sometimes exceeds the available supply, the City has implemented an irrigation schedule that takes reclaimed water availability offline for one day during the week to allow time to replenish supplies in the water storage tanks. When needed, raw groundwater is blended with reclaimed water to meet peak demand. This concession by SWFWMD allowed for the expansion for the reclaimed water customer base and achieves an overall net decrease in groundwater withdrawal.

### **3.5. Innovative approaches**

Lord Kelvin once said, 'If you cannot measure it, you cannot improve it'. Improved efficiency in the management of the urban water cycle requires more than being reactive to impacts on water supply. Adopting innovative approaches ensures higher effectiveness. Investing in water infrastructure technology, coordinating among utilities and upholding sustainable practices were approaches that served to reinforce this City's success.

#### **3.5.1. Smart grid technology**

Investing in smart grid technology for both potable and reclaimed water customers has contributed to Dunedin's success in water conservation. AMR (Automated Meter Reading) technology does more than save money by eliminating the labor required to read meters manually. Since AMR tracks water usage in real time, it can help pinpoint elusive water leaks in a relatively short timeframe, serve as a deterrent to those violating watering restrictions and help water managers anticipate water demands tied to seasonal trends, to name a few.

#### **3.5.2. Coordination between utilities**

Coordination between the WTP and WWTP is needed in order to supply the City with drinking water. These plants are inextricably bound by the by-product streams produced by the RO plant. Since the high concentration of dissolved solids in the waste streams can adversely affect the microorganisms (at the WWTP), the volume and the timing of when the by-products are sent must be coordinated with the WWTP. In essence, the City's ability to provide drinking water is not only dependent on the availability of source water, but also on the WWTP's ability to assimilate the waste streams.

Coordination also occurs between the City utilities and the power company. As a high energy user, the power company offers the water facility a reduced rate during low demand times, such as during the late evening. The water plant takes advantage of this opportunity to produce water at a reduced cost to the water utility. In return, the power company may request the WTP to shut down during peak energy demand times. During these times, the plant's backup power generators provide the flexibility to operate independently from the power company as well as during emergency situations, such as during extreme weather events.

#### **3.5.3. Commitment to sustainable practices**

Success in sustainable practices didn't happen by chance; it required a collaborative effort between City administrators, staff, community leaders and members. Dunedin has clearly shown its commitment to sustainability by embracing green building rating systems. Dunedin has led by example through its Community Center which was among the first in the region to attain United States Green Building Council's (USGBC) LEED® Silver certification. LEED® accredited professionals have been added to City staff, positioned to guide and educate citizens and developers in sustainable practices. As a result, there are now several certified green communities within Dunedin.

## **4. CONCLUSION**

This presentation highlights four different operational strategies in which IUWM, not as a physically integrated system of infrastructure, but as a resource efficient paradigm, manages water as a single resource. This case study illustrates how the entire urban water cycle can be sustainably managed by closing loops and implementing sustainable operational strategies.

The Dunedin urban wellfield was protected by using the *Sippy Straw Approach*, a two-step method of extract high quality groundwater without subjecting their only drinking water source to the threat of SWI. Recycling wastewater is an important step in closing the loop water cycle in Dunedin; it makes up over 40% of the water demand. Conservation measures for both water supply sources, potable and reclaimed, served to minimize extraction from their sensitive coastal aquifer. Investing in AMR technology for both drinking water and reclaimed water distribution systems served to accurately assess demands, educate water consumers and to quickly pinpoint leaks before thousands of precious gallons of potable water are lost. Capturing waste streams at different points in the City significantly supplemented the available volume of wastewater to ultimately serve to mitigate reclaimed water demand. Closing these loops served as examples of efficient use of resources, minimized waste and augmented the available reclaimed water by nearly 40% over the course of a year which would have otherwise been discharged to the Gulf. It is important to note that water treatment processes in Dunedin, RO and wastewater recycling, are both energy intensive processes. However, every drop of water that is reused is one less drop that is extracted from the aquifer and treated to drinking water quality. In essence, water resource efficiency and conservation equals energy savings as well.

The outcomes of these practices serve to illustrate how the efficient use of resources can minimize waste and simultaneously augment water sources to satisfy demands. Educating water consumers within the City created the synergistic opportunity reducing environmental impacts (less extraction) and protection of drinking water sources. Reduced demands also translate into reduced amounts of energy consumed in the treatment and pumping.

Dunedin continues to seek opportunities for efficient use of resources and to augment their sources of water. Most recently, the City has negotiated to obtain effluent from an industrial producer in order to augment their reclaimed water volumes. This could potentially reduce the amount of raw groundwater that is being extracted further and again reduce discharges into their recreational waters. Further research includes modelling the urban water cycle as an essential tool to understand the dynamic interactions between water treatment facilities in the City. It will also serve to explore trade-offs between providing reliable water supply, energy use and the impacts to the environment (sustainability).

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# Water cycle and its modern sustainable aids

Zuzana Poórová\*, Zuzana Vranayová

Technical University of Kosice, Faculty of Civil Engineering, Vysokoskolska 4, Kosice 04001

## ABSTRACT

**Aims:** The water cycle is broken in urbanized dwellings. The aim of this article is to provide basic background information about the natural water cycle and how it is broken and modern possibilities of improving it, explained on example of ASLA green roof.

**Study design:** Study of this research focuses on theoretical knowledge on water cycles, the great and the small, defining 4 waters and their roles. Theoretical information about water cycle presents two main options (green roof and green wall) of keeping water cycle in its natural way. The article presents research of green roof focusing on water retention.

**Place and Duration of Study:** Roof of the building of the American Society of Landscape Architects in the heart of Washington D.C, period between July 2006 and January 2007

**Methodology:** Processes that were monitored on ASLA green roof are: process to track storm water retention, temperature, water quality and plant performance. This article focuses mainly on water retention qualities.

**Results:** Green roof retained nearly 75% of the total rainfall, kept 105 000 liters out of the city sewer system, retained 100% of rainfall, did not add any nitrogen to the runoff. Water runoff contained fewer pollutants than typical water runoff.

**Conclusion:** This project might be seen as a small example of what might be done on a much larger scale, taking into an account the fact, that small green roof like this has an influence on water cycle in its environment.

*Keywords: condensation, evaporation, hydrological cycle, precipitation, runoff*

## 1. INTRODUCTION

There is about 1400 million km<sup>3</sup> of water on the Earth in all its states. Water in the seas, water on the land, water in the atmosphere and water in living organisms. In this paper, different forms of water are described and their roles in the water cycle are mentioned.

### 1.1. Water in the Seas

The water of the seas and oceans covers 70,8% of the Earth's surface and forms the largest part, up to 97,25%, of all water on the Earth. The seas and the oceans have a key global thermoregulation function on the planet. Their temperature changes during the year minimally. However, if there were no seas and oceans, the planet would suffer from extreme temperatures, which would make life as we know it impossible. Even a slight fluctuation of temperature compared to the current temperatures could have fatal consequences for food security on our planet [1].

\* Tel.: +421 55 602 4231

E-mail address: zuzana.poorova@tuke.sk

## **1.2. Water on the Land**

Water in solid form (ice and snow) forms 2,05 % of all water on the Earth and locks away up to 70% of the world's freshwater supplies. Visible surface water in rivers forms only 000001 % and in lakes (including salt lakes and inland seas) 0,01 % of all water on the Earth. Groundwater and water forming soil moisture presents 0,687 %. Besides eccentrically placed glaciers groundwater exceeds several times the volume of water in all rivers and lakes. Water in the soil is more important than water in rivers in terms of benefits it provides. This undiscovered treasure is in many countries misunderstood, overlooked, neglected and destroyed [1].

## **1.3. Water in the Atmosphere**

The volume of water in the atmosphere, in all three states is approximately 10 times bigger than the volume of water in all the rivers. Theoretically, if all water in the atmosphere fell as precipitation at the same time, it would create a 25 mm layer of water on the ground. Just like the seas and oceans have key global thermoregulation role on the planet, water in the atmosphere has crucial local thermoregulation function [1].

