New methodologies for increasing the sustainable performance of Urban Water Systems in developing countries

Kenneth Muniina
Environmental and Water Resource Engineering Section
Department of Civil and Environmental Engineering
Imperial College London

This dissertation is submitted for the degree of

Doctor of Philosophy

December 2018
I would like to dedicate this thesis to my loving family, my loving wife Pamela, my children Philina, Manuela, and Zephaniah who have stood with me through it all. Words are not enough to express my appreciation.
Declaration

I declare that this thesis

“New methodologies for increasing the sustainable performance of Urban Water Systems in developing countries”

is my own work and that where any material could be construed as the work of others, it is fully cited and referenced, and/or appropriate acknowledgement is given.

Kenneth Muniina
December 2018
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Acknowledgements

First and foremost, I am grateful to the Commonwealth Scholarship Commission (UK) for the scholarship that facilitated this study under the Commonwealth Scholarships. I wish to thank my employer, National Water and Sewerage Corporation (NWSC-Uganda) for allowing me time to work on this research and providing support in many ways during the study and in particular the former Managing Director Dr William Muhairwe (of National Water and Sewerage Corporation) for his support to pursue this study. Special thanks also go to the Director Eng Alex Gisagara (who was Acting Managing Director then) and Managing Director Eng Dr Silver Mugisha for their encouragement and support, especially during the data collection period.

I would also like to extend my profound gratitude to my PhD supervisors: Professor Cedo Maskimovic and Professor Nigel Graham for their scientific guidance and constructive advice, and suggestions during the research implementation and thesis write-up. Without your tireless support and encouragement, I could not have accomplished this research study. Your tireless support and encouragement, I could not have accomplished this research study. I am deeply indebted to Professor Nigel Graham for the guidance during the trying time when I had to leave the UK prematurely.

I would also like to extend my gratitude to the Jakana family (Alex, Penny (late), Darren, Dione, and Divine), the Kamya family (Jonathan, Nissi, Nessia), Auntie Rhoda, Kenneth and Mim Babigumira (including their daughter Scarlet), Kenneth and Jackie Olara for their wonderful assistance and friendship to us during our stay in London. Guys, you made our stay in London, memorable - may the good Lord bless you so generously for your kindness and generosity. You will forever be in our hearts.

I would like to particularly thank Eng Sonko Kiwanuka, Dr Frank Kizito, Gilbert Akol, Ms Justine Nakibuule, my colleagues at NWSC for their special support during the data collection. Not forgetting too Mr Benjamin Sekamuli of Nile Basin Initiative in Entebbe for
his assistance in collecting river flow data.

Lastly, and most importantly, I thank the wife of my youth, Pamela Muniina for a great sacrifice during this challenging time of my studies. I love you, sweetheart. Thank you for the patience, the hard work at home to fill the gap, the encouraging words of wisdom, it is a blessing to have you, by my side always. My children Philina, Manuela, and Zephaniah though you were not quick to express your frustrations to Daddy’s absence, your patience is highly appreciated.

Now, to Him who is able to do exceedingly, abundantly, above all that I can ever imagine..., through the power that is at work in me...! He, who has begun a good work in me, shall bring it to a successful completion...! Amen
Abstract

The study presented in this thesis places its focus on urban water systems of the developing world, which are defined in terms of their component subsystems (the water supply subsystem, the stormwater subsystem, and the sanitation subsystem). These urban water systems experience poor sustainable performance across their sanitation subsystems, across their stormwater subsystems lead to the pollution of their receiving water bodies. In these systems, there is an interaction between the constituent urban water subsystems, which drives the overall sustainable performance of the urban water system.

The main objective of this study therefore is to generate insights into urban water management of urban water systems of the developing world by generating methods, methodologies and revelations to into their sustainable performance. The study started by introducing methods and methodologies to utilize the limited readily available data of these systems to model their water end-use behaviour, to model their integrated behaviour, and also to simulate their integrated assessment when applied with numerous individually-applied urban water interventions.

The study generated a novel methodology for evaluating the water end-use volumes of a developing world urban community, a novel methodology for the integrated modelling of the hydrology of water, stormwater and wastewater flow, and finally a methodology for the integrated assessment of the sustainable performance of urban water systems.

Utilising these methodologies, this study showed that of all the individually-applied 28 urban water interventions, none of them provided a significant positive sustainable performance across all the three urban water subsystems. In conclusion, it was recommended that to generate an all-round sustainable performance of these urban water systems, the option of ‘multiple interventions in combination’ should be given consideration. It was further concluded that the use of ‘multiple interventions’, not only improved the number of available urban water management options but also generated a higher overall sustainable performance than individually-applied interventions.
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Symbols

Integrated Urban Water Models

ICBMs Integrated Component Based Models

IUDDM Integrated Urban Drainage Models

IUWCM Integrated Urban Water Cycle Model

IUWM Integrated Urban Water Management

IUWSMs Integrated Urban Water Systems Models

IWSMs Integrated Water Supply Models

UVQ Water and contaminant daily simulation model of the total water cycle, developed by Mitchell & Diaper (2006)

UWS Urban Water System

Aquacycle Integrated urban water balance model, developed by Mitchell et al. (2001)

City Drain Integrated urban stormwater flow model, developed Achleitner (2006)

City Water Balance Integrated urban water balance model, developed by Last (2010)

CWB City Water Balance

UWOT Integrated urban water balance model, developed by Makropoulos et al. (2008)

WaterMet Integrated urban mass balance model, developed by Behzadian & Kapelan (2015)
Symbols

Mathematical Notation

\( BFI \) Base Flow Index

\( C_d \) Capillary draw-up

\( E_p \) Potential Evapotranspiration

\( ERA \) Effective Area proportion

\( IL \) Initial Loss

\( IRUN \) Impervious Area Runoff

\( NEAR \) Non-Effective Area Runoff

\( P \) Precipitation depth

\( PS1 \) Pervious Store 1

\( PS2 \) Pervious Store 2

\( A1 \) Proportion of total household area underlain by PS1

\( A2 \) Proportion of total household area underlain by PS2

\( E \) Evaporation

\( EXC \) Excess Soil Moisture

\( GWR \) Ground Water Recharge

\( II \) Infiltration Index

\( ISI \) Infiltration into Wastewater system

\( K \) Muskingum’s routing algorithm storage parameter - reach travel time approximation

\( PRUN \) Amount of stormwater flow exiting a sub catchment

\( PRUN \) Pervious Area Runoff

\( RIS \) Infiltration

\( SMD \) Soil Moisture Deficit
X  Muskingum's routing algorithm storage parameter

**Acronyms / Abbreviations**

**AWBM**  Australian Water Balance Model

**BGI**  Blue Green Infrastructure

**BMP**  Best Management Practices

**CAF**  Cross Amplitude Function

**CDF**  Cumulative Density Function

**CGF**  Cross Gain Function

**COF**  Cross Coherence Function

**CPF**  Cross Phase Function

**DM**  Demand Management

**GrWH**  Grey Water Harvesting

**HC**  House-Connected Household

**HH**  Household

**LID**  Low Impact Development

**RWH**  Roof Rain Water Harvesting

**SD**  Sustainable Development

**SISO**  Single In Single Out

**SUDS**  Sustainable Urban Drainage Systems

**SWH**  Storm Water Harvesting

**SWITCH**  European Union funded Action Research Project on Sustainable Urban Water Management

**TSA**  Time Series Analysis

**WSUD**  Water Sensitive Urban Design
### Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$YT$</td>
<td>Yard Tap Connected Household</td>
</tr>
<tr>
<td>AWWA</td>
<td>American Water Works Association</td>
</tr>
<tr>
<td>IWA</td>
<td>International Water Association</td>
</tr>
<tr>
<td>SC</td>
<td>Sub-catchment</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

1.1 Introducing urban water systems

The study described in this thesis focuses on the practice of urban water management in a city of the developing world. One of the challenges of studying urban water systems is the lack of a standard typology for describing and defining urban water systems, let alone urban water systems in the developing world. In this chapter, the scope, themes and philosophies of urban water systems, as studied in this thesis, are described.

1.1.1 Urban Water Systems (UWS)

In this study, the description of urban water systems suggested by Butler & Davies (2011) was employed. That is, that ‘urban water systems’ is a term used to describe a set of infrastructure located in an urban setting that:

- Collects water from different locations, then transports and distributes it to different water users (termed as urban water supply subsystem in this study),

- Collects human waste water from the different water users, then transports it and discharges it to a receiving water body (termed as urban water sanitation subsystem in this study)

- Collects rainfall run-off off the streets of the urban centre, then transports it and discharges it to a receiving water body (termed as urban water stormwater subsystem in this study)

The philosophy employed to manage this system, the technologies employed in the system, the location of the system are some of the fundamental characteristics that are all-together
employed to classify and categorise an urban water system. Urban water systems are usually
classified as either conventional or alternative urban water systems with regards to the
philosophy employed to manage them.

1.1.2 Conventional urban water systems

Conventional urban water systems are characterised by supply-side, centralised and usually
large scale developments (Al-Jayyousi, 2003; Brandes & Maas, 2004). Their management
philosophy places heavy emphasis on meeting the 'demand' or the 'need' of the urban water
inhabitant, without placing major consideration to other stakeholders in the urban centre such
as the environment. Section 1.2 of this thesis, showed that these systems originated out of
the need to alleviate the public health concerns that were affecting decentralised urban water
systems then.

Their water supply subsystems usually source large quantities of water, from available and
nearby water resources, to meet all the water needs of the urban inhabitants (Sharma et al.,
2010). Their storm water and sanitation subsystems consist of a system of pipes to convey
the storm water and the human waste water away from the city inhabitants (so as to provide
public health protection) to any adjacent water resources (Butler & Davies, 2011; Schreier,
2014). In conveying the storm water and the waste water to the receiving environment,
the philosophy of these systems places a emphasis on disposing the waste water into the
receiving water environment, as compared to ensuring that the receiving water environment
is not at risk of pollution.

In summary, it can be concluded that conventional urban water systems place a significant
amount of emphasis on the water users (i.e. the city inhabitants), and a low amount of
emphasis on the environmental protection. It is therefore of no surprise that this paradigm
leads to serious degradation of the environment (Al-Jayyousi, 2003). Then, the degradation
of the environment in turn imparts on the performance of the other urban water subsystems.
However despite these weaknesses, the conventional system of urban water management is
still the most popular and the most applied urban water management philosophy.

It is becoming accepted that conventional urban water systems across both the developing
and developed world are struggling to sustain the provision of adequate water supply services
to their users and to sustain the prevention of continuous environmental degradation. The
unsustainable behaviour of these systems is related to their inherent weaknesses that are
centred on the lack of integration between their component urban water subsystems. In these
1.1 Introducing urban water systems

systems, the component urban water subsystems are managed, analysed, and assessed in isolation from one another (Cook et al., 2013) which in turn makes the conventional urban water system vulnerable to any external pressures (Loftus, 2011).

As a result of this unsustainable behaviour, the conventional urban water management paradigm or model is being ruled out as the most appropriate system for the sustainable urban water systems management (Cook et al., 2013; Loftus, 2011; Sharma et al., 2010; Zhang et al., 2007) in cities of both the developing and the developed world. As a consequence of this failure, the conventional urban water management model has led many authors such as Bdour et al. (2009); Blackmore & Plant (2008); Closas et al. (2012); Fidar et al. (2010); Loftus (2011); Memon et al. (2005); Porto et al. (2007a); Sharma et al. (2010); Zhang et al. (2007) to advocate for an alternative urban water systems management model that will lead an improved sustainability performance within urban water systems.

1.1.3 Alternative urban water systems

Alternative urban water systems, according to Al-Jayyousi (2003); Gleick (1998); Nhapi & Hoko (2004); Schreier (2014); Zhang et al. (2007), are urban water systems that evolved out of the need to alleviate the weaknesses observed within conventional urban water systems and to direct urban water systems towards sustainable performance. In the scientific literature, alternative urban water systems have been described using numerous terms such as sustainable urban water systems, decentralised systems, alternative systems, unconventional systems, etc. At the same time, these systems are also usually described along side a number of strategies such as innovative approach, a new management approach, a clean product approach, self organisation approach, integrated urban water management approach, soft path, water sensitive urban design, and or blue-green infrastructure, etc.

Table 1.1 illustrates the evolution of urban water management paradigms of alternative systems through time. It shows that since 2010, alternative urban water paradigms have evolved to focus on integrated urban water management, which involves the application of interventions across the whole urban water cycle (Porto et al., 2009; Tejada-Guibert & Maksimovic, 2007) including achieving a specified level of sustainable development. The trends in designing alternative urban water systems have recently shifted focus to the ability of the urban water systems to adapt to external pressures through the system’s internal flexibility or adaptability mechanisms. In essence, it can be said that the current ’state’ of the alternative urban water paradigm places system adaptability (driven through urban water integration) as the core strategy to address the lack of sustainable behaviour in conventional
Introduction

Table 1.1 Evolution of the alternative urban water systems paradigms

<table>
<thead>
<tr>
<th>Year</th>
<th>Target UWS Subsystem</th>
<th>Paradigm Principle</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>Urban Water Systems</td>
<td>Flexibility</td>
<td>Loftus (2011)</td>
</tr>
</tbody>
</table>

urban water systems (Philip & Silian, 2011).

Therefore, integrated management of urban water systems places emphasis on the need for exploitation of the interactions between the component urban water subsystems to yield a sustainable urban water system performance (Tejada-Guibert & Maksimovic (2007), Makropoulos et al. (2008)). This management system depends on the synergy the subsystems’ interaction contributes to the successful behaviour of the urban water system, which in the end leads to the revelation of hidden insights driving the required sustainable performance.

In summary, in this study, alternative urban water systems were considered to consist of strategies, that target a specific urban water subsystem at a time, and are designed to address a specific inherent weakness of the conventional urban water system. Such strategies are encapsulated into approaches such as demand management, rain water harvesting for the urban water supply subsystem; sustainable drainage systems for stormwater subsystems; and urine reuse or recycling for urban sanitation subsystems.
1.1 Introducing urban water systems

1.1.4 Sustainability performance of urban water systems

In this study, the performance objective of an urban water system was related to its sustainability. However, in the same way there is an absence of a standard typology in defining an urban water system, there is also an absence of a standard typology for defining the sustainable performance of an urban water system.

1.1.4.1 Sustainable urban water systems

The precise definition of Sustainable Development (SD) is debatable (Ashley et al., 2005). The Brundtland Commission reported in Langhelle (1999) defined sustainable development as a development that fulfils the needs of the present generation, without compromising the ability of the future generations to fulfil their needs. Then the Water21 project (a European Research Project on sustainability in water policy) described in Rijberman & van de Ven (2000) concluded that a system is sustainable when the supply of “natural capital” is maintained. In other words, the use of renewable sources, such as water, should not exceed the rate of their renewal.

In this study, the scope of is limited to urban water systems, therefore the concept of sustainability had to be extended to urban water management. Lundin (2003) describes a sustainable urban water system as one that over a long time provides the required services, while protecting the human health and the environment, with a minimum of scarce resources. (Loucks, 1997; Lundin, 2003) refined this description by stating that a sustainable UWS should be one that can sustain its service provision at economic, environment, social and technical levels for a long time. This description of a sustainable urban water system was adopted in this study.

1.1.4.2 Performance of an urban water system

The description of a sustainable urban water system provided by (Loucks, 1997; Lundin, 2003) has been translated into a sustainability measure of an urban water system through the process of defining specific indicators on the urban water system to generate a sustainability performance score of the urban water system (Stanhre et al., 2008). Studies by Ashley et al. (2003); Hellstrom et al. (2000); Lai et al. (2008); Lundin (2003) refined this assessment methodology further by proposing a series of criteria and indicators for the assessment of sustainability across an urban water system. Their proposal is summarised in figure 1.1.
This approach is adopted in this study, though an update of this approach proposed by Venkatesh et al. (2017) is closer. Venkatesh et al. (2017) recommends that any form of sustainability assessment of urban water systems must (1) include the dimensions of social, environmental, economic, asset and governance sustainability. And (2) the sustainability assessment should be done by examining the estimated effects of the various interventions and how their implementation through time using a predefined set of performance metrics or indicators. These performance indicators should correspond to the sustainability objectives (or dimensions described above).

Venkatesh et al. (2017) further proposed that for the generation of the sustainability performance indicators urban metabolism procedures should be employed. Urban metabolism here involves the quantification of the inflows, outflows, storage and production of energy and materials within the bounds of an urban setting. Using these approaches, the performance indicators covering each of the domains -that is environment, economic, physical are therefore generated.

In this study however, the scope of sustainability assessment was limited to the environment criteria only. This criteria was given preference only for study purposes, not because it holds any superiority over the other criteria. And the urban metabolism procedures (such as integrated modelling of the urban water system) were applied, but the scope of analysis was limited to only the water and nutrients inflows and outflows.
1.1.5 Urban water systems of the developing world

The final fundamental property of urban water systems that was of interest to this study - is that of location. Location, in this study, implied the host country of an urban water system, that is whether it is a developed country or a developing country. It was observed that the urban landscape of cities in the developing world is different from that of a city in the developed world (Porto et al., 2009). Hence, with these significant differences between cities of the developing world and those of the developed world, it is expected that there will be or there needs to be a difference in management approaches of the urban water systems they comprise of.

Sperling & Chernicharo (2002) and Tejada-Guibert & Maksimovic (2007) observed that in the developed world, the emphasis in the management of urban water systems is on the fine tuning of these systems to provide a more reliable service, with efforts such as obtaining cost-effective sustainable urban water practice. While in the developing world, the emphasis in managing urban water systems is on providing the basic urban water services such as adequate water supply and sanitation (Porto et al., 2009; Tejada-Guibert & Maksimovic, 2007) or on the reduction of environmental pollution of receiving waters (Nyenje et al., 2010).

1.2 Background

1.2.1 Portfolios of urban water systems

One of the major (and silent) attributes of urban water systems is their component subsystems. It has been mentioned in section 1.1.1 that urban water systems can be described as an aggregation of urban water supply subsystems, urban stormwater subsystems, and urban sanitation subsystems. The nature and characteristics of these component urban water subsystems drive the overall behavioural characteristics of the 'mother' urban water system. This trait of urban water systems is illustrated through the observed historical evolution of urban water systems.

Vigneswaran et al. (2009) and Brown et al. (2009) describe how sets of urban water systems consisting of different kinds of urban water systems subsystems in a city transition through time. The historical evolution path of urban water systems (observed mainly in European, American, and Australian cities) reveals several 'silent' attributes associated with urban water systems, that are of high relevance in characterising the performance of urban water systems.
<table>
<thead>
<tr>
<th>Urban Water Systems</th>
<th>Characteristics</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>FIRST Generation</td>
<td>Time</td>
<td>Before 1000 BC</td>
</tr>
<tr>
<td></td>
<td>Portfolio</td>
<td>Decentralised Water Supply, Decentralised (Natural) Stormwater, Decentralised Sanitation</td>
</tr>
<tr>
<td></td>
<td>Performance</td>
<td>No failure</td>
</tr>
<tr>
<td>Pre-SECOND Generation</td>
<td>Time</td>
<td>19th Century</td>
</tr>
<tr>
<td></td>
<td>Portfolio</td>
<td>Centralised Water Supply, Centralised (Sewered) Stormwater, Decentralised (Flushing Toilets) Sanitation</td>
</tr>
<tr>
<td></td>
<td>Performance</td>
<td>Public health concerns (Cholera epidemic)</td>
</tr>
<tr>
<td>SECOND Generation</td>
<td>Time</td>
<td>Late 19th - Early 20th Century</td>
</tr>
<tr>
<td></td>
<td>Portfolio</td>
<td>Centralised Water Supply, Centralised Stormwater, Centralised Sanitation (no waste water treatment)</td>
</tr>
<tr>
<td></td>
<td>Performance</td>
<td>Environmental Degradation concerns</td>
</tr>
<tr>
<td>THIRD Generation</td>
<td>Time</td>
<td>20th Century to date</td>
</tr>
<tr>
<td></td>
<td>Portfolio</td>
<td>Centralised Water Supply, Centralised Stormwater, Centralised Sanitation (with waste water treatment)</td>
</tr>
<tr>
<td></td>
<td>Performance</td>
<td>still has Environmental Degradation concerns</td>
</tr>
<tr>
<td>NEXT Generation</td>
<td>Time</td>
<td>Future</td>
</tr>
<tr>
<td></td>
<td>Portfolio</td>
<td>Unknown</td>
</tr>
<tr>
<td></td>
<td>Performance</td>
<td>expected to perform satisfactory against all pressures</td>
</tr>
</tbody>
</table>
1.2 Background

Table 1.2 summarises these transition states of urban water subsystems through time. It illustrates that, despite the continued description of an urban water system as centralised or decentralised, this characteristic is more applicable to each of the component urban water subsystems. Also, that the combination of these different subsystems’ characteristics provided a more elaborative description of the behaviour of each of the urban water systems.

In addition, it has been argued by numerous authors such as Chanan et al. (2009) that this trend of urban water systems evolution illustrates how an urban water system in any city (a city in the developed world) would naturally evolve from one state to another (with human intervention). In other words, this evolution of urban water systems, shows that the change of states:

1. is driven by the level of demand the system experiences, which in turn is determined by its level of inhabitant population and or urbanisation,

2. can take on a variety of states, the states which are dictated by the nature of urban water management paradigm the city employs (either decentralised or centralised).

In summary, it can be said that, urban water systems should not only be characterised as a whole but also in due consideration of the nature of the component urban water subsystems they comprise of. The performance or the nature of the component urban water subsystems drive the overall performance of the urban water system. In addition, the performance behaviour of urban water systems (and subsystems) is dominated by the level of urbanisation (and or the rate of population growth) it is facing.

1.2.2 Cities of the developing world and their urban water systems

One of the observations depicted in the historical evolution of urban water systems that proves accurate with developing countries, is that the state of their urban water systems is also driven by their level of urbanisation and population. Hardoy & Satterthwaite (1986) observed that most of the cities in the developing world are driven by high population growth rates, but their population growth does not evolve at the same rate as their economic development. Cities of the developing world usually have low economic development rates, which when combined with the high population growth rates lead to cities that contain a high proportion (50 – 70%) of low-income urban dwellers (Tejada-Guibert & Maksimovic (2007), Chinyama et al. (2012), Kiggundu (2014)) living in the along-side high-income dwellers. The level of income refers to the nature of households (as well as their location) within an urban city. The households employed by low-income (including their location) is significantly different from
that of high-income dwellers.

Shah & Kulkarni (2015) confirmed this trait in cities in the developing world, by re-iterating that they consist of a highly heterogeneous urban resident population. The population is consists of an urbanised nucleus surrounded by less urbanised peri-urban suburbs. In the urbanised nucleus centralised urban water systems are employed, while in the peri-urban suburbs decentralised urban water systems are utilised. Therefore, in the cities of the developing world there is both centralised and decentralised urban water systems. This is not observed in the historical background of cities of Europe and North America.

In summary, it can be said that the historical evolution of urban water cities appears to confirm that:

- urban water systems of the developing world are indeed different from those of the developed world
- urban water systems of the developing world are following an evolution or development path, that is different from that of the developed world

Thus, if indeed these two urban water systems are different and are following different paths, should the change of state (from centralised to decentralised or vice versa, which is usually triggered by an intervention) for the cities of the developing world be expected to follow the development path observed in the cities of the developed world? Tejada-Guibert & Maksimovic (2007) advises that the urban water management approaches applied in the developed world may not work as expected in the developing world. That is one of the research questions of this study.

1.3 Improving the performance of urban water systems

1.3.1 Introduction

The interventions designed for urban water systems can be classified too - in terms of either conventional or alternative urban water interventions. Conventional systems interventions advocate for centralised large scale urban engineering approaches, while alternative systems advocate for smaller localised technological approaches. However, the alternative urban water interventions do not necessarily rule out large centralised technological approaches, so long as they applied following an alternative or integrated urban water management paradigm (this is described further in section 2.3 of this thesis). Hence, it can be concluded that to
1.4 Assessment of integrated urban water systems

improve the sustainability performance of a conventional urban water system, the alternative approach involves the consideration of both the conventional and the alternative urban water technologies (Sapkota et al., 2014).

In recent times, it has been further suggested that, in addition to the numerous technological options available, total system solutions should also be give due consideration (Closas et al., 2012; Mitchell, 2006; Sapkota et al., 2014)). These solutions should involve application of these technologies (individually or in combinations) across the component urban subsystems.

In the scientific literature, the application and study of these performance improvement schemes across urban water systems is limited. Therefore, this study is also providing input into this knowledge gap. This is another research question this study is addressing.

1.3.2 Within urban water systems of the developing world

Despite the presence of an adequate number of urban water interventions that could be applied to improve the performance of urban water systems of the developing world. Sperling & Chernicharo (2002) observed that in the developed world the emphasis of improving urban water systems is on optimising their performance to provide more reliable urban water service. While in the developing world the emphasis is on developing urban water systems that provide the basic urban water services such as adequate water supply and sanitation (Porto et al., 2009), the reduction of polluted waste waters flows to the receiving waters, etc. (Nyenje et al., 2010).

With such significant differences between urban water systems of the developing world and those the developed world, will urban water improvement strategies designed for urban water systems of the developed world function as expected in situations of the developing world? This, is another research question of this study.

1.4 Assessment of integrated urban water systems

1.4.1 Introduction

The alternative urban water systems improvement strategy mentioned in section 1.3 advocates for integrated urban water management of the urban water system. This integrated development strategy requires a form of urban water systems assessment that places emphasis
on the integrated behaviour of the urban water system.

Traditional approaches to the assessment of urban water systems consider the water supply subsystem in isolation from the sanitation subsystems, in isolation from the storm water subsystems (Mitchell et al. (2001), Makropoulos et al. (2008)), and finally in isolation from the whole urban water system (Bach et al., 2014b). This kind of urban water assessment generates misleading assessments of an urban water system, which in turn when relied upon for interventions design will lead to interventions with unforeseen side-effects in the long term (Pahl-Wostl, 2007; Urich & Rauch, 2014). In the end, this form of urban water systems’ assessment has exposed the relevance the interactions (that is, the integration) between the different urban water subsystems have on the overall performance of an urban water system (Makropoulos et al., 2008).

Mitchell et al. (2001) and Mitchell et al. (2007) observed that significant advances have been made in the development of integrated modelling tools that allow for this integrated assessment of urban water systems. Applying these modelling tools to an urban water system allows for the utilisation of the complex and dynamic interactions between the water supply subsystem, the sanitation subsystem, and storm water subsystem at different spatial and temporal scales (Makropoulos et al., 2008; Urich & Rauch, 2014), leading to further understanding of the interactions between these subsystems. This then can be utilised for the investigation and quantification of the interactions between the subsystems which in turn helps identify the future possibilities and the limitations of different subsystems within the context of sustainable water management for the whole urban water system (Makropoulos et al., 2008). This form of integration and integrated assessment is what the sustainable urban water improvement strategies require. To apply these strategies effectively, an integrated modelling system that simulates and quantifies these strategies for their sustainable performance is a fundamental requirement.

1.4.2 Existing integrated modelling systems

In the scientific literature, numerous integrated urban water modelling tools that have been defined. One of their categories, of interest to this study, is termed as integrated urban water cycle models (IUWCMs), which focuses on the integration of the different urban water subsystems (Bach et al., 2014b). That is, the integration of the urban water supply system, to the storm water subsystem, and then to the sanitation subsystem. Mitchell et al. (2001) and Mitchell et al. (2007) recommend that the IUWCMs are the most appropriate sets of tools required for the assessment of strategic options involving the use of alternative urban
1.4 Assessment of integrated urban water systems

water interventions that cut across both decentralised and centralised spatial scales. In other words, the integrated urban water modelling tool required for this study should belong to this category.

However, this category of integrated modelling tools is still in its infancy, and as such the number of integrated modelling tools (let alone case studies) in this category is still low (Bach et al., 2014b; Mitchell et al., 2001). In the scientific literature, the number of integrated modelling systems and studies included the Aquacycle system (Mitchell et al. (2001) and Mitchell et al. (2007)), the UWOT system (Makropoulos et al. (2008)), the UrbanCycle system (Hardy et al. (2005)), City Water Balance system (Last (2010)), and the WaterMet system (Behzadian & Kapelan (2015)). These modelling tools comprise of a significant level of variability within their internal fundamental methodologies (or processes). These tools in general are site specific and have been designed for applications specifically in the developed world.

Mitchell et al. (2007) concluded that there is no integrated urban water systems modelling tool that can be applied across all the urban water systems of both the developing and developed world. And hence, there is a need to tailor existing tools to the specific requirements and circumstances of the developing world.

1.4.3 Integrated urban water modelling in the developing world

In the scientific literature, there is an absence of integrated urban water modelling studies carried out on cities in developing countries (Poustie & Deletic, 2014), let alone countries from sub-Saharan Africa. For one to study the performance improvement methodologies for a city in a developing country, that includes water supply, sanitation, and stormwater subsystems, an integrated urban water cycle modelling tool is required. However, due to the specific urban landscape (in terms of the heterogeneous household behaviour, the unique natural oriented urban landscape, and the use of unique sanitation practices), such an integrated modelling tool for this kind of city is non-existent.

Despite the lack of a sufficient integrated modelling tool for the developing world, there is another challenge in studying urban water behaviour in developing countries, that is the lack of sufficient data. In most urban water systems of the developing world, there are no gauging or monitoring stations to monitor the behaviour of their water supply, sanitation, and stormwater subsystems (Porto et al., 2009). The population data upon which urban water systems studies are based on, is also highly uncertain (Cohen, 2004). Therefore, the nature of
Introduction

the descriptions of urban water systems found in literature are not only generalised without any precise quantifications or definitions, but also uncertain if not inaccurate.

In addition, cities in the developing world experience a unique set of urban water system challenges. Their water supply, their sanitation, and their storm water subsystems experience weaknesses that impact each other interchangeably. It is observed that weakness in the water supply subsystem, have an impact on the sanitation system, which in turn is driven by the storm water system (Porto et al., 2009). Therefore, it is prudent to presume that urban water systems of the developing world require an unique set of interventions compared to their counterparts in the developed world. Also, those urban water interventions will require a holistic approach to generate a more precise understanding of their effect on the urban water system.

In summary, designing an integrated urban water modelling system appropriate for a city in the developing world. And then employing this system to discover the nature of urban water interventions appropriate for an urban water system of developing world, is another research question this study addresses.

1.5 Research Aims

1.5.1 Research gaps

The scope of this study focuses on bridging the knowledge gaps within the urban water management of cities in the developing world. It is based on the presumption that urban water systems of the developing world are different (in urban landscape and in urban water systems behaviour) from those of the developed world.

These differences then trigger the need to understand how these systems should be strategically designed to improve their sustainability performance. Specifically:

- there is need to understand the specific characteristics of urban water systems of the developing world that drive their unique urban water behaviour,

and after understanding the specifics of these urban water systems:

- there is need to understand which interventions should be applied to these systems to boost their sustainable performance.
1.5 Research Aims

The precise description of these sets of information are missing from the urban water systems’ body of knowledge. However, to generate an understanding of these urban water systems to this level:

- there is need for the application of a series of modelling tools,
- modelling tools that are appropriate and applicable for these kind of urban water systems.

But the existing modelling tools are designed for cities and urban water systems of the developed world, hardly for the developing world.

Therefore, the study intends to introduce innovative modelling strategies and tools that aid the advanced understanding of the urban water systems of the developing world. Then apply these tools to generate a detailed description of the behaviour of urban water systems of a developing country.

In addition, it is expected that intervening in an urban water system of the developing world with alternative systems will boost the sustainable performance behaviour of the system. However, the details of this performance (that is, which interventions can be applied, when and where they are applied, and to which consumer groups) and its measure is largely undocumented and may be unknown.

1.5.2 Main Objective

Therefore, the main objective of this study is to investigate and generate appropriate methodologies to improve and measure the sustainable performance of urban water systems of the developing world.