## **1.4. Water in the Biota**

Water is not just around us, but it is inside us. In living organisms, water volume is about 0,00004% of all water on the Earth. Human body contains more than 60% of water, and all the physiological processes take place in a medium whose main component is water. The water content in plants varies depending on the species and often is much higher than water content in animal tissues. The volumes of water accumulated in the vegetation cover are not negligible, just like the volumes of water stored in the soil due to the existence of vegetation. The vegetation on the land, among other functions, has in particular the critical role in the regulation of evaporation from the soil. Therefore, on the land greatly aids thermal stability. Upon which depends its own prosperity and even its existence. On the existence and prosperity of vegetation depends consequently all higher life on the Earth [1].

Water in the biota is the most important form of water in this article. Vegetation on the roofs, vegetation on the façades of the buildings, on the horizontal and vertical areas, in the city in terms of microurbanism, in the interior of the building, biota and water in it can be found everywhere around us. As mentioned above, volumes of water accumulated in the vegetation are not negligible. The existence of vegetation in many forms is crucial. In this article, the most common ways of keeping water in the vegetation near humans are described and explained; water in roofs and facades.

## **2. MATERIAL AND METHODS**

Water is very unique. At temperatures common on Earth can naturally exist in all three states. The solid state, the liquid state and the gaseous state. During the change of state heat is consumed, respectively released. During the change of state from solid or liquid state to gaseous state, it gains high mobility thanks to which it is capable of quick motion. Thanks to the motion, is capable of quick moving in large volumes in horizontal and vertical directions. Water also has the highest specific heat capacity, thus the ability to receive thermal energy from known materials. With its ability to bind and release energy, and transfer skills, reflection and dissipation of energy, water in all its states according to the needs cools or heats the planet. It is keeping it at a temperature that supports life on Earth.

### **2.1. The Great Water Cycle**

The great water cycle is an exchange of water between the ocean and the land. About 550000 km<sup>3</sup> of water evaporates into the atmosphere each year. From the seas and the oceans around 86% evaporates, from the mainland 14% of the total evaporation from the surface of the Earth. Out of the total atmospheric precipitation, which arise from the evaporation, 74% drops over the seas and the oceans, and 26 % drops over the land. The seas and the oceans through the evaporation and precipitation subsidize land with some

volume of water. This amount of water by the atmospheric and thermodynamic flows is getting through long distances over continents where expires (or falls in the form of snow).

### **2.1.1Balance of the great water cycle**

Part of water from precipitation soaks into the ground and if it reaches the level of the underground water, it join the ground water runoff (outside of drainless areas). Part of water uses vegetation and part of water is again evaporated. The rest runs off to the channel network and back into the seas and oceans. This is how the great water cycle is completed. Under the equilibrium conditions, from the continents into the seas and oceans runs off the same volume of water, this was subsidized by the world's oceans in the form of precipitation. Even relatively small fluctuations in this steady state can cause on the continents major problems, especially if they are long term and refer to bigger part of the basin. If to the ocean flows more water from the continents than the rain allocation of the ocean to the land is, the land loses water and it drains out. This happens for example when humans with their activities systematically reduce the infiltration of rainwater into the soil (deforestation, agricultural activities, urbanization) and water is drained into the rivers and then into the sea. Reducing of soil moisture, groundwater level drop, fading of vegetation and reducing of evaporation happened in this case. If the volume of the flow in water from the continents to the oceans and the seas increase and the evaporation of water from the seas and oceans will not change, respectively will not increase accordingly (due to the global warming evaporation), increased inflow of water from the continents (including increased melting of glaciers) subsidizes the rising of sea levels [2,3,4].

### **2.1.2Human and other effect**

In addition to changes in the global water balance, caused by phenomena beyond the reach of man (solar cycle, changing the position of the Earth to the sun, volcanic activity ...), due to his unaware activity causes further fluctuations. This is how he contributes to the drainage of the continents. Due to his conscious activity in the opposite direction, thus planned retention of rainwater on the continents could stop continual drainage and return the missing water to the continents [4].

## **2.2. The Small Water Cycle**

The small water cycle is a closed water cycle in which vaporized water falls in the form of precipitation over the same terrestrial environments on the land. Just like the small water cycle exists over the land, it exists over the sea or ocean. Between the small water cycles, over the large territories with different morphology and surfaces with varying humidity, ongoing interactions are going on. The small water cycle performs horizontal water circulation, but unlike the great water cycle, it is characteristic vertical movement for it. Evaporation from neighboring areas with different temperatures can cooperate on the design and conduct of cloud. We can say that small water cycles circulate around the country at the same time. We can say that above the landscape the water is circulating in many small water cycles that are donated by the amount of the great water cycle.

### **2.2.1Evaporation from land and rainfall**

The title the small water cycle is not the best because it gives the impression that it is only a small amount of water in the cycle. It is not true. The land is subsidizing a greater part of its precipitation from its continental evaporation. Amount of precipitation in the area is involved in the saturation of soil with rain water and through the small water cycle it is approximately one half to two thirds of rain water (50-65 %) and it participates in the formation of reverse precipitation over the land. Humans cannot indefinitely transform and drainage the country, without the prejudice to its precipitation and its thermal regime. If we want a balanced rainfall over land, we need to ensure constant evaporation from the land. Evaporation from the land is at a certain simplification the difference of precipitation and runoff. If we have a large outflow from the land, it is at the expense of evaporation. Subsequently the rainfall decrease. Gradually the volume of water in the small water cycle over land is decreasing. On the other hand, reducing runoff we can gain greater evaporation [4].

### **2.2.2. Water circulation in a healthy land**

The small water cycle is short, closed, and characteristic for the hydrological and healthy country. In the country saturated with water and water vapor the water circulates in small amounts and for relatively short distances. This happens due to the reduction of different temperatures between day and night, or between sites with different temperature regime induced by water vapor. Most of the water is evaporated, again collided in the area or in its environment. Frequent and regular local precipitation backwards maintain higher water table and thus vegetation and evaporation, and the cycle may be repeated again and again. country [5].

### **2.2.3 The collapse of the water cycle**

If there is a widespread disruption of vegetation cover (deforestation, agricultural activities, urbanization), solar energy hits all the surfaces with low vapor and a part is converted to heat. This is how extreme gives rise to a significant variations in temperature and the temperature difference between day and night, or only between sites with a different temperature regimes grow. Air circulation will increases, hot air is drifted away and most of the evaporated water from the country is being lost. Small and frequent rainfall decrease and more powerful and less frequent rainfall from the sea increase. The cycle opens, the great water cycle starts to dominate, which is in contrast to the small one characteristic with erosion and washing away of soil and nourish to the sea. Restoring the dominance of the small water cycle, which is for man, vegetation and landscape suitable depends on the functional recovery of plant cover area and water areas in the country [5].

## **3. RESULTS AND DISCUSSION**

In this article, forms of water and two main water cycles are described. Few tools/ possibilities of sustaining the water cycle in its natural way, ways and possibilities of beating the collapse of the water cycle are explained and presented here. Green roofs and facades as tolls for sustaining the water cycle.

### **3.1. Extensive Green Roofs**

Extensive green roofs are lightweight veneer systems of thin soil or substrate layers of drought tolerant self-seeding vegetated roof covers. Extensive green roofs require special types of plants. Plants are usually native from dry locations, semi-dry locations, stony surfaces such as alpine environment. These kinds of plants have typical mechanisms to survive extreme conditions. Mechanisms like water storage organs, thick leaves, thick leaves surfaces, narrow leaves etc. Extensive green roofs are known by using colorful sedums, grasses, mosses and meadow flowers requiring little or no irrigation, fertilization or maintenance after establishment. Extensive green roofs can be constructed on roofs with slopes up to 33%. Also, they can be constructed on existing structures with little, or no additional structural support. Construction of this kind of roof is mostly single-wall, or double-wall [2].