1.5.3 Specific Objectives

To achieve this objective, the study will focus first on understanding the behaviour of a urban water system of the developing. That is:

1. To investigate and characterise the impact the city’s decentralised urban water use has on its centralised mains water use

2. To investigate and characterize the component water end-use dynamics that city
Introduction

Then after the characterising the urban water behaviour of an urban water system of the
developing world, the study will:

3. Develop an integrated urban water systems model to characterise the mains water
use, the stormwater flow, and the pollutant load contribution from each of the sub-
catchments in the city

4. Define the improved sustainable performance, holistically across all the urban water
subsystems, of the system resulting out of the application of different conventional and
alternative urban water interventions to the urban water system

5. Define the possibility of optimising and improving the sustainable performance of
urban water systems, through the choice of adequate urban water system interventions,
applied individually or in combination

1.6 Structure of the Thesis

This thesis is organised into eight (8) chapters, each dealing with an aspect of integrated
urban water management that contributes to the achievement of the study objectives. The
thesis therefore is outline as:

Chapter One  Introduction

This chapter provides a general outline of current issues in urban water management,
from a general perspective, and then focus on the particular case of a developing
countries. The chapter also provides an outline of decentralised urban water systems
as an alternative approach to modern urban water management, that however needs
further investigation. The chapter concludes with an outline of knowledge gaps and
objectives of the study.

Chapter Two  Review of tools and methods for urban water systems assessment

This chapter starts by providing a general introduction to urban water systems, defining
their typologies and descriptions to set the stage for the study to concentrate on the
nature and attributes of urban water systems to be focused on in this study. The
chapter then continues by dwelling deeper into the characteristics of different urban
Philosophies of improving their sustainable performance, [4] within the perspective
of urban water practice in the developing world. The chapter then concludes by
introducing and describing aspects of integrated modelling of urban water systems as
the missing link in adequately assessing urban water systems for sustainability.
1.6 Structure of the Thesis

**Chapter Three  Methods**
This chapter provides a general description of the case study city, as a typical developing country, including its unique characteristics, as regards to urban water management, including highlighting the research gaps. The chapter then proceeds to describe the possible methodologies and tools of intervening in this kind of city to improve sustainable performance.

**Chapter Four  Characterising the longitudinal water use dynamics**
This chapter presents the innovative approach, generated in this study, to characterise the longitudinal dynamics of mains water use behaviour, and account for the centralised and decentralised water use, within an environment of poor data availability.

**Chapter Five  Modelling and characterising the water end-use dynamics**
This chapter also describes, another output of this study, an innovative approach of modelling the water end uses of low income town, despite the lack of data.

**Chapter Six  Integrated Modelling of an urban water system of the developing world**
This chapter describes the methods employed in the study to model and simulate the integrated behaviour of the urban water system, an urban water system of a city in the developing world.

**Chapter Seven  Performance Assessment of urban water interventions**
In this chapter, the integrated performance of urban water interventions is described, and their relative performance evaluated - both when applied individually and in combination.

**Chapter Eight  General Discussions and Conclusions**
This chapter provides a general discussion of the validity of the results presented in the preceding chapters by (1) pooling them together to provide a coherent global analysis of the results, then (2) comparing them to results from comparable studies in literature, (3) filter out the effect of the model uncertainty and weakness on the results. The chapter will then summarise the main findings of the study and suggest recommendations.
Chapter 2

Review of methods and tools for urban water assessment

2.1 General introduction to urban water systems

2.1.1 Defining urban water systems

In scientific literature, there is no standard definition of what is meant by urban water systems (UWS). However, texts such as Bahri (2012); Butler & Davies (2011); Loftus (2011); Taylor (2009) describe urban water systems as a set of water services infrastructure within a city (and at city-wide scale). This thesis found the definition by Loucks & Beek (2005) more appropriate and was adopted in this thesis. Loucks & Beek (2005) defined an urban water system as:

as a set of infrastructure in a township or city that is responsible for the provision of water supply, storm water drainage, and sanitation services (which altogether will be termed as urban water services) to the city inhabitants.

Fundamentally, the infrastructure of an urban water system typically consists of (1) water collection facilities at source sites, (2) water transport system from the source to the water treatment systems, (3) the water treatment system, (4) storage and distribution systems, then (5) waste water collection (sometimes called urban drainage) systems, and (6) waste water treatment systems which in the end dispose their effluent into (7) receiving waters. Water to be supplied to the urban inhabitants is usually sourced from natural surface and/or ground water resources through the water source facilities. Since the inhabitants require their water to meet a high quality, sourced water (also called raw water) is treated through a water
Review of methods and tools for urban water assessment

treatment system. Treated water is then distributed within the urban centre, to each of the urban inhabitants through a network of storage tanks and pipes (known as the distribution system). This part of the urban water system, through which 'clean water' progresses from the water body to the user is was denoted as the urban water supply subsystem in this thesis.

After use, the human 'waste water' is collected through a network of waste water pipes (or 'sewers') leading to a waste water treatment plant or to the discharge site, if the town practices a centralised sanitation system. The sewers collect waste water from households, to convey it through a network of pipes (or sewers) to a wastewater treatment plant. The waste water treatment plant then removes some of the pollutants in the waste water before it is discharged into the receiving water environment. In some systems, the wastewater is not centrally collected, but disposed off at its point of origin, through an on-site wastewater treatment system. This part of the urban water system that collects and conveys human waste water was denoted as the urban sanitation subsystem in this thesis.

In addition, an urban water system usually receives rainwater, originating from rainfall storms that the town receives. The rainfall storms lead to stormwater runoff that is conveyed through sewers (or open channels) to the receiving waters. The part of the urban water system that collects and conveys storm water was denoted as the urban stormwater subsystem in this thesis.

In summary, it can be said that a typical urban water system consists of three categories of infrastructure:

1. urban water supply subsystem
2. urban sanitation subsystem
3. urban stormwater subsystem

which together were described as the component urban water subsystems of an urban water system, and are utilised to provide the urban water services to the inhabitants of a city.

Tejada-Guibert & Maksimovic (2007) and Butler & Davies (2011) summarise the urban water services provided by an urban water system as:

1. to meet the water supply needs of the city inhabitants
2. to ensure that their hygienic public health does not depreciate through disposing off the waste water generated from the use of the water supplied
3. to carry out these services without harming the environment

2.1.2 Attributes of urban water systems

2.1.2.1 Urban water subsystems

In many instances in the scientific literature, urban water systems are usually categorised as either urban water supply systems, urban sanitation systems, or urban storm water systems in urban water literature texts such as Butler & Davies (2011); Loucks & Beek (2005); Porto et al. (2009) to describe a particular subsystem of the urban water system. In other instances, it has become a norm for authors to focus their study on a particular urban water subsystem, but describe their system as an urban water system. For example, the Tjandraatmadja et al. (2005) study focuses on urban water sanitation system, but the study is titled as urban water systems. In this thesis, the term urban water system will be used to denote the whole urban water system, while the corresponding subsystems will be denoted by their specific names. Table 2.1 summarises these descriptions.

2.1.2.2 Urban water paradigms

In addition, it was found in urban water literature that urban water systems are also described as either centralised or decentralised. In this classification, as shown in table 2.1, urban water systems were classified according to the scale of their spatial area of control. Decentralised systems were described as systems that start and end the chain of their urban water processes within the same scale (at household scale) while centralised systems start the urban water chain of processes from one spatial location and end at another spatial location away from start point. This form of categorisation was also adopted in this thesis.

More recently urban water systems are increasingly being categorised according to the design and operation paradigm (sometimes called service model as in Cook et al. (2009) and in Cook et al. (2013)) that is employed to design or operate them. That is, either conventional or unconventional (or alternative). In conventional urban water systems, the emphasis is on the provision of the services to the inhabitants, that is, the bulk water supply to them and bulk water withdrawal of waste water and storm water from the city. Unconventional systems, on the other hand, are usually designed to mitigate the weaknesses and limitations of conventional systems, by managing urban water systems according to principles of integrated urban water management. These principles involve the use of the principle of fit-for-purpose in water supply, as well as in waste water recycling or reuse. This form of categorisation of
### Table 2.1 The different terms and categories used to describe urban water systems

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Categories</th>
<th>Description</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A. Sub systems</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Water Supply</td>
<td>is an UWS in which emphasis is placed on the 'clean water' section of the UWS</td>
<td>Butler &amp; Davies (2011)</td>
<td></td>
</tr>
<tr>
<td>2. Storm water</td>
<td>is an UWS in which emphasis is placed on the 'rainfall runoff conveyance' section of UWS</td>
<td>Butler &amp; Davies (2011)</td>
<td></td>
</tr>
<tr>
<td>3. Sanitation</td>
<td>is an UWS in which emphasis is placed on the 'wastewater' conveyance, treatment and disposal section of the UWS</td>
<td>Butler &amp; Davies (2011)</td>
<td></td>
</tr>
<tr>
<td><strong>B. Spatial Scale</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Centralised</td>
<td>is an UWS system (or a section) where the 'start UWS process' is located at a distance far away from the 'end UWS process'</td>
<td>Cook et al. (2009)</td>
<td></td>
</tr>
<tr>
<td>2. Decentralised</td>
<td>is an UWS system (or a section) where the 'start UWS process' and the 'end UWS process' are all in the same location</td>
<td>Cook et al. (2009)</td>
<td></td>
</tr>
<tr>
<td>3. Hybrid</td>
<td>is an UWS system (or section) where both decentralised and centralised technologies are employed</td>
<td>Sapkota et al. (2014)</td>
<td></td>
</tr>
<tr>
<td><strong>C. Paradigm</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Conventional</td>
<td>is an UWS involves either of bulk transfer of water to the city, or bulk withdrawal wastewater</td>
<td>Cook et al. (2013)</td>
<td></td>
</tr>
<tr>
<td>2. Alternative</td>
<td>is an UWS system (or a section) that employs IUWM principles for its design and operation</td>
<td>Cook et al. (2013)</td>
<td></td>
</tr>
</tbody>
</table>

Urban water systems is central to the study presented in this thesis.

Finally, also conventional urban water systems are equally described as centralised systems (for example in Cook et al. (2013)) in the scientific literature. While alternative urban water systems are described as decentralised systems (for example in Sharma et al. (2010) and in Cook et al. (2013)). In as much as most conventional systems are centralised and that most centralised systems are conventional, in this thesis these generalisations are not utilised. Each urban water system's attributes were described independently.

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2.1 General introduction to urban water systems

2.1.2.3 Location

Daigger (2009) presents a classification and a description of countries as either a developing or a developed country. This characterisation of countries as either developed or developing has an impact on the nature and behaviour of urban water systems found within the country (as shown in table 2.2).

Table 2.2 A description of the nature of urban water systems expected in the different countries (source: Daigger (2009))

<table>
<thead>
<tr>
<th>Country Type</th>
<th>Existing Urban Water Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Developed Countries, constant or declining population</td>
<td>Generally traditional centralized water supply and waste water management systems, which provide adequate service but are increasingly judged not to be sustainable. Significant improvements needed to reduce net water consumption, reduce energy, and recover nutrients.</td>
</tr>
<tr>
<td>Developed Countries, growing population</td>
<td>Generally traditional centralized water supply and waste water management systems, which provide adequate service but are increasingly judged not to be sustainable. Significant water supply problems in areas with growing populations, which are driving increased use of novel water supply approaches, such as water reclamation and reuse</td>
</tr>
<tr>
<td>Developing Countries</td>
<td>Water provided by public water supply generally not considered to meet potable water standards and often not available in poorer sections. Waste water collection often is present in more affluent areas, but is absent in poorer sections. Significant efforts to install centralized systems in more rapidly developing urban locations</td>
</tr>
<tr>
<td>Underdeveloped Countries</td>
<td>Water provided by public water supply generally not considered to meet potable water standards and often not available in poorer sections. Waste water collection often is present in more affluent areas, but is absent in poorer sections. Little progress being made to improve water supply and sanitation.</td>
</tr>
</tbody>
</table>

The classification of countries into developing or developed, has its origins in how international development organisations like the United Nations Development Programme (UNDP), the World Bank, and the International Monetary Fund (IMF) categorise countries according to their economic performance (Nielsen, 2011). The countries are classified through a flexible classification criteria that considers a number of national economic variables to group all countries in the world into four income groups. In 2011, the World Bank group classified countries into four income groups according to their Gross National Income into Low-income, Lower-middle income, Upper middle income, and Higher income.
Daigger (2009) presents a classification and a description of countries according to their population growth rate and also according to their changes in standards of living, that is, either a developing or a developed country. In developed countries (whether with stagnant or growing population), the urban water management practices are well established. The principal issue within these systems is that of sustainability, that is the financial and physical ability to sustain the infrastructure without the associated environmental effects.

2.1.2.3.1 Developed countries
For developed countries with growing population like the United States of America, even though sufficient water supplies do not exist to provide the required supply, water utilities are continuously employing unconventional sources (like water reclamation, reuse and desalination) to meet the required supply. In developing countries, the emphasis is still on the extension of water and sanitation services, there is a higher rate of extension in developing countries than in underdeveloped countries. In both cases, centralised systems are being extended, though there is increased attention to decentralised systems in both countries.

2.1.2.3.2 Developing countries
One of the first major characteristic of developing countries (as compared to the developed countries), is that they comprise mostly of relatively smaller cities (also called secondary cities) compared to large cities found in the developed world (Cohen, 2004). Their primary cities are mostly of population size less than 5 million, while their secondary cities have populations between 500,000 – 1 million. However in the scientific literature, both secondary and primary cities of the developing world are usually considered to be similar urban centres, but Sundaravadivel et al. (1999) revealed that these two cities exhibit completely different urban water behaviours.

Another unique important characteristic of urban centres in the developing world is the nature of their evolution path. The urban centres in the developing world have high population growth rates (Cohen, 2004) compared to cities of the developed world. Though, this population growth (especially for sub-Saharan Africa) is not synchronised with the economic development rate of their host countries Cohen (2004); Hardoy & Satterthwaite (1986). This kind of population growth rate which is not synchronised with the rate of growth of major urban infrastructure (urban water, housing, etc.) leads to an inequitable distribution of infrastructure across the developing world city. Hence, this kind of urban population growth is responsible for the heterogeneity of urban residents in the city (Hardoy & Satterthwaite, 1986). Therefore, in the city of the developing world, this heterogeneity is reflected through
a significant divide of the urban population into (1) a proportion (about 50 – 70%) living in unplanned settlements (commonly known as slums) (Chinyama et al., 2012) and (2) a proportion living in the well planned part of the city. And in each of the heterogeneous groups, the housing and urban water behaviour is completely different.

2.1.3 Portfolios or States of urban water systems

As mentioned in the section 2.1.2, urban water systems can be classified through the nature of their subsystem components as either urban water supply systems, urban storm water systems, or urban sanitation systems. Given that the component subsystems of an urban water system can be either centralised or decentralised, Vigneswaran et al. (2009) and Brown et al. (2009) used this characterisation of an urban water system to generate another form of classifying urban water systems. This characterisation of urban water systems has its origin through observations made of the transition states of urban water systems through time. Vigneswaran et al. (2009) provided five transition states (or portfolios) of urban water systems through time, a period of starting 1000 BC. While Brown et al. (2009) provided six transition states of urban water systems through time, starting around the 19th century.

Before 1000 BC, Vigneswaran et al. (2009) characterised urban water systems as First Generation urban water systems. This state is not mentioned by Brown et al. (2009). In this urban water system, water supply was obtained through decentralised systems like wells, springs, and or streams (Burian et al., 2000; Chanan et al., 2009; Domenech, 2011; Vigneswaran et al., 2009). Sanitation was provided through cesspits (that is decentralised sanitation systems) or on-site sanitation systems. The storm water systems though not mentioned, were presumed to rely on natural drainage systems. In other words, this portfolio of urban water systems comprised of a decentralised urban water supply system, a centralised or natural storm water system, and a decentralised sanitation system but serving a low community population. This kind of system did not show any symptoms of poor performance.

As the population and urbanisation in the cities increased, storm water subsystems were the first to evolve to sewered storm water systems (around 1000 BC) while both sanitation and water supply were still employing decentralised systems (Burian et al., 2000; Domenech, 2011). In 1600 AD, a technology innovation of flushing toilets (due to the need to safely handle faeces) was added to the urban water systems which triggered the evolution of both the sanitation systems and the water supply systems. The increased use of water (within the flush toilet) led to higher waste water volumes as well as the need for higher water supply volumes. But the water supply systems were still decentralised. As a consequence, this urban
water system consisting of increased water usage through to increased waste water volumes (in a decentralised sanitation system) led to significant system failures, in form of widespread epidemic outbreaks.

This failure of existing urban water systems then led to a sanitary reform that culminated into the birth of "large" centralised urban water systems late in the 19th century and into the 20th century (Domenech, 2011; Langeveld et al., 2003). This led to the wide application of "big engineering solutions" that significantly improved sanitation and hygiene in urban areas, and perhaps because of this, they soon became a universal standard for urban water systems design across the western world (Montgomery & Elimelech, 2007), and thus leading to the abandonment of decentralised systems. This portfolio of urban water systems was denoted as the Second Generation of urban water systems by Vigneswaran et al. (2009) and as the Water Supply City by Brown et al. (2009).

In the mid and late 1800s, after the outbreak of the cholera and typhoid epidemics across the European cities, and after the development of reticulated urban water supply systems, cities were involved in the development of reticulated sewerage systems to dispose off human waste effluent to receiving waters. Brown et al. (2009) termed these urban water systems as the Sewered City. Vigneswaran et al. (2009) does not describe these states of urban water systems. Then in mid 20th century, after the second world war, and due to a high rate of urbanisation, European cities developed techniques and strategies for a rapid and efficient conveyance of storm water out of the cities to receiving water environments. Brown et al. (2009) termed these states of urban water systems as the Drained City. Vigneswaran et al. (2009) does not describe these states.

In the 20th and the 21st centuries, centralised urban water supply systems continued to remain the dominant urban water systems in most cities. However, from the start of 20th century, driven by the push to protect the environment, an awareness of the effects urban water systems have on the natural environment increased. A number of international policy instruments like UN Agenda 21 (1992), the EU Water Framework Directive (2000) were set up to influence the operation, design and strategic assessment of these urban water systems (Burian et al., 2000; Hardy et al., 2005). Despite these efforts, urban water systems continued to have a detrimental effect on the environment. This set of circumstances led to the Third Generation urban water systems phase which is focused on a cost-effective sustainable management approach to the management of urban water systems (Vigneswaran et al., 2009).
2.1 General introduction to urban water systems

Brown et al. (2009) termed these urban water systems as the Waterways City.

Beyond the Third Generation classification of cities, Vigneswaran et al. (2009) does not extend the classification any further. Brown et al. (2009), however, introduces another two categories of urban water systems. A Water Cycle City is introduced as one, due to the response of the current limits of traditional urban water systems, introduces an integrated or total water cycle approach in the urban water systems management of the city. A further Water Sensitive City was introduced by Brown et al. (2009) which is an all-round sustainable urban water management city, where inter-generational equity of water resources including resilience to climate change is emphasised. Brown et al. (2009) also noted that there is no recognised example of such a kind of city in the world currently. According to Vigneswaran et al. (2009), this is termed as a city for the future. Bozovic et al. (2017) described this city as the Blue-Green Dream and goes further than Vigneswaran et al. (2009) description to describe methodologies and technologies that should be employed in this city, in order to achieve this all-round sustainability.

In summary, it can be concluded that Vigneswaran et al. (2009) and Brown et al. (2009) provide another set of urban water systems typologies that show the different kinds of urban water systems portfolios, a city goes through as it transitions through time. The typology reveals several ‘silent’ attributes that are associated with urban water systems, that confirm the importance of characterising urban water systems according to the nature of their component urban water subsystems.

These states of urban water systems are summarised in table 1.2. It must be noted that though these urban water systems are described in Vigneswaran et al. (2009) and Brown et al. (2009) as different urban water states through time. They can also be taken to represent different entities of urban water systems. That is, two different urban water systems can be characterised by the nature of the nature of their component urban water subsystems. Though, this philosophy of characterising urban water systems is not given priority in the scientific literature, in this thesis this characterisation of urban water systems was given priority and emphasized.
2.2 Conventional urban water systems

2.2.1 Introduction

Conventional urban water systems evolved out of the 19th century urban water practice within various European and American cities as a way to alleviate the challenges (and system failures), the urban water systems were experiencing when their population and urbanisation pressure increased (Domenech, 2011). This system of urban water practice (or paradigm) is characterised by centralised and large scale infrastructure (Al-Jayyousi (2003), Brandes & Maas (2004)), developed with the focus of meeting the urban water need of the city inhabitants (Gleick, 1998) without placing any consideration of the other inter-related processes.

2.2.2 Conventional urban water supply subsystems

The urban water supply subsystem, of the conventional UWS, involves the sourcing of large quantities of water from nearby water resources systems, transporting it over large distances to meet the drinking water requirement of the city inhabitants, hence the name supply-side system (Sharma et al., 2010). However, due to the one-sided supply of water, the system treats the fresh water resources as virtually a limitless resource (Brandes & Maas, 2004), indicating its heavy reliance on the availability of a reliable water source. Therefore, as the population and urbanisation within the city grow, more source water resources will have to be located (in most cases further away from the city) to satisfy the growing water demand of the city (Domenech, 2011). The heavy reliance of the system on a limited resource implies than any uncertainty in the availability of the resource induces a water supply performance risk to the urban water system. On the other hand, since the system focuses on meeting the water demand of the city inhabitants, then any increase their water consumption demand (due to population increase, urbanisation or change in standard of living) will require an equivalent increase the system's water source.

These two issues reflect the inherent weakness of conventional urban water supply subsystems - that is, the inability to deal with changes in either the demand or the supply. As a consequence of the system focusing on supplying water to the inhabitants without consideration of the state(s) of the water resource, has led to over-exploitation of the supply water resources (Gleick (1998), Al-Jayyousi (2003)) or has led to intermittent water supply within the city (Porto et al., 2009). Further, the supply-side orientated urban water management system of conventional systems without due consideration of the nature of water use.
in the community has led to inefficient water use technologies and paradigms within the cities.

Figure 2.1 illustrates these challenges through a system’s schematisation of the conventional urban water system. It shows that urban water supply subsystem is bounded on the side by an uncertain water resources supply source, and on the other side by dynamically varying and uncertain water users. The supply side of the water supply system is affected by the uncertainty due to natural variability (including climate change) of the water resource. The urban water use, on the other hand, is affected by the growth in population (and urbanisation) which indirectly induces a change in water use. All these uncertainties subsequently induce vulnerabilities (or inefficient behaviour) within the urban water supply system.

### 2.2.3 Conventional urban stormwater subsystems

Conventional urban stormwater subsystems are developed essentially to provide conveyance of the stormwater away from the city (in order to prevent flooding inconvenience and damage) then to receiving water environments for disposal (Butler & Davies (2011), Schreier (2014)). However, in disposing the stormwater into the receiving environment, urban stormwater systems also have a responsibility of minimising the degradation of the environment. This system, just like conventional urban water supply system, has provided successful urban water performance (from a city inhabitants perspective) (Sarukkalige, 2012).

As shown in figure 2.2, conventional urban storm water systems do not possess a direct linkage with inhabitants. It is the actions of the inhabitants (like urbanisation that change the urban landscape) that impact the storm water behaviour of the city (Porto et al. (2009), Sarukkalige (2012)). Hence, population growth, though indirectly, significantly affects the
Review of methods and tools for urban water assessment

Fig. 2.2 Schematisation of an urban water supply system detailing its controlling and driving factors

behaviour and consequently performance of conventional urban stormwater systems.

From a system perspective, urban storm water systems are bounded by the rainfall (along with the city landscape which is in turn controlled by the city inhabitants) on one-side, and the receiving water environment on the other side. The actual storm water system consists of artificial pipes, with overflow structures, draining storm water sometimes via storm water treatment system, and then to the receiving environment. Therefore, an urban storm water system is directly driven and controlled by both the amount of rainfall it is receiving and the nature of urbanisation practised in its city. The relationship between the incident rainfall with the storm water system is considered in the conventional design of urban storm water systems.

Butler & Davies (2011) demonstrates the impact of urbanisation on a storm water system as one that leads to an exponential increase in the amount of storm water run off to the system. In other words, urbanisation transforms (in volume and time) the storm water load incident to the stormwater system, and if the storm water infrastructure is not modified equivalently, this load will lead to increased flooding as well as increased downstream effects to the receiving water (Sarukkalige, 2012).

Hence, the uncertainty within the rainfall (due to climate change) and that within the urban landscape (due to population growth) will directly have an impact on the performance of a storm water system, as illustrated in figure 2.2.
2.2.4 Conventional urban sanitation subsystems

Conventional urban water sanitation subsystems usually comprise of a sewerage (or sewage conveyance) system, a waste water treatment system, and a receiving water environment, as illustrated in figure 2.3. The subsystem is designed to provide conveyance of human waste water, generated as an effluent from the urban water supply subsystem, to a wastewater treatment plan, before disposal to a receiving environment. The wastewater is drained away from the city inhabitants to prevent the emergence of fatal health risks (Butler & Davies, 2011).

![Diagram of urban sanitation system]

Fig. 2.3 Schematisation of an urban sanitation system detailing its controlling and driving factors

Conventional urban sanitation systems have found great success in conveying wastewater away from the vicinity of the city inhabitants, however, they still struggle to maintain sustainable environmental protection (Zhang et al., 2007). Despite the presence of a waste water treatment plant, it is not a guarantee that the system will not pollute the environment eventually (in terms of the irreversible flow of nutrients to the receiving water bodies) (Butler & Parkinson, 1997).

As shown in figure 2.3, the sanitation subsystem is controlled by the water supply subsystem (in the upstream end) and the wastewater treatment system (in the downstream). The urban water supply subsystem is the supplier of the human wastewater transport through the sewerage system, as well as providing the water to transport of the waste solids (Butler &
Review of methods and tools for urban water assessment

Parkinson, 1997). Therefore, because of this dependence on the water supply subsystem, any uncertainty or variability within the water supply subsystem directly impacts the operation (and performance) of the sanitation system.

The capacity of receiving environment, on the other side, to receive and safely dispose the treated wastewater, provides the second limitation of urban water systems. This capacity can easily be limited by any additional national or international legislation imposed on the urban water system.

2.2.5 Conventional urban water systems: Holistic View

![Diagram of conventional urban water systems]

Fig. 2.4 Systematic representation of a conventional urban water system

One of the weaknesses and limitation of the conventional design and analysis of urban water systems is that every subsystem is looked at independently, in isolation from the other subsystems (Butler & Davies, 2011; Diaz-Granados et al., 2010). A conventional urban water supply system is driven by the need to meet the water demand of the water users (Al-Jayyousi, 2003) without consideration of any other factors. Stormwater and sanitation subsystems, on the other hand, were developed to convey wastewater (or stormwater) as quickly as possible.
from the water users (Al-Jayyousi, 2003; Gleick, 1998) without consideration of the state of the receiving environment.

A systematic assessment of figure 2.4 reveals that both the water users and the environment are the most fundamental subsystems of a conventional urban water system. Therefore, any dynamics (including uncertainty) within the water users due to processes such as population growth and urbanisation induces a controlling effect on the overall behaviour of the urban water system. In addition, since the conventional paradigm places a lot of emphasis on the water users, but hardly any emphasis on the environment, it is no surprise that this paradigm leads to serious degradation of the environment (Al-Jayyousi, 2003).

2.3 Alternative urban water systems

2.3.1 Introduction

It has been concluded, from section 2.2 of this thesis, that the weaknesses and limitations of conventional urban water systems were the main reason why many authors such as Al-Jayyousi (2003); Butler & Parkinson (1997); Furlong et al. (2017); Pahl-Wostl (2005); Sharma et al. (2010) are advocating for a change in urban water systems management. Alternative urban water systems are, in principle, urban systems that have been developed to mitigate these weaknesses and limitations observed within the conventional urban water systems.

2.3.2 Defining alternative urban water systems

Despite the absence of standard typologies of describing alternative urban water systems, Cook et al. (2009) and Cook et al. (2013) proposed descriptions and definitions of an alternative urban water system. Cook et al. (2009), after a detailed literature review, recommended a definition of an alternative urban water system as:

Alternative urban water systems can be defined as systems provided for water, wastewater and stormwater services at the allotment, cluster and development scale that utilise alternative water resources; including rainwater, wastewater and stormwater; based on a ‘fit for purpose’ concept. These systems can be managed as standalone systems, or integrated with centralised systems. Wastewater streams are partially or completely utilised at or close to the point of generation. At cluster and development scale, stormwater is also managed as part of an
Review of methods and tools for urban water assessment

integrated approach that aims to control the quality and quantity of runoff at or near the source to minimise the impact of the development on the natural ecosystem.

According to this definition, it can be deduced that alternative urban water systems:

• are designed for water, wastewater, and stormwater services (that is for each of the urban water subsystems)

• are applied at a variety of scales (that is, from household, to development, and finally up to the whole city)

• utilise alternative water sources (that is rainwater, or recycled wastewater, or stormwater) based on a fit for purpose concept.

The definition further clarifies that within alternative urban water systems:

• wastewater streams can be completely or partially utilised at or close to the point of generation, including end of the pipe wastewater stream;

• stormwater is managed as part of an integrated approach, at or near the source, to minimise environment impact (as well as providing an additional water resource for water usage).

In other words, alternative sanitation systems and alternative stormwater systems can employ both decentralised (on-site) or centralised (off-site) wastewater or stormwater treatment systems.

Finally, the definition still suggests that these systems:

• can be managed as standalone systems or integrated as with centralised systems.

These characteristics of alternative urban water systems indicate some similarities with conventional systems, in that they both are designed to provide water, wastewater and stormwater services. Though, conventional urban water systems are not applied at a variety of scales, neither do they employ alternative water sources nor allow for any wastewater management near the point source. However, since alternative water systems are allowed to integrate with conventional systems, then it implies that any conventional system that is intervened with alternative urban water subsystems, does in a way become another option for alternative urban water systems.

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2.3 Alternative urban water systems

2.3.3 Paradigm employed in alternative urban water systems

Alternative urban water systems evolved in paradigm over a long period of time, as a result of urban water practitioners searching for improvement in the performance of conventional urban water systems. In the course of this evolution, the paradigm or principles driving the employment of alternative urban water systems have kept on evolving as illustrated in Table 1.1.

In the late 1990s till mid-2000s, the earliest calls for better performance of conventional urban water systems were driven by the need for more sustainable systems (sustainability, in this case, implied the need for sustainable environmental protection (Butler & Parkinson, 1997)). This sustainability advocacy was driven by increased awareness of the impacts cities can have on the environmental (Butler & Parkinson, 1997). However, despite the paradigm popularity and drive, the sustainability paradigm drive did not mature enough to transform into real practical specifics on how to implement sustainable practices into urban water systems (Gleick, 1998).

Consequently, after the mid-2000s, alternative urban water paradigms started dwelling deeper into the strategies required to achieve sustainability performance of urban water systems. As shown in table 1.1, more specific guidelines such as soft-path approach, clean-product approach, Water Urban Sensitive Design, etc. were developed to represent the cluster of interventions that can be applied to induce sustainability performance in conventional urban water systems. In other words, in this period, alternative urban water systems matured to practical levels.

Approaching 2010, the alternative urban water paradigm started to evolve to integrated urban water management. This paradigm called for the application of interventions across the whole urban water cycle (Porto et al., 2009). Whereas various authors such as Moglia et al. (2010) still advocated for this integration, the alternative urban water paradigms evolved even further to start focussing on the ability of the urban water systems to adapt to external pressures, through inherent flexibility or adaptability of the urban water systems. This integration, though not clearly defined in most texts, appears to represent the integrated urban water management paradigm. At this stage the alternative urban water management paradigm has matured further, to involve a series of guidelines (described in section 2.3.5), which provide several strategies.
Review of methods and tools for urban water assessment

Currently, the alternative urban water paradigm has grown to target other facets of the urban centre beyond the urban water system. Blue-Green paradigm places emphasis on utilisation of naturally-oriented technologies to improve the sustainable performance of the urban water cycle as well as contributing to the amenity of the city by bringing water management and green infrastructure together (Lamond et al. (2015), Bozovic et al. (2017)). This paradigm builds on the progress made by the WSUD and the SUDS paradigms (Bozovic et al., 2017).