Fig. 1. Extensive green roof in Bucharest

### 3.2. Intensive Green Roofs

Intensive green roofs are designed to look like gardens, landscapes. They need similar management as ground gardens. Urban rooftops are really challenging places for design. We could say they are useless places. But these typical useless spaces in our towns are becoming a remedy of constructing healthier environment through more sustainable practices. People in the city on the roof usually look for the view. Positive change happens, when habitant of the city is not forced to be looking for the views, because it is in front of him on the rooftop. Unexpected blue and green grasses, colourful flowers in the middle of concrete, steel and glass. Contemporary technological conditions allow many things. Waterproof membranes help to capture water for irrigation, drainage support growing medium and resist invasion of roots of plants. During the day, temperature of asphalt roof is unbelievably high. On green roof, soil mixture and vegetation act like an insulation. Reducing heating, cooling the building. When it is raining, water floods down to city's artificial canyons. A living roof absorbs water, filters it and slows it down [7].



Fig. 2. Intensive green roof in Buffalo

### 3.3. Green Facades

Green facades use climbing plants (lianas, vines and scramblers) to cover building walls, offering a flexible and adaptable tool for environmental design. Like other forms of green infrastructure, they cool building walls by intercepting and absorbing solar radiation (shading), providing cooling, increasing albedo (reflecting solar radiation), providing a thermally insulating air cavity, depending on the distance of the green facade from the wall and reducing surface wind speed on the wall.

Green facades offer many benefits to their surrounding environment including buffering building temperatures, cooling the local air temperature, providing air filtration, reducing storm water runoff, ameliorating noise pollution, removing carbon from the air, providing shade, and creating habitats for plants and animals. In many cases, green facades are intended to be

aesthetically pleasing. Research shows this aesthetic makes people more relaxed, productive, studious and mentally healthy.

Green facades can potentially reduce energy consumption. Plants on the facade shade a structure's surface, as well as cool the surroundings through the process of evapotranspiration. Green facades reduce wall surface temperatures by as much as 25°F (14°C) compared with exposed wall surfaces [2].



**Fig. 3. Green wall in Madrid**

#### **4. ASLA**

Michael Van Valkenburgh has created little 130 m<sup>2</sup> green roof for the building of the American Society of Landscape Architects in the heart of Washington D.C that was installed in April 2006 [8]. The project was undertaken with the goals of demonstrating the environmental and aesthetic benefits of green roofs.

Extensive green roof system is coverage of the roof placed in the central zone and access path of the roof. This part of the green roof is covered by an aluminum grating walking surface to maximize both usable space and environmental benefits. The area under the grating has soil depth of 70 mm. The grating floats 70 mm above the soil surface, when mature. Walking on the grating helps the sedum trim back. Of course it is anticipated that the sedum growth is going to appear in some places of the grating. Design of the top of the stairway is also green, but the roof designed here is intensive. 300 mm of soil and roses. Design of the top of the elevator shaft is covered with 500 mm of soil and sumac trees. Metal trellis on the elevator shaft and on the stairway is designed for several species that are being trained to grow on it. An irrigation system is placed on both of the sides to facilitate watering [9].

##### **4.1. Monitoring**

Processes that are being monitored on ASLA green roof are: process to track stormwater retention, temperature, water quality and plant performance. Here are few extensive and semi-intensive green roof performance data of full report focusing on water retention: From July, 2006 to January, 2007, the green roof retained nearly 75% of the total rainfall (736mm). This kept 105 000 liters out of the city sewer system. The roof typically retained 100% of (25 mm) rainfall. Water quality: The green roof did not add any nitrogen to the runoff. Water quality testing shows that the water runoff contains fewer pollutants than typical water runoff. Most significantly, the roof is reducing the amount of nitrogen entering the watershed [9].

This project might be seen as a small example of what might be done on a much larger scale, taking into an account the fact, that small green roof like this has an influence on water cycle in its environment.

#### **5. CONCLUSION**

The green roof, extensive or intensive, green wall or facade is a very well known sustainable tool that can be used for solving many ecological issues [10,11,12]. All named problems in the article are pointing at failing the water cycle. Lack of soil, vegetation, moisture, water, wet lands, drainaging continents. One possible way how to help humans thus Earth is to start

building green roofs on the tops of the buildings that took place from nature and turned it into piece ruining the water cycle. Creating natural surface on the top of the building means creating natural surface that will help the small thus great water cycle. The problematic of green roofs is not the point of this article, the aim was to show the importance of water in urban area and the idea of green roof that might be solving this problem in easy way. In the end of this article is an example of built green roof with monitored processes focusing mainly on water retention, it is obvious that situated green roof on the top of the building has positive effects on rainfall retention, reducing pollutants in water runoff. On green roof, soil and vegetation act like an insulation. When it is raining, water floods down to city's artificial canyons. A living roof absorbs water, filters it and slows it down. This system helps to reduce overflows, extends drain system's life, returns water to surrounding watershed, thus helps to keep natural water cycle.

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# Principles of Transition Paths: Purposeful Conversion of Water Infrastructure Systems to Multi Stream Variants

Kirsten Maier\*, Heinrich Söbke, Jörg Londong

Bauhaus-Universität Weimar, Bauhaus- Institute for Infrastructure Solution, Coudraystr. 7,  
99423 Weimar, Germany

## ABSTRACT

**Aims:** The introduction of New Alternative Sanitation Systems (NASS) in existing structures requires often severe system changes. On the other side, water infrastructure systems (WIS) are known for their cost-intensiveness and durability. We consider phenomena as path dependency and lock-in costs as one major barrier for the successful spread of NASS, which increase the efficiency of WIS. For these reasons we develop a framework to overcome these obstacles by means of transfer of the underlying technical systems.

**Methodology:** We develop the concept of transition paths. A transition path transfers a WIS from the current status over a probably long period of time into a future-oriented, adaptable WIS using system-enhancing technology and adhering to edge conditions as uninterrupted functionality and affordability. We propose a pattern language as a framework for the development of such transition paths and identify design principles ("patterns") for the by and by introduction of NASS-oriented water infrastructure. A case study of a village in a rural German area is used to demonstrate the applicability of the proposed principles.

**Results:** Results of our work are the idea of a transition path and the description of a pattern language. The applicability of both concepts is demonstrated in a case study.

**Conclusion:** Transition paths are an instrument to overcome path dependency. Their design can be supported by patterns. Therefore the provided pattern language provides a documentation tool, which could support the diffusion of knowledge about successful implementation of NASS into the field.

**Keywords:** New Alternative Sanitation Systems; transition path; water infrastructure systems; system change; path dependency; knowledge management; design patterns; pattern language

## 1. INTRODUCTION

Planning of Water Infrastructure Systems (WIS) under more and more volatile conditions, as they are found nowadays, demands consideration of various technical solutions. The scientific community names in particular demographic and climate change, increasing energy prices and nutrient scarcity as main challenges, which will affect WIS in future. Conventional grid-bound infrastructure is in use over a long period and additional has high investment and maintaining costs. Here New Alternative Sanitation Systems (NASS) can extend the range and enable resource recovery and efficiency improvement. Especially establishing substance flow cycles and recovering heat from wastewater are appropriate measures [1]. Furthermore recovery of naturally limited resources as phosphorus contributes to a sustainable handling of natural boundaries [2].