In conclusion, the current state of alternative urban water paradigm places system adaptability (driven through urban water integration) as the core strategy to deal with unsustainability. Figure 2.5 illustrates the evolution of the alternative urban water paradigms. It specifies that originally the alternative urban water paradigm was centred on looking for specific technologies targeting a specific urban water subsystem at a time (for example the stormwater management subsystem as shown in figure 2.5), but now has transformed into a system that employs a broad principle, that targets the whole urban cycle of a city. However, the strategies and technologies it employs are still the same, though the methodologies it follows to utilise these technologies are the ones evolving over time. Fletcher et al. (2015) concluded that over the past decades, there has been a shift in alternative urban water management from the largely narrowly focused approaches (such as reducing flooding, increasing water supply, etc.) to approaches leading to multiple urban cycle objectives.

2.3.4 Sustainable urban water systems

It has been mentioned that paradigm driving the generation of alternative urban water systems, is that of sustainability. But the precise description of what is meant by a sustainable urban water system is not provided.

The precise definition of Sustainable Development (SD) is debatable (Ashley et al., 2005), however the Brundtland Commission reported in Langhelle (1999) defined sustainable development as a development that fulfils the needs of the present generation, without compromising the ability of the future generations to fulfil their needs. Then the Water21 project (a European Research Project on sustainability in water policy) implies that sustainability is where the supply of "natural capital" is maintained. In other words, the use of renewable sources, such as water, should not exceed the rate of their renewal (Rijsberman & van de Ven, 2000). In these definitions, three important themes of a sustainable system are highlighted, as Rijsberman & van de Ven (2000) noted: (a) needs of the present generation must be met; (b) needs of future generations must be cared for in the design; and (c) carrying capacity of
2.3 Alternative urban water systems

Fig. 2.5 A classification of alternative urban water paradigms and strategies according to their primary focus and specificity. Source - Fletcher et al. (2015)

supporting systems (or quantity and quality of supporting systems) should be considered.

Lai et al. (2008) gives a background and chronology of the concept of the principles of sustainable development. That is, the principles of SD first appeared in the 1972 Stockholm Conference introduced by the International Union for the Conservation of Nature (IUCN). The notion was formally published in the World Conservation Strategy by the same institution in 1980. These principles were further promoted through international consensus by the World Commission on Environment and Development (WCED) Brundtland Commission’s report Our Common Future in 1987, the 1992 Rio summit conducted by the United Nations Conference on Environment and Development and again at the World Summits on Sustainable Development in 2002 and 2005.

The concept of sustainability is extended to urban water management as dictated in Agenda 21 with a clearly defined objective (Lai et al., 2008). Lundin (2003) further described a sustainable urban water system should over a long time perspective provide required services while protecting human health and the environment, with a minimum of scarce resources.
Review of methods and tools for urban water assessment

Ashley et al. (2003) while studying the UK water industry states that a sustainable urban water system should aim to provide water services at reasonable cost, while conserving natural resources, protecting the environment and meeting social needs. Therefore, in conclusion, a sustainable urban water system should be one that provides water services to its users, meeting environmental standards of conservation, at a reasonable cost over a long term.

Therefore, a sustainable UWS has been defined as one that can sustain its service provision at economic, environment, social and technical levels for a long time (Loucks, 1997; Lundin, 2003). However, the popular assessment methods of sustainability in UWS usually depend on indicators that are not related to the UWS internal state variables (Kelly, 1998). Secondly, this assessment is carried out as a cross-sectional study at a certain point in time, without consideration of longitudinal variation of sustainable performance. Therefore, to keep in line with the definition of sustainable UWS, any sustainability assessment approach for a UWS should apply indicators that are related to the UWS characteristics at the four levels, and analyse them continuously over a long period of time.

2.3.5 Alternative urban water strategies

In the urban water scientific literature, there are numerous documented ‘alternative’ urban water system strategies (aka methodologies). These include Australian-based Water Sensitive Urban Design, WSUD (URS Australia Pty Limited (2004), City of Melbourne Water (2006)), the EU-based city of the future design guidelines (Philip (2011c), Philip (2011a), Philip (2011b), and Philip et al. (2011)), the North-American based Low Impact Development (LID) guidelines (in Credit Valley Conservation Authority and Toronto and Oregon Conservation Authority (2010)), the UK-based Sustainable Urban Drainage Systems (SUDS) guidelines (in Polito & Tassi (2012) and in Graham et al. (2012)), and the Blue-Green (or Green) Infrastructure philosophy (in Fletcher et al. (2015) and Bozovic et al. (2017)) . In addition, there are numerous research journal publications, which are not necessarily guidelines, that provide detailed description of alternative urban water strategies such as Burkhand et al. (2000), Turner et al. (2008), Kayaga & Smout (2011), Global Water Partnership Plan (2012), and Bahri (2012).

These strategies have two major characteristics. Usually, depending on their origin, they place emphasis on a particular urban water subsystem. For example, the present technologies are skewed towards improving the sustainable performance of an urban water subsystem, neglecting the other subsystems. LID guidelines focus on improved stormwater management only. In addition, because of the nature of the urban population of the country of origin of
2.3 Alternative urban water systems

the guideline, their technologies are also skewed towards the urban water use characteristics of that population.

The LID, SUDS, BMP, and Green Infrastructure strategies, however, place their focus on only the stormwater management subsystem. These are strategies that grew out of the need to control stormwater management in the later 20th century across North America and the United Kingdom. They provide technologies that employ nature in the sustainable control of stormwater (Fletcher et al., 2015). These strategies grew out of the need to discourage large end-of-catchment or pipe systems (Tejada-Guibert & Maksimovic, 2001) due to its inability to meet catchment-wide hydrologic restoration.

Water Sensitive Urban Design (WSUD) is a paradigm developed in Australia with the aim of minimising the environmental impacts urban water systems have on the environment (City of Melbourne Water, 2006). The guidelines recommend for integrated management of urban water resources through the utilisation various unconventional technologies such as the utilisation of local catchment system to minimise the dependence of the urban water system on external catchments. Specifically, the guideline promotes the incorporation of local decentralised solutions as the main technology strategy to deal with the challenges faced across the urban water supply, urban stormwater, and urban stormwater subsystems.

SWITCH was a European Union funded action research project aimed to develop, apply and demonstrate tested solutions and approaches to achieving sustainable urban water management in the city of the future (Howe et al., 2015). Just like the other strategies, SWITCH grew out the UN International Hydrology Program V (Tejada-Guibert & Maksimovic, 2001) which called for ways to cope and to hold off the impending collapse of the conventional urban water management system. Just like WSUD, SWITCH also provides strategies that focus on the whole urban water systems. Its core objectives include (1) to manage the urban water system in an integrated way, (2) to develop a strong scientific basis for urban water management decision making, etc.. SWITCH too mentioned a series of decentralised interventions that should be applied across the whole urban water system to induce sustainable performance.

Recently, building upon the success of the WSUD and SWITCH strategies, researchers have advocated for the Blue - Green Infrastructure strategy that advances the employment of nature based solutions, not only for the whole urban water cycle but also for the air pollution, the heat transfer (Bozovic et al., 2017; Lamond et al., 2015). BGI proposed the use of nature-based solutions to provide multiple benefits for multiple stakeholders within an urban
Review of methods and tools for urban water assessment

centre (Bozovic et al., 2017). This strategy extends the integrated urban water management to services such as water resources efficiency, air quality, flood mitigation, biodiversity, water quality, etc.. Therefore, because of the increase in scope, BGI adds to the urban water technologies, to introduces ones that can generate the ‘out-of-urban-water’ benefits.

2.3.6 Alternative urban water technologies

2.3.6.1 Water supply subsystem

As an urban centre grows (population and urbanisation), its water needs increase accordingly. Conventional urban water system management usually calls for an equivalent increase in the supply of water to the city. The alternative urban water supply management system, on the other hand, argues that increasing mains water supply to the city is not the only means in which a city can ensure water needs are satisfied, in the face of increasing demand. The integrated approach considers alternative options such as:

- reduction of mains water demand through the employment of alternative water sources like rainwater harvesting, greywater harvesting, wastewater or stormwater harvesting

- reducing wasteful water use by supplying water according to the quality of the end-purpose, or through the employment of demand management procedures

as a means of maintaining the supply-demand balance within the water supply subsystem.

The technologies employed to generate the reduction in water demand (the demand side of the supply-demand equation) are usually tagged as a water demand management (City of Melbourne Water, 2006; Kayaga & Smout, 2011). There are also other technologies that stretch across the whole urban water supply system such as water loss management, technologies that lead to the reduction in water use (such as the use of low-capacity in-house water appliances), economic tools like water use pricing or tariff management, and social tools such as water use marketing.

2.3.6.2 Stormwater subsystem

The alternative stormwater management, on the other hand, aims to provide the flood conveyance of stormwater, in a way that reduces the flood volumes (as they travel downstream), as well as provide water quality treatment of the stormwater to remove pollutants, before the stormwater reaches the aquatic environments. In all the stormwater management technologies, described in urban water scientific literature, the major stormwater management
2.3 Alternative urban water systems

Table 2.3 Alternative urban storm water strategies and technologies

<table>
<thead>
<tr>
<th>Category</th>
<th>Technology</th>
<th>Scale</th>
<th>Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infiltration Systems</td>
<td>Permeable Pavements</td>
<td>Local</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>Infiltration Basins</td>
<td>Regional</td>
<td>++</td>
</tr>
<tr>
<td></td>
<td>Swales</td>
<td>Regional</td>
<td>++</td>
</tr>
<tr>
<td>Detention [Storage] Systems</td>
<td>Ponds</td>
<td>Regional</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>Constructed Wetlands</td>
<td>Regional</td>
<td>++</td>
</tr>
<tr>
<td></td>
<td>Green Roofs</td>
<td>Local</td>
<td>+</td>
</tr>
</tbody>
</table>

+ presence of wastewater treatment process(es)

Technologies proposed are sub-categorised into either infiltration systems or detention systems (Burkhand et al., 2000; Fletcher et al., 2015). These technologies are presented in table 2.3 including their scale of application as well as whether they involve water quality treatment.

2.3.6.3 Sanitation subsystem

In terms of urban water sanitation system management, the major alternative urban water systems paradigms (that is, WSUD and SWITCH) appear to diverge from one another. In WSUD, alternative sanitation management focuses on reducing the wastewater flowing downstream through adoption of (1) demand management technologies, (2) stormwater reuse, and/or (3) wastewater reuse (greywater recycling, urine reuse, or faeces reuse). The challenge with this strategy is that it does not question whether to improve on the existing conventional sanitation management processes (that is, through a series of technologies right from the toilet use to the wastewater treatment) or to provide a completely new strategy.

The SWITCH guideline appears to go step further than WSUD by recommending a series of cyclic processes (sanitation management systems) that encourage separate collection, treatment, and reuse of urine, faeces, greywater and stormwater, as the alternative sanitation technologies. This approach acknowledges and exploits the linkages between water and urban development as a whole. Decisions in this system are made based on a holistic analysis of the whole sanitation system rather than on an artificially isolated part of the system - that
Review of methods and tools for urban water assessment

is putting into consideration the linkages between various subsystems.

Luthi et al. (2011) further confirms this paradigm by describing alternative urban water sanitation systems as a system of multi-step processes (or technologies) of managing different human excreta and domestic sewage technologies to achieve a sustainable operation of the overall sanitation system (as illustrated in figure 2.6). With the sanitation system represented as a series of multi-step processes, fundamental variables in an urban sanitation system whose variation leads and generates various permutations of alternative urban water systems, are allowed to demonstrate their impact on the whole system. It should be noted though that Luthi et al. (2011) described conventional urban sanitation systems one of the possible permutations of alternative urban sanitation systems. This then allows the conventional sanitation systems to be considered as just one of the possible sanitation system options possible in an urban centre, in the same way as low-income sanitation systems are.

In conclusion, in this thesis alternative urban sanitation systems were considered from the point of view that sustainable urban sanitation management requires the consideration of the many linkages between wastewater, urban water cycle, and urban development as a whole (as Bozovic et al. (2017); Philip et al. (2011) deduced). This involves the consideration of the linkages between the various subsystems to enable for a more integrated form of decision making.

2.4 Urban water systems of developing world

2.4.1 Urban water supply subsystems in developing world

In the developing world too, conventional urban water supply systems are still the most popular. However, due to the heterogeneous distribution of water users in the city, there is a mixed supply and mixed use of urban water in the city. A majority (> 70%) of the urban inhabitants are serviced with mains supplied water supply system, while the remaining inhabitants depend on decentralised sources such as boreholes, ground water springs etc. (Howard & Bartram, 2005; Porto et al., 2009) which are usually polluted and located in remote areas. With such a dual supply of water, the urban water supply systems of the developing world can be described as ones that comprise of both conventional and unconventional systems.

Within the mains supplied water users, the reliability of the mains water supply system in the developing world is poor (Howard & Bartram, 2005). The systems are usually characterised
Fig. 2.6 A figure showing the fundamental variables that drive the nature of sanitation systems that are or can applied in an urban centre, as described in Luthi et al. (2011).
Review of methods and tools for urban water assessment

by intermittent failures (Vairavamoorthy et al., 2001), due to the poor state of the urban water system infrastructure (Howard & Bartram, 2005), consequently leading to further inequitable distribution of mains water supply across the urban population, not to mention the risk of severe pollution which leads to water borne diseases.

In addition, given that developing world cities comprise of poor sanitation systems, then it is expected that their urban water supply systems would find difficulty in locating appropriate water sources to supply water. The poor sanitation systems in the cities lead to the environmental deterioration of available water resources (Kivaisi, 2001), making them inadequate for water supply.

All in all, in the developing world, all the issues reported on urban water supply systems, can be compounded into one of water scarcity (Porto et al., 2009; Vairavamoorthy et al., 2001) that is reflected through the poor reliability of the urban water supply systems. On one side, the urban water supply system employs low capacity water supply sources while on the other side, the system experiences a high water demand resulting out of high population and urbanisation growth rates. The combination of these two dominant drivers of urban water use will result in a stressed urban water supply system, that is prone to intermittent mains water distribution system behaviour.

2.4.2 Urban water sanitation subsystems in the developing world

In similar ways to urban water supply systems, sanitation systems in the developing world comprises of a mixture of different sanitation system types (Murray & Buckley, 2010) - both decentralised and centralised systems. The planned areas of the cities, usually about 40% of the urban residents (including the central business district) employ either centralised piped sewerage sanitation systems or septic tanks on-site sanitation systems, mainly because of availability of adequate water supply in these areas. The unplanned areas on the other hand, because of the unavailability of adequate water supply, employ pit latrines (on-site) sanitation systems (Chipeta et al., 2017).

Though, pit latrines provide a sanitation solution to a variety of low-income inhabitants of developing country cities, when the pits fill up they present a challenge. In most cases, where space allows (eg in planned environments) mechanised pit emptying trucks are employed (Chipeta et al., 2017; Gibson et al., 2018; Sico et al., 2015). In the informal settlements, due to economic costs involved or due to the lack of accessibility for the emptying trucks, residents usually resort to manual emptying techniques such as buckets or mechanical augers.
(Chipeta et al., 2017; Gibson et al., 2018).

In Uganda, it has been reported that in some instances when the pits are full, the norm is to abandon the old pit and excavate a new one (Gibson et al., 2018). And in other cases, the sludge removed from the pits is disposed off in nearby shallow holes or into nearby stormwater channels.

This kind of sanitation practice in the developing world presents a challenge from an environmental management point of view and from a public health point of view (Porto et al., 2009). The unavailability of adequate water supply undermines any development in adequate sanitation within these cities (Howard & Bartram, 2005). The sanitation systems in the developing world has been reported to allow untreated waste water to exit into receiving waters leading to their pollution (Kivaisi, 2001; Nyenje et al., 2010; Rodriguez et al., 2009; Sundaravadivel et al., 1999). Therefore, this kind of sanitation system results in poor environmental sustainability performance.

2.4.3 Urban water stormwater subsystems in the developing world

Stormwater drainage systems in the developing world, are not adequately documented in scientific literature (Jacobsen et al., 2013). In the developing world, as mentioned in section 2.1, urban water systems are still aiming at providing basic services, and as such it is expected that the stormwater systems in the developing world are developed to provide basic stormwater services. Further, in the developing world there is a high level of unpaved surfaces (Porto et al., 2009), hence it is expected that the stormwater system has a high dependence on the natural stormwater flow channel system.

Despite these unique differences in urban landscape, the conventional urban stormwater system is still employed in developing world cities. Urban storm water management in these cities is expected to consist of open surface channels for stormwater conveyance (with a mixture of either of natural or lined). Though, this system does not include any treatment before the stormwater exits to the receiving waters nor the use of stormwater as a resource.

However, the interaction of this kind of urban stormwater system with the sanitation system in existence in the developing world drives the urban water system’s environmental performance. Nyenje et al. (2010) and Withers et al. (2011) observed that the infiltration of stormwater to the subsoil interacts with the waste effluent from the septic tanks and or pit latrines to lead to the regular discharge untreated waste effluent to the receiving waters.
2.5 Improving the performance of urban water systems

2.5.1 Introduction

In the scientific literature, there is hardly any work, that places emphasis on the evolution paths urban water systems should follow in order to improve their sustainability performance. Only works by Furlong et al. (2017) could be found that attempted to define this process of urban planning. The majority of literature, however, places emphasis on the sustainable performance comparison between conventional (or traditional) and alternative urban water system approaches. This section, therefore, provides a review of literature focused on improving the sustainability performance of urban water systems.

2.5.2 Technology Options

In traditional urban water planning, the planning involves steps that include: (1) problem definition, (2) identification of the possible options, and (3) then selection of the the options Furlong et al. (2017). The process of identifying the possible options of intervening in the urban water systems is one various authors have attempted to define.

Sapkota et al. (2014) extended the concept of improving the sustainability performance of urban water systems, by suggesting that all the technology options available should be considered for a given urban water system. Without categorising the paradigm employed when applying these technologies, assembling all the possible technologies together (shown in figure 2.7) provides numerous technological options for improving the performance of an urban water system. The figure reveals that a combination of both alternative urban water and conventional technologies to generate even higher number of options and permutations for the design and improvement of urban water systems.

2.5.3 Paradigm Options

In-spite of the intervention alternatives for the sustainable boost of urban water systems performance, the paradigm through which they are applied plays a key role in their success. The conventional assessment of urban water systems considers each of the subsystems (of water supply, storm water, and sanitation systems) as isolated subsystems. In a conventional paradigm environment, each of these options in applied or designed for a specific subsystem of the urban water system.
2.5 Improving the performance of urban water systems

![Urban Water System Table]

Fig. 2.7 A holistic view of urban water system improvement options

Mitchell (2006) and Closas et al. (2012) extend the paradigm by suggesting that total system solutions should be designed which involve a combination of various technological options distributed across different urban subsystems. This approach, which is housed in the integrated approach of urban water systems, considers a holistic paradigm of designing urban water systems. Therefore, a consideration of integrated urban water management approaches to the improvement of urban water systems induces more urban water improvement options.

2.5.4 Strategies for improving urban water systems of the developing world

The discussion on developing strategies for improving the performance of urban water systems in the developing world has long been neglected (Koné et al., 2010). Developing countries, in a way, present a unique challenge for urban water practice, a challenge that does not require not only innovate solutions, but also a series of solutions (Jacobsen et al., 2013; Vairavamoorthy et al., 2001). In addition, due to the unique urban landscape and behaviour of urban water systems in the developing world, more appropriate tools are required to provide a more realistic assessment of these systems Kivaisi (2001); Porto et al. (2009); Vairavamoorthy et al. (2001).

In the developing world, there is an urgent need for a change in urban water planning (also known as design or management) paradigm to improve the performance of their urban water systems (Porto et al., 2009; Scott et al., 2010)). However, despite the call for a change in
Review of methods and tools for urban water assessment

paradigm, conventional urban water systems are still popular in these countries (Barbosa et al., 2012). Though, it is also argued that it is unlikely that conventional systems will be able to provide adequate improvement of urban water system of a future developing country city (Jacobsen et al., 2013).

The majority of urban water interventions in the scientific literature on developing countries is focussed on water supply and sanitation systems, hardly on stormwater systems. In the urban water supply system, the need for alternative water conservation measures is suggested as the main intervention to overcome the urban water scarcity (Vairavamoorthy et al., 2001), in addition to wastewater recycling (Jacobsen et al., 2013), and demand management (Vairavamoorthy et al., 2001). The use of wastewater reuse was also mentioned as a strategy to mitigate water supply shortages in the developing world.

In the urban sanitation system, wastewater reuse for agriculture in Kivaisi (2001); Koné et al. (2010); Murray & Buckley (2010) was suggested as the most popular intervention to improve the performance of the sanitation system. This strategy was suggested mainly because of its ease of applicability in the developing world (including application to low-income communities) (Jiménez et al., 2010), and also because of the added economic benefit wastewater adds to urban agriculture, in addition to reducing on the environmental degradation.

Conventional sanitation systems are discouraged for urban water systems of the developing world, mainly because of their economic cost to the urban residents. It is believed that a majority of the urban water residents in a city of the developing world, cannot afford conventional systems connection (Koné et al., 2010). Other sanitation interventions suggested for developing countries include the use of urine-diverting toilets, the use of low-cost sanitation sewerage systems to provide reticulation for the on-site septic tanks, and the use of natural wastewater treatment systems (Murray & Buckley, 2010).

However, it should also noted that in all this literature, most of the strategies are suggested without any concrete study or illustration of their efficiency.
2.6 Performance assessment of urban water systems of the developing world

2.6.1 Sustainability assessment of urban water systems

Venkatesh et al. (2017) recommends that any form of sustainability assessment of urban water systems must include the dimensions of social, environmental, economic, asset and governance sustainability. The sustainability assessment should be done by examining the estimated effects of the various interventions and how their implementation through time using a predefined set of performance metrics or indicators. These performance indicators should correspond to the sustainability objectives.

Venkatesh & Brattebø (2013) recommends the use of a life-cycle assessment and metabolism approach in the assessment of urban water systems sustainability assessments, where annual emissions, environmental impacts, and costs are quantified as a consequence of physical flows (water, materials, chemicals, energy carriers, wastes) within the system. The TRUST project in Australia concludes a set of 13 sustainability indicators for urban water system, that is, 3 for social sustainability, 2 for environmental sustainability, 1 for economic sustainability, 4 for governance, and 3 for asset sustainability.

An innovative framework for the assessment of urban water systems has been suggested that involves the use of the concept of urban metabolism Venkatesh et al. (2017). Urban metabolism, in this case, involves the quantification of the inflows, outflows, storage and production of energy and materials within the bounds of an urban setting.

Integrated modelling of an urban water cycle, as a special case, involves the quantification of water-related flow and fluxes in complex urban environments. The urban metabolism approach was applied to integrated modelling of urban water services in Behzadian & Kapelan (2015), the study demonstrated that integrated modelling is a subset of urban metabolism modelling. Integrated modelling of urban water systems gives an opportunity for generating extensive information on the potential life cycle of environmental impacts associated with the processing of physical flows (water, materials, chemicals, energy carriers, wastes, recovered resources, etc.) in addition to information on the quantities of the physical flows themselves.
Review of methods and tools for urban water assessment

The performance indicators covering each of the domains - that is environment, economic, physical are therefore generated for an urban water system, and reported on an absolute basis or per cubic metre or per capita basis.

2.6.2 Integrated urban water modelling

2.6.2.1 Relevance of integrated modelling

In the traditional assessment and design of interventions (or the performance improvement schemes) for urban water systems, approaches consider the water supply subsystem in isolation from the sanitation subsystems, in isolation from the storm water subsystems (Makropoulos et al., 2008; Mitchell et al., 2001), in isolation from the sanitation subsystem, and also in isolation from the whole urban water system (Bach et al., 2014b). Interventions designed this way ignore the importance (and benefits) of interactions between different urban water subsystems, their inter-subsystem non-linearities, or the time delays between their feedback mechanisms (Kiggundu, 2014; Pahl-Wostl, 2007). This kind of urban water assessment or planning leads to problematic designs which despite the short term successes lead to unforeseen side-effects in the long term (Pahl-Wostl, 2007; Urich & Rauch, 2014). In the end, this form of urban water systems’ assessment has exposed the relevance of the exploitation of the interactions (that is, the integration) between the different urban water subsystems (Makropoulos et al., 2008).

Mitchell et al. (2001) and Mitchell et al. (2007) observed that significant advances have been made in the developing modelling tools that allow for this integrated assessment of urban water systems. Applying this kind of modelling tool to an urban water system allows for the utilisation of the complex and dynamic interactions between the water supply subsystem, the sanitation subsystem, and the storm water subsystem at different spatial and temporal scales (Makropoulos et al., 2008; Urich & Rauch, 2014) to generate further understanding of the performance of these subsystems and the whole system as a whole. This, then allows one to investigate and quantify the interactions of the subsystems and to identify the future possibilities and the limitations of different systems within the context of sustainable water management for new developments (Makropoulos et al., 2008).

In the end, the opportunities provided by an integrated modelling system are designed to bridge the gap created by the traditional assessment of urban water systems. This section is therefore providing a detailed description of what is meant by an integrated urban water
2.6 Performance assessment of urban water systems of the developing world

modelling system, its weaknesses and opportunities within the perspective of an urban water system of the developing world.

2.6.2.2 Existing integrated modelling platforms

In most integrated modelling urban water studies, integration is taken to imply the modelling of different physical systems that allows for interactions between the different subsystems (Mitchell et al., 2007). In certain instances, urban water integration has been extended to boundaries beyond the urban water system infrastructure to include the social, or the economic systems (Bach et al., 2014b). The differences in the integrated modelling approaches, are therefore reflected in the nature of the subsystems that are represented in the integrated urban water model.

As an approach to generate a standard typology for integrated urban water modelling systems, Bach et al. (2014b) categorised integrated urban water modelling systems into four groups according to their scope, as follows:

1. **Integrated component-based models (ICBM)s** which concentrate on the components within a local urban water sub-system,

2. **Integrated Urban Drainage Models (IUDM)s** or **Integrated Water Supply Models (IWSM)s** that integrated subsystems of either urban drainage (wastewater, stormwater) or water supply streams (treatment and transport processes) respectively.

3. **Integrated Urban Water Cycle Models (IUWCM)s** that links the water supply and urban drainage stream into a common framework (sometimes described as total urban water cycle models).

4. **Integrated Urban Water System Models (IUWSM)s** is the highest level of integration, and combines different water infrastructures and disciplines (climate, economics, actor behaviour etc) of the total urban water cycle.

The focus of this research is on the integration of urban water subsystems across the water supply, the stormwater, the wastewater or sanitation subsystems. Therefore, it appears that the integrated urban water cycle models (IUWCMs) are the appropriate integrated modelling tools for this kind of study. IWCMs models have been recommended by Mitchell et al. (2001) and Mitchell et al. (2007) for the assessment of any urban water strategic options involving the use of alternative urban water interventions that spread across both decentralised and centralised spatial scales.
2.6.2.3 Integrated Urban Water Cycle Models (IWCMs)

Mitchell et al. (2001) and Bach et al. (2014b) stated that the number of IWCM integrated modelling tools developed is still low, and also that some of their fundamental theories are still in their infancy. In scientific literature, the IWCM integrated modelling systems found included (1) Aquacycle (Mitchell et al., 2001, 2007), (2) UWOT (Makropoulos et al., 2008), (3) UrbanCycle (Hardy et al., 2005), (4) City Water Balance (Last, 2010; Mackay & Last, 2010), and (5) WaterMet (Behzadian & Kapelan, 2015).

Also, there are numerous studies in scientific literature that employed different IWCMs though these models were not given a trade mark name such as Fagan et al. (2010); Hochstrat et al. (2005); Paton et al. (2014); Soares et al. (2005).

These integrated urban modelling systems however, despite belonging to the same category, their component methodologies and processes are significantly not similar. This variability is described further in this section:

2.6.2.3.1 The modelling approach

In general, these modelling systems employ a mass balance approach (for both water and contaminants in some cases) to provide a complex modelling of all processes which occur within an urban water hydrologic cycle (that is the water supply, the waste water disposal, and the storm water run off). Most of the modelling systems except the one in Fagan et al. (2010), employ a discrete water budgeting approach across different temporal and spatial scales, when following various water flow streams across an urban landscape.

In the modelling systems, where contaminant(s) transport is studied (such as Aquacycle and City Water Balance), the contaminants mass balance budgeting is carried out assuming a conservative flow of the contaminant across both the temporal and spatial scales.

2.6.2.3.2 Temporal Scales

The temporal scales in most of the modelling systems employed daily time scales apart from UrbanCycle and the Fagan et al. (2010) which employ sub-daily time steps. The daily time steps despite missing out on the peak flows that occur at sub-diurnal steps, are considered to be appropriate to provide sufficient information for the strategic urban water assessment of various conventional and alternative interventions.
2.6 Performance assessment of urban water systems of the developing world

2.6.2.3.3 Spatial Scales

On the other hand, the approaches these systems employed to address the variability of spatial scales across the entire urban area is generally not uniform. For most modelling tools, there is a general agreement that the household scale (which implies a building in an urban centre) should be the smallest spatial unit upon which the whole urban water system should built on. The household scale is then cascaded upwards to generate the entire spatial domain of the urban centre (in a similar way as a network typology), that is from household scale to the largest scale possible (Hardy et al., 2005) - that is the city-wide scale.

Aquacycle, City Water Balance, and WaterMet cascade the households to clusters (group of homogeneous households) then to a development or a sub catchment scale (group of clusters), and finally to catchments. UWOT and the Fagan et al. (2010) system, on the hand, cascade up to the development scale only. It is not clear though whether the development scale employed in UWOT or in the Fagan et al. (2010) system physically represents the natural watersheds of the urban centre.

2.6.2.3.4 Local Hydrology

In representing the water flow across the urban water cycle, the existing IWCMs follow the cascading system set up for the description of the spatial landscape of the town. The local hydrology at a household scale is computed first, then aggregated through the urban centre to the clusters, and finally to the development or the sub-catchment or catchment scale.

2.6.2.3.5 Water use quantification

At household scale, the water use is broken down in micro-components (or end-uses) of the individuals within a given household. The micro-components are then aggregated to generate any water or wastewater stream required. However, there is a wide variation in the approaches the different IWCMs employ to compute the water use micro-components.

The IWCMs generate the water-use micro-components from the according to the type of household and also according to the sanitation system interface employed within that household. Since the existing integrated modelling tools were designed for a city of the developed world, it was assumed in them that all the households employed household water appliances. Further still, more differences in micro-components computations within the integrated modelling systems were found in the nature of end-uses modelled, and in the approach employed to compute each of the micro-components.
2.6.2.3.6 Stormwater flow computation

Also, at the household scale the local stormwater flow hydrology (and human waste water hydrology) are represented and computed. The household surface is broken down into pervious and impervious portions, from which the stormwater runoff from each surface is computed and aggregated to generate total surface run off effluent from the household. The outflows from each individual household plots are then routed along the preferential pathways to the inlets of the tertiary storm drainage networks.

In computing stormwater runoff, there is also a wide variation in how the IWCMs represent the rainfall-runoff processes across a household. In the majority of the IWCMs (except WaterMet), the systems depend on the distributed urban landscape represent the urban catchment hydrology. The stormwater flow is computed across each of the numerous households’ surfaces. In addition, some of the models (only in Aquacyle and City Water Balance) employ a soil-water accounting model (the Austrian Catchment Water Balance Model in Boughton (2004)) as part of their rainfall-runoff routing computation.

WaterMet however employs a catchment rainfall-runoff modelling algorithm, the Rational Method, for its rainfall-runoff routing across a catchment. The challenge with the Rational method is that it do not provide any consideration for the role gravity plays in driving the flow of stormwater downstream through a catchment. In addition, the Rational Method cannot be relied upon to develop a comprehensive temporal dynamics of the stormwater runoff.