## **1.1. Introduction of innovative multi-stream water infrastructure as a complex process**

The introduction of multi-stream based water infrastructure systems mirrors a change of paradigms: these systems replace the primacy of end-of-pipe-solutions by recycling and reuse. As a consequence old and new systems are no longer compatible with each other. For example if black water should be collected separately, this requires at least either a new black water pipework or black water tanks. In addition volume and concentration of the remaining wastewater are reduced, which may influence transport and treatment procedures. The system operator has to provide new infrastructure elements and the end-user has to adapt to this new infrastructure with in-house fittings. Such system changes are complex multidimensional processes involving many different stakeholders [3]. Among these are organizational aspects, legal requirements and acceptance issues [4]–[6]. Besides such considerations there is the requirement of an appropriate and fundable technical foundation. Although the technical development in this field is still an ongoing process, major components of NASS are available and field-tested in green field implementations. The challenge arises when these components have to be integrated into existing water infrastructure.

Furthermore, the introduction of NASS may require a change of the interface of system and user. This may be crucial for user acceptance, as there are no direct advantages to the user: economic savings are not significant in the small scale. An increased flexibility of the complete system will unfold its advantages only after the lifecycle of a stream-based system. In addition, an improved environmental impact mitigates only for a part of the users changes in the user experiences (for example “strange” sounds caused by vacuum toilets or the different user handling of a separation toilet). The decision pro or contra introduction of a multi-stream-based water infrastructure system is not a decision which is made by a single user of the system, but has to be planned purposeful by system operators. Changed infrastructure has to be provided.

Lock-in cost and path dependency describe a phenomenon which occurs often in the context of technical infrastructure [7]. The field of WIS also faces this problem of decisions which have been taken in the past and which impact still decisions in the presence, even if the foundations for the past decisions have fallen away. An example for such a decision is a central wastewater treatment plant, which provides an overcapacity due to wrong estimations of demographic development. The requirement to exploit the provided capacity may lead to planning decisions, which aim at mitigating the overcapacity effects, but are not optimized in a local context.

Summarizing all, the introduction of NASS into conventional WIS is coined by specific characteristics: A large set of stakeholders is affected; the most prominent of them are users and operators of infrastructure components. Probably the perception of users is more influenced by changed operating procedures of toilets and facilities than by ecological and economical gains of such systems. This system change requires almost a complete substitution of the existing components. Path-dependency has to be overcome. So in general, introduction of NASS is a complex task.

## **1.2. Technical infrastructure and their transformation**

Water infrastructure systems are one part of technical infrastructure. Other commonly named parts of technical infrastructure are transportation, energy, communication and solid waste management. These fields may face similar challenges when they have to integrate innovations. Therefore these fields may provide proven solutions, which can be an inspiration for approaches to introduce NASS into water infrastructure systems.

In general there is the question how innovative technologies emerge and diffuse into the field. Van den Ende & Kemp [8] describe technological transformations (TT) using the example of different computer technologies. They point out, that TTs are not only a matter of technologi-

cal innovations, but also require social and organisational changes. Geels [9] seizes the term of TT and frames it as a multi-dimensional process, involving various stakeholders. Among them are financial networks, suppliers, producers, user groups, public authorities and societal groups. Hekkert et al. [10] describe in their framework "functions of innovation systems", another approach to provide a theoretical foundation for technical change.

Change of technical infrastructure has been discussed with regard to specific fields. In his long term review of technological innovations in the telecommunication sector, Davies [11] points out the characteristic of a continuing evolution in a framework of technology, economics and politics. Economic factors have a driving impact. For the energy sector Sagar [12] argues that "Gaps in the energy-innovation system are not likely to be filled until the gaps in our understanding of this system are filled". Jacobsson & Bergek illustrate the necessity of aligned policies using the example of renewable energy technology [13].

In the field of water infrastructure systems Hiessl et al. [14] present a general framework for the continuing evolution of water infrastructure systems. They suggest integration of all stakeholders in the development process. This integration comprises education for policy makers and public participation in order to include citizens. Technical reports as issued by DWA [15] provide instructions to implement NASS on a detailed level.

Concluding and summing up, during our literature search we found theoretical foundations for integrated transformation, the description of processes of change in certain fields of technical infrastructure and specifically guidelines to establish flexible WIS. Regarding our problem, to describe a systemic technical transformation process, which establishes a NASS into existing housing, we could not detect any written knowledge.

### **1.3. Aims of our work**

In the previous sections we have pointed out, that introduction of NASS into the field is a demanding challenge. Our literature review shows that the process of innovation itself and spreading these innovations is at least partly well researched. However, as far as the technical implementation process is concerned, there is barely information available. From our observations there are experts, who are able to plan an implementation process, but this knowledge is neither widespread nor documented. This lack of knowledge can be considered as harmful for the spread of NASS. Therefore the contribution of this work is the provision of a frame for the formal documentation of experience based knowledge. In this concern we want to contribute an instrument of knowledge management. We aim at the documentation of procedures and decisions of the design and implementation process. This more technical approach neglects deliberately other important aspects of NASS introduction as there are, among others, legal restrictions, public participation, financing models and operator models. Rather we want to focus on technical implementation steps and their applicability. In the following section we describe the theoretical foundations of our approach. Then we develop problem-solutions pairs, which can be considered as a toolset in order to design appropriate and feasible transition paths. Finally we present the case study of a 500-citizen village in a rural area of the German federal state of Thuringia in order to test the developed design pattern language.

## **2. FOUNDATIONS OF THE PROPOSED APPROACH**

### **2.1. Transition of water infrastructure**

Our proposed approach to the challenge of NASS-introduction into conventional WIS requires the fragmentation of the necessary measures in sequential, single steps. We define a *transition path* as the process of transfers a WIS from the current status over a (probably) long period of time into a future-oriented target system. In our assumption the purposeful design of such transition paths leads to more efficient WIS over time. Whereas the target system de-

scribes what system should be built, the transition path describes, in which steps the target system is developed. In general the target system has not to be defined exactly at that moment when the transition path starts. In some cases it is thinkable, that only a range for the envisioned target system or a certain number of alternatives is known at the starting point. Parts of the transition path then depend on the development of boundary conditions, as environmental and economic factors or demography. For the scope of this work, however, we assume that the transition path is completely known at the beginning. Furthermore, the design of an optimized target system for a certain area depends strongly on the local conditions in this area. The advantages of NASS are drawn from individually to local circumstances adapted solutions. This is the reason, why there are no sample solutions, but only principles and elements of solutions which have to be applied individually in accordance with local conditions.

If there are no sample solutions, it is obvious, that there cannot be sample transition paths either: Transition paths have to be designed specifically as well. However, in both cases – target system and transition path – their quality needs to be measured. Therefore a methodology to assess the quality of these artefacts is needed. During the whole course of a transition path, the underlying WIS has to meet certain requirements uninterruptedly. Financial feasibility and acceptance of the users are among them. These requirements can be divided into ecological, economical and social factors. An example for an economic requirement is the financial viability: if the transformation of the system requires more than the available financial resources, it is not acceptable. An ecological requirement is given by legal restrictions for emissions of the system: during the complete transformation phase, certain threshold values must not be exceeded by purpose. The uninterrupted ability to work is a requirement from the social point of view: user acceptance is reduced significantly if during the transformation process there is the need for a temporal relocation of the inhabitants.

As a systematic approach to measure the fulfilment of requirements and quality we suggest the use of standardized assessment frameworks for WISs. Such frameworks are designed to include all essential measurements for WIS. Therefore they are suitable to assess completely. If the indicators of such a framework fall below certain boundary values for a significant period of time during the planned transition path, that path has to be discarded as inapplicable. Hein et al. [16] develop such a system, which is able to assess WIS from an holistic prospective. In contrast to other assessment frameworks for conventional WIS it considers resource gains, an important aspect of NASS.

## 2.2. Documentation by patterns

The intention of this work is to document expert knowledge in small, manageable portions of instruction which are easy understandable. These requirements are fulfilled by the artefact of a design pattern. This term has been coined by the architect Christopher Alexander [17]: “Each pattern describes a problem, which occurs over and over [...], and then describes the core of the solution to that problem”. So a pattern in general can be considered as a problem-solution pair. Besides their contribution to knowledge management, design patterns fulfil also other functions. As an important purpose they ease communication. In daily communication a pattern has not to be described, but to be named. In this way they form a pattern language, which consists of a set of patterns. Another advantage is that a pattern can be considered as validated when it reaches this status. It has been applied in numerous situations and therefore has been hardened.

The metaphor of patterns has spread over to various other disciplines. Among them are video game design [18], supervising academic theses [19], organizational patterns and software development processes [20]. Also pedagogical patterns have been described, for learning games [21] or online learning environments [22]. A prominent instantiation has been provided by Gamma et al. [23] in the field of software design. By various adoptions of pattern languages the term pattern has been widened, not all pattern languages provide patterns in the definition given by Christopher Alexander. This may be true for the suggested language here, too. However, from our point of view it does not impact its usefulness and is therefore a valid attempt.

### 3. DESIGN PATTERNS IN THE CONTEXT OF TRANSITION PATHS

#### 3.1. Pattern Description

To apply the pattern metaphor to another field, first it is necessary to define a scheme for the pattern description. We adjusted the schemes given by [23] and [24].

The structure of each pattern is designed consistently. It comprises seven sections which help to find the appropriate measure for each transition step. A distinct identification is enabled by a clear *Pattern Name*. In particular the *Intent*, *Motivation* and *Application* are sections, which clarify the specific situation when this pattern can be applied in a meaningful way. The remaining three sections *Components*, *Requirements* and *Related Pattern* give further hints to other patterns, measures or tasks which have to be considered while implementing the pattern. Table 1 contains all description elements and their meaning.

**Table 1. Elements of pattern description**

Description element	Meaning
Pattern Name	The name of each pattern illustrates succinctly the central aspects.
Intent	A short definition which describes the objectives of the pattern.
Motivation	A description of a scenario to illustrate a problem and the solution the pattern provides.
Applicability	Naming the possible field of application by answering the question, in what situations this pattern can be used.
Components	Catalogue of all elements which are part of the pattern.
Requirements	A brief summary of all conditions which have to be fulfilled to implement the pattern.
Related Patterns	A list of all patterns which are connected to the named one including the joint and the differences.

#### 3.2. List of Pattern

Based on experiences from previous NASS implementation projects and furthermore interviews with experts we have collected a list of patterns. According to the description scheme, which is documented in Table 1, the identified patterns are illustrated in Table 2. This is a selection of the found results. In a first attempt we present them using a table. In order to enhance comprehensibility, further explanations are given in the use case section.

**Table 2. List of identified pattern**

<b>Pattern Name</b>	<b>Intent</b>	<b>Motivation</b>	<b>Applicability</b>	<b>Components</b>	<b>Requirements</b>	<b>Related Patterns</b>
<i>Co-digestion</i>	Increase organic load to anaerobic digester	Villages may not produce sufficient amount of faeces to operate a digester sufficiently.	Situations, when a great amount of co-substrate is available.	<ul style="list-style-type: none"> <li>• Wastewater</li> <li>• Co-substrate</li> <li>• Digestate</li> <li>• Biogas</li> </ul>	Adaptation of legal framework to use “faecal” digestate as fertilizer.	Gradual migration Local exploitation
<i>Flexible technologies</i>	Facilitation of resilient technologies	Technological progress provides efficient solutions	Can be applied in states of volatile boundary conditions	<ul style="list-style-type: none"> <li>• Technology component</li> </ul>		
<i>Gradual migration</i>	Stretch a transition step.	A sudden separation of wastewater streams may not be accepted by users or may be technically impossible.	Use it, when acceptance for separation technology inside houses is low.	<ul style="list-style-type: none"> <li>• Separation technologies</li> <li>• Specific system to transport and treat each stream</li> </ul>	Implementation of measures on private property needs incentives or compulsion.	Purpose-realignment Co-digestion Temporal component
<i>Integrating Reuse</i>	Reuse of existing components in new components	Existing components may be used as part of the new WIS.	Situations, when components are still useable.	<ul style="list-style-type: none"> <li>• Old component</li> <li>• Integrating component</li> </ul>		
<i>Local exploitation</i>	Increase efficiency by avoiding transport	Avoid efforts of transport	Use it when the system is producing substances of great volume or transport leads to losses.	<ul style="list-style-type: none"> <li>• Stream</li> <li>• Product</li> <li>• Utilization technology</li> </ul>	Advanced knowledge of local conditions and utilization possibilities.	Co-digestion
<i>Purpose-realignment</i>	Reusing existing components for a new purpose	Old components may still usable for another objective	Use it, if old components are not usable anymore but can be adapted.	<ul style="list-style-type: none"> <li>• Old component</li> <li>• Usage</li> </ul>		Gradual migration
<i>Temporal component</i>	Enable intermediate steps	Efficient transition paths may require intermediate steps as anchor points	Can be applied, when a new technology requires fundamental change.	<ul style="list-style-type: none"> <li>• Temporal component</li> </ul>	Establish temporary exceptional state to use outdated technology.	Gradual migration
<i>Tier-orientation</i>	Enable substitutability through modularity	Standardized format to convert all components (collection, transport, treatment, product)	Situation when planning of components is not provided by one stakeholder.	<ul style="list-style-type: none"> <li>• Interfaces (transfer station from one tier to another)</li> </ul>		

## 4. A CASE STUDY AND APPLIED PATTERNS

We developed a transition path for model region of our research project in a rural area. During the course of this transition path, several of the before described patterns could be applied. Thus we demonstrate how transition can help to overcome impediments especially in rural areas.

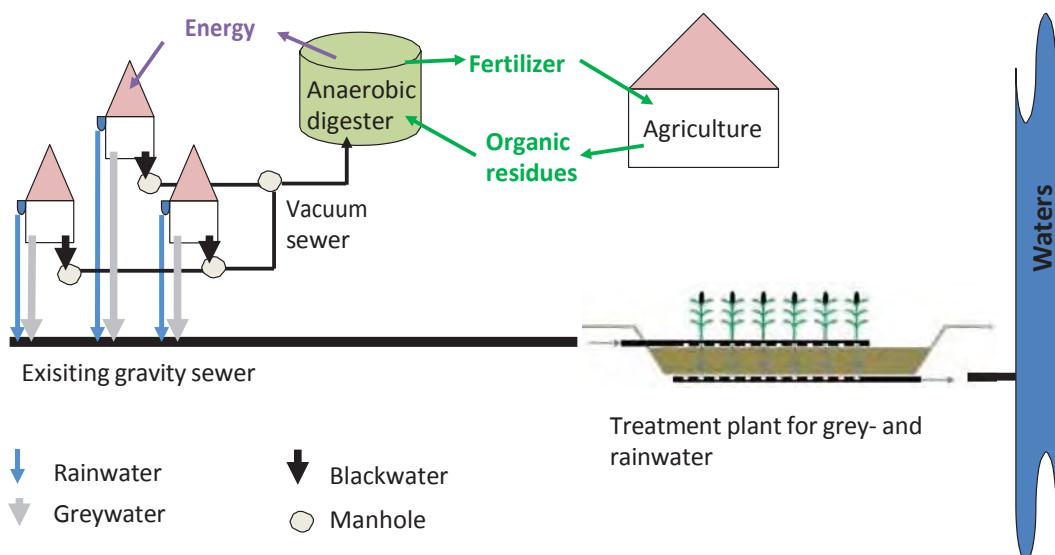
### 4.1. Case study area

The village under investigation is situated in the middle of Germany in Thuringia. Currently in this village live 460 inhabitants. Due to a nearby growing city, the total population of 460 inhabitants remains stable though demographic change leads to a decline in population in the region. The immediate area is mainly characterized by rural settlements and large-scale farms.