Human wastewater flow quantification

In addition, the ICWMs also consider human wastewater that originates from the household water use. The household human waste water is aggregated directly from the water used within that household. In UWOT however, the wastewater volume in separated into different streams (such as urine, black water, or grey water) for purposes of integrated urban water designs.

Contaminant flow

Contaminants (such as Total Phosphorus or Total Nitrogen) flow across households is also placed into consideration these systems, and all pollutant(s) is represented as a conservative constituent of the water flow streams.
2.6 Performance assessment of urban water systems of the developing world

2.6.2.4 Global hydrology

In all the IWCM systems, all the water flow streams from the households are aggregated cumulatively to clusters then to developments, to sub-catchments, and finally to catchments (whichever is the largest scale). The subcatchments’ flow then aggregates to generate the wastewater volume effluent exiting a city. However, in all the IWCMs, no provision is made for the gravity-driven flow of wastewater from subcatchment to subcatchment. This implies that for cities with significantly rolling terrain, these modelling tools do not make provision for role gravity plays in driving the wastewater and/or stormwater flow.

2.6.2.4.1 Sanitation system

In all the tools, the sanitation system employed is assumed to employ indoor household water appliances (such as flushing toilets, water sinks, dish washing machines, etc). In Aquacyle, City Water Balance, and UWOT wastewater from the toilets is then channelled to a combined sewerage system. In City Water Balance, the use of septic tanks was added to the conventional sanitation system. Any other sanitation systems like the use of pit latrines or open defecation, which are usually found in cities of the developing world are not represented in these tools.

2.6.2.4.2 Urban water interventions

Finally, the alternative urban water interventions addressed in the IWCM systems is quite varied and not uniform. In UWOT system and in City Water Balance, the interventions addressed were limited to only demand management and sustainable urban drainage systems (SUDS). Aquacycle, though, addresses a wider range of interventions ranging from local rain water harvesting to regional storm water storage, to on-site wastewater treatment, and finally to conventional waste water treatment. However, alternative interventions that are conducive for developing countries like use of constructed wetlands, urban wetlands are not represented in these tools.

2.6.2.5 Summary

In summary, the IWCM integrated modelling systems explored in this section, demonstrate that significant progress has been made in the paradigm of integrated assessment of urban water systems. Their fundamental processes of cascading the urban water hydrology right from the household to a catchment and to the whole urban centre, represent one of their major strengths. However, despite their progress these systems are quite varied in the fundamental processes they utilise to represent a particular urban water system. As a conclusion, this
section has illustrated that these systems appear skewed towards modelling urban water hydrology of a city in the developed world, leaving out the developing world.

In reviewing integrated urban water systems, Mitchell et al. (2007) concluded that no integrated modelling tool is suitable for all urban water applications across the world and hence there is need to tailor existing tools to the specific needs and circumstances of an urban water system of the developing world. Therefore, to apply the integrated modelling paradigm to a city in the developing world, the existing IWCMs will have to be tailor-made to accurately represent the major features of these kind of cities.
Chapter 3

Methods

3.1 The Case Study

3.1.1 Introduction

Mbarara city (or town) in south-west Uganda (East Africa) was chosen as the case for this study. Mbarara town is a city (or town) located 266 kilometres from the capital Kampala (see figure 3.2(a)) with a residential population of about 195,000, according to the 2014 national census. Kiggundu (2014) concluded and described Mbarara town is one of the major secondary cities of Uganda.

Politically and nationally, Mbarara town is one of the major cities in the country. It houses the political and administrative headquarters of Mbarara district. It is also the major business centre of the south-western region of Uganda, which also doubles as the major trading town along the transport corridor into central Africa (that is connecting to neighbouring countries Rwanda, Burundi, and the Democratic Republic of Congo).

The town is located within the larger watershed of River Rwizi, and with the river forming part of its main drainage features, as shown in figure 3.2(b). Hence as a consequence, river Rwizi is employed by the urban water system in the town as both the source for the water supply (as shown in figure 3.1(a) and figure 3.1(b)), and also as the receiving water environment for the waste water (human waste water and stormwater) exiting the town.

The topography of the town, can be described as both rolling and hilly, with sharp hilly areas separated by deep valleys. In the valleys various tributaries of the river traverse the town. In addition, due to the high variation in altitude across the town, a significant
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Fig. 3.1 The existing urban water system in Mbarara, that is: (a) and (b) showing the River Rwizi with its flood lines, (c) and (d) showing the urban water supply subsystem, (e) and (f) the urban stormwater subsystem, (g) and (h) the urban sanitation subsystem.
3.1 The Case Study

![Map of Uganda showing the location of Rwizi Catchment](image)

![The relative position of Mbarara Town in River Rwizi Catchment](image)

Fig. 3.2 Location of Mbarara Town within the Rwizi catchment

... proportion (about 60%) of the town residential areas that reside within the valley strips are unplanned settlements. Kiggundu (2014) confirms that Mbarara town consists of 11 unplanned settlements, all located with the town valleys.

### 3.1.2 Climate and rainfall

The region experiences a bimodal rainfall pattern, with the first season occurring from March - May whilst the second occurs from September to December (illustrated in figure 3.3(a)). The daily rainfall received in the area has an annual mean of about 2.60 mm/day but can peak up to 114.70 mm/day (see figure 3.3(b)).

Mbarara experiences moderate temperatures throughout the year. The mean daily temperature is 28°C
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(a) Monthly rainfall distribution

(b) Daily rainfall distribution

Fig. 3.3 The distribution of rainfall received within the study area
3.1.3 Urban water supply subsystem

The town comprises of both a centralised conventional urban water system and a series of decentralised urban water systems for the supply of both domestic and non-domestic water use in the city. The mains water (or conventional) system serves about 82% of the urban population leaving the other residents to depend on the decentralised sources like protected springs, boreholes, and localised rain water harvesting. The distribution of decentralised urban water use behaviour is summarised in figure 3.4 (and illustrated in figure 3.1(b)), which shows that localised rain water harvesting is the most popular decentralised urban water system employed in the town.

As described in chapter 2.0 of this thesis, the mains water supply system in this developing country is faced with a number of challenges. The mains water supply is distressed significantly by the river flow variation that is responsible for severe water shortages (during the dry season) within the town. In addition, because of the availability of rainfall in the area, a significant proportion of the mains water supplied water users also employ decentralised water sources (such as localised rain water harvesting) as a secondary water source to complement the unreliable centralised mains water.

This observation confirms the characteristic trait of urban water practice in a developing country city, that is, that the town consists of a mixture of mains water and alternative water
supply use. However, the rate at which alternative water use affects the mains water use is not documented.

3.1.4 Urban stormwater subsystem

The storm water drainage system in Mbarara, can be best described as a conventional system that comprises of series of open channels to convey stormwater away from the city to receiving water body (River Rwizi in this case). The channels employed consist of a mixture of both lined and unlined channels, that traverse the town to drain into river Rwizi. However, it should observed that these residents that reside around the banks or valleys of the river, within unplanned settlements (as illustrated in figure 3.1(e) and figure 3.1(h)).

3.1.5 Urban sanitation subsystem

Sanitation in the town in provided through a mixture of centralised (3%) and decentralised (97%) systems. Data collected in the study area showed that only 3% of the town (mainly the central business district) employs the centralised system. The centralised sewerage system employs low cost waste water treatment systems (that is waste stabilisation ponds as shown in figure 3.1(g) and in figure 3.1(g)) at three different locations that is, Kigongi, Katete, Kakoba, Kizungu (along the shores of River Rwizi). The treatment systems dispose their effluent into River Rwizi.

The remainder of the town residents employ decentralised household sanitation, of either pit latrines (54%) or septic tanks (45%). There is also a presence of ’wastewater-transportation-trucks’ within the town that provide alternative transport for some of the waste water from septic tank users to the centralised systems’ treatment plants. It was observed that there was no adequate monitoring system of the environmental performance of this sanitation system. A study by Egor et al. (2014) revealed that there was significant increase in the concentration of contaminants in the river as a consequence of the inadequate environmental performance of this sanitation system.

3.1.6 Mbarara Town - Summary

All in all, Mbarara Town has characteristics typical of a secondary city in a developing country. It consists of a centralised urban water supply system (which is influenced and affected significantly by decentralised water supply use), a mainly decentralised urban sanitation system (with only 5% centralised sanitation use), and a conventional storm water system that
follows the natural storm water drainage system (with low levels of urbanisation).

These characteristics appear to confirm that the existing integrated urban water modelling tools (described in section 2.6.2), would be inappropriate to represent this town. Hence, for an integrated modelling system of this town, it is important that the existing systems are tailor-made to represent their specific characteristics.

### 3.2 Methods I - characterising urban water use

It has been mentioned in section 1.5 (as part of the aims of this study) that in a community that employs significant amounts of localised rain water harvesting (RWH) to complement the unreliable centralised mains water use, it is important to understand whether the localised rain water harvesting has any significant impact on the level of the mains water consumption. This information once specified provides additional contribution to the characterising of the specific water use behaviour of the urban water system of a community of the developing world.

This section therefore describes the methods applied in this thesis to meet this objective.

#### 3.2.1 Introduction

Urban water supply systems of the developing world are usually characterised by a rain-fed water supply, that is, their water source is directly or indirectly fed by rainwater falling on the urban catchment. The urban water supply subsystem in this study was not even different.

The urban water supply system in Mbarara town consists of a centralised mains water supply system, that sources its water from River Rwizi, a local river with a catchment stretching a couple of square kilometres outside the city. This river is highly sensitive to the amount of rain falling on the urban catchment, that during the dry season its water levels significantly fall affecting the volume of mains water supply to the city (leading to an unreliable mains water supply system in the city). In addition, due to the unreliable mains water supply to the city residents, a significant number of the residents utilise localised household storage tanks, to complement the overall system storage. It was also measured in this study (see figure 3.4), that about 80% of the town residents utilise localised rain water harvesting as a secondary water source for their water supply needs.
Methods

With such an urban water system and with an urban water monitoring regime measures only on the rainfall and the mains water use, understanding the temporal dynamics of the overall water use in the community becomes a challenge. The situation is further complicated, by the poor level of systems documentation across the city. It is thus important that an innovative approach is developed that allows for the generation of information on the water use behaviour, utilising the available limited data. These unique challenges justified the need for an approach to describe the relationship between rainfall-input, mains water use, and decentralised rainwater use in an urban water system of the developed world.

3.2.1.1 Introducing time series analysis (TSA)

As an analogy, urban water systems in the developing world, are in a way synonymous with many complex natural water systems, which have one-input one-output data series as the only available data to deduce the hydrological and hydraulic functioning of the system. For example, complex ground water systems (Bailly-Comte et al., 2008; Gelhar, 1974; Jemcov & Petric, 2010; Mathevet et al., 2004) with only rainfall input and measured ground water flow (represented by the measured ground water level) as the only data series available, also complex river catchments (Bourodimos, Efstatious & Oguntuase, Abiose, 1974; Chow, 1969; Lafreniere & Sharp, 2003)) with only the input rainfall and output catchment river flow as the only available data series. In these natural systems, a time series analysis methodology is usually employed to deduce their fundamental hydrological and hydraulic behaviour. The information generated from this analysis is of relevance to the systems future strategic development.

Therefore, because of this analogy in physical circumstances between these natural water systems and the urban water systems in the developing world, this study then introduced time series analysis methodology as the methodology to assess the hydrologic and hydraulic functioning of the urban water system of the developing world.

3.2.2 Time Series Analysis - the study design

In this town, it is evident that localised rainwater harvesting (at household scale) is widely practiced in the town. It is also evident that a conventional or centralised urban water supply system that receives water from a local river is employed. The centralised water supply is pumped to a central reservoir of about 4000 cubic metres in volume, from where it is distributed to various households within the town. At most households, due to the unreliability of the centralised water supply, residents improvise with localised storage tanks of about
3.2 Methods I - characterising urban water use

![Diagram of urban water supply system in Mbarara](image)

Fig. 3.5 Visualisation of the urban water supply system in Mbarara

5 – 10 cubic metres. The unreliability of the centralised water supply, drives the extended use of localised rain water harvesting (that is a decentralised source of water) to complement the mains water supply. This system is illustrated in figure 3.5.

The utilisation of time series analysis requires the representation of the urban water supply system within the town as a Single-In-Single-Out (SISO) black box system. As a Single-In-Single-Out (SISO) black box system, the urban water system receives rainfall as the main input (to cater for both the centralised and decentralised sources) while the mains water consumption as the single output. Though, it can be argued that the local rain water harvesting volumes should perhaps be part of the output. Even if this is practically accurate, it was presumed that in cases where localised rain water is employed rain water is given first priority over the mains water. In this way, assuming that the total household water demand does not vary significantly, then it is expected that any rain water harvesting the household practices can be deduced from the mains water consumption variations. With this presumption, it was not considered a limitation to the study if rainwater harvesting records were not added - but a strength of the TSA approach if the rain water harvesting behaviour could be interpreted from the mains water consumption behaviour.

3.2.2.1 Data input

The linear analysis of rainfall against water consumption requires a comparison of data sources that occurred within the same time frame. Water consumption data, which is usually
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Fig. 3.6 The mains water use and rainfall input into the urban water system in Mbarara

measured, at monthly scale was collected from the national utility for the period 2008 – 2012. This data consisted of the total monthly mains water meter readings ($m^3$) of the numerous households.

Within the same period, monthly rainfall data was computed from the measured daily rainfall (mm), from daily rainfall measurements at a national weather station located within the town. These two datasets were then employed for the time series analysis (see figure 3.6). Since it was essentially an independent analysis of each time series, there was no need for a change of units (of the rainfall depth to volume).

3.2.2.2 Model development

The mathematics followed in the time series description of the system is provided in Appendix A. These methods were coded within the Matlab technical computing environment.

3.2.3 Time Series Analysis - the modelling concept

The methodology schematizes an urban water supply system as a "black box system" (with a single water input, through the system, leading to a single water output) that filters or modulates the input stochastic signal (or time series) to generate an output stochastic signal (Mathevet et al., 2004). This is illustrated in figure 3.7. In this analysis, the urban water supply system was extended to rainfall as the single input, while the mains water use was
3.2 Methods I - characterising urban water use

Fig. 3.7 How time series analysis reveals the fundamental dynamics of an urban water supply system

taken as the single output. However, in reality, mains water use is not the only output from the water supply, these include river stormwater runoff, evaporation, infiltration, and leakages all contribute to the water out from the urban water system. In this system, mains water use is the most downstream output of the system (as well as the one with the most reliable data) and hence was considered as the single output for the time series analysis.

Then analysis of this modulation effect between the rainfall and the mains water use will generate an understanding of the fundamental temporal hydrological functioning of the urban water supply system. Since the system is studied from rainfall to the mains water use, this analysis will certainly generate hydrological information that extends beyond that generated by the IWA/AWWA methods.

The modulation effect is viewed through the insights generated from the advanced statistical methods of autocorrelation and cross-correlation analysis of the input/output stochastic time processes (Labat et al. (2000), Bailly-Comte et al. (2008)).

Essentially and analytically, the mains water consumed from the urban water system is considered to be an integral sum of (1) the system input rainfall, (2) the landscape hydrology leading up to the river flow, (3) the centralised and localised water supply system storage, and (4) any significant water losses, as hinted by Chow (1969). Then this mathematical relationship is assessed through time series techniques of autocorrelation, cross correlation,
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autospectral analysis, and cross-spectral analysis.

It should be noted, however, that kind of insight is similar mathematically to the representation of an urban water system through the IWA/AWWA urban water accounting approaches. Therefore, the time series analysis methodology, in a way provides an alternative urban water balance assessment. However in this approach, the hydrological functioning of the system is generated through the advanced statistical analysis of the system. And since the two data series are not 'connected' directly through an equation, the time series analysis provides a way of describing a relationship between rainfall and mains water use, even if they are both in different metric units.

3.2.3.1 Correlation Analysis

The autocorrelation assessment (of the input time series separately from the output time series) is used to quantify any linear dependency of successive values in either of the input or the output series. This individual assessment of each series characterises the nature and structure of each of the input or output time series, which then gives an indication of how the output series is transformed relative to the input, and in so doing outline the effect of water supply system memory on the output series (Mathevet et al., 2004). That is, if an event has a long term influence on any of the time series, its output auto-correlogram slope is expected to decrease gradually as a function of the lag time. In summary, the auto-correlation analysis provides an insight into the individual stochastic structure of each of the input and or output time series, and their linear inter-dependency over a given time period.

The cross correlation assessment of the input series against the output series was used to show which of the two series dominates (or leads) the other, through the water supply system. If there is a lead, an estimate of that lead or delay time was estimated as the lag time difference between the initial (lag time = 0) and the point of maximum cross-correlation. This lead or delay time estimation is usually taken to represent the peak impulse response time (or a representation of the storage capacity) of the system. Hence, the cross correlation function can be used to estimate the approximate time lags at which the two series are well-correlated. Any delay or lead in time lags between the input-output series is a reflection of the 'measure' of internal hydrological dynamics of the urban water system. The input, in this case, is rainfall series, the output is the mains water use.
3.2 Methods I - characterising urban water use

3.2.3.2 Spectral Analysis

The autocorrelation and cross correlation analyses, are carried out in the time domain. Time series analysis provides further analysis through the frequency domain. In the frequency domain, further analysis of the impulse response (now called frequency response) of the system is represented through both the auto-spectral and cross spectral analyses. For the auto-spectral density function of each of the series, a large value (usually spike) of the spectral density is taken to respond to the frequency that is strongly represented in each of the series (Mathevet et al., 2004; Molenat et al., 2000). The comparison of the input series (the rainfall) spectral behaviour against output (the mains water use) spectral behaviour reveals which periodicities (or frequencies) within the input series are still prevalent in the output series, which is a further indication of the impulse response (or the internal hydrodynamic behaviour) of the water supply system.

The cross-spectral density analysis of the rainfall against the mains water use was interpreted as a measure of the covariance between the respective frequency components in the two series, in a way showing how the input rainfall signal is modified by the system on its way to mains water use. However, the frequency response of the system (which is equivalent to the systems impulse response in the time domain) is characterised fundamentally by the Cross Gain and Cross Phase Functions, which are all indirectly further modules of the cross spectral analysis.

The Cross Gain Function (GGF) expresses whether, at each frequency, the mains water use series is amplified (> 1) or attenuated (< 1) relative to the rainfall series by the water supply system. The Cross Phase Function (CPF) estimates the extent to which, at each frequency component, one series leads or lags the other (i.e the delay of output with respect to input). The time equivalent of this lead or lag is estimated through the slope of the phase function at a given frequency, assuming the phase function is linear at that frequency. Hause, John (1971) denotes this time lag (or lead time) as a characteristic time of the urban water supply system. For the case of a water supply scheme, this characteristic time was taken to represent the measure of a time representation of the storage capacity of the system or the mean transfer time of water through the urban water system.

The final module of the cross spectral analysis computed for comparison of the rainfall (input) against the water mains use (output) is the cross coherency function (COF), which is used to show the linear correlation between the frequency components of the two series. It shows whether variations in the main water use (output) series respond to the same type of
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variations in the rainfall (input) series, and thereby indicates the presence or absence of any linearity in the input-output relationship (Tam et al., 2005). A system is linear if $COF \approx 1$, and implies that a change in the input series creates a proportional change within the output series. If the COF shows a very chaotic pattern with values much greater than unity, that is $COF > 1$, non-linearity very likely exists in the system and other input factors should be considered in the description of the system. However, the COF should not be interpreted by itself, but in conjunction with other functions.

3.3 Methods II - characterising urban water end-use

The alternative urban water supply service models designed to improve sustainability performance of urban water systems are characterised by provision of water services through the utilisation of alternative water resources such as rainwater, waste water and storm water, centred on a fit-for-purpose water distribution principle (Cook et al., 2009, 2013). This fit-for-purpose principle requires that water is supplied to the water users according to the quality requirements that each specific water end-use requires (Sharma et al., 2010). In summary, such kind of design of an urban water intervention requires the total water use in the community to be broken into a series of streams of the various water end-uses (Loftus, 2011).

This section therefore provides a description of the methods followed in characterising the urban water end-use of a community of the developing world. This work was carried out in fulfilment of one of research aims of this thesis shown in section 1.5.

3.3.1 Study design

3.3.1.1 Proposed methods

In urban communities of low-income countries, this kind of design would face a challenge, due to the unavailability of water end-use information that is specific to these communities. In the developed world, water end-use information is collected through high-resolution metering experiments, as demonstrated in Al Amin et al. (2011); Athuraliya et al. (2008, 2012b); Beal & Stewart (2011); Dziegielewski et al. (2000); Heinrich (2007b); Heinrich & Isaacs (2008); Jethoo & Poonia (2011); Keshavarzi et al. (2006); Lu & Smout (2010). In the developing world, high-resolution metering of end-uses would be inappropriate and impractical owing to its high financial resources requirements. Hence, leaving social survey methods as the only feasible approach to estimate water end-use volumes in these communities.
3.3 Methods II - characterising urban water end-use

3.3.1.2 Characterising the urban water heterogeneity

As earlier stated in section 5.1 of this thesis, the study was carried out on a small urban community (Mbarara town) from south-west Uganda, as a representative of a typical urban water community of the developing world. Mbarara town, like most urban centres in the developing world, consists of a highly heterogeneous water use population, as such introducing a huge challenge of representing the water end-use information of such a community. The approach employed in this study, was to first group the community water users into different homogeneous groups.

It is common knowledge that water use in urban communities differs by the nature of the water use functionality. That is, water users are usually grouped according to either residential, or commercial, or industrial water use groups. In this community this was no different, the water users were first classified as either residents, commercial, institutions, or government institutions. The details of the users in each of these groups are shown in figure 3.8.

![Diagram showing water use categories](image)

Fig. 3.8 The representation of a developing country community through the categorisation of water use in the community (including the different water end-uses of each category).
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The second grouping, which is unique to a developing country, was the grouping according to either house-connected or yard-tap-connected water users. House-connected water users (33% of the mains supplied resident population) represent households that receive water directly into the house building, and as such expected to employ in-door water appliances like flushing toilets, showers, hand-wash basins. Yard-tap water users (67% of the mains supplied water users) represent households that receive water through an out-of-house tap, and hence use the water through water containers. Such water users also employ on-site sanitation facilities such as pit latrines, and hence do not employ any in-house water appliances. This classification is novel. In Al Amin et al. (2011); Athuraiya et al. (2012a); Beal & Stewart (2011); Mayer et al. (1999) and many more, the water end-use studies are carried out assuming a homogeneous in-door water use community across the whole urban centre. Even in communities where it is expected that both house- and yard-connected water users exist like communities in Nyong & Kanaroglou (1999) and in Thompson et al. (2001) this classification was not given preference.

3.3.2 Data collection

For each of water user community groups, water end-use data and the household monthly water consumption data was collected. The monthly water consumption data was accessed from the local water utility operator operating the piped water supply system in the town.

End-use volume data was collected with aid of household interviews from a sample of randomly selected households (sample size of 425) during the dry season. The sample size required for household interviews was estimated with aid of standard statistical methods, as shown in equation 3.1 below.

\[ ME = t \frac{s}{\sqrt{n}} \]  

(3.1)

where \( ME \) is the household number margin of error, \( t \) is the normal distribution score for the confidence interval, \( s \) is the household number standard deviation, and \( n \) is the required sample size.

In this study, the margin of error required for the estimation of the sample size was taken as 20 households, the standard deviation of households taken as 100, with a 99% confidence interval leading to a sample size of 167 households. During data collection, a sample size of 425 households was interviewed.
3.3 Methods II - characterising urban water end-use

The nature of the end-uses for each group of water users was defined aided of with local socio-economic experts (as shown in figure 3.9). For each of the end-uses interviewed, data was collected on the (1) water use intensity (or volume) per end-use, and (2) on the frequency of various end-uses. The questionnaire employed in the data collection is provided in Appendix B.

Secondly, to ease the measurement of the volume or intensity of water used. Water users were asked to estimate their usage intensity in units of jerry cans (or in terms of cans or basins employed in the area). The water user locals in the area have a better sense of the number of cans they employ than in terms of litres or cubic metres. For end-uses like toilet use (for house connections), hand washing (for both yard tap and house connections), showering (for house connections) that require further parameters to complete the end-use computation, data from the high-resolution metering study by Athuraliya et al. (2008) in Australia was employed. This study was chosen because it was the closest to the study location, because of the similar day temperatures in both locations. Further as an assumption, all the end-uses were assumed to have a penetration rate of 1.0, expecting all the water users to employ them on a daily scale or weekly scale.

The other set of data employed in the study, that is, the measured monthly consumption (in terms of billing) was accessed from the national utility, National Water and Sewerage Corporation. In this community, like many other developing countries urban communities, all mains supplied water users connected to are metered and hence their monthly consumption is regularly monitored through the utility.

3.3.3 Model development

The methods, data analysis, and modelling concepts were coded from scratch within the Matlab technical computing environment.

3.3.4 Urban water end-use modelling concept

3.3.4.1 Introduction

In each water user group, the overall water use was represented as a stochastic mathematical model of water consumption or water use for each household in the group. At household scale, the water use modelling is similar in principle to pulse demand modelling works in Buchberger & Wu (1995), Buchberger & Wells (1996), Rauch et al. (2003), Memon et al.
(2005), Haarhoff (2006), Blokker et al. (2010), and Creaco et al. (2016) but closer in detail to works by Haarhoff (2006) and Blokker et al. (2010). In these studies, each end-use is usually modelled with two major variables: the intensity of water use and the frequency of use. The intensity represents the volume of water consumed per end-use event per unit time (which was days or weeks in this study) while the frequency represents the number of end-use events per unit time. A product of these two quantities (intensity and frequency) yielded the amount of end-use water consumed per capita in a given time unit (day). The per-capita water quantity was then further multiplied by the per-household population (no of adults per household) to yield the total end-use volume of water used per day in that household.

The components (that is the frequency and or the intensity) of each end-use were represented as a probability distribution model. Since data collected through household interviews is susceptible to human errors (or is uncertain), the probability distribution model of each water end-use component was considered to represent its uncertainty or statistical spread. However, the position and spread parameters of the probability distribution model adopted for each water end-use component was calibrated to improve the predictability of the overall water end-use model in estimating the overall monthly water use of the community. Thus, the calibrated end-use stochastic models are taken to represent the actual end-use volume distribution of the water users in that town.

In summary, the modelling leads to the generation of water use volumes, through the aggregation of respective water end-uses (across different households) to generate the overall water demand of the community. In this study though, socially collected water use data is used as an input to the stochastic model, and also the study is applied to a low-income community. Though, the pulse demand models mentioned earlier (as summarised in Rathnayaka et al. (2011) and Creaco et al. (2016)) focus on applications in high-income communities.

For purposes of predicting water demand or water use in a community, Creaco et al. (2016) stated that there is a high volume of scientific studies that have been carried out in the development of water use or water demand models. These models can be classified into those that break the water use into micro-components (or water end-uses) and those that lump the water use as one. This study focuses on the former. Models that break the water use into micro-components, spatially and temporally cascade the water component pulses (across different households) through a bottom-up approach to generate the overall demand.
3.3 Methods II - characterising urban water end-use

3.3.4.2 The community

In this study, the community was schematised spatially and temporally to build its water end-use model shown in figure 3.9. The residential mains water users in the community were categorised into two groups - the house connected users (group 1) and the yard-tap connected users (group 2). It was noted that there were significant differences in the water end-use behaviours between these two groups, as explained in section 2.2 of this paper, that warranted their separation. And within each group, the constituent households were considered to be homogeneous.

Rathnayaka et al. (2011) observed that the concept of representing the spatial heterogeneity of a community across different household types is common in various water end-use models. This concept has been applied in Haarhoff (2006) and in Blokker et al. (2010). This study extended this concept to a community of a low-income country - hence introducing a new set of heterogeneous household groups.

3.3.4.3 The Household

At household level, the general principles used in the generation of the total household water use are similar in principle to works by Buchberger & Wu (1995), Buchberger &
Methods

Wells (1996), Rauch et al. (2003), Memon et al. (2005), Haarhoff (2006), Blokker et al. (2010), and Creaco et al. (2016) but closer in the modelled water end-use details to works by Haarhoff (2006) and in Blokker et al. (2010). In all these works, each water end-use pulse was generated as a product of two independent pulses: the intensity of the water end-use and its frequency. Though Creaco et al. (2015) and Creaco et al. (2016) recommend that the duration and its corresponding intensity of an end-use should be modelled as dependent variables, in this study they were maintained as independent variables.

The intensity of the water end-use represents the volume of water used for that end-use event per unit time (which was days or weeks in this study) while the frequency of the end-use represents the number of end-use events per unit time. A product of these two quantities yielded the amount of end-use water used per person in a given time unit (day). The per-capita water quantity was then further multiplied by the household population (no of adults per household) to yield the total end-use volume of water used per day in that household. Water end-use events showering and dish washing of the house-connected users’ group had their intensity broken down further as a product of the event duration (in minutes) and the event flow rate (litres per min.).

In Memon et al. (2005), Jacobs & Haarhoff (2006), and Haarhoff (2006), the end-use volume parameters of intensity and frequency were generated from community averaged intensities and frequencies of end-uses of all the households in the community. Statistically, the use of community averaged position and spread parameters presumes that the household population water uses follow a symmetric distribution such as Normal distribution. In this community, however, this presumption would be a misrepresentation of the community water use, since the socially collected data of this community showed that most of the water use distributions across the community were skewed, and hence not symmetric. Therefore, the approach employed in Blokker et al. (2010) and Rauch et al. (2003) that involves the probabilistic distribution of each water end-use parameter was also applied in this study. This approach was preferred for this study because it does not prescribe any pre-requisite distributions to any parameters, and is also well-suited for studies involving relatively small sample sizes.

All in all, mathematically the overall water use in a household (and then across all households of a group) was represented as:

\[ Q = \sum_j \sum_i [a_{i,j} \cdot b_{i,j} \cdot n_j] \]  

(3.2)
3.3 Methods II - characterising urban water end-use

where \( a_{i,j} \) represents the volume (or intensity) of water consumed per end-use \( (i) \) per person in a household \( (j) \), \( b_{i,j} \) represents the frequency of use events of end-use \( (i) \) per person in a day in household \( (j) \), and \( n_j \) is the number of adults in household \( j \). The summation is done for all end uses considered, and for all the households in the group.

The parameters \( (a_{i,j}, b_{i,j}, n_j) \) are instances of probability density distribution models. For each consumer group and for each constituent water end-use parameter (that is its intensity and its frequency), their statistical position and statistical spread values were estimated from the socially surveyed data of the community. The histogram of each water end-use parameter was then fitted to each of the native probability density distributions (like Normal, Lognormal, Gamma, Weibull, Exponential, Rayleigh, and Chi-Squared), from which the probability distribution with the closest fit (as measured by a correlation coefficient) was taken as the most appropriate probability distribution model of that end-use parameter. The details of the appropriate probability distributions chosen for each water end-use parameter is represented in figure 5.3, figure 5.4 and figure 5.5.

3.3.4.4 Temporal Resolution

The product \( (a_{i,j} \times b_{i,j} \times n_j) \) in equation 3.2 represented the total water volume consumed in a single day (for toilet use, showering, hand washing) or in a single week (for laundry, for general cleaning). To simulate the water consumed over a month, the daily flow water end-uses were multiplied by 30, while the weekly flows were multiplied by 4.3. In other words, the time space was modelled as a deterministic variable in this study.

In Blokker et al. (2010), a methodology that originated from Buchberger & Wells (1996) and extended by Creaco et al. (2016) is used to describe the time space. This method considers each time ordinate as an output of a Poisson probability distribution model. Therefore, in a modelling system with small time steps, for example, one second simulating up to one hour (or to a day), this would create a large enough sample space to allow for statistical consistency in applying this probability distribution model.