Our case study village is part of a compound association of 24 villages, which takes care of all wastewater components. Concerning wastewater the villages is separated in two parts. A newly constructed part, which covers half of the area (230 inhabitants), is connected to a central wastewater treatment plant. This facility is located in a distance of 5 km. In contrast, in the old village center each house still holds its own settling tank. The pre-treated wastewater is either discharged into an old sewage system, which also collects the rainwater, or directly into a small water stream.

### 4.2. Application of patterns

The responsible wastewater disposer is now seeking for an affordable system which meets the state of the technology. Considering all boundary conditions we design a NASS (shown in Figure 1), which enables a local cycle management of reusable substances.



**Figure 1: Case study village: recommended wastewater system (adapted from [25])**

Based on the identified five transition steps, which help to realize the recommended NASS, the application of listed pattern in Table 2 is presented. The transition path consists in particular of installing a vacuum sewer system, build an anaerobic digester, realize the in-house

separation of wastewater, building a treatment plant for greywater and restoring the old sewage system.

The first measure towards the aimed system is *installing a vacuum sewer system* in the old village center to discharge wastewater. The applied patterns here are “flexible technologies”, “temporal component” and “tier-orientation”. Even though nowadays the demographic situation in the case study area appears stable, implementing a more flexible technology was preferred. The accrued advantages of vacuum systems are shorter depreciation and a higher technological resistance to changing wastewater characteristics. Temporal components in this sewer system are the interface manholes on the private property connecting the conventional in-house system with the new vacuum wastewater system. This also applies the idea of modularity by interfacing collection and transport.

*Building an anaerobic digester* or making use of an already existing agricultural digester involves the patterns “co-digestion” and “local exploitation”. The utilization of agricultural residues as a co-substrate for producing energy by digesting high-concentrated wastewater enables economic sufficiency. The process of finding customers for the produced biogas, heat and digestate has the biggest influence on finding the best location.

The next step within the transition path is to realize *in-house separation* of the different wastewater streams by using the patterns “tier-orientation”, “integrating reuse” and “gradual migration”. In the case of using the separation technology including vacuum toilets the before built interface manholes of the vacuum system can be removed. Since the acceptance of such fundamental change on private property may require special incentives to homeowners a gradual migration of this transition step appears necessary. Pipe-in-pipe systems enable stream-based collection by pulling in two pipes in one existing pipe and are therefore an example for integrating reuse (of existing pipes).

To prevent the now separated greywater from being discharged untreated into the water body a *central treatment plant* for the old village center is built. This measure is based on the patterns “purpose-realignment” and “temporal component”. The old sewer system which in the initial system was used for discharging mechanical pre-treated wastewater, rainwater and groundwater is during this transition step discharging untreated greywater, rainwater and groundwater even though it is not meeting the current state of technology. Therefore a temporary exceptional state has to be established before the last transition step is realized.

The recommended wastewater system is finally completely implemented when the *restoration of the gravity sewage system* is completed.

## 5. DISCUSSION AND CONCLUSION

The transformation of a WIS into a NASS based WIS is a complex process. Among the reasons for the complexity are the inherent necessity of a system change and the diversity of involved stakeholders. Expert knowledge is necessary in order to conduct such a transformation successfully. In the context of our work the sequence of measures in this transformation process is called transition path. A transition path consists of a number of measures. In our observation there are rules to combine these measures to appropriate transition paths. Until now these rules are undocumented expert knowledge. The contribution of this work is a proposal for a documentation methodology in order to provide this expert knowledge to affected persons, e.g. engineers and planners. We suggest using the pattern metaphor. Patterns as problem-solution pairs are an approved method in many other disciplines. We have defined a description scheme for patterns applicable for transition paths and have identified a set of patterns, a so-called pattern language. We consider this set as definitely not yet complete. Björk & Holopainen [18] handled the potential incompleteness of a pattern language by offering a wiki, which facilitates a dynamic development of the pattern collection [26]. In the context of WIS, affiliated organizations and their working groups could offer such a wiki, a similar approach which led to a guideline to implement NASS [15].

As already stated in the introduction technical transformations have to be considered as complex processes involving many different perspectives [8], [9], a mere reduction on technological steps is not sufficient to solve the problem of introducing NASS holistically. However, the definition of a complete guideline to the introduction of NASS with all their facets is not the focus of this work. It should provide a sound systemic-technical foundation.

In this article we presented first the list of patterns and thereafter pointed to the patterns in a case-study-given transition path. This line of presentation serves mainly the comprehensibility of the approach, but is not a sequence of the work in this context. These patterns have been deduced from the experiences of previous NASS-introducing projects.

The provided pattern language is an approach to document knowledge. More common ways of accomplishing this task in the field of engineering are worksheets and standards. However, these kind of documents describe predominantly qualities and characteristics of a product (here: transition path), but not steps ensuring an efficient transformation process.

By providing a pattern language to design transition paths to NASS-principle employing WIS, this work should help to spread knowledge about enabling such systems and therefore support the efficiency of WIS. A major task still to be done is amending and hardening the proposed pattern language. This comprises the application in the design of transition paths for further, preferably urban model areas. Furthermore, solutions may change when applied to other areas than rural Germany. The pattern description itself may require adjustments, in order to optimize it for the target groups. Another amendment could be the collection of negative patterns (or anti-patterns): measures which do not lead to the intended result [18].

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## COMPETING INTERESTS

One of the authors is (additionally to his occupation at a research facility) employed at the wastewater association where the examined village is part of.

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# Use of Sustainable Criteria for Water Management in Higher Education Buildings: A case Study of the UFG/Jataí Library

V.R Brandão, L.P. Carvalho, B. Rosa, M.A.S.Campos\*

School of Civil Engineering! Federal University of Goias - University Square Goiania. Brazil

## ABSTRACT

**Aims:** We aimed to assess, from a technical and economical point of view, the implementation of water conservation actions in higher education buildings, based on the criteria of three environmental certification - LEED, AQUA AND SBTool<sup>PT</sup>.

**Study design:** The study is a descriptive case study research

**Place and Duration of Study:** Library of the Federal University of Goias in Jataí,, Brazil, between January 2014 and December 2014.

**Methodology:** We conducted the analysis of the criteria established by each certification studied. To realize that, we had to estimate the water consumption in the building under study and to propose changes in the original design, in order to meet all possible criteria. After all the changes, we calculated the new predicted water consumption and then, calculated the Net present value and payback to determinate the economic feasibility of these changes.

**Results:** We verified that most of the criteria were applicable to the studied situation and the estimated amount of water that could be saved is around 22.000 m<sup>3</sup> what would represent almost 40% of total consumption expected. When related to economic feasibility, the payback is around eighteen month and net present value around US\$ 16,600.00

**Conclusion:** We hope that this study can stimulate the real application of concepts and procedures that contribute to the economy of water.

**Keywords:** Water savings, Sustainability seals, Economic feasibility, Water management.

## 1. INTRODUCTION

The population's growth that can be observed since the beginning of the 20<sup>th</sup> century has increased the use of natural resources, especially water. The lack of water supply in many regions of the world is justified, beyond this overgrowth, by the changes in habits and geographical irregular distribution [1].

In Brazil, many urban areas suffer with problems of water supply. Irregular distribution of water sources and , associated with lack of awareness of Brazilians, culminated in serious problems of scarcity of this resource, affecting especially urban centers, resulting, in some cases, in water volumes per capita lower than indicated for a healthy living [2].

\* Tel.: +55 62 32096084; fax: +55 62 32096087.

E-mail marcusscampos@gmail.com

Forefront institutions realized that the use of sustainable actions was necessary because, in addition to accomplish the environmental requirements, they would also have a new tool to attract new customers. Over the years, the idea of sustainable and certified products became popular, which created a need to standardize aspects that the companies should fulfill. In construction industry, the environmental certifications systems are the responsible to ensure the right procedures to the sustainable buildings [3].

From latest years, the number of these certifications has increased. One of the reasons to that is the high consumption of natural resources of the construction industry, which is responsible from 15% to 50%, what it causes major concerns [4]. Example of theses seals are: LEED certification, and AQUA SBTool<sup>PT</sup> [5].

The United States Green Building Council (USGBC), a non-governmental organization, created the certification system LEED - Leadership in Energy and Environmental Design, in 1998 in the United States. It evaluates the following categories: Sustainable sites, water efficiency, energy & atmosphere, materials & resources, indoor environmental quality, innovation in design or innovation in operations, and, finally, regional priority credits [6].

To the audit, the buildings must provide pre-requisites in seven categories, which will secure the achieved score, ranging from 40 to 110 points, giving the building respectively, from the approved label to Platinum label [6].

Created in October 2007, AQUA - High Environmental Quality - was the first Reference Technician Certification of Sustainable Building from Brazil. It is based on HQE - *Haute Qualité La Environnementale*, its French correspondent and the Foundation Carlos Alberto Vanzolini implemented it [7].

AQUA is divided into 14 categories, which are inserted in four different bases of action: eco-construction, eco-management, comfort and health. The categories are also divided into criteria (or sub). Each of these categories or criteria can be classified as: Good (B), Superior (S) and Excellent (E). To obtain the AQUA certified, the enterprise must submit a maximum of seven categories with a good performance level and at least three categories with a level of excellent performance [7].

The Sustainable Building Tool (SBTool) is a very flexible international method that can be adapted to different contexts. In 2009, iiSBE Association Portugal - International Initiative for the Sustainable Built Environment - in collaboration with the LFTC- a and the Ecochoice adapted it to Portuguese reality, creating the SBTool<sup>PT</sup>, an Portuguese evaluation method for sustainable construction [8].

This certification consists of three dimensions of sustainable development: environmental, social and economic. These dimensions are divided into nine categories, which are divided into 25 criteria [9]. The score is performed by an equation that relates the referenced and measured values what give a classification for the evaluated criteria. New weighting is done, based on the average of the performance of social, environmental and economic dimensions, what allows a final classification that can be "regular practice" or "best practice" [10].

The UFG is implementing a series of actions to make their campuses more sustainable. For existing buildings, the waste management and the reduction of water and energy consumption are actions that should be done immediately. For new buildings, the designs should include actions that allow the environmental certification of these buildings.

However, with the severe economic crisis that Brazil is going through this year, some budget cuts hit the federal universities. Therefore, any increase in budget standard costs must be justified. The actions to be implemented in new buildings should consider, in addition to being sustainable, the reduction of operational costs.

From this fact, the objective of this research is to evaluate, by technical and economical point of view, the implementation of water management actions in higher education buildings, based

on the criteria from these three environmental certification methods, through a case study in the library of campus Federal University of Goias (UFG) in Jataí, Goias.

## **2. METHODOLOGY**

### **2.1 Criteria Analysis**

We analyzed all the criteria related to water conservation of the three environmental certifications object of this study. In each criteria, we considered the requirements to achieve the maximum level of the certifications. We also verified which criteria were present in all the certifications studied and those that were applicable to building under study.

### **2.2 Case Study**

We selected the building of the Library of the Campus Jatoba of Federal University of Goias (UFG), in Jataí - GO- Brazil. We chose this building because we had easy access to design, budgets, rates, demand forecasting, among other information that would be necessary. Thus, the characterization of the design was done with details of the building, for example, floor and catchment area, amount of plumbing facilities and expected population. Other reason to choose this building because it can be repeated in other new campuses of the university.

Once we defined the building, we raised all the information necessary to analyze it by the certification's criteria: plumbing fixtures, expected population, catchment area, garden area and rainfall data from the last 20 years.

#### **2.2.1 Original design verification in relation to the criteria set**

From the characterization of the original design, we verified if the criteria were fulfilled. We used Brazilian researches and National Standards as reference values.

#### **2.2.2 Design Changes to accomplish criteria**

After identifying the criteria that were not accomplished, we could verify all the necessary changes in design to modify the original evaluation.

### **2.3 Economical Analysis of the design changes**

After we realized all the necessary changes, we estimated the costs of these changes and the reduction of drinking water consumption.

To estimate the costs, we use the spreadsheets from official organizations. In the case of reduction of the drinking water's consumption, we verified the value that this action will have on the water bill, by using the water/sewage rates from the local water company (SANEAGO).

Once we obtained the value of the investment and the return value, we determined the economic feasibility of these actions, by calculating the net present value (NPV) and payback.

## **3. RESULTS AND DISCUSSION**

### **3.1- Analysis of the Criteria at the original Scenario**

We created seven groups to classify the criteria. These groups were: reduction of consumption; reduction of the operating system; reduction of waste water; plot rainwater management, wastewater management; irrigation management and miscellaneous. After that, we classified them in one of these groups. The results are shown in Table 1.

We focus our work only in the criteria that could reduce the water consumption of this building. So criteria 1B, 2D, 2E, 2F were not evaluated.

The first group we analyzed was the reduction of the consumption of potable water. To do so, it was necessary to estimate the consumption of the building and compare it with the reference design. To this building, the reference value was 50 l/person/day, what results in a consumption of 14400 l/person.year. [11].

The second step is to determinate the consumption of the building. The building in this study has a ground floor with an area of 1305 m<sup>2</sup> and a top floor with 1255 m<sup>2</sup>. The garden area is 4486 m<sup>2</sup>. It has eight restrooms, a kitchen and a laundry area. The plumbing system appliances are 24 flushing toilets; 24 washbasins with water saving taps; 4 individual urinals d; 8 water filters; 8 drinkers, 2 sinks and 2 tank. The number of uses of these appliances and their respective flows are shown on Table 02.

According to information provided by the architectural design, the library's floating population is 509 people and, based on data extracted from the library building of UFG in Goiania, in Campus I, the fixed population of employees is 29 people. Thus, the total value of individuals used to calculate the water demand in the library was 538 users. In addition, the library remains closed on Sundays.

We could calculate the consumption per person in the building and the results are shown on Table 3.

The average of use of the library is 24 days/month, what results in an average of 5100 l/person.year. When we compared this value to the reference one, we can noticed that there is a reduction of 64,58%, what accomplish criteria 1A and 2A (see Table 1) respectively from LEED and AQUA. The requirement of the SBTOOL<sup>PT</sup> is also accomplished once this value is lower than 23.000 l/person.year, the reference value of this certification.

Other point that can reduce the water consumption is the criteria 2B, that is related to the reduction of the operating pressure. The Aqua Certification worries about pressure over 300 kPa. This building has an upper reservoir that supply water to the entire building. This reservoir is 10 m above the lowest point of use. It results in operating pressure lower than 300 kPa. That way, this criterion is accomplished.

Other criteria were related to the existence of rainwater harvesting system and reuse system. There isn't any non-potable water system installed in this building, so criteria 1D, 2C, 2D, 3B, 3C weren't accomplished.

There isn't also any irrigation system installed. So the criterion 1C won't be accomplished. Meanwhile, there isn't a cooling tower, food crushers or any special equipment that use water. That way, criteria 1E, 1F and 1G are accomplished.

### **3.2 Modifications of the original design**

After the evaluation of the criteria that were or were not accomplished at the studied building, we decided to modify the original design. These changes had the main goal to reduce the total of potable water that will be used in the building, based on the criteria analyzed.

We evaluated the following actions to guarantee this reduction: water saving devices, rainwater harvesting system, greywater reuse and irrigation system.

Table 1 - Comparison of groups with the criteria presented in selected environmental certifications.