In this study, the time evolves from a single day to one month (30 time ordinates) for toilet, showering and handwashing water end-uses and from a single week to a month (4.3 ordinates) for laundry and general cleaning water end-uses. These time space sample sizes are not adequate to ensure statistical consistency of the outputs, justifying the need for a simplified representation of the time space.
Methods

![Diagram showing methodology]

(a) Social Surveying
(b) Stochastic Modelling
(c) Measured Monthly consumption (billing)
(d) Model Calibration

Fig. 3.10 Methodology employed to calibrate the water end-use models

3.3.5 The case of the developing world

In most water end-use modelling or data collection studies, approaches are not provided to address the uncertainty or variability involved in the urban water use. In water end-use data collection studies such as Mayer et al. (1999), Heinrich (2007a), Athuraliya et al. (2008), Al Amin et al. (2011), and Fan et al. (2013), the data collected is not assessed for its uncertainty despite the low sample sizes employed in some of the studies. While in water end-use modelling studies such as Memon et al. (2005) and Jacobs & Haarhoff (2006) no effort is provided in confirming whether the suggested end-use model description parameters are representative of the household water consumption. Blokker et al. (2010) however addresses the water end-use uncertainty. Though, in their study high-resolution metering was employed as the source of the raw water end-use data. These high resolution metering experiments are not readily available or practical in the developing world.

Therefore, a novel approach had to be employed in this study to utilise the data available (that is the imprecise household interviews) to improve the accuracy of the water-end descriptions of the community including its uncertainty. Rauch et al. (2003) demonstrated that the variability (or uncertainty) associated with the local household water use is of much relevance to urban water management, that it has an impact on the urban water management strategies of the community. It is, therefore, an objective of the water end-use modelling

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of this study, to not only provide a quantitatively accurate description of the end-use but also provide an accurate global description of the water end-use variability across different households. Hence, the need for a novel approach.

Figure 3.9 shows the hierarchical representation of the water end-use streams in the low-income community, and how they were aggregated to generate the total water used in a water use group. In each group, the characteristics (frequency and intensity) of each end-use, collected through the social survey, was fitted to an appropriate probability distribution model. Since data collected through household interviews comprises of human errors, as water users have to recall the actual water use volumes they used (Athuraliya et al. (2008), Otaki et al. (2008)). The fitted probability distributions for each water end-use were taken to represent the uncertainty or statistical spread of that water end-use. However, the position and spread parameters of the probability models were had to be calibrated to improve their accuracy in estimating the overall monthly consumption. Then the calibrated end-use stochastic models are taken to represent actual end-use volume distribution of the water users in that town. This global methodology is illustrated in figure 3.10.

3.3.5.1 Making the water end-use model more realistic

In general, the purpose of the water end-use model development was to provide a platform upon which the surveyed or measured water end-use volumes can be justified as representative of the water used in the community. Therefore, the water end-use model also had to be modified further to make it more representative of the water consumed in the community, and also more representative of the monthly billing measurements.

In the measurement of household water use (for the billing process), household metering errors are experienced. Two, it was revealed from the analysis of the socially collected data that a significant proportion of the community mains water users employ rain water harvesting. The model was therefore updated to include: a parameter for household metering errors, a parameter for the effect of rainwater harvesting on the household, and finally a parameter to allow for temporal summation of the end-use volumes for all the days of the month (that is 30 for daily end-uses, and 4.3 for weekly end-uses). The temporal evolution parameter was introduced because it is expected there could be a temporal evolution trend with the water consumption that was not considered in the model development.
Methods

The final updated stochastic water end-use for the community model that estimates the total amount of mains water consumed by a group of households in a month was represented as:

$$Q_s = \sum_{i=1}^{h} \sum_{j=1}^{e} \left[ m_j \times rw_j \right] \times \left[ a_{i,j} \times b_{i,j} \times n_j \right] \times [ts_i]$$ (3.3)

where \( h \) and \( e \) represent the total number of households and end-uses considered respectively. The parameters are still represented the same way as in equation 3.2, except for the rain water harvesting parameter \( rw_j \), the temporal frequency parameter \( ts_i \), and the metering error parameter \( m_j \) that were added.

In addition, the monthly water consumption data for the community shows that the number of households is not a constant from month to month, it varies randomly. Because of this, the water end-use model was therefore modified to compute the total monthly consumption of each month independently for each month, in that the number of households billed in that month was used as an input into the stochastic model (for the number of households simulated).

Further, since this was a stochastic simulation, each month was simulated for a thousand 1000 times (under a Monte Carlo simulation) to provide a distribution of monthly consumptions, from which a monthly consumption distribution was generated.

3.3.6 Model calibration and validation

In summary, the water end-use model in equation 3.3 generates instances of the monthly consumption of the community - which should statistically and numerically be equivalent to the measured monthly (and billed) water consumption of the community. And if the two datasets (the computed and the measured water consumptions) are both statistically and numerically equivalent, then their statistical centralised values (mean or median) and their cumulative density functions (a representation of their statistical frequency distribution) should converge. Therefore, the comparison of these datasets is not one of comparing statistical moments like mean or median, but also of their cumulative frequency distributions.

This calibration approach for stochastic models has been applied in similar works by Blokker et al. (2010) and by Creaco et al. (2016). In both works, the authors agree that total monthly water consumptions can be generated by summing up the individual ordinate consumptions, confirming the procedures applied in this model. Again, both authors employ cumulative
density functions as a calibration procedure to confirm the statistical consistency between the simulated and measured observations. Therefore, the objective of the calibration was to ensure that the measured (billed) monthly total water consumption falls within the 95% confidence interval bounds of the monthly total water consumption simulations and that the both cumulative density functions are similar in shape. Mathematically, this is illustrated as:

\[
\text{Minimise } (1) \quad |Q_s - Q_m| 
\]

\[
\text{Minimise } (2) \quad |CDF_s - CDF_m| 
\]

**BY: adjusting various water intensity end-use and household size parameters.**

$Q_s$ represents the median of the simulated total monthly water end-use volumes, while $Q_m$ represents the measured or billed total monthly water consumption in the community. $CDF_s$ is the cumulative distribution function of the simulated median total water use volume, while $CDF_m$ is the cumulative distribution function of the measured or billed water volumes. Objective one (1) was not necessarily focussed on ensuring that the median simulated water volume is comparable to the measured volumes, but on ensuring that the measured volumes are within the simulated 95% confidence interval boundaries.

One of the major weaknesses of the social surveying of water end-use investigation was the estimation of the water use volumes, that is, the water end-use intensities. The calibration procedure, therefore, focused on the adjustment of the water end-use intensities. Each water use intensity parameter (the position and or spread) of interest was increased or decreased incrementally with a factor, till both calibration objectives above were satisfied. The final factors employed in the calibration are shown in table 3.1. In addition, the household size was another parameter that was calibrated. According to the recently released national census details of household size, the survey data collected in this community showed minor variations with those shown in the national census. This difference warranted a modification of the household size as a calibration parameter. The calibration results are shown in figure 5.1 for yard-tap connected water users and figure 5.2 for house-connected water users.

As shown in figure 5.1 and figure 5.2, the calibration procedure was carried out for months during the dry season, while the wet season months were employed to validate the calibration. In this, it was assumed that the only difference between the wet and dry seasons, was the rate of rain water harvesting taking place between both periods. So, in the validation period,
Methods

Table 3.1 Calibration Parameters

<table>
<thead>
<tr>
<th>Category</th>
<th>Water end-use</th>
<th>Factor</th>
<th>Remark [Target Parameter]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yard Taps</td>
<td>Bathing</td>
<td>0.7</td>
<td>No. of Jerry cans</td>
</tr>
<tr>
<td></td>
<td>Washing Dishes</td>
<td>1.4</td>
<td>No. of Jerry cans</td>
</tr>
<tr>
<td></td>
<td>Household Size</td>
<td>1.18</td>
<td>General Increase</td>
</tr>
<tr>
<td></td>
<td>Metering Error</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>House</td>
<td>Connect-</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Toilet Use</td>
<td>0.5</td>
<td>No. of flushes</td>
</tr>
<tr>
<td></td>
<td>Showering</td>
<td>0.5</td>
<td>Intensity Volume</td>
</tr>
<tr>
<td></td>
<td>Washing Dishes</td>
<td>0.5</td>
<td>Flow Rate</td>
</tr>
<tr>
<td></td>
<td>Household Size</td>
<td>1.35</td>
<td>General Increase</td>
</tr>
<tr>
<td></td>
<td>Metering Error</td>
<td>0.1 - 0.2</td>
<td>Uniform Distribution</td>
</tr>
<tr>
<td>General</td>
<td>Rain Water Use [Dry]</td>
<td>0.15 - 0.25</td>
<td>Uniform Distribution</td>
</tr>
<tr>
<td></td>
<td>Rain Water Use [Wet]</td>
<td>0.23 - 0.50</td>
<td>Uniform Distribution</td>
</tr>
<tr>
<td></td>
<td>Temporal Evolution factor</td>
<td>1.0</td>
<td>-</td>
</tr>
</tbody>
</table>

only the rain water harvesting parameter was adjusted all the other parameters were not adjusted any further. The validation comparisons between the measured and the simulated total monthly consumptions were comparable.

3.4 Methods III - Integrated urban water modelling

In section 1.4 of this thesis, in reviewing the suitability of existing integrated modelling systems for modelling a developing world city, it was concluded that these systems are lacking in explicitly representing certain critical features of these cities. Hence, as mentioned in section 1.5, as an objective it was recommended that there is need to tailor existing tools to the specific complexities of urban water systems of the developing world.

This section therefore describes the methods employed in developing an integrated urban water modelling system in fulfilment of one of the research aims of this thesis.
3.4 Methods III - Integrated urban water modelling

Table 3.2 Detailed distribution household across the city of the developing world

| Catchment ID | Domestic |  |  | Commercial |  |  | Institutions A |  |  | Institutions B |  |  |
|--------------|---------|----------|---------|-----------|----------|----------------|---------|----------|-----------------|---------|----------|---------|----------|
|              | Pits*   | STs*     | Swd*    | Pits*     | STs*     | Swd*           | Pits*   | STs*     | Swd*           | Pits*   | STs*     | Swd*    |
| 1            |         |         |         |           |           |                 |         |           |                 |         |           |         |
| 2            |         |         |         |           |           |                 |         |           |                 |         |           |         |
| 3            |         |         |         |           |           |                 |         |           |                 |         |           |         |
| 4            |         |         |         |           |           |                 |         |           |                 |         |           |         |
| 5            |         |         |         |           |           |                 |         |           |                 |         |           |         |
| 6**          | 2500    | 536      | 120     | 707       | 339      | 684             | 21      | 12       | 22             | 37      | 34       | 40      |
| 7            | 5        |         |         |           |           |                 |         |           |                 |         |           |         |
| 8            |         |         |         |           |           |                 |         |           |                 |         |           |         |
| 9            |         |         |         |           |           |                 |         |           |                 |         |           |         |
| 10           | 81       | 10       |         | -         | -         | -               | -       | -         | -               | -       | -         | -       |
| 11           | 143      | 29       | 4        | 8         | -         | -               | 3       | -         | -               | -       | -         | -       |
| 12           | 292      | 9        | 4        | 13        | -         | -               | 31      | -         | -               | -       | -         | -       |
| 13           | 139      | 18       | -        | 11        | -         | -               | 2       | -         | -               | -       | -         | -       |
| 14           |         |         |         |           |           |                 |         |           |                 |         |           |         |
| 15           |         |         |         |           |           |                 |         |           |                 |         |           |         |
| 16**         | 4147     | 1108     | 180     | 319       | 529      | 26              | 103     | 167      | 53             | 181     | 158      | 222     |

*STs* - Septic Tanks, Swd - Sewered, Pits - Pit Latrines
**Includes low-income households

3.4.1 Urban water features of a city of the developing world

In section 3.1 of this thesis, Mbarara town, a secondary city from a developing country was introduced as the case for this study. This city was described to comprise of features which are unique and different from those of a developing world city. This difference was described as the driver for the additions required to appropriately model a city of the developing world. This section summarises these features as a background to introduce their integrated modelling requirements.

This city comprises of:
Methods

Table 3.3 Integrated urban water modelling of the developing world - required features

<table>
<thead>
<tr>
<th>At city scale</th>
<th>At local scale</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hydrology</strong></td>
<td></td>
</tr>
<tr>
<td>Mass and Contaminant balance</td>
<td>Both in-house &amp; out-house</td>
</tr>
<tr>
<td>Soil moisture accounting</td>
<td>water use</td>
</tr>
<tr>
<td>Gravity-driven flow routing</td>
<td>Stochastic water end-use</td>
</tr>
<tr>
<td>Both centralised &amp; decentralised</td>
<td>Both flush and no-water toilets</td>
</tr>
<tr>
<td>(STs and Pits) sanitation</td>
<td>Local HH stormwater hydrology</td>
</tr>
<tr>
<td><strong>Landscape</strong></td>
<td></td>
</tr>
<tr>
<td>SCs as watersheds</td>
<td>Various HH types, by water use,</td>
</tr>
<tr>
<td>Both paved and unpaved</td>
<td>by in-house/out-house, and</td>
</tr>
<tr>
<td>Public open spaces</td>
<td>by sanitation type</td>
</tr>
<tr>
<td></td>
<td>Both paved and unpaved</td>
</tr>
</tbody>
</table>

*STs - Septic Tanks, SCs - subcatchments, HH - Household

- an urban water supply subsystem consisting of centralised mains water supply system complemented with decentralised local household rain water harvesting

- an urban water sanitation subsystem consisting of a centralised sewerage sanitation system coupled with extended decentralised on-site sanitation systems (of septic tanks and pit latrines)

- an urban stormwater system, in a dominantly unpaved urban landscape, consisting of numerous natural earth channels

The city’s inhabitants can be categorised into major water use groups (domestic (80%), institutional (3%), commercial (16%), and government-oriented customers (2%)), which can be further sub-categorised into either house-connected water users or yard-tap water users. This further categorisation expands the water user groups of the community to eight (8) in total, and is illustrated in figures 3.9 and 3.8, showing the component households of each groups, as well as its characteristic water-end-use profile. This categorisation provides a representation of the water use heterogeneity within the city. In addition, as mentioned in section 3.1, there is a significant level of low-income unplanned settlements (or slums) within the yard-tap water users.
3.4 Methods III - Integrated urban water modelling

Finally, these households are located within different watersheds across the city. Therefore, another level of categorisation can be added to the description of households across the city, that is by sub-categorising them further according to the watershed the household is located. The city was delineated into 16 watersheds or subcatchments (see section 3.4). The numerous homogeneous water use groups in this city of the developing world, represents the complexity of the water use heterogeneity across these cities.

The combination of the 12 water users groups (the 4 water use groups by 3 sanitation-based groups plus 2 low-income settlement groups) and the 16 subcatchments generated a distribution of the urban water community of the city as shown in table 3.2, giving a total of 16 by 12 homogeneous water user groups. This distribution was applied to provide an appropriate foundation of the urban water hydrology of a city of the developing world.

This characterisation of the urban landscape in a developing world represented one of the major additions, of this study to the integrated urban water modelling environment. In cities of the developed world, the heterogeneity is described through only 4 – 5 water use groups, as described in Blokker et al. (2011); Last (2010); Mitchell et al. (2007). In these cities, it is presumed that all the communities are homogeneous at sanitation and internal household water use level.

3.4.2 The modelling concept

3.4.2.1 The model overview

The urban water use schematisation described in section 3.4.1 of the city provided the foundation upon which an integrated urban hydrological modelling system (denoted as WaterCycle) was built for this city. In WaterCycle, the urban water system catchment of the city was delineated (automatically using GIS software from a 90m grid SRTM DEM downloaded from the United States Geological Society (USGS)) into 16 subcatchments (or watersheds) as shown in figure 3.11(a), that follow the natural stormwater drainage network of the city. The stormwater network (at global level) was then schematised into a drainage network model (shown in figure 3.11(b)) with the subcatchments as nodes and the stormwater flow paths as segments.

Then within each subcatchment, the constituent urban water hydrology (and household landscape) was defined and described. The resident households’ of each subcatchment were then cascaded into numerous household groups or clusters (including their large open spaces) as illustrated in figure 3.11(c). The household cascading methodology, applied in the existing
Methods

integrated models, applied in WaterCycle, instead here it was extended to add more household groups. Table 3.2 and figure 3.8 show the household distribution and schematisation employed in each subcatchment. In each household group and in each subcatchment, the hydrology components of the mains water use and the stormwater flow are aggregated to generate the overall stormwater (and or wastewater) outflow effluent (see figure 3.11(d)).

In a localised household group, the number of households was the major input, that drove the computation of the volume of mains water use and/or the volume of stormwater outflow from that group. The mains water use, which consequently led to the human wastewater generation, was developed from the computation of the various households’ water end-uses (according to the nature of the household group), as illustrated in figure 3.11(e). The water end-uses considered for each household type was carried out following the household schematisation defined in figure 3.8. Finally, rainfall input was added to the household group to allow for the development of the stormwater hydrology across the various households. The urban landscape of the households was broken down into both the impervious stormwater hydrology (in figure 3.11(f)) and the pervious stormwater hydrology (in figure 3.11(g)) to generate the overall surface stormwater flow output from the cluster. In essence, the cluster hydrology block (in figure 3.11(d)) represents the heart of the integrated modelling system, from its computations that the two major outputs - the human wastewater and or the stormwater runoff, in both quantity and quality are generated for a given subcatchment. It is these outputs that are conveyed downstream out of a subcatchment.

3.4.2.2 Modelling mains water use

The figure 3.11(e) represents the module in each households group, that models the mains water used and consequently wastewater generated from that group (of households). This modelling system follows the household water use schematisation illustrated in figure 3.9 showing that the mains water use is computed following the aggregation of the water end-uses of the households in a given group. In WaterCycle, a novel approach introduced within study (as described in section 3.3) that employs a stochastic mathematical description of the unique water end-use of a community in the developing world was applied.

The waste water generated from a group of households was either directed to the pervious surfaces (for households that employ on-site sanitation systems such as pit latrines and septic tanks) or to the sewer (for households that employed off-site sanitation systems). For households employing septic tanks, all the wastewater is directed to an on-site wastewaster treatment system (from which provision is made for wastewater treatment - that is the per-
Fig. 3.11 The integrated urban water modelling (modularised modelling) procedure
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centage reduction in contaminant concentration), before disposing the wastewater into the pervious stormwater hydrology system (see figure 3.11(e)). However, for households employing pit latrines (which included the slums), their mains water use was treated separately from their black (toilet water) wastewater generation. The grey wastewater generated from the mains water use (which included laundry water, bathing, and kitchen water use) was directed to the pervious stormwater system without any treatment, while the toilet wastewater flow was introduced as an independent black waste water system (of urine plus solids) that was directed to an on-site treatment system (with a percentage reduction factor defined for pit latrines), and finally back to the pervious stormwater system. In other words, the pervious stormwater system receives localised wastewater from all households employing on-site sanitation systems. This represents one of the major novelties, WaterCycle brings to the integrated modelling body of science.

The households that employed sewered sanitation directed all their wastewater to a sewer, which in turn was directed to an off-site waste water treatment system, and finally added to the stormwater effluent exiting a given subcatchment.

This discretisation of the community was employed to generate a stochastic model of water use regime of the community. The stochastic model was preferred because preliminary water use data of the community revealed the water use distribution to be highly skewed. Further, this stochastic water use representation provided a platform for describing the urban water use uncertainty or variability in a developing world community. This variability as Rauch et al. (2003) describes, has a significant impact on the behaviour of the urban water system downstream.

### 3.4.2.3 Stormwater Hydrology

#### 3.4.2.3.1 Modelling overview

As illustrated in figures 3.11(d), 3.11(f), and 3.11(g), the stormwater hydrology in WaterCycle comprised both impervious and pervious hydrology. The approaches employed in WaterCycle for urban stormwater hydrology were not novel but extended on approaches already employed in the existing integrated models. Every household or group of households was modelled to receive input from the rainfall and household human wastewater effluent, which together pass through the system, to output as evaporation, stormwater runoff, and/or as sewer wastewater.
Each household space was divided into four surfaces that can generate runoff, that is roof, pavement, open space, and road. At the cluster scale, it assumed that the group of households contains a larger public open space (such as a park, or golf course) that was added to the stormwater space delineation (see 3.11(c)). These surfaces are grouped as either impervious (road, roof, pavement) or pervious (household open space, and public open space). The runoff running off the impervious surfaces drains to the pervious surface, which in turn drains to the stormwater drainage system (as it exits the subcatchment).

Pervious surfaces (illustrated in figure 3.11(g)) receive runoff from the impervious surfaces and model their runoff generation following a soil-moisture water flow accounting algorithm, following the methods introduced by Mitchell et al. (2001) and utilised also by Last (2010). This algorithm was chosen for this study because it is well suited for areas with high levels of evapotranspiration and intense rains (Last, 2010) - similar to the tropical conditions experienced in this case city. In addition, this soil-moisture accounting algorithm is important for this city due to the interaction between the stormwater system and the sanitation system.

Within a cluster of households, the urban water system was schematised as shown in figure 3.11d, which is illustrated further in figure 3.13. Every household or group of households was modelled to receive input from rainfall and mains water supply, which together pass through the system, to output as evaporation, stormwater runoff, and or as sewer wastewater (depending on the household type).

Each household space (and hence cluster of households) was divided into four surfaces that can generate runoff, that is, roof, pavement, open space, and road. At the cluster scale, it
assumed that the cluster contains a larger public open space. These surfaces are grouped as either impervious (road, roof, pavement) or pervious (household open space, and public open space). The runoff off the impervious surfaces drains either to the pervious surface or to the stormwater drain (the river system). The approach thus divides a catchment into areas that produce runoff (contributing areas) and those that do not during a rainfall-runoff event.

3.4.2.3.2 Impervious stormwater hydrology

Stormwater flow from impervious surfaces is modelled in the same way as described in Last (2010); Mitchell (2005); Mitchell et al. (2001). Impervious surfaces (roof, paved, road) are each modelled as single storage runoff saturation excess process. The water retained in the store represents the initial losses due to interception and depression storage. Initial loss is computed as:

\[ IL = \max(0, P - IntLoss - EvapLoss) \]  \hspace{1cm} (3.6)

where \( P \) represents the rainfall depth (m), \( IntLoss \) is the interception loss (m), and \( EvapLoss \) is the evaporation loss (m) off the impervious surface. The Evaporation loss was taken as the maximum evaporation rate that the surface can face (potential evaporation).

Then the runoff from impervious surfaces is diverted either to pervious surfaces (denoted as \( NEAR \) in the equation 3.7) or to overland flow (denoted as \( IRUN \) in equation 3.8). Assuming no depression storage, computed as the overflow over the depression loss:

\[ NEAR = \sum_i (1 - ERA) \times (P - IL) \times A_i \]  \hspace{1cm} (3.7)

\[ IRUN = \sum_i ERA \times (P - IL) \times A_i \]  \hspace{1cm} (3.8)

where \( i \) represents each of the paved areas of a typical household like road, roof, etc.

ERA represents the effective road areas proportion, \( P \) is the rainfall depth falling on the household (m), \( IL \) is the interception and evaporation loss (m) evaluated as shown in equation 3.6, \( A_i \) is the proportionate area of a roof, a road, or paved sections of a household cluster (\( m^2 \)). Effective areas are defined as that portion of the stormwater flow that is directed stormwater drainage system, while the non-effective is directed to the pervious surfaces to traverse through the pervious hydrology system.

Figure 3.13 provides a schematisation of this urban stormwater hydrology.
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3.4.2.3.3 Pervious stormwater hydrology

The pervious surfaces receive input from both the rainfall and the runoff from the impervious surfaces. The overland runoff off the pervious surfaces is modelled to follow physical process of water flow through subsurface soil mass. The pervious hydrology is modelled in the same way as represented in Mitchell et al. (2001) and in Last (2010), which utilises a soil-moisture accounting algorithm known as the Australian Water Balance Model (AWBM), also known as the Partial Area Model. The computation of water flow through pervious surfaces was based on the Partial Area model was chosen for this study because it is well suited for areas with high levels of evapotranspiration and intense rains (Last, 2010), just like the study area which is located in tropical conditions.

The AWBM model is operated at either daily or hourly time steps. At each time step, rainfall is added to each of the surface stores and evapotranspiration is subtracted. If there is any excess from any store, it becomes runoff and is divided between surface runoff and baseflow (see figure 3.14). The baseflow index (BFI) is the fraction of total flow that appears as baseflow.
The model splits the pervious area into a number of stores (two stores in this case), with different storage depths and different areas. Input to the pervious stores is split between the two stores proportional to their relative surface area. The pervious store 1 (PS1) and pervious store 2 (PS2), each have different storage depths and different areas. The two pervious stores receive water (input) from precipitation, wastewater and surface runoff from impervious areas, as shown in figure 3.13. There are no flows between the stores. The amount of excess water (overflow) from these stores is calculated separately, then combined according to their respective proportional areas of the catchment. The only outflow from the stores is evaporation until the capacity of the store is exceeded, as shown in equation 3.9. The excess water above the capacity is divided between groundwater recharge and overland flow (pervious surface runoff). These divisions are dependent upon the user-defined proportions for each cluster. The overland flow from pervious stores is directed to the stormwater drainage system (the river in this case).

The actual evapotranspiration in the study assumes that the supply of water (to the evaporation plant) is a linear function of available water in the root zone. The maximum amount of evapotranspiration that can occur in a given day is termed $E_p$, the potential evapotranspiration rate. Actual evapotranspiration is the amount which did actually transpire in that day, given the potential rate, the soil moisture content in the pervious stores (pervious store level) and
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the capacity of the vegetative cover to transpire \((E_{pc})\). This was computed as:

\[
E = \min(E_p, (A1 \times PS1_{cur}/PS1_{cap} + (1 - A1) \times PS2_{cur}/PS2_{cap}) \times E_{pc})
\]  

(3.9)

where \(E_p\) is the daily potential evaporation rate (m), \(E_{pc}\) is the capacity of vegetative cover to transpire (m), \(PS_{cur}\) pervious store current level (m), \(PS_{cap}\) pervious store capacity level (m), \(A1\) is the proportion of the total household area underlain by \(PS1\). The maximum evapotranspiration rate has a fixed value and is used as a second control on evaporation from pervious areas.

The capillary drawup is modelled using equation 3.10. When the groundwater is deeper than a specified depth there is no capillary draw up. If it rises above this level, then draw up occurs up to a maximum daily potential evaporation. If the ground water level rises above the base of the soil, then it is assumed that the whole soil profile becomes saturated. If the groundwater level rises above then it contributes to stormwater system.

\[
C_d = E_p \times (SMD/SMD_{max}) \times (GWL - D_c)/(S_{base} - D_c)
\]

(3.10)

where \(SMD\) is the soil moisture deficit that is \(PS_{cap} - PS_{cur}\) (m), \(GWL\) is the ground water level above datum (m), \(S_{base}\) is the soil column thickness (m), \(D_c\) is the maximum capillary action depth (m).

Excess water above the capacity is divided between ground water recharge (GWR) and overland flow (PRUN), as shown in figure 3.13, according to a base flow infiltration parameter (BI). It is assumed that overflow from the pervious stores is directed to the storm water system. The amount of excess soil moisture is calculated for the two pervious stores and combined according to the proportional area of each store, according to the following equation:

\[
EXC = \max(P + PS1 - PS1_c, 0)] \times A1 + \max(P + PS2 - PS2_c, 0)] \times (100 - A1)
\]  

(3.11)

where \(PS1_c, PS2_c\) (m) are the field capacity levels of either partial stores, and \(PS1, PS2\) are the current soil moisture levels. \(A1\) is the percentage of pervious model \(PS1\) across the whole catchment. The excess proportion of the excess soil moisture recharges the ground water store. The ground water store is drained according to a recession function, creating baseflow.

\[
GWR = BI \times EXC
\]

(3.12)
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The amount of pervious surface runoff contributing to the total stormwater flow (SRUN) is equal to the excess soil moisture less the sewer infiltration (in equation 3.14) and the groundwater recharge (in equation 3.13).

\[
SRUN = EXC - RIS - GWR
\]  

(3.13)

In this study, as much as the impact of groundwater recharge on runoff is recognised, but the ground water store was not modelled. Hence, the impact of baseflow on the stormwater runoff was not represented. This was due to the unavailability of ground water flow data. However, further details of the impervious storage, pervious storage, and ground water storage are found in Mitchell (2005).

The flow to groundwater is further split into either infiltration or ground water recharge. The capacity of the infiltration flow depends on the pervious surface soil moisture, which is equivalent to the field capacity. The groundwater store is assumed to be unconfined, and is expected to contribute base flow to the river. However in this study, ground water flow was not considered and thus not pursued any further in the model.

Stormwater infiltration into the wastewater sewerage system occurs during periods of excess soil moisture storage. The infiltrated water (RIS) from the soil moisture enters into a temporary infiltration storage, then drains into the wastewater sewerage system (INF) as shown below:

\[
RIS = II * EXC
\]  

(3.14)

\[
INF = IRC * \sqrt{INFS}
\]  

(3.15)

The inflow of stormwater into the wastewater system is represented as a proportion of the total surface runoff generated:

\[
ISI = IFRate * (SRUN + IRUN)
\]  

(3.16)

3.4.2.3.4 Total stormwater flow

Stormwater runoff is usually separated into two components for modelling purposes, these being surface runoff and base flow. Surface runoff from urban areas is further separated into components sources from pervious and impervious surfaces due to the differing hydrological response of these surface types. Impervious surfaces can be further divided up into roofs, roads, and paved areas. Pervious surfaces include grassed areas such as lawns and parks as
well as garden beds and bare soil. Therefore, four surface types are used in the model; i) pervious areas, ii) roofs, iii) paved areas, and iv) roads, with each surface generating runoff.

The total amount of water discharged as stormwater runoff, $R_s$, is given by the following equation:

$$R_s = IRUN + SRUN - ISI$$  \hspace{1cm} (3.17)

where

*IRUN* represents contribution from the **impervious surface runoff**,  
*SRUN* the **pervious surface runoff**,  
*ISI* the **infiltration to the wastewater sewerage system**.

### 3.4.2.3.5 Subcatchment - Subcatchment flow modelling

Within the existing integrated modelling systems (Aquacycle, City Water Balance, Water-Met), the flow of water from one subcatchment to another follows only a mass balance approach, without allowing for gravity to impact momentum (and consequently the final hydrograph) on the flow as is experienced in natural stormwater ways (Mitchell *et al.*, 2001). In stormwater drainage systems, gravity alone provides the force to move the liquid downstream (Walski *et al.*, 2007), and hence it is important that gravity is allowed to control the flow of stormwater downstream. Behzadian & Kapelan (2015) however, attempted to address this limitation by introducing the Rational Method, but this was applied only to flows within a given subcatchment, not for flows from one subcatchment to another.

Therefore in WaterCycle, this gap was alleviated by introducing the Modified Muskingum routing approach to model the flow of stormwater downstream from one catchment into another, for the whole urban water system. The Modified Muskingum flood-routing procedures provide a more realistic gravity-controlled flow of stormwater downstream. The addition of a more advanced stormwater flow routing methodology is another novelty this study adds to existing integrated modelling systems.

The flow of stormwater downstream a channel is represented accurately in three-dimensions through the Navier-Stokes systems of equations, which are then simplified to the St. Venant equations (Achleitner, 2006) based on the assumption that the flow is one-dimensional, the pressure distribution is hydrostatic, the length of the channel is much greater than its flow depth, and that the water density is constant (Walski *et al.*, 2007). The St. Venant equations are based on the assumption that the average velocity in a cross-section is adequate
to describe the flow and water surface only slopes in the direction of the flow.

However, due to the complexity involved in fully solving numerically the Navier-Stokes or the St. Venant equations, a variety of hydrological rainfall-routing conceptual models have been introduced and applied to describe the flow of stormwater downstream a channel. All these methods in principle provide a simplified representation of the St. Venant equations under certain assumptions (Walski et al., 2007). The Modified Muskingum routing method is one of those methods, and was utilised in this study.

Hydrologic routing methods, such as the Muskingum routing approach, track the flow and momentum effects of the stormwater flow downstream, through an approximation of the temporary storage across each channel reach, using simplified storage equations. The approach is based on equation (which is an expression of mass balance):

\[ I - O = \frac{dS}{dt} \]  \hspace{1cm} (3.18)

where

\( I \) is the inflow rate
\( O \) is the outflow rate,
\( S \) is the storage, and
\( t \) is the time.

Then, the expression for storage in a channel reach used in the Muskingum approach is:

\[ S = K[XI + (1 - X)O] \]  \hspace{1cm} (3.19)

where \( K \) and \( X \) represent storage parameters.

For most streams, \( X \) is approximated as 0.2, while \( K \) is an approximation to the travel time of the reach. There are numerous formulae in literature to estimate the travel time of a reach that depend on its topographical parameters.

The discharge from a reach is then given by:

\[ Q_i = c_{i-1}I_{i+1} + c_iI_i + c_{i+1}O_i \]  \hspace{1cm} (3.20)
where $i$ represents a given time step. The coefficients are given by (where $t$ is the time step duration):

$$c_{i-1} = \frac{0.5t - KX}{K - KX + 0.5t}$$  \hspace{1cm} (3.21) \\
$$c_{i} = \frac{KX + 0.5t}{K - KX + 0.5t}$$  \hspace{1cm} (3.22) \\
$$c_{i+1} = \frac{K - KX - 0.5t}{K - KX + 0.5t}$$  \hspace{1cm} (3.23)

Achleitner et al. (2007) encapsulated this algorithm, into an open-source modelling system, denoted as CITY DRAIN (also developed within the Matlab/Simulink environment). This platform was employed in this study to represent the flow of stormwater downstream from subcatchment to subcatchment.

Using the physical characteristics of each subcatchment (as represented by its topography), the travel time of each subcatchment was computed. This computation was used to represent the $K$ constant in the Muskingum approach of the modelling system, so that the geographical representation (and consequently gravity) of each sub-catchment dominates the stormwater flow downstream. In this way, a more realistic contribution of each catchment can be represented in the overall urban water modelling system. The dimensionless $X$ constant was taken as 0.25.

3.4.2.3.6 Modelling Contaminant Flow

In integrated modelling, due to the overall complexity of the physical system being modelled, most practitioners recommend that only the dominant processes (and pollutants) should be represented, and described quantitatively (Achleitner, 2006). Nyenje et al. (2010), in describing the components of pollutants rising out cities of the developing world to the receiving waters, concludes that the nutrient load produced in these cities is extremely high.

It is for this reason that in WaterCycle a total nitrogen module was added to provide an indication of how the urban water system affects the receiving water environment. In detailed modelling systems such as the Soil and Water Assessment tool (SWAT), nitrogen within a catchment is modelled as an unstable element through the nitrogen cycle (Neitsch et al., 2011). In WaterCycle, the modelling of Total Nitrogen (TN) followed the concepts outlined in UVQ (Mitchell & Diaper, 2005) and in City Water Balance (Last, 2010). The contaminants are modelled conservatively, so no account is taken of their conversion or degradation across the
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nitrogen cycle was provided.

Contaminants are input into WaterCycle through the water end-use characteristics. Their flow across the urban water system is then followed in parallel with the water flow. However, when they find a treatment system such as a septic tank, a wastewater treatment plant (such as waste stabilisation ponds), or pit latrine, the waste water contaminant concentration is reduced according to the treatment efficiency of that waste treatment system. Also, whenever two or more waste water streams combined in the urban water system, their wastewater concentration is aggregated.

3.4.2.4 Data Input

3.4.2.4.1 Terrain data
In WaterCycle, first the urban water system catchment of the city was delineated (automatically using GIS software from a 90m grid SRTM DEM downloaded from the United States Geological Society (USGS)) into 16 subcatchments (or watersheds). Therefore, the DEM was the first input data to WaterCycle.

3.4.2.4.2 Rainfall data
Rainfall data employed in WaterCycle was obtained from a national meteorological weather station located within and around the town (Bugamba station ID 9030027) for the period 01 January 1960 - 31 December 2004. However, for the model simulation only data from 01 January 1960 - 25 September 1962 was used.

3.4.2.4.3 Household sizes
In summary, for each subcatchment, the number, type, and characteristics of the constituent households located within that subcatchment were defined (from the actual field data). Then within each household or households groups, these characteristics (including the water use and physical properties) were transformed into parameters which were utilised in the computation of the mains water requirement, the household wastewater and the stormwater runoff (both in quantity and quality). These computations were carried out from subcatchment to subcatchment, from time step to time step (daily) across the whole urban water cycle. The distribution of households across the various subcatchments is shown in table 3.2.

The soil moisture accounting in the model was represented by defining parameters as shown in table 3.5. These parameters are usually estimated from detailed catchment soil data survey.
and or calibrated with aid of the catchment flow monitoring records. However, due to the absence of these data(s) of this catchment in this study, these parameters were estimated from consultancy studies carried out in other regions of the country.

### 3.4.2.4.4 Household physical characteristics

For each subcatchment, utilising utility data overlaid with digital images, an average household area was defined for each subcatchment. This is shown in table 3.4. Then from the plan areas, the impervious and pervious plan areas for each household type was estimated (see table 3.6). It should be noted however that low-income communities were assigned considerably reduced household areas compared to other households.
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Table 3.5 Pervious hydrology-related parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC wide Road Area Proportion</td>
<td>0.1</td>
<td>Estimated</td>
</tr>
<tr>
<td>SC wide Pervious Area Proportion</td>
<td>0.9</td>
<td>Estimated</td>
</tr>
<tr>
<td>Potential Evaporation [mm]</td>
<td>1.5</td>
<td>Estimated</td>
</tr>
<tr>
<td>Maximum Evapotranspiration [mm]</td>
<td>0.5</td>
<td>Estimated</td>
</tr>
<tr>
<td>Field Capacity [mm]</td>
<td>2.0</td>
<td>Estimated</td>
</tr>
<tr>
<td>Infiltration Rate [-]</td>
<td>0.095</td>
<td>Estimated</td>
</tr>
<tr>
<td>Effective Runoff Rate [-]</td>
<td>0.6</td>
<td>Estimated</td>
</tr>
<tr>
<td>Percolation Rate [-]</td>
<td>0.55</td>
<td>Estimated</td>
</tr>
<tr>
<td>Initial Loss [mm]</td>
<td>2.0</td>
<td>Estimated</td>
</tr>
<tr>
<td>Sewer Infiltration Rate [-]</td>
<td>0.05</td>
<td>Estimated</td>
</tr>
</tbody>
</table>

3.4.2.4.5 Subcatchments data

From the topographical characteristics of the subcatchments as shown in table 3.7, the time of concentration of stormwater through each subcatchment was computed. In WaterCycle (as done in CITYDRAIN), the time of concentrated was reflected as a number of sub-reaches (see table 3.7). The number of reaches was then was used to represent the K constant in the rainfall-routing algorithm. The dimensionless X constant was taken as 0.25.

3.4.2.4.6 Contaminants data

Finally, to account for the ingress of contaminants in the urban water system, the source of the human contaminants through the urban water system was considered as the household. Therefore contaminant (total nitrogen in this case) parameters was defined that represents the amount of contaminant for each stream of water in the urban water system. These parameters are shown in table 3.8.

3.4.3 Integrated urban water modelling tool - summary

In this study, therefore, an integrated urban water modelling tool (denoted as WaterCycle) was developed. The development of WaterCycle is was one of the principal objectives of this study.

WaterCycle was designed to employed a novel methodology for the integrated modelling of urban water use, urban stormwater flow, and contaminant flow in a developing country town. It models the town from the household scale to the whole city. The modelling system has

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Table 3.6 Internal Households’ data as employed in WaterCycle

<table>
<thead>
<tr>
<th>Household Plan Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Plan Area (sq. m)</td>
</tr>
<tr>
<td>Roof Area Proportion</td>
</tr>
<tr>
<td>Road Area Proportion</td>
</tr>
<tr>
<td>Pervious Area Proportion</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Household Local Storage (cubic metres)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domestic Households</td>
</tr>
<tr>
<td>Commercial Households</td>
</tr>
<tr>
<td>Institutions A Households</td>
</tr>
<tr>
<td>Institutions B Households</td>
</tr>
</tbody>
</table>

been designed to improve on the concepts of existing integrated modelling systems (that is Aquacycle, UVQ, UWOT, City Water Balance, WaterMet) in four principal areas:

- the water end-use representation and modelling across the city
- the spatial characterisation of households and the physical terrain of the city
- the addition of on-site sanitation systems to the catchment hydrology
- the modelling of stormwater flow downstream through the city

In Water Cycle, land use is characterised in a hierarchical fashion, in similar ways to the spatial discretisation employed in the existing integrated urban water modelling tools. The smallest scale of the city was prescribed as the household (and the open space) which was then cascaded to the sub-catchments (watersheds) scale. At the household scale, the urban area is sub-categorised into both pervious (open spaces) and impervious spaces (road, paved, roof). This discretisation is then assembled into numerous households (and larger open spaces) to form clusters, clusters are then aggregated to form the subcatchments, and finally subcatchments to the whole city.

WaterCycle, just like Aquacycle, UVQ, UWOT, City Water Balance, and WaterMet can be described as a urban water interventions scoping models that allow for the strategic planning sustainable water management systems rather than their detailed engineering design. A daily time step was therefore thought appropriate for this kind of model. Although this level of
Table 3.7 A distribution of the gravity flow parameters across the sub-catchments

<table>
<thead>
<tr>
<th>Sub-Catchment ID</th>
<th>Area [ha]</th>
<th>Length [m]</th>
<th>Slope, So</th>
<th>Time** [hrs]</th>
<th>Sub Reaches [No.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>244.8</td>
<td>4846.4</td>
<td>0.011</td>
<td>0.61</td>
<td>24</td>
</tr>
<tr>
<td>2</td>
<td>130.3</td>
<td>3526.4</td>
<td>0.010</td>
<td>0.46</td>
<td>18</td>
</tr>
<tr>
<td>3</td>
<td>399.1</td>
<td>9255.2</td>
<td>0.002</td>
<td>27.78</td>
<td>111</td>
</tr>
<tr>
<td>4</td>
<td>230.1</td>
<td>7817.4</td>
<td>0.009</td>
<td>1.08</td>
<td>43</td>
</tr>
<tr>
<td>5</td>
<td>875.4</td>
<td>11091.9</td>
<td>0.002</td>
<td>3.46</td>
<td>138</td>
</tr>
<tr>
<td>6*</td>
<td>614.6</td>
<td>6607.2</td>
<td>0.011</td>
<td>0.83</td>
<td>33</td>
</tr>
<tr>
<td>7</td>
<td>573.7</td>
<td>7397.5</td>
<td>0.008</td>
<td>1.07</td>
<td>42</td>
</tr>
<tr>
<td>8</td>
<td>541.6</td>
<td>8269.5</td>
<td>0.002</td>
<td>2.22</td>
<td>89</td>
</tr>
<tr>
<td>9</td>
<td>236.0</td>
<td>5570.3</td>
<td>0.006</td>
<td>0.91</td>
<td>36</td>
</tr>
<tr>
<td>10</td>
<td>43.9</td>
<td>3224.9</td>
<td>0.010</td>
<td>0.42</td>
<td>17</td>
</tr>
<tr>
<td>11</td>
<td>193.7</td>
<td>3224.9</td>
<td>0.011</td>
<td>0.45</td>
<td>18</td>
</tr>
<tr>
<td>12</td>
<td>301.1</td>
<td>5640.6</td>
<td>0.013</td>
<td>0.63</td>
<td>25</td>
</tr>
<tr>
<td>13</td>
<td>376.2</td>
<td>8697.7</td>
<td>0.013</td>
<td>1.00</td>
<td>40</td>
</tr>
<tr>
<td>14</td>
<td>216.1</td>
<td>5898.0</td>
<td>0.007</td>
<td>0.91</td>
<td>37</td>
</tr>
<tr>
<td>15</td>
<td>181.8</td>
<td>4051.5</td>
<td>0.009</td>
<td>0.55</td>
<td>22</td>
</tr>
<tr>
<td>16a,b,c*</td>
<td>327.2</td>
<td>2785.9</td>
<td>0.003</td>
<td>0.15</td>
<td>6</td>
</tr>
</tbody>
</table>

* Includes decentralised, centralised, and low-income sub-units
** Watersheds’ time of concentration

Aggregation results in the loss of diurnal flow variation, it provides sufficient information for the comparison of different water management options, especially for long term simulations, necessary for sustainability assessments (Last, 2010).

3.4.3.1 Software Platform

The development environment selected for the integrated urban water modelling model is Simulink, which forms part of the MATLAB suite of tools developed by Mathworks. Simulink enables the modelling, simulation, and analysis of dynamic systems, whose outputs change over time. Simulink was chosen as it facilitates the representation of processes and flows in a in a block-wise modelling manner. This modularised or block-oriented approach is convenient for the creation of coupled models. Blocks are connected to each other providing
3.4 Methods III - Integrated urban water modelling

Table 3.8 Contaminants data

<table>
<thead>
<tr>
<th>Household Contaminant (TotN) Loading (g per cu.m per day)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Urine</td>
<td>10.4</td>
</tr>
<tr>
<td>Faeces</td>
<td>1.5</td>
</tr>
<tr>
<td>Showering water</td>
<td>1.0</td>
</tr>
<tr>
<td>Washing Dishes water</td>
<td>1.0</td>
</tr>
<tr>
<td>Laundry water</td>
<td>1.0</td>
</tr>
<tr>
<td>General Cleaning water</td>
<td>1.5</td>
</tr>
<tr>
<td>Rainfall water</td>
<td>0.01</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wastewater Treatment Efficiency</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Septic Tanks</td>
<td>60%</td>
</tr>
<tr>
<td>Pits</td>
<td>30%</td>
</tr>
<tr>
<td>Waste Stabilization Ponds</td>
<td>80%</td>
</tr>
</tbody>
</table>

information flow between each other. Then also, the detailed computational algorithms of a given block are created with aid of pre-existing blocks provided by Simulink and or the creation of own blocks that can contain user created routines created through by coding in either m-functions, s-function or Cpp languages. This approach was employed for the development of the modelling system.

The first step in building WaterCycle was to add to modify the CityDrain Matlab/Simulink platform to the specifics of a developing world community. City Drain, as described in Achleitner & Rauch (2007), was designed to simulate the flow of storm water flow in urban centres following the different spatial units (sub-catchments). Though, from an integrated urban water system perspective, City Drain was designed to model and represent downstream portions of an urban water system, it does not describe any urban water upstream systems for example the water supply system. The system in its form has found applications in the Achleitner & Rauch (2007); Achleitner et al. (2008); Freni et al. (2008); Rauch et al. (2002); Rodriguez et al. (2009, 2013); Rodriguez & Díaz-Granados (2011) but only for the downstream urban water systems. Therefore, in this study, City Drain platform was utilised as the baseline platform to encapsulate the subcatchment to subcatchment flows. Then within each subcatchment blocks upstream modules of mains water usage, wastewater generation, impervious/pervious hydrology were added to complete an integrated urban water modelling.
3.5 Methods IV - Integrated assessment of urban water systems

In section 1.5 of this thesis, one of the research aims of this study, is to dwell into the definition of the sustainable performance of various interventions across the urban water systems of the developing world. This section therefore describes the methods applied in this study to meet this objective.

3.5.1 Methodology overview

3.5.1.1 Modelling urban water interventions

In section 3.4 above, an integrated urban water modelling tool, WaterCycle, was introduced in this study to characteristically model the integrated urban water behaviour of an city of the developing world. However, to assess the integrated performance of numerous interventions across an urban water system, it was necessary to find a way to model and simulate the multitude of urban water interventions within a single integrated urban water modelling system. Therefore numerous urban water interventions were modelled and added to WaterCycle.

The interventions studied included a spectrum of conventional, alternative, water-supply-related, stormwater-related, and sanitation-related interventions. The approaches taken to represent and model each of the urban water interventions within WaterCycle are illustrated in table 3.9.

The interventions shown in table 3.9 were added to WaterCycle against the technical background of WaterCycle described in section 3.4. And as such:

- households’ data shown in section 3.4.2.4 has been employed unless as specified in table 3.9,

- urban landscape data shown in section 3.4.2.4 was employed unless specified in table 3.9,

- Contaminants’ data shown in section 3.4.2.4 was employed unless specified in table 3.9, and

- the model was simulated for the same period (2 years) at a daily time-step.

In addition, in the modelling of these interventions, given the short simulation time, it was assumed that the interventions have a high penetration rate without any significant hindrances.
### 3.5 Methods IV - Integrated assessment of urban water systems

Table 3.9 How the various urban water interventions were modelled in WaterCycle

<table>
<thead>
<tr>
<th>Intervention</th>
<th>Modelling Concept</th>
<th>Scope</th>
<th>Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A. Water Supply Interventions</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Conventional</td>
<td>Increase the mains water use by a factor (20%) for showering, dish washing, laundry, and general cleaning water uses</td>
<td>All HHs</td>
<td>Local</td>
</tr>
<tr>
<td>2. DM Toilets</td>
<td>reduce the toilet water use by a reduction factor. Factor sourced from Makropoulos et al. (2008)</td>
<td>HC HHs</td>
<td>Local</td>
</tr>
<tr>
<td>3. DM Showers</td>
<td>reduce the shower or bathing water use by a reduction factor. Factor sourced from Makropoulos et al. (2008)</td>
<td>HC HHs</td>
<td>Local</td>
</tr>
<tr>
<td>4. DM Taps</td>
<td>reduce the handwashing water use by a reduction factor. Factor sourced from Makropoulos et al. (2008)</td>
<td>All HHs</td>
<td>Local</td>
</tr>
<tr>
<td>5. Rainswater Harvesting</td>
<td>Roof rain water collected, stored and employed for all water uses. Excess to drainage</td>
<td>All HHs</td>
<td>Local</td>
</tr>
<tr>
<td>6. Stormwater Harvesting</td>
<td>Storm water collected, stored and employed for only potable water uses. Excess to drainage</td>
<td>All HHs</td>
<td>Local</td>
</tr>
<tr>
<td>7. Greywater Harvesting</td>
<td>Grey water collected, stored and employed for non-potable water uses. Excess to drainage</td>
<td>HC HHs</td>
<td>Local</td>
</tr>
<tr>
<td><strong>B. Storm water Interventions</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Infiltration Boxes</td>
<td>Storm water collected, stored and infiltrated to soil moisture module. Excess to drainage</td>
<td>All HHs</td>
<td>Centralised</td>
</tr>
<tr>
<td>2. Infiltration Drains</td>
<td>Increase HH pervious proportion, Increase infiltration rate, Increase percolation rate, by a factor</td>
<td>All HHs</td>
<td>Local, Centralised</td>
</tr>
<tr>
<td>3. Infiltration Strips</td>
<td>Stormwater directed to the large open spaces of the catchment</td>
<td>NA</td>
<td>Centralised</td>
</tr>
<tr>
<td>4. Pervious Pavements</td>
<td>Stormwater directed to the large open spaces of the catchment</td>
<td>NA</td>
<td>Centralised</td>
</tr>
<tr>
<td>5. Conventional</td>
<td>Effective Runoff proportion reduced, Infiltration rates reduced</td>
<td>NA</td>
<td>All HHs</td>
</tr>
<tr>
<td>6. Storage Ponds</td>
<td>Stormwater directed to the large centralised storage. Excess to drainage</td>
<td>NA</td>
<td>Centralised</td>
</tr>
<tr>
<td><strong>C. Sanitation Interventions</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Urine Diversion</td>
<td>Total Nitrogen (of Urine) Concentration reduced significantly.</td>
<td>All HHs</td>
<td>Local</td>
</tr>
<tr>
<td>2. Solids Reuse</td>
<td>Total Nitrogen (of Excreta) Concentration and toilet water use (for HC HHs) reduced significantly.</td>
<td>All HHs</td>
<td>Local</td>
</tr>
<tr>
<td>3. Solids &amp; Liquids Reuse</td>
<td>Total Nitrogen (of Excreta and Urine) Concentration and toilet water use (for HC HHs) reduced significantly.</td>
<td>All HHs</td>
<td>Local</td>
</tr>
<tr>
<td>4. Greywater Harvesting</td>
<td>All greywater produced, directed and stored, then employed for toilet and general cleaning use</td>
<td>All HHs</td>
<td>Centralised</td>
</tr>
<tr>
<td>5. Conventional (No Slums)</td>
<td>All human wastewater directed to sewer, but not for low-income settlements</td>
<td>All HHs</td>
<td>Centralised</td>
</tr>
<tr>
<td>6. Conventional (All HHs)</td>
<td>All human wastewater directed to sewer</td>
<td>All HHs</td>
<td>Centralised</td>
</tr>
</tbody>
</table>

DM - Demand Management, Conventional water supply - mains water supply, Conventional storm water - separate storm water sewerage, Conventional Sanitation - separate sanitary sewerage
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And during this period, the intervention is expected to be performing at its highest capacity. This assumption was employed to allow for the assessment of the potential impact of these interventions when employed within city of the developing world. Nevertheless, it is expected that in reality these interventions may have lower penetration rates across the community or their performance will deteriorate with time.

3.5.1.2 Modelling the sustainable urban water system performance

The second addition of this study to WaterCycle was the performance measurement regime of an urban water intervention and consequently the urban water system. The performance assessment of an intervention was designed to relate to the main objective of an urban water system, which is to boost its sustainable performance. As mentioned in section 1.1.4 and section 2.6 of this thesis, that since the precise definition of Sustainable Development (SD) is debatable, this study adopted the description of a sustainable urban water system by Lundin (2003) that prescribes an urban water system as one that provides its water services to its users including preventing environmental degradation, over a long term.

3.5.2 Methods - modelling the urban water interventions

This was undertaken by first modularising the fundamental unit processes that cascade together to generate the various urban water interventions. It was found that the interventions can include some or all of the following unit processes: storage, infiltration, water flow reduction, and/or (contaminants reduction). These unit processes are illustrated in figure 3.15. An intervention was then represented as a combination of the various component unit processes. The details of how each of the urban water interventions was represented within WaterCycle are illustrated in table 3.9.

3.5.2.1 The storage unit process

As shown in figure 3.15, a number of the urban water interventions (e.g. rainwater harvesting, greywater harvesting, ponds, wetlands, infiltration boxes) employ storage as one of their unit fundamental processes. In WaterCycle, storage was modelled by extending the algorithm described in Dixon et al. (1999); Fewkes & Wam (2000); Ward et al. (2008). It involves the representation of a single storage entity that collects source water (which could be rain water or greywater depending on the intervention being designed) as an input and water exits the storage system either as overflow, or to meet a specific water-use demand, or as a controlled exit (for storm water options). The input to the storage is either rainwater (for rainwater harvesting), stormwater (for stormwater reuse), or wastewater (for wastewater storage).
3.5 Methods IV - Integrated assessment of urban water systems

Fig. 3.15 A venn diagram showing how urban water interventions were categorised in this study according to their fundamental processes of (a) Storage, (b) Infiltration, (c) Reduction Factors, and (d) Treatment

reuse), depending on the interventions employing the storage. If the storage is exceeded, the excess water (overflow) passes directly to the pervious system to join the overland flow (or to the sewer for households employing centralised sanitation). The yield from the storage system represents the controlled or required output, which could be directed to satisfy the required component demand or the controlled exit directed to the overland flow. If the yield is to meet the required demand, it is added to the mains water supply. The outflow from the storage, for a controlled exit, was modelled to follow uniform steady flow (with a normal depth), in a similar manner to that described by Mackay & Last (2010) and Last (2010).

3.5.2.2 The infiltration unit process

The infiltration process involved the diversion of storm water from the overland flow path to the ground water flow path. Within WaterCycle, the infiltration process for a given intervention was introduced through an increased infiltration rate. The interventions of infiltration drains, pervious gardens and pervious pavements all employed infiltration to improve their urban water performance. Bioswales and infiltration boxes, however, employ a combination of infiltration and storage or reduction of contaminants (or treatment) respectively.
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3.5.2.3 The wastewater treatment unit process

The contaminant treatment process was represented here as the percentage ‘reduction’ of the concentration of contaminants, across any water or wastewater stream (as per the intervention) within the integrated model. The percentage reduction is a representation of the treatment efficiency of the intervention. Wetlands, green roofs, urine diversion, solids diversion, and low-cost sewerage all employed wastewater treatment as part of their processes.

3.5.2.4 The low-cost sewerage process

In addition to the treatment process, in WaterCycle, low-cost sewerage sanitation systems were added by introducing a specific pathway for the waste streams, from their source (households) to their disposal and then to the receiving water. If the households were originally employing on-site sanitation, their wastewater was not diverted to a sewer but to a septic tank or a pit latrine. For the households employing centralised sanitation, sewers were employed to direct the wastewater flow to the centralised treatment system.

3.5.2.5 The capacity reduction process

The demand management interventions (that is the use of low flushing capacity toilets, the use of low capacity showers, and or the use of low capacity taps) were modelled through an introduction of a percentage reduction its corresponding water end-use. For low capacity showers, a reduction in showering end-use was applied, for flushing toilets on the flushing water end-use, and for tap or cistern water use on the tap water end-use. This kind of demand management representation is also employed in Makropoulos et al. (2008) and Rooijen (2010).

3.5.3 Methods - modelling the sustainable performance of an urban water system

The scope of this study was to assess the integration of the urban water subsystems to the environment, and as such only environmental criteria of the Ashley et al. (2003) classification was employed. Though, in this study the indicators were extended to define an urban water system’s performance, according to the subsystem the indicator represents. In each case, the performance indicators were computed as the relative change between the new urban water system (with the intervention) and the original (baseline) urban water system.
3.5 Methods IV - Integrated assessment of urban water systems

3.5.3.0.1 *Urban water supply subsystem performance*
In the urban water supply subsystem, the mains water savings indicator was employed (in similar ways to studies by Chatfield & Coombes (2007); Fewkes & Wam (2000); Rootjen (2010); Schuetze & Santiago-Fandino (2013). Mains water savings were defined to reflect the level of mains water use that has been conserved within the new system (with the intervention) relative to the original (baseline) system. It was presumed that an increase of mains water use would reflect a less sustainable urban water supply subsystem, since an increased mains water use is attributed to increased environmental degradation.

3.5.3.0.2 *Urban stormwater subsystem performance*
For the urban stormwater subsystem, a sustainable performance was reflected through the total volume of stormwater runoff discharged, (in similar ways to studies by Burns *et al.* (2012); Chatfield & Coombes (2007); Fagan *et al.* (2010); Huang *et al.* (2014); Li & Babcock Jr (2013); Rodriguez (2012).

3.5.3.0.3 *Urban sanitation subsystem performance*
For the urban sanitation subsystem, this was assessed through the total mass of contaminant (total nitrogen in this case) discharged from the urban water system.

3.5.3.1 *Sustainable performance indices*
In this study, despite the employment of indicators as is usually employed in other urban water studies, the novelty of the approach is the generation of all three indicators (in combination, not in isolation) to assess an urban water system.

As WaterCycle is a stochastic model, it can generate numerous outputs (simulated 1000 times) of the total mains water use hydrograph, the hydrograph of the final stormwater flow effluent from the urban water system, and the total nitrogen pollutograph of the stormwater flow effluent from the urban water system. Then from the simulated hydrographs, a median hydrograph of each case was computed from which the performance indicators were generated: these being the mains water saving indicator (as the representative measure of the urban water supply subsystem performance), the reduction in stormwater flow effluent (as a representative measure of the urban stormwater subsystem performance), and the reduction in contaminant effluent (as the representative measure of the urban sanitation subsystem performance). In addition, the attributes of each intervention were considered, such as (1) the intervention type (either a water supply intervention, a stormwater intervention, or a sanitation intervention), (2) its scale of application (either local or centralised), and finally
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(3) whether the intervention involves recycling, reuse or none of them. Populating the performances and the attributes of the interventions generated a rare dataset of the urban water systems that were then statistically analysed to generate information about the sustainability performance of the urban water system.

For each intervention (or urban water option), the integrated modelling system presents its water use hydrograph, its stormwater outflow hydrograph, and its contaminant pollutograph. Generating these results for each urban water option is a novel output from this study. However, due to the significantly high number of interventions studied, the relative overall performance output of each urban water intervention was given preference, and hence presented in this thesis. The additional information related to say the temporal behaviour of each urban water option was not given preference in this study. The overall performance of an intervention is measured relative to the baseline.
Chapter 4

Characterising the temporal water use dynamics

One of the specific objectives of this study, is to propose and introduce methodologies for characterising urban water use within a town of the developing world, in conditions where there is inadequate availability of reliable water use data. This chapter of the thesis correlates, aggregates and reports work done in this study to address this knowledge gap.

Part of the work presented in this chapter was submitted as an international journal, and is shown in appendix A.

4.1 Background

Chapter 3 (section 3.1 in particular) of this thesis, provided a comprehensive description of the known behaviour of water use in urban water systems of the developing world. That is, that their urban communities employ both centralised (mains water) and decentralised water sources. With this kind of behaviour, it generates uncertainty on the whether the measured mains water use in the community, is representative of the actual water demand of the community. Since the study is heavily dependent on the mains water use, as one of the principal data sources, it was therefore prudent to characterise the information accruing from any measured mains water use analysis. In particular, the study focuses on generating an understanding of the impact rain water harvesting has on the mains water use.
4.1.1 Existing approaches - urban water balance

In usual urban water practice, for one to understand rain water use impacts mains water use, an urban water balance approach of the water flow through the urban water system would be carried out. In urban water supply systems, in particular, water balance computations are characteristically carried out and denoted as an urban water accounting procedures.

Urban water accounting implies the process of describing the numerical relationship between the urban water system’s input water volume, to the system’s water losses, to the system’s storage dynamics, and finally to the water consumption (Mutikanga, 2012), which can also be termed as the urban water system’s output. This approach has been advocated for as one of the tools that should be employed to improve the sustainable performance of urban water supply systems (Kayaga & Smout, 2011; Mutikanga, 2012), in that it provides a tool to assess and monitor the performance of the urban water system. However, despite the popularity of this approach in urban water supply system’s assessment (Chanan et al., 2010; Cook et al., 2009; Mitchell & Cleugh, 2008), urban water accounting has been reported in the scientific literature in many applications with each yield different interpretations. In conventional urban water supply systems, water accounting is usually practised either through the IWA/AWWA water balance approach and/or through hydrological water balance modelling.

The IWA/AWWA water balance approach is developed with the objective of estimating or evaluating the water lost in an urban water supply system (Klingel & Knobloch, 2015). It is based on the principle that system’s input volume (SIV) is equal to the sum of the water consumed and the change in volume inventory (storage and pipelines) if there is no leakage in the system.

\[ V_{SIV} = V_C + \delta V + V_L \]  \hspace{1cm} (4.1)

where \( V_{SIV} \) is metered system input volume, \( V_C \) metered water use, \( \delta V \) system storage volume, and \( V_L \) system leakage. The SIV is compared with the authorised consumption to estimate the water loss components. The SIV and the authorised consumption should be measured accurately as possible to obtain reliable results for the water losses (Klingel & Knobloch, 2015). If unmetered components of authorised consumption exist (which usually do in systems of the developing world), they have to be determined as accurately as possible by suitable approaches. In other words, for accurate application of this approach, the measured water volumes should be accurately measured, and while the ‘unknown’ volumes should be estimated accurately. Both Klingel & Knobloch (2015) and Mutikanga (2012) conclude
that the success of this approach depends on the efficiency and adequacy of the methods employed to estimate the various water components of equation 4.1.

4.1.2 Hydrological modelling approaches

The hydrological modelling approach, such as the double mass curve, is similar in principle to the IWA/AWWA water balance approach. It is based on a principle, similar in that represented in equation 4.1, except that in this case, the focus is on establishing the storage requirement of the system (Mutesi et al., 2006; Raghunath, 2006). It is however assumed instead, that the raw water input, the mains water output, and the water losses can be accurately estimated or measured.