	<b>LEED</b>	<b>AQUA</b>	<b>SBTOOL<sup>PT</sup></b>
<b>Reduction of the consumption of potable water</b>	Reduction of 40% of the building's potable water consumption compared to the certification reference values (1A).	Use of saving systems to ensure a reduction of drinking water consumption up to 50% of the reference project (2A).	Reduction of the annual volume of water consumed within the building for up to 23m <sup>3</sup> /person.year (3A).
<b>Reduction of the operating pressure</b>		Use of pressure relief valves, if the pressure is greater than 300 kPa (2B)	
<b>Wastewater management</b>	50% reduction in the generation of wastewater (1B)	Replace 50% of the drinking water demand on devices that do not require it (cisterns, urinal,s cleaning, watering) by any source non-potable-water (2C)	A greywater system Reuse (3B).
<b>Plot rainwater management</b>		Pre-treatment of rains occurring strictly greater more often than the standard occurrence (2D)	A rainwater harvesting system (3C).
		The overall imperviousness coefficient after realization is lower than 65% (2E).	
		The soil-sealing ratio should be less than 60%. For highly urbanized areas, the percentage of improved waterproofing coefficient should be greater than 10% (2F).	
<b>Irrigation management</b>	The potable water consumption must be 50% less than a typical scenario (1C)		
	It must have a Landscape that does not require permanent irrigation or the irrigation that uses only non-potable water (1D).		
<b>miscellaneous</b>	Do not use cooling towers (1E)		
	The building can't have any food crushers (1F).		
	The building can't have any special equipments that use a lot of water (1G)		

Table 2 - Data to estimate water consumption of the Library of UFG

Appliance	Flow	Frequency of use		OBS
		Jan, Feb, Jul	Rest of the year	
Flusing toilets [11]	6.8 l/flush	0.9 use/day	0.9 use/day	
Washbasin taps [11]	0,1 l/s	1.75 uses/day	1.75 uses/day	Each use 7.34 sec.
Irrigation [11]	2.4 l/m <sup>2</sup>	Mondays, Wednesday, Fridays	It won't happen	
Cleaning [11]	0.5 l / m <sup>2</sup>	Monday through Friday	It won't happen	
	1 l / m <sup>2</sup>	Saturday		

Tabela 3 - Potable water demand at the original design.

Month	Weekdays	Total Daily Demand (L/person.day)	Appliance Daily Demand (L/person.day)	Irrigation Daily Demand (L/person.day)
January and February	Monday .- Friday	5.56	5.56	0
	Saturday	6.75	6.75	0
March	Monday .- Friday	11.13	11.13	0
	Saturday	13.51	13.51	0
April, May, June, August, September, October , November and December	Monday, Wednesday and Friday.	31.14	11.13	20.01
	Tuesday and Thursday	11.13	11.13	0
	Saturday	13.51	13.51	0
July	Monday, Wednesday and Friday.	25.58	5.56	20.01
	Tuesday and Thursday	5.56	5.56	0
	Monday, Wednesday and Friday.	6.75	6.75	0

The first change was the implementation of a rainwater harvesting system. This system was sized to supply rainwater in activities where potable water isn't necessary, as toilet flushing, landscaping irrigation and floor's cleaning.

Considering double flushing toilets, we estimated that in this situation 75% of flushes would have a 3.4 liters volume, and 25% would have a 6.8 liters volume, including the urinals' water demand [11]. The water consumption is 2057.85 liters/day. For irrigation, water consumption is still the same considered at the original design, 10766.40 liters/day, whenever there will be irrigation.

For the design of the rainwater harvesting's tank, we used Netuno software [12]. The volume obtained by the software to this situation was 23,500 liters. With this volume, the software estimates that 69.09% of the predicted use will be supplied with rainwater along the year.

The second change analyzed was the implementation of a greywater reuse system. The demand for water to toilet flushing and urinals in the modified project will be 2057.85 liters/day. To a reuse system for this building, only water from the water basin and sinks could be reused, what would give us a total of 203.4 liters/day. The amount of water for reuse is less than 10% of the demand and it does not justify the implementation of greywater reuse. The only way it could be feasible it would be a greywater reuse system for the entire campus.

We designed an irrigation system using rainwater. This system makes it possible to achieve a reduction of 33.05% of potable water that was used for irrigation. This result is lower than required by LEED certification, which requires 50% reduction in consumption of potable water. In addition, for the garden, we selected plant species with low irrigation demand.

The last changes at the original design was to guarantee a reduction of the potable water consumption. Although not necessary, we verified that the building had a great potential to reduce even more the water consumption. To do so, we predicted a double flush toilet instead of a regular flush, as it was at the original design. This action will cause a reduction of 16.25%.

With the installation of water saving devices and rainwater harvesting system, the average reduction of the consumption was 39.70%. If we considered just the sanitary appliances, this reduction was 44.64% and only for irrigation, 33.05%. The Table 4 illustrates the consumption and the reduction percentage considering the original design.

Table 4 - Drinking water demand in three different scenarios.

Month	Original Design (liters/person. day)	Design with installation of saving appliances (liters/person. day)	Reduction (*)	Design with installation of saving appliances and rainwater use (liters/person.day)	Reduction (*)
January	5,76	4,13	28,30%	2,2	61,81%
February	5,76	4,13	28,30%	2,2	61,81%
March	11,53	8,26	28,36%	4,48	61,14%
April	21,53	18,26	15,19%	12,81	40,50%
May	21,53	18,26	15,19%	15,87	26,29%
June	21,53	18,26	15,19%	17,28	19,74%
July	15,77	14,13	10,40%	13,67	13,32%
August	21,53	18,26	15,19%	17,08	20,67%
September	21,53	18,26	15,19%	15,09	29,91%
October	21,53	18,26	15,19%	12,54	41,76%
November	21,53	18,26	15,19%	10,46	51,42%
December	21,53	18,26	15,19%	8,6	60,06%
Average	17,59	14,73	16,25%	10,61	39,70%

(\*) On the demand of the original design.

### 3.3 Economic Evaluation

After we decided what technologies we would build in the building, we realized the economic evaluation of these. To do so, some variables were necessary to determinate. We considered the lifetime of the system would be equal to the life of the tank. According to the Brazilian standards, this should be at least 20 years to fiberglass tank [13].

The water tariffs will be readjusted once a year [14]. For future readjustment, the rate used was the same sequence of readjustment recorded between the years 2008 and 2014. Based on the definition of these values, we repeated around the lifetime of the system.

The total investment of the modified system would be R\$34,047.34 (US\$ 13,044.96). These changes would bring a total return of 21,634,520 liters. This value was converted for real

through the current price of the cubic meter of water and considering the adjustments of rates used for the calculation, totaling R\$208,452.57 (US\$ 79,866.88).<sup>1</sup>

The discount rate indicated is the minimum attractiveness rate, which will be used for determining the net present value. It has been selected, in this study, an attractiveness rate of 10% per year, equivalent to approximately 0.80% per month [11]. This value was set by the similarity between the studies, the uncertainty of economic values projected for the future and also because both works consider investments in technologies that promote sustainability.

Therefore, in this case study, the NPV is equal to R\$ 43,517.95( US\$ 16,673.54) characterizing the economic viability of the project, since its value is positive. The payback is eighty-three months, which is over a third of the lifetime of the system.

#### **4. CONCLUSION**

With this work, we realized the importance of conducting a critical analysis of certifications, to ensure that their application is appropriate for each context, adapting the design to the specific needs.

The technical analysis showed that most of the criteria related to water conservation are achievable and convenient to the same standard constructions of the building displayed in analysis.

From the original design, a significant amount of criteria is already accomplished. The number of criteria satisfied increases significantly with a relatively small investment. From an economic point of view, the net present value and payback demonstrate the economic viability of the system. Thus, in addition to environmental impacts, the use of these technologies can bring economic benefits to the university community.

We expected that the guidelines of plumbing system design and water management at this campus building and any other campuses contemplate these actions, making higher education institutions a place where sustainable practices occur every day. Even if the actions taken to reduce potable water consumption do not meet all the criteria that certifications require, it is important to note that the partial fulfillment of these actions already show favorable results.

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<sup>1</sup> The Exchange rate was 1 US\$ - R\$ 2,61 on December, 10<sup>th</sup> 2014

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