4.1.3 Weaknesses of the Water Balance approach

Therefore, despite the similarity in these methods, they place emphasis on different aspects of the urban water system and hence generate completely different sets of information. It must be also emphasized that these approaches do not extend the urban water system up to the rainfall input, but only to the raw water system input. In addition, the measured water use in the system is always assumed to represent only the metered mains water use, not any other decentralised water use in the community. Hence, in urban water systems that involve the significant decentralised water use in addition to the centralised mains water use, these approaches would face a challenge.

As a consequence of this limitation, in the traditional urban water accounting approaches in characterising the water supply or water use volumes of an urban water supply system, justified the need for an investigation into any novel approaches for understanding further the water systems dynamics within an urban water supply system. However, as mentioned in the section 4.1, urban water supply systems in the developing world are characterised by rainfall as their major system’s input with the mains water use (complemented with decentralised rainwater harvesting use) as their major output. However, for these urban water systems, the rainfall input and part of the output (that is mains water consumption) are the are usually the most reliable and available data series.

Therefore, for any urban water balance study (with either of the IWA or the Double Mass Curve methodologies), the other data requirements of urban water systems input (such as the raw water input, the water losses, the storage, the decentralised rainwater use) are occasionally known with the required precision. The absence of this data fundamentally
Characterising the temporal water use dynamics

limits the application of these urban water balance approaches to an urban water system of
the developing world. Since the systems are all rain-fed, it is the rainfall input that should be
considered in the urban water balance assessment, in addition to the raw-water system’s input.
In other words, the relationship between the rainfall-input, the mains water consumption
output, and the decentralised rainwater use, should be given much emphasis in any strategic
planning and management of these urban water systems. But this relationship is hardly
studied in urban water literature of the developing world.

4.1.4 Research gap

These unique challenges justified the need for a novel approach that can be employed to
describe the relationship between rainfall-input, mains water use, and decentralised rainwater
use in a system of the developed world. And in carrying out this activity, this section of the
study fulfilled specific objective one (1) of this thesis (see section 1.5).

This information once specified provides additional contribution to the characterising of the
specific water use behaviour of the urban water system of a community of the developing
world.

4.2 A review of the methods employed

In section 3.2 of this thesis, a time series analysis methodology was introduced (and described
in detail) as the innovative methodology to provide this assessment.

Time series analysis, in principle, is a systematic approach of applying mathematical and
statistical analysis to data, that fundamentally relies on the assessment of time correlations
within time series data (Shumway & Stoffer, 2011). As a method, it is not a novel approach
to data analysis, except that it does not have any documented applications in urban water
systems. As mentioned in section 3.2, this method basically provides an analysis of the
input and output data series of the urban water system to provides an understanding of the
fundamental temporal hydrological functioning of the system. The analysis depends on the
revelations provided by statistical methods of autocorrelation and cross-correlation of the
input/output stochastic time processes of the urban water supply system. And in this study,
the urban water system is considered to be an integral sum of the system input rainfall, and
the mains water use output.
The methodology was introduced against the background that the symptoms observed in urban water systems in the developing world, are in a way synonymous to the symptoms of many complex natural water systems. Both water systems depend on one-input one and one output data series as the only available data sources for one to use to understand their hydrological and hydraulic behaviour. For example, complex ground water systems as described in Bailly-Comte et al. (2008); Gelhar (1974); Jemcov & Petric (2010); Mathevet et al. (2004) depend on only rainfall input and only the measured ground water flow (represented by the measured ground water level), also complex river catchments (in Bourodimos, Efstatious & Oguntuase, Abiose (1974); Chow (1969); Lafreniere & Sharp (2003)) also depend on only the input rainfall and on only output catchment river flow.

In all these natural systems, a time series analysis methodology is had been employed to deduce their fundamental hydrological and hydraulic behaviour. The hydrological information generated from this analysis is of strategic relevance to the development of these systems. It is against this background, because of this analogy in physical circumstances between these natural water systems and the urban water systems in the developing world, that time series analysis methodology was introduced as a methodology to assess the hydrologic functioning of the urban water system of the developing world.

The proceeding sections of this chapter therefore describe the results generated in employing time series analysis to the rainfall input and mains water use output to assess the urban water balance of the case community of this study.

4.3 Results

4.3.1 Temporal domain analysis

4.3.1.1 Auto correlation

The rainfall correlogram in figure 4.1 reveals that the input rainfall system consists of oscillations of a period approximately 3 months, with minimal damping. The mains water consumption correlogram (in figure 4.1) reveals that the mains water consumption does not contain significant oscillations in spite of significantly periodic input. The output correlogram is though slowly descending, with a few minimal oscillations.

The gradual descent of the output correlogram is usually taken as an indication of the influence of a system’s internal memory (which is a representation the catchment hydrological
Characterising the temporal water use dynamics

Fig. 4.1 Autocorrelation correlograms for the INPUT (rainfall) and OUTPUT (mains consumption)

processes from rainfall to stormwater, then to the urban water mains water system with its variables such as the mains water storage that is both centralised and localised) on the input, as it transforms into the output. However, recomputing the output correlogram without the effect of the long-term [as a way to magnify the oscillations in the output], as shown in figure 4.2, reveals that the mains water consumption is also comprised of significant oscillations, oscillating around the long terms mean main water consumption. The oscillations in the mains water, do not appear to be directly corresponding in lag time to the oscillations in the input. This is a preliminary indicator that the temporal dynamics of mains water use in the urban water system is not entirely dominated (or driven) by the rainfall the urban catchment receives.

Following the sequential variation of the mains water consumption verses the sequential rainfall, provides some insights into the possible causes of the water mains consumption periodicities. The mains water changes gradient (from a high descent gradient to gradual descent gradient) at a time lag 1, while the rainfall, though still descending, changes gradient to a gradual descent at the same time lag. The rainfall then changes the gradient further at lag 3 to start increasing, while the mains water consumption changes to a slower descent gradient but still descending. The mains water consumption continues the descent till lag 6, at which point the rainfall peaks. The rainfall starts to decrease again at lag 6, while the mains consumption is still rising for a further one lag the starts decreasing. This trend seems to suggest that there could be an inverse input-output interaction between the rainfall and
mains water consumption, one that figure 4.2 supports as the more realistic existing water supply structure in the town.

This inverse relationship puts into question, the assumed centralised water supply structure that is usually expected in most developing country urban water supply systems. For the mains and rain water to have an inverse relationship, then the household water consumption should have been a sum of both the mains water consumption and the localised rain water consumption (as shown in figure 4.3). In this way, for a constant total household consumption,
the mains water and rain water will vary interchangeably, that is when rain water increases mains water decreases and vice versa.

4.3.1.2 Cross correlation

The figure 4.4 and figure 4.5 of cross correlation illustrates further the complex relationship between the rainfall and the mains water consumption. Cross Correlation analysis confirms that the (dominant) periodicity observed in the rainfall is responsible for the (dominant) periodicity observed within the mains water consumed. However, on eliminating the long term trend from the mains water series, that is removing the dominating effect of the rainfall on the mains water use, alternative oscillations are observed that get more pronounced. These oscillations appear to imply that mains water use is controlled by another set of processes, in addition to the rainfall dynamics.

Comparison of the cross correlogram with the rainfall, the effect of a combined household water consumption model described in section 4.3.1.1 is illustrated further. The cross correlation starts increasing while the rainfall is still decreasing at lag 2, the mains water consumption starts reducing while the rainfall is still increasing at lag 5. The rainfall starts increasing again at lag 7 while the rain is still decreasing, only to peak at the same time as the rain approaches its minimum lag time. This observation goes on to reaffirm that in a given household, both mains water and rain water harvesting are employed concurrently, one to supplement the other. And that mains water is used maximumly when rainfall is at its minimum, and vice versa.

4.3.1.3 Temporal domain analysis - conclusion

The temporal domain analysis reveals that the input rainfall is periodic with a 3 months lag time period. The output mains water consumption, however, is not as periodic as the input but has an additional set of oscillations that do not seem to correspond (in timing and amplitude) to the input. This could signify an additional driver of the system that is not specified in this analysis or that the system introduced further oscillations in the output, such as the widespread use of localised rain water harvesting across the community. This section further showed that input rainfall has an inverse relationship with the mains water consumption, in that when the rainfall is at its minimum, the mains water consumption is at its maximum, and vice versa. This inverse relationship was attributed to the widespread use of localised rainwater harvesting in the community, that it affects the mains water consumption trends.
4.3 Results

![Cross Correlation - Raw Data vs Detrended Data](image)

Fig. 4.4 The Cross Correlation Function between Rainfall and Mains Water Consumption (No Long term Mean)

4.3.2 Frequency domain analysis

4.3.2.1 Auto spectral analysis

The rainfall input spectrogram (shown in figure 4.6) shows that the rainfall (input) has two major oscillations (of periods 6, 3 months) and a series of minor oscillations. The mains water consumption output spectrogram (figure 4.6) shows that the mains water consumption has one major oscillation (of period 6 month), two secondary oscillations (of periods 3, and 12 months), and numerous minor oscillations. The rainfall input, therefore, has some part role in the oscillations observed in the mains water consumption but not for all of them.

The change of the major frequencies, from the input (of period 6 months) to the output (of period 3 months), coupled with numerous minor frequencies (of periods of approximately 3, 2, 1 months) in the output, signifies the presence of another driver in the system not considered in this time series analysis. The other driver could be a reflection of the impact of the upstream catchment, the mains water storage, or the localised rain water harvesting has on the mains water use.
Characterising the temporal water use dynamics

Fig. 4.5 The Cross Correlation Function superimposed with Rainfall Correlogram

4.3.2.2 Cross spectral analysis

The cross amplitude function (figure 4.7) shows that the major oscillations observed in the mains water are a result of the rainfall input into the system. Though, not all the oscillations in the cross amplitude function correspond to the major and minor frequencies in the input.

With this correspondence in oscillations, it is expected that the system will behave linearly (implying that the input just traverses through the system with minimum delay) at all corresponding frequencies as confirmed in the coherence plot in figure 4.8. The coherence plot shows that the system is linear \((r \geq 0.5)\) at frequencies \(5/24, 7.5/24, 14/24, 20/24\) which correspond to periodicities of wavelengths 6, 3, 1.7, 1.2 months. All these periodicities appear to originate from known water supply system drivers, some from input system like the rainfall (6 months, 3 months), and the others (1.7 months, 1.2 months which can approximated to 2 and 1 monthly periods) from the household water consumption behaviour (daily, weekly, monthly). However, the system behaves linearly highest (frequency correlation \(r \geq 0.8\)) at the monthly periodicity - this period can synchronise with both drivers (rainfall and the household water use behaviours). Following this description, this period can be reduced further to daily periods and still synchronise with both drivers to produce high linear coherence, however, this could not be confirmed in our analysis since the data employed was at monthly time steps.
4.3 Results

![AutoSpectral Analysis - Rainfall (IN)](image1)

![AutoSpectral Analysis - Mains Water Consumption (OUT)](image2)

Fig. 4.6 Auto-spectrograms for both Rainfall and Main Water Consumption

Table 4.1 The urban water supply subsystem residence times at various frequencies (with their associated drivers)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual</td>
<td>0.95 / -0.92</td>
<td>0.15 / -0.15</td>
<td>4.5 / -4.4</td>
<td>Rainfall / HH Consumption</td>
</tr>
<tr>
<td>Bi-annual</td>
<td>-1.43</td>
<td>-0.23</td>
<td>-6.8</td>
<td>HH Consumption</td>
</tr>
<tr>
<td>Quarterly</td>
<td>1.57 / -1.78</td>
<td>0.25 / -0.28</td>
<td>7.5 / -8.5</td>
<td>Rainfall / HH Consumption</td>
</tr>
<tr>
<td>Every 2 Months</td>
<td>-0.42 / 1.12</td>
<td>-0.07 / 0.18</td>
<td>-2.0 / 5.3</td>
<td>HH Consumption / Rainfall</td>
</tr>
</tbody>
</table>

The phase function shows a dome-like or trough-like shape at each of the linear frequencies except the 6 month period as shown in figure 4.9. The dome-like shape can be interpreted as two lines that change gradient within and around that frequency. This change in gradient from positive to negative or the mixture of both positive and negative gradients can be interpreted as a mixture of two processes during that cycle. At one time, the water is draining through the system (that is the rainfall is leading), and at another time the system is filling up with water (so the mains water is leading). Using the phase function, characteristic times were computed for the system, which corresponds to the water response time of the system (hence the time it takes the system to drain or the system to fill up) as shown in table 4.1.
Characterising the temporal water use dynamics

The characteristic times of the system show a system filling time that varies from 2.0 days to 8.5 days with an average of 5.78 days. The draining characteristic times range from 4.5 days to 7.5 days with an average of 5.43 days. In both the filling and draining times the average times are comparable, the draining and filling times could be corresponding to the amount storage that is available in the urban water supply system, which takes approximately 5.0 days to restore the system from a dry season to wet season, and vice versa.

In the design of conventional urban water supply systems, the required storage to balance the system is evaluated through a linear comparison of the rainfall or input series with the mains water use. A rule of thumb for the design of storage is usually taken as 50% of the maximum day demand. In other words, the pre-requisite storage for an urban water system is designed through the time domain.

The frequency analysis of the rainfall verses the mains water use shows that the urban water system requires multiple days storage to stabilise. In other words, for the stability of this urban water system, a major reservoir is required.

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4.3.2.3 Frequency domain analysis - conclusion

The frequency analysis of the system shows that the system is driven partly by the rainfall (input) and the household water consumption behaviours. The coherence frequency plot shows that the systems behaves linearly (highest) at monthly periodicities, which can be fined tuned to daily time steps. The phase function plot shows that the urban water supply system has an average transfer time of about 5.8 days for filling, and 5.4 days for draining. Hence, the urban water supply system requires multiple-days storage for stability.

4.4 Discussion

4.4.1 Relevance of time series analysis to urban water systems assessment

This chapter describes a times series approach as a method for hydrodynamic assessment of urban water supply systems. The approach provides fundamental insights into the performance and operation of the urban water system, insights that are not necessarily available through the conventional urban water balance approaches.
In rain-fed water supply systems for which the overall water source is the catchment rainfall, the traditional water supply assessment approaches would require a tremendous amount of computational effort to generate a dynamic relationship between the rainfall falling on the catchment and the water consumption in the system. These weaknesses of the traditional water supply systems assessment are what makes this method of time series analysis relevant for modern urban water supply performance assessment.

4.4.2 Revelations and new knowledge generated by time series systems analysis approach

This time series analysis methodology provides insights about the water supply system that are not only of relevance to traditional urban water system design, but cannot be easily generated by the traditional methods.

4.4.2.1 Temporal domain

The temporal domain analysis revealed the mains water consumption has an inverse relationship with the input rainfall as a consequence of localised rain water harvesting use within the area. This relationship cannot be generated through conventional IWA/AWWA or Double
4.4 Discussion

Mass Curve methodology.

The inverse relationship between mains water use and rain-water is supported by the data collected of the study area. In section 3.1, it was shown that over 80% of the residents utilise rain-water as a secondary source to supplement mains water as the household water source. And given that mains water comes at a cost while rain water comes free, when rain water is available it instantly becomes the primary household water source. In other words, rain water is utilised when it rains implying low mains water use then, then mains water is utilised highest when the supply of rain water is low or not available. This behaviour explains the revelations contained in the temporal domain analysis.

4.4.2.2 Frequency domain

The frequency domain analysis of the system revealed that the urban water system is driven partly by the rainfall input, diverting from the IWA/AWWA approaches that advance the pumped water system input as the driver of the urban water system.

Further, the frequency domain provided new revelations of the time response of the urban water system. Taking the response time as an indicator of the storage requirements of the system, the study revealed that the system requires between 4 – 9 days of storage to stabilise (in addition to the available centralised and decentralised storage). This revelation could not be generated through the existing urban water balance approaches.

4.4.3 Weakness of the time series analysis approach

The time series systems analysis methodology despite its major strengths does exhibit some weakness. For a successful volume of insights, a large volume of time series data is required (preferably at smaller temporal scales). In this study, monthly data was employed, implying that certain insights that occur at daily or smaller scales, could not be generated.

Also, it must be mentioned that this approach, provides only indicative insights into the hydrodynamic behaviour of an urban water system. Insights, which in spite of being unique to the traditional hydrological methods, they cannot replace the information provided by the existing traditional methods. Therefore, this approach can only be employed to supplement the existing traditional urban water assessments.
4.5 Conclusion

This chapter has introduced and illustrated a method of time series analysis that provides fundamental insights into the interaction of an urban water system’s major processes (that is rainfall and mains water consumption). Even if, this type of analysis does not aim to describe the detailed urban hydrology of the urban water supply system, it captures the mean hydrological behaviour of the urban water supply system, as well as estimate some of the system’s characteristic time scales. Hence, this method can be employed as the first diagnostic tool for the analysis of the urban water supply system especially in the preparation of any centralised or decentralised interventions, or in performance assessment of an urban water system.

The chapter also shows that time series analysis provides insights about a water supply system, that require considerable effort to estimate using traditional hydraulic or hydrologic modelling assessments. Therefore, this approach is relevant to modern urban water management and will be of significant importance as a first diagnostic tool to complement traditional modelling approaches.

4.6 Summary

This chapter of the thesis demonstrated that even with minimal amounts of data, a problem characteristic of urban water supply systems of the developing world, it is possible to generate fundamental insights into the behaviour of the urban water system. The study introduced and employed time series analysis as a novel approach to generate knowledge about the fundamental hydrodynamics within an urban water supply system of a developing country.

This approach (time series analysis from a systems perspective) has found applications within mainly water resources applications, but hardly in urban water resources applications, and because of that this approach is described in this thesis as novel. With urban water systems in the developing that lack adequate data (but rainfall and monthly billings), this data can be used to deduce various originally unknown fundamental dynamics about the system.

The first revelation the study provided is that part of the temporal dynamics of mains water use in a urban water system of the developing world are driven by the longitudinal dynamics of the input rainfall despite the presence of storage with the system. However, those dynamics reflect an inverse relationship between the rainfall and the mains water consumption due to
the presence of rain water harvesting with the town. Hence, as a recommendation this study reveals in the design of interventions across urban water supply systems, the influence of rainfall dynamics should drive the storage requirements of the system.

Finally, as a novel revelation, this study provided insights into the actual storage time an urban water supply system of the developing world requires. This approach provided an estimate of 4 – 9 days of storage for the urban water system to perform satisfactorily.
Chapter 5

Modelling and characterising the water end-use dynamics

5.1 Introduction

In section 1.5 of this thesis, it was mentioned that one of the research aims of this thesis is to investigate and characterise the water end-use dynamics of a city of the developing world. This characterisation was generated as a pre-requisite to introduce integrated assessment of the urban water system.

The objective of this chapter, therefore, is to describe the methodology introduced in this thesis (including its revelations) to generated water end-use estimates of a community of the developing world. Part of this work was submitted and published as an international journal - the paper is shown in appendix B.

5.2 Background

It has been introduced in the section 1.1 of this thesis that the alternative urban water supply service models which were introduced as the alternative to improve sustainability with conventional urban water systems, are characterised by provision of water services through the utilisation of alternative water resources such as rainwater, waste water and storm water, centred on a fit-for-purpose water distribution principle. This fit-for-purpose principle requires that water is supplied to the water users according to the quality requirements that each specific water end-use requires. In summary, such kind of design of an urban water system requires the total water use in the community to be broken into a series of streams of
Modelling and characterising the water end-use dynamics

the various water end-uses.

In other words, this section introduced that for successful management (to ensure sustainable performance) of a conventional or alternative urban water system, there is a need for knowledge on the urban water end-use of the community. However, for urban water communities of the developing world, this information is not reliably available. And that due to the unavailability of this water end-use information that is specific and characteristic to these communities, this kind of urban water system design would face a challenge.

The objective of this chapter, therefore, is to describe the innovative methodology (and its revelation) to improve the water use estimates generated from the household interviews so as to generate a more representative and expanded quantification of the water end-uses of this urban water community.

5.3 A review of methods employed

In section 3.3 of this thesis, it was discovered that in urban communities of the developed world, this water end-use information usually generated through high-resolution metering experiments, such as was demonstrated in Al Amin et al. (2011); Athuraliya et al. (2008, 2012b); Beal & Stewart (2011); Dziegielewski et al. (2000); Heinrich (2007b); Heinrich & Isaacs (2008); Jethoo & Poonia (2011); Keshavarzi et al. (2006); Lu & Smout (2010). In other words, according to urban water literature, high resolution metering experiments provide the most reliable approach for the estimation of urban water end-use of a community.

In the developing world, high-resolution metering of end-uses would be inappropriate and impractical owing to its high financial resources they require. This then leaves social survey methods as the only feasible approach to estimate water end-use volumes in these communities. However, employing social survey methods to estimate volumes of water end use, generates imprecise and uncertain water use data despite its ease. The method involves asking residents to recall their water use quantities instead of physically measuring them, leading to virtually imprecise results (Athuraliya et al. (2008), Otaki et al. (2008)). It is for this reason that innovative approaches are sought to generate more accurate water end-use information of the community.

To characterise the specific water use data of this community, water use data was collected of the case community. The water use data collected were then analysed and modelled
statistically to generate the characteristic water use data of the community.

The precise methods followed in collecting the water end-use data, developing the statistical models (including their calibration and validation) are described in detail in section 3.3 of this thesis.

## 5.4 Results I - Domestic water end-use

### 5.4.1 Model calibration and validation

![Graphs showing comparison between simulated and measured data for dry and wet seasons.](image)

**[a]** Simulated and measured total water use (10^3 m^3) over months for the dry season. **[b]** Simulated and measured total water use (10^3 m^3) over months for the wet season. **[c]** Cumulative frequency of measured and simulated total water use (m^3) for the dry season. **[d]** Cumulative frequency of measured and simulated total water use (m^3) for the wet season.

[*] The order or nature of the month was not a subject of the research apart from the number of households measured in that month, each month was simulated independently. That is why the months are not labelled on the x-axis. [**]** Total Water Use - represents the total water used up by all the households in a given group in a given month.

Fig. 5.1 Overall calibration process results for total monthly water consumption for yard-tap water users during (a) dry season and (b) wet season, and also for their respective cumulative distribution functions in (c) and (d).
Modelling and characterising the water end-use dynamics

The results of the calibration procedure are shown in figure 5.1 for yard-tap water users and figure 5.2 for house-connected water users. The aim of the calibration exercise was to use the end-use volume stochastic models to predict the monthly water consumption for each of the yard-tap and the house-connected water users, hence confirming the appropriateness of the computed water end-use volumes in representing overall water consumption in the community.

**DRY SEASON**

- **(a)** Total Water Use** (x10^3 m³)

- **(c)** Cumulative Frequency (%)

**WET SEASON**

- **(b)** Total Water Use** (x10^3 m³)

- **(d)** Cumulative Frequency (%)

[*] The order or nature of the month was not a subject of the research apart from the number of households measured in that month, each month was simulated independently. That is why the months are not labelled on the x-axis. [**] Total Water Use - represents the total water used up by all the households in a given group in a given month.

Fig. 5.2 Overall calibration process results for total monthly water consumption for house-connected water users during (a) dry season and (b) wet season, and also for their respective cumulative distribution functions in (c) and (d).

The calibration exercise showed that the stochastic model provides a good representation of the end-use volume consumption in the area. For all the months simulated (simulated independently), the observed monthly consumption(s) were within the interquartile range
of the model simulations as shown in figure 5.1a and figure 5.2a for the dry season. The cumulative frequency distributions were compared graphically (in figure 5.1c and figure 5.2c - for the dry season) as well as analytically using the Kolmogorov-Smirnov test. As shown in the figures, both the simulations and the measured data appear to have the same distribution, which was confirmed by Kolmogorov-Smirnov test for all user groups (KS test $h = 0$ at 5% significant level). Hence, it can be concluded that fitted probability distributions are an appropriate representation of the water end-use in the community.

As described in section 3.3.6, the same procedure was applied to validate the stochastic model using consumption data of the wet season. The models were validated for both the yard-tap connected water users and house-connected water users as shown in figure 5.1 for yard-tap connected water users and in figure 5.2 for house connected water users.

5.4.2 Characteristics of the community water end use

5.4.2.1 Global distribution of the community water uses

Figure 5.3, figure 5.4 and figure 5.5 show the results of probability fitting process of the socially collected water consumption end-use data of the community, as well as the parameters of their respective distributions. The strength of the fit was measured with aid of the correlation coefficient (not reported in the figures) which was moderately high ($> 0.8$) for most of the end-uses, and hence showed good model representation of the end-uses by the probability distributions.

The results showed that the majority of the communities’ water end-use frequencies and volumes or intensities required highly-skewed probability distributions such as log-normal or gamma, and in a few scattered cases with Normal and Weibull probability distributions. This implied that the highest proportion of the residential water users in the community consists of lower-end water users, with very small proportions of very large water-users.

5.4.2.2 Distribution of household size

The number of adults per household was fitted to a log-normal distributions (in figure 5.3a, and in figure 5.4a), with a geometric mean of 4.1 persons per household (for yard-tap connected users) and of 4.8 persons per household (for house-connected users). This study also showed that house connected water households contain a relatively higher number of adults than yard tap connected water users.
Fig. 5.3 Probability fit models (continuous line) used to represent frequency distribution data (black dots) of (a) household size and water uses (of (b) bathing, (c) dish washing, (d) laundry, (e) external use, and (f) general cleaning) across yard-tap water users
Fig. 5.4 Probability fit models (continuous line) used to represent frequency distribution data (black dots) of (a) household size and water uses (of (b) Laundry, (c) dish washing, and (c) general cleaning) across house-connected water users.
Modelling and characterising the water end-use dynamics

(a) SHOWERING

Number (per HH)

Relative Frequency

0 0.2 0.4 0.6
0 2 4 6 8

Lognormal
(0.4,0.5)

Frequency (per person per day)

Relative Frequency

0 0.2 0.4 0.6
0 5 10 15

Lognormal
(0.7,0.7)

Duration (mins) per event*

Relative Frequency

0 0.1 0.2
0 5 10 15

Lognormal
(1.6,0.5)

Flow Rate (Litres per min)*

Relative Frequency

0 0.1 0.2 0.3
0 5 10 15 20

Normal
(7.0,4.5)

(b) TOILET USE

Number (per HH)

Relative Frequency

0 0.2 0.4 0.6
0 2 4 6 8

Lognormal
(0.5,0.6)

Frequency (per person per day)*

Relative Frequency

0 0.2 0.4 0.6
0 2 4 6 8

Lognormal
(1.3,0.5)

Flush Volume (Litres) per event*

Relative Frequency

0 0.1 0.2
0 2 4 6 8 10 12

Chi-Squared
(5.9)

(c) HAND-WASHING

Number of Hand Basins (per HH)

Relative Frequency

0 0.2 0.4 0.6
0 0 5 10 15

Lognormal
(0.9,0.6)

Frequency (per person per day)

Relative Frequency

0 0.2 0.4 0.6
0 0 5 10 15

Uniform
(4.0 - 6.0)
[Blokker et al (2011)]

Volume (Litres) per event

Relative Frequency

0 1
0 0 1

Constant
(1.0)
[Athuraliya et al (2012)]

*Employed data from Yarra Valley Residential Water Use Study (Australia) in Athuraliya et al (2012)

Fig. 5.5 Probability fit models (continuous line) used to represent frequency distribution data (black dots) of more water uses ((a) showering, (b) toilet use, and (c) hand-washing) across house-connected water users in the community.
5.4 Results I - Domestic water end-use

5.4.2.3 Distribution of water used for bathing or showering

Bathing (and or showering) frequency was modelled with a Weibull distribution in yard tap households (in figure 5.3b) and as Log-normal in house connected households (in figure 5.5e). The average frequency of bathing or showering in both groups was observed at about 2.0 times per day, which is higher than the average frequency of 0.7 recorded for a Dutch community in Blokker et al. (2010) or 0.73 per person per day in Athuraliya et al. (2012a). This is one of the major cultural (and may be due to climate) differences between communities in sub-Saharan Africa and those of the developed world. The volume of bathing, on the other hand, used in the yard tap connected water users was estimated at an average of about 27 litres per person per day which is comparable to studies carried out in other African countries in Nyong & Kanaroglou (1999), Thompson et al. (2001), and Otaki et al. (2008).

5.4.2.4 Distribution of water used in kitchen use

The frequency of washing dishes (shown in figure 5.3(c) and 5.4(c)) for both yard tap and house connection water users was approximated with a geometric mean of 2.0 per household per day (and 2.5 for yard connected households). This frequency rate relatively higher than that observed in developed communities in Athuraliya et al. (2008) and Blokker et al. (2010), of about 0.3 – 0.5 per household per day. This significant difference could be because of the use of dish washing machines in the developed world verses typical hand-dish-washing in this community. Dishes are washed more frequently in the developing world but at lower volumes than in the developed world. The volume of dish washing, on the other hand, for yard tap users was measured at approximately 24.4 litres per household which is moderately higher than other studies in the developing world recorded in Nyong & Kanaroglou (1999), Thompson et al. (2001), and Otaki et al. (2008).

5.4.2.5 Distribution of other water end-uses

The frequency of laundry events in the community was comparable to other countries, both with a geometric mean of 0.3 times per day (and 0.4 – 0.7 times per day for the developed world in Athuraliya et al. (2008) and Blokker et al. (2010)). The laundry use volume or intensity of water end-use this study generated a geometric mean of 54.0 litres per capita for house-connected water users while in the developed world provided 50.1 – 93.0 litres per capita per day. Both external water use and general cleaning end-uses could not be compared to documented end-uses of the developed world. However, it should be noted that the external water end-use data could not be fitted with a model fit, and in addition, the external water

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Fig. 5.6 The relative spread of computed household water use volumes for house-connected in plot (a) and yard-tap users in plot (b)

end-use required a negative binomial distribution (not shown in figures) to cater for a 42% penetration rate in the usage of external water services.

5.4.3 Evaluating water use and wastewater volumes

Table 5.1 Details of the computed water use volumes for both the yard-tap users and the house connected users

<table>
<thead>
<tr>
<th>House Type</th>
<th>End uses</th>
<th>per HH (litres)</th>
<th>per capita (litres)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>min</td>
<td>median</td>
<td>max</td>
</tr>
<tr>
<td>Yard Taps</td>
<td>Bathing</td>
<td>117</td>
<td>152.7</td>
<td>200.1</td>
</tr>
<tr>
<td></td>
<td>Hand Washing</td>
<td>55.7</td>
<td>78.9</td>
<td>172.1</td>
</tr>
<tr>
<td></td>
<td>Laundry</td>
<td>19.7</td>
<td>26.8</td>
<td>34.4</td>
</tr>
<tr>
<td></td>
<td>Washing Dishes</td>
<td>68.6</td>
<td>77.4</td>
<td>89.7</td>
</tr>
<tr>
<td></td>
<td>General Cleaning</td>
<td>8.39</td>
<td>12.0</td>
<td>16.4</td>
</tr>
<tr>
<td></td>
<td><strong>Total</strong></td>
<td><strong>347.9</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Toilet Flushing</td>
<td></td>
<td>87.6</td>
<td>131.4</td>
<td>213.2</td>
</tr>
<tr>
<td>Showering</td>
<td></td>
<td>123.9</td>
<td>280.0</td>
<td>486.0</td>
</tr>
<tr>
<td>Hand Washing</td>
<td></td>
<td>26.3</td>
<td>43.5</td>
<td>88.0</td>
</tr>
<tr>
<td>Laundry</td>
<td></td>
<td>13.2</td>
<td>19.1</td>
<td>27.8</td>
</tr>
<tr>
<td>Washing Dishes</td>
<td></td>
<td>81.8</td>
<td>105.7</td>
<td>142.6</td>
</tr>
<tr>
<td>General Cleaning</td>
<td></td>
<td>5.0</td>
<td>6.6</td>
<td>8.9</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>586.2</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*HH1 - household
The final calibrated end-use volumes are detailed in Table 5.1 and in Figure 5.6 showing the spread and median of the simulated end-use volumes for both yard-tap connected water users and house-connected users. The house connected households were evaluated to have a median total consumption of approximately 586.2 l/HH/day (109.2 l/capita/day) while yard tap households consume have a median consumption of 347.9 l/HH/day (60.2 l/capita/day). These consumption values are comparable to other end-use studies documented in the scientific literature as shown in Figure 5.7. For house connections, small to medium cities in comparable tropical climate were measured to have total household water consumption in the range 77 – 130 l/capita/day as described in Nyong & Kanaroglou (1999), Keshavarzi et al. (2006), Athuraliya et al. (2008), and Lu & Smout (2010). For Yard Tap consumers, the studies concentrating on water users in a rural setting of low to medium developing countries in Nyong & Kanaroglou (1999), Fan et al. (2013), Keshavarzi et al. (2006), and Jethoo & Poonia (2011) were measured to have relatively end-use consumption of 68 – 123.5 litres per person per day. However, these household end-use consumptions should be compared with caution.

For both house-connected water users and yard-tap users, showering or bathing was evaluated as the largest household end-use (45.5% in the house-connection users, and 43.8% in yard tap-connected users). This was followed by toilet use in house-connected users and hand-washing in yard-tap users. Secondly, it is also worthwhile to note that hand-washing in yard-tap water users and showering in house-connected water users generated the most variable or
Modelling and characterising the water end-use dynamics

Fig. 5.8 Relative comparisons between the water use volumes in a typical household of a yard-tap user against one of a house-connected water user

uncertain water end-uses as shown in figure 5.6. Further, it is worth noting that proportion of non-potable water end-uses were 82.8% in yard-tap and 77.7% in house-connected users. These details are further illustrated in figure 5.8.

5.5 Results II - Non Domestic water end-use

The volume and dynamics of water use (and consequently waste-water generation) were represented in the model at a household level. Each household was grouped (and hence classified) according to the nature of the water use it employs, that is either as a domestic, commercial, institution, or large institution. Within each household, according to the nature of the household’s water use and also according to the sanitation type employed within the household, appropriate water end-uses were apportioned to each household (as shown in figure 3.9 and 3.11).

The detailed methodology employed for the quantification of water end-use volumes within the town are detailed in section 3.3.5. This methodology was applied for the estimation of water used in the town, in terms of the water end-use(s) the specific household employs. However, the methodology and methods described in the preceding sections of chapter 5 had only been applied to domestic users, in this section, this methodology was extended to other users in the community.
5.5 Results II - Non Domestic water end-use

![Calibration and validation plots of water consumption estimation](image)

Fig. 5.9 Calibration and validation plots of water consumption estimation by the stochastic models for House-connected water users. (a), (c), (e), (g) show the water volume use calibration the measured (dots) against the computed bounds (lines), while (b), (d), (f), (h) show the cumulative density distributions of the measured versus the computed.

Households with similar end-uses were grouped into the same group to generate a total of eight(8) groups (as shown in figure 3.9), that is domestic, commercial, general institutional and or large institutions, and also according to nature of sanitation employed at each location. Commercial group users compromise of water consumers like business offices, shops, restaurants, while small institutions compromised of mainly churches, mosques, clinics. Large institutions consisted of users that have a high concentration of adults in a small area for example universities, schools, hospitals that allow for accommodation-related end-uses. The user groups were further sub-divided (in each group) according to the nature of sanitation practice employed, that is house connection or yard tap connection. This kind of grouping provided a way to cater for the heterogeneity of the various users found in the town community.
Modelling and characterising the water end-use dynamics

Fig. 5.10 Calibration and validation plots of water consumption estimation by the stochastic models for Yard-connected water users. (a), (c), (e), (g) show the water volume use calibration the measured (dots) against the computed bounds (lines), while (b), (d), (f), (h) show the cumulative density distributions of the measured versus the computed.

For domestic water users, the end-use system was modelled with the same parameters as those employed in equation 3.2. However, for the other user groups (commercial, small institutions, and large institutions), the model above had to be re-calibrated. It is assumed that the per capita end-use volumes of domestic users (for corresponding end-uses), are similar to those of other groups but differ on the number of users (adults) per household or account. That is, the non-domestic user groups were designed as a replicas of the domestic user groups but with different household size parameters, and different component end-use types. For all groups, this model was calibrated against the monthly billed consumption for all the household population in the user groups (as shown in figure 5.9 for House Connected Users and in figure 5.10 for yard tap connected users).

The calibration plots in figure 5.9 and figure 5.10 showed a good performance of the models in estimation of the monthly consumption volumes since the measured consumptions were
within the boundaries (minimum and maximum) of the estimated consumption volumes. The
distribution of the computed median volumes relative to the distribution of the measured
volumes showed a varied calibration. The distribution validation performed relatively poor in
case of commercial and large institutions (under yard-tap connection). This poor performance
was presumed to be the result of poor data availability in both of these categories.

5.6 Discussion

5.6.1 Water end-use estimation methodology

White et al. (1999) states that one of the limitations of characterising the end-use behaviours
and volumes of a community is the lack of reliable data on how and where water is being
used. Survey data of a sample of the end-uses employed in the community can in general
be collected for a community with relative ease and with lower resources compared to
high-resolution metering exercises. Survey data collection therefore, would be a suitable
approach for estimating water end-use characteristics of a low-income community. However,
since water end use survey data is imprecise, and cannot accurately measure all community
water end uses (Athuraliya et al., 2008; Otaki et al., 2008), then such end-use data collected
through survey exercises should be applied in urban water design assessments with caution.
This is particularly true for low income communities, and this study therefore has presented
a novel methodology to compensate for this limitation. The methodology improves on the
accuracy of end-use data collected by social surveys by describing the end-use data through
calibrated probability distribution models that describe the statistical spread of water end-use
in the community.

In a community of the developing world, monthly metering of all water utility water users is
a common practice, which makes available a representative dataset of monthly consumption
of the community. This study has illustrated how this readily available dataset can be utilised
to improve the estimation of water end-use approximations within a community. Monthly
consumption billing data is hardly ever employed in end-use volume estimations, due to the
limitations of accurately describing the temporal evolution of daily consumption to monthly
values, as observed by Mayer et al. (1999), Rathnayaka et al. (2011). Hence, its employment
in this study to calibrate the aggregation of end-use models is a novel approach.
5.6.2 Mathematical modelling of water end-use in a low-income community

In general, the mathematical model concept employed in this study to represent water end-use (as a building block for overall water demand) is not novel. In scientific literature, models of a similar nature were employed in Blokker et al. (2010, 2011); Haarhoff (2006); Jacobs (2007); Jacobs & Haarhoff (2007, 2006); Rauch et al. (2003) and reviewed in Rathnayaka et al. (2011); White et al. (1999). However, these models were applied to high income communities that are socially different from low income communities studied in this paper. Therefore, to adopt this concept to a low-income community these models had to be tailor-made by aggregating water end-uses that are specific to the low-income community.

Nonetheless, due to the high volume of data required for the development of water end-use models, and also due to the limited availability of community data in low-income communities. A novelty is introduced by this study related to how the study overcomes these challenges of data limitations to develop and calibrate a water end-use model of a community in the developing world.

5.6.3 Water end-use estimations

The results of the analysis of end-use water consumption evaluated in this study are comparable to other studies as shown in figure 5.7, although these comparisons should be interpreted cautiously. Firstly, it is recognised that house-connected households in Uganda significantly different to typical households in the developed world, the nature of their end-uses are not entirely the same. In the Ugandan community studied here, house connected households employ water for general household cleaning which is not represented in the end use structure of the developed world household communities.

Further, in the developed world communities, the households employ significant amounts of water for out-door irrigation (during the summer) which contributes the majority of outdoor water usage. While in this Ugandan community, (1) external water use is limited, and (2) where it is employed, it is used mainly for car washing instead of irrigation. The yard tap connected users, on the other hand, in this community, do not employ water for toilet flushing which is the major difference from house-connected users. Even for similar end-uses like the indoor water uses, this study has shown that there are still significant differences in the water consumption end-use parameters.
The differences in water end-use parameters drive the major differences between the household end-use proportions of both communities, as shown in figure 5.7. In this community, due to the high frequency of showering, this is the largest proportion of the overall household water use (43.8% in yard-tap users, and 45.5% in house-connected user) compared to only 24% in most developed world communities. This implies that integrated urban water interventions that target showering or bathing or hand-washing will most likely lead to a more significant impact on the performance of urban water systems in the developing world than in the developed world.

In addition, the developed methodology provides a way of describing water use in a community of the developing world, a more holistic description of water use in the community than what the socially collected end-use data can provide. The water end-use mathematical model and the methodology generated suggested by this study can be employed or extended in the design and assessment of urban water systems, especially in uncertainty or sensitivity analysis, and or, in studies that require a breakdown of water use for different water uses.

5.7 Summary - new revelations

This chapter generated an innovative approach to deal with the lack of data in the city of the developing world by improving on the applicability of the limited existing data in the community. It demonstrated a novel approach for simulating and evaluating water end-use volumes in an urban community of a developing country, by improving the accuracy of the household surveyed end-use data, through a stochastic modelling simulation. The modelling approach involved grouping the community into eight (8) heterogeneous subgroups (4 user groups, and each either of house-connected users and yard-taps users). For each subgroup, probabilistic regression models were developed for each category of water end-uses. The probability models for all the end-uses were then aggregated to generate the monthly consumption of the group, which was then calibrated - using the group’s measured monthly billing as the "true" consumption, to get representative end-uses volumes and distributions for the community.

The evaluated water end-use volumes of the community revealed that, most of the end-uses (their components of frequency and intensity) displayed highly-skewed distributions (log-normal) characteristics. This implied that the majority of water users in the community are low-capacity water users. The approach also showed that a typical household in the community has consumption volumes of 109.2 L/cap/day for house connected user and 60.2
Modelling and characterising the water end-use dynamics

for yard connected users.

The simulated end-use volumes of house-connected users (who were assumed to be comparable to developed country communities) were found to be relatively lower than comparable communities in the developed world. At the same time, the yard-tap users (who were assumed to be relatively comparable to rural communities) were found to have higher end-use volumes than rural communities. The principal differences in the water end-use behaviour were found to be hidden in (1) the presence or absence of certain end-uses in this community verses developed country communities, (2) within similar end-uses, some of the end-use parameters were significantly different, reflecting a difference in water use culture of both communities. This study therefore concludes with a caution that water end-use characteristics of one community should be employed carefully in the assessment or design of decentralised systems of another community, otherwise to misleading results will be generated.

The simulated end-use volumes of house-connected users (who were assumed to be relatively comparable to developed country communities) were found to be relatively lower than comparable communities in the developed world. At the same time, the yard-tap users (who were assumed to be relatively comparable to rural communities) were found to have higher end-use volumes than rural communities. The principal differences in this water end-use behaviour was found to be hidden in (1) the presence or absence of certain end-uses in this community verses the developed country communities, (2) and even within the similar end-uses, some of the end-use parameters were significantly different, reflecting a difference in water use culture of both communities. This study therefore concludes with a caution that water end-use characteristics of one community should be employed sparingly to assess or design decentralised systems of another community, otherwise they might lead to misleading results.

The study also showed that showering (or bathing) water end-use is, by average volume, the largest household water use for in both house-connected users and yard-tap connected households. The study also showed that in yard-tap customers, hand-washing is the most variable household water end-use, while within house-connected water users showering was the most variable water end-use.
Chapter 6

Integrated modelling of an urban water system of the developing world

6.1 Introduction

In section 1.5 of this thesis, it was introduced that one of the objectives of this study, that to increase the understanding of its unique urban water behaviour of an urban water system, an integrated urban water modelling (that involves the integration of the mains water use, the stormwater flow, and the pollutant load conveyance) of the area had to be developed.

The need for an integrated urban water modelling tool, originated from the the fact that, in reviewing existing integrated modelling systems (carried out in section 3.4 of this thesis), it was concluded that no integrated modelling tool is applicable for all the different urban water systems (that is of either the developing or the developed world). It was therefore imperative, that the existing integrated urban water modelling systems are tailor-made to the specific site characteristics of urban water systems of the developing world.

This chapter, therefore, places focus on the methods and revelations generated in this study to extend and modify existing integrated urban water modelling systems to the specific traits and characteristics of urban water systems of the developing world. Part of the work presented in this chapter was submitted as an international journal and is shown in appendix C.
6.2 Background

Integrated management of urban water systems places emphasis on the need for exploitation of the interactions (or the integration) between the different urban water subsystems to yield a sustainable urban water system performance (Makropoulos et al., 2008). This management system depends on the synergy the subsystems’ interaction contributes to the successful behaviour of the urban water system, which in the end leads to the revelation of hidden insights driving the poor performance of the urban water system.

Integrated modelling of an urban water system, in essence, refers to the development of a computational system that allows for this integration of the different constituent urban water subsystems within an urban area (city). That is the integration of the urban water supply subsystem, to the storm water subsystem, to the sanitation subsystem (Bach et al., 2014b), and vice versa. It is presumed that the hydrological processes within each of these subsystems have an influence and an effect on the global hydrological behaviour of the urban water system. The integrated modelling approach then allows for the revelation of these influences and/or effects. Mitchell et al. (2001) and Mitchell et al. (2007) advocate that such kind of urban water modelling should be at the centre of the development of any urban water strategy especially one that involves the employment of urban water interventions that spread across both decentralised and centralised spatial scales.

Currently, tools developed specifically to allow for integrated urban water modelling of urban water systems are few and many still in their infancy (Bach et al., 2014b; Mitchell et al., 2001). In the scientific literature, the integrated modelling systems that could be located included the Aquacycle system (Mitchell et al., 2001, 2007), the UWOT system (Makropoulos et al., 2008), the UrbanCycle system (Hardy et al., 2005), City Water Balance system (Last, 2010), and the WaterMet system (Behzadian & Kapelan, 2015). These tools were found to be highly site specific in their representation of an urban water system, in that their representation places a high level of emphasis on urban water characteristics specific only to developed world cities. For cities in the developing world particularly sub-Saharan Africa, no integrated urban water modelling tool to describe them was found in scientific literature.

An integrated urban water modelling tool suitable for a city in the developing world must, as part of its basic foundation, appropriately describe the specific and unique urban landscape of the developing world. In these cities (compared to the developed world), the water use heterogeneity is much more, the storm water flow is dominated by a larger percentage of
6.3 Review of the methods employed

natural unpaved surfaces, and the sanitation practices are dominated by the use of on-site systems (that is pit latrines and/or septic tanks). These characteristics and practices of this city the urban water hydrology of this city to generate a behaviour that is different from that of a developed country city.

This unique behaviour of urban water systems of the developing world is illustrated through their observed behaviour. Porto et al. (2009) observed that the weaknesses within the water supply subsystem in these cities are related to the deficiencies within the sanitation subsystem, which in turn affect the performance of the storm water subsystem. In other words, the performance of the water supply subsystem is influenced by the performance of the sanitation subsystem, which in turn influences the performance of the storm water subsystem. Therefore, despite the lack of integrated modelling systems for cities of the developed world, there is no doubt that their urban water systems also require a holistic and integrated form of assessment in order to assess and optimise their performance.

6.3 Review of the methods employed

It was introduced in section 1.4 and described in section 3.4 of this thesis, that the existing integrated urban water modelling tools (found in scientific literature) that is: Aquacycle, UWOT, UrbanCycle, City Water Balance, and WaterMet under represent the fundamental features of a city of the developing world. And as such, to fulfil the requirements of research objective 4 of this study, there is a need to update of the existing integrated urban water modelling body of knowledge to the requirements of a city of the developing world.

6.3.1 The modelling concept

In section 3.4 of this thesis, the modelling concept used to generate this integrated modelling tool was described. The concept started with introducing an alternative and more detailed characterisation of the urban water community, in order to precisely describe the higher level of heterogeneity. Using this description, the community was separated into water use groups that are located within different watersheds across the developing world city, a total of 16 by 12 homogeneous water user groups (shown in table 3.2. This characteristic schematisation of the city provided the foundation upon which an integrated urban hydrological modelling system (denoted as WaterCycle) was built for this city.
n summary, for each subcatchment, the number, type, and characteristics of the constituent households located within that subcatchment were defined (from the actual field data). Then within each household or households groups, these characteristics (including the water use and physical properties) were transformed into parameters which were utilised in the computation of the mains water requirement, the household wastewater and the stormwater runoff (both in quantity and quality). These computations were carried out from subcatchment to subcatchment, from time step to time step (daily) across the whole urban water cycle.

It was also observed that the existing integrated modelling systems (Aquacycle, City Water Balance, WaterMet), do not precisely represent the flow of water from one subcatchment to another. In this study, the Modified Muskingum routing approach was introduced to alleviate this gap.

The methodologies and approaches developed in generating an integrated urban water modelling, in this study, was encapsulated into a modelling system, denoted as Water Cycle. The precise of details of the methods used in the generation of this modelling system are described in detail in section 3.4 of this thesis.

6.3.2 Input data

Various forms of data were collected of the community were employed in WaterCycle. The households data employed in the model was shown in table 3.2, table 3.2, and table 3.6.

The soil-water hydrology data employed in the system are shown in table 3.5. The topographical parameters that affected the stormwater flow across each subcatchment, as employed in the model, is specified in table 3.7. The rainfall data employed in the area is described and specified in section 3.4.

The contaminants flow hydrology was specified through parameters specified in table 3.8.

6.3.3 Software Platform

WaterCycle was developed with aid of the Matlab/Simulink modelling environment.
6.4 Results

WaterCycle generates was designed to generate three major outputs to reflect the hydrological behaviour of an urban water system, that is, the total mains water use or demand, the surface storm water flow quantity, and the surface stormwater contaminant water quality.

6.4.1 WaterCycle Outputs

6.4.1.1 Mains water use

As mentioned above, the WaterCycle computes the mains water use utilising a stochastic algorithm. Figure D.1a shows a typical mains water use hydrograph - a mean simulation overlayed with a single simulation instance. WaterCycle generates a random water mains consumption pattern, that is not normally distributed as the data collected of the area required.

The mains water use simulated, was also shown to be not normally distributed, as the figure 6.1b shows. The simulated water use volumes tended to be skewed towards the smaller volumes.

6.4.1.2 Stormwater flow hydrograph

With the ability to let the terrain drive the stormwater flow downstream, WaterCycle was able to generate a stormwater flow hydrograph that is similar in shape to a natural river flow hydrograph. In addition, the utilisation of the Muskingum algorithm, WaterCycle was able to simulated flood peaks, that are usually missed out when gravity is not allowed to drive the stormwater flow downstream. These observations are shown in figure D.1b.

6.4.1.3 Stormwater flow pollutograph

Finally, WaterCycle generates the stormwater flow nutrients pollutograph (utilising total nitrogen in this case). The graph (figure 6.3) shows the concentration of total nitrogen (as the pollutant) as it exits the urban catchment. This nitrogen in the system is followed in the modelling system right from the its input at household level through human water use.

In addition, the pollutograph generated in WaterCycle, has the capability to represent the impact of the mains water use on the stormwater flow concentration. In this case, due to the ability of WaterCycle to allow for a stochastic use of water, the downstream wastewater flow hydrology allows for the generation of these stormwater flow concentration peaks (peaks shown in figure 6.3).
Integrated modelling of an urban water system of the developing world

(a) Mains water use hydrograph

(b) Simulated mains water use normal probability plot

Fig. 6.1 Mains water use simulation generated from WaterCycle
Fig. 6.2 Simulated stormwater hydrograph

Fig. 6.3 Simulated stormwater flow concentration pollutograph (with the 95% CI)
Integrated modelling of an urban water system of the developing world

![Graph showing measured vs simulated and regression lines for simulated urban runoff against measured river flow.](image)

Fig. 6.4 Calibration of the Simulated Stormwater Runoff

### 6.4.2 Calibration and validation

#### 6.4.2.1 Mains water use

For all household groups, the mains water use output was calibrated against the monthly mains water use measured by the city water utility (see figure 5.9 and figure 5.10). This calibration and validation was already carried out and described in section 5.4.3 of this chapter.

#### 6.4.2.2 Stormwater Runoff

The urban catchment in this study was not gauged for stormwater flow and as such there was no direct stormwater flow data source to calibrate the stormwater flow computation. However, the river that traverses the city has a gauging station (see figure 3.2). Though, since the river has a catchment that extends beyond the town, the shape of its hydrograph can be taken to provide a realistic representation of the stormwater flow exiting the city. Therefore, this hydrograph was used to calibrate the stormwater computation of WaterCycle. This calibration is represented in figure 6.4 where the simulated surface water runoff is compared
6.4 Results

Table 6.1 Stormwater flow validation

<table>
<thead>
<tr>
<th>Subcatchment (SC)</th>
<th>Peak Flow (cumecs)</th>
<th>TRRL*</th>
<th>WaterCycle</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC1</td>
<td>15.27</td>
<td></td>
<td>12.78</td>
<td></td>
</tr>
<tr>
<td>SC2</td>
<td>8.64</td>
<td></td>
<td>9.81</td>
<td></td>
</tr>
<tr>
<td>SC3</td>
<td>10.35</td>
<td></td>
<td>55.97</td>
<td>over estimates</td>
</tr>
<tr>
<td>SC4</td>
<td>10.77</td>
<td></td>
<td>34.82</td>
<td></td>
</tr>
<tr>
<td>SC5</td>
<td>22.49</td>
<td></td>
<td>51.49</td>
<td></td>
</tr>
<tr>
<td>SC7</td>
<td>30.00</td>
<td></td>
<td>23.77</td>
<td></td>
</tr>
<tr>
<td>SC8</td>
<td>17.72</td>
<td></td>
<td>87.24</td>
<td>over estimates</td>
</tr>
<tr>
<td>SC9</td>
<td>12.22</td>
<td></td>
<td>44.56</td>
<td>over estimates</td>
</tr>
<tr>
<td>SC10</td>
<td>2.73</td>
<td></td>
<td>3.17</td>
<td></td>
</tr>
<tr>
<td>SC11</td>
<td>13.31</td>
<td></td>
<td>5.01</td>
<td>under estimates</td>
</tr>
<tr>
<td>SC12</td>
<td>18.88</td>
<td></td>
<td>14.28</td>
<td></td>
</tr>
<tr>
<td>SC13</td>
<td>19.45</td>
<td></td>
<td>12.03</td>
<td></td>
</tr>
<tr>
<td>SC14</td>
<td>11.04</td>
<td></td>
<td>32.17</td>
<td>over estimates</td>
</tr>
<tr>
<td>SC15</td>
<td>11.49</td>
<td></td>
<td>27.74</td>
<td>over estimates</td>
</tr>
<tr>
<td>SC16c</td>
<td>10.25</td>
<td></td>
<td>2.70</td>
<td>under estimates</td>
</tr>
</tbody>
</table>

*TRRL is formally documented as 'The East African Flood Model' (see Fiddes (1976))

to the measured river flow.

The calibration procedure involved the adjustment of the K and X constants until the shape of the stormwater runoff hydrograph was as close as possible to that of the observed river flow hydrograph. However, since both hydrographs represent different watersheds, their correlation was used to measure their convergence, as shown in figure 6.4, with a positive correlation coefficient of 0.3 ($p < 0.05$). It must be emphasised however that since the river flow represents a much larger catchment than the urban stormwater flow simulated by the model, then a positive relationship between both flows can be taken as a realistic representation of the storm water flow in the modelling system.

In addition, to ensure that the WaterCycle accurately simulates the stormwater hydrology of the urban catchment. The stormwater flow output from WaterCycle was compared to
stormwater flow output from a lumped catchment hydrology model (the East African flood model) developed specifically for this area (developed by Fiddes (1976) and documented in Fiddes (1976) and in Ministry of Works and Transport (2010)). The model is designed to compute the peak stormwater flow output out of a given watershed at a given return period. The peak flow simulations (2-year return period) from this model were compared to the peak flow simulations from WaterCycle (see table 6.1).

WaterCycle was modified to generate stormwater simulations output for each of the watersheds within the urban area. Peak flow for each of these watersheds was then also computed for the same watershed using the East African flood model. The simulations revealed that of the 15 subcatchments in the study area, WaterCycle provides comparable peak flow estimates for 8 of the subcatchments. This confirmed that despite the absence of data, WaterCycle accurately simulates (to some extent) the stormwater runoff from the urban catchments.

6.4.2.3 Stormwater Concentration - Pollutograph

In the same way, there was no measured data for the stormwater flow, there was also no measured data for the river water quality. However, the national water utility can some records of the wastewater effluent from the wastewater stabilisation ponds. These records were taken every other month, with no regularity. It is these records that were employed to compare with the stormwater flow effluent from the urban catchment.

The pollutograph confidence intervals (medians of the 5% and 95% signals) were compared to the 95% intervals of the observed effluent exiting the waste water treatment plants in the systems. Both intervals are comparable (shown in figure 6.3). However, there was not enough to provide enough water quality data to allow for a linear comparison of the measured and observed pollutographs. Nevertheless, despite the absence of sufficient water quality data, the urban water sanitation system modelling in WaterCycle provided a reflection of a relatively sufficient estimation of the urban water sanitation system of the developing world city.

6.4.3 Sensitivity analysis

Further to characterise the performance of WaterCycle, a sensitivity analysis was carried out on a number of key parameters, as shown in table 6.2. A local sensitivity analysis method was employed (method defined in Loucks & Beek (2005)) was carried on to investigate the impact of the key parameters on model outputs (that is the mains water use, the stormwater
Table 6.2 WaterCycle - Sensitivity Analysis

<table>
<thead>
<tr>
<th>Parameter (Units)</th>
<th>Range*</th>
<th>Demand</th>
<th>Sensitivity (%)</th>
<th>Flow</th>
<th>Flow Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Household Population (Pits)</td>
<td>+10%</td>
<td>5.6</td>
<td>88.6</td>
<td>-15.3</td>
<td></td>
</tr>
<tr>
<td>Household Population (STs)</td>
<td>+10%</td>
<td>3.1</td>
<td>89.3</td>
<td>-18.6</td>
<td></td>
</tr>
<tr>
<td>Household Population (Sewered)</td>
<td>+10%</td>
<td>0.0</td>
<td>88.6</td>
<td>-20.2</td>
<td></td>
</tr>
<tr>
<td>Urine N** Content</td>
<td>-10% - +10%</td>
<td>-</td>
<td>-4.7</td>
<td>-1.3</td>
<td></td>
</tr>
<tr>
<td>Faeces N** Content</td>
<td>-10% - +10%</td>
<td>-</td>
<td>-1.2</td>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td>Household House Area</td>
<td>-10% - +10%</td>
<td>-</td>
<td>-22.0</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>Manning’s n</td>
<td>0.001 - 0.1</td>
<td>-</td>
<td>66.9</td>
<td>-11.2</td>
<td></td>
</tr>
<tr>
<td>Muskingum X</td>
<td>0.1 - 0.5</td>
<td>-</td>
<td>1.4</td>
<td>-11.4</td>
<td></td>
</tr>
<tr>
<td>Field Capacity (mm)</td>
<td>10 - 100</td>
<td>-</td>
<td>-2.5</td>
<td>5.0</td>
<td></td>
</tr>
<tr>
<td>Infiltration Capacity</td>
<td>0.0855</td>
<td>-</td>
<td>-0.5</td>
<td>3.6</td>
<td></td>
</tr>
<tr>
<td>0.1045</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Percolation Rate</td>
<td>+/- 10%</td>
<td>-</td>
<td>-0.5</td>
<td>-1.1</td>
<td></td>
</tr>
<tr>
<td>Max Drainage Depth</td>
<td>+/- 10%</td>
<td>-</td>
<td>-1.1</td>
<td>-2.2</td>
<td></td>
</tr>
<tr>
<td>Drainage Factor</td>
<td>0.5 - 0.9</td>
<td>-</td>
<td>0.1</td>
<td>-2.9</td>
<td></td>
</tr>
<tr>
<td>Soil Column (cm)</td>
<td>30 - 450</td>
<td>-</td>
<td>-21.4</td>
<td>-36.8</td>
<td></td>
</tr>
<tr>
<td>Impervious Proportion</td>
<td>+/- 10%</td>
<td>-</td>
<td>-0.5</td>
<td>-1.1</td>
<td></td>
</tr>
</tbody>
</table>

*Percentage change in default value or the actual range of values considered
**Total Nitrogen Content

flow, the stormwater pollutants contaminant).

The mains water use was sensitive to the household population especially the pits household (see table 6.2). The stormwater flow was observed to be sensitive to household population, households size, Manning’s coefficient, and the soil water column depth. And the stormwater flow quality (or pollutants contamination) was observed to be sensitive to households population, Manning’s coefficient, Muskingum’s X, and soil column depth.

In general, it was also observed, that the parameters that are sensitive to stormwater flow were equally sensitive to the stormwater flow quality (that is to the stormwater effluent from the catchment). Surprisingly, the parameters such as the total nitrogen content (for either Urine or Faeces) did not contribute as much sensitivity as the flow-related parameters.
6.5 Discussion

6.5.1 WaterCycle

One of the main objectives of this study was the development of an integrated urban water modelling system for a city of the developing world. WaterCycle is an integrated urban water modelling system that was developed to achieve this objective.

WaterCycle is a conceptual, simulation type, mass and contaminant balance based model which quantifies the water and contaminant flows across an urban water system (that is across the water supply subsystem, the storm water subsystem, and the sanitation subsystem) of a city of the developing world. This model was developed with an objective of filling the knowledge gaps in integrated urban water modelling described by Mitchell et al. (2007). In terms of typology, WaterCycle can be said to belong to the category of Integrated Water Component Modelling Systems (IWCM), according to the criteria by Bach et al. (2014a).

The review by Mitchell et al. (2007) of existing integrated urban water systems stated that their poor handling of the urban spatial scale as one of the major set-backs in their development. As a consequence of this limitation, these systems provide a poor representation of the urban water infrastructure of a developing world city. WaterCycle attempted to fill this gap. Therefore, WaterCycle placed emphasis on developing an integrated urban water modelling system that precisely represents the major urban water features (such as a unique mains water use structure, a predominantly naturally-based storm water drainage, and a predominantly on-site sanitation system) of a city in the developing world. The integration of these features in an urban hydrological system for such a city is the major novelty WaterCycle adds. This interaction allows WaterCycle to illustrate the impact of any on-site sanitation-based or land-use based urban water interventions on the environmental performance of the urban water system.

WaterCycle alleviates another weakness highlighted in Mitchell et al. (2007) of the current integrated urban water modelling systems. In the existing integrated urban water systems (Aquacycle, UWOT, CWB, WaterMet), mains water use is represented principally through a centralised (with the aid of arithmetic average) water end-use, which consequently represents the wastewater generated in the model. In WaterCycle, a stochastic mains water use algorithm to develop a more-realistic approach to describe the mains water use variability across the whole city was employed instead. This algorithm is of much relevance to integrated urban water management in that it allows WaterCycle to illustrate the impact of mains water use on the environmental performance of an urban water system, a concept that demonstrated by
6.5 Discussion

Rauch et al. (2003).

WaterCycle, in addition, relative to existing integrated modelling systems employs an advanced rainfall-runoff stormwater flow routing algorithm to model the flow of stormwater downstream. This new methodology provides this addition by allowing the Muskingum rainfall-runoff approach to dominate the flow from sub-catchment to subcatchment, and finally downstream to the receiving waters. This functionality in the integrated modelling allows WaterCycle to reproduce the flow and contaminant peaks experienced by most urban water systems. This behaviour allows plays a role in illustrating the role played by water supply subsystem and stormwater subsystem in the operation and design of appropriate urban water interventions.

Finally, with the new additions to WaterCycle, it provides an appropriate platform for the design, assessment, and performance testing of integrated urban water design schemes for a city of the developing country. This modelling system has been extended for the assessment of various decentralised system interventions involving water supply subsystems, storm water subsystems, and sanitation subsystems. The paper has demonstrated that existing integrated modelling systems are highly inappropriate in the design of integrated urban water management schemes for cities of the developing world.

6.5.2 WaterCycle Simulations

WaterCycle, just like existing integrated urban water models, simulates the mains water use within the community, the stormwater flow (and its corresponding contaminant effluent) from the catchment. Though, because of the methodological additions WaterCycle adds to integrated modelling, the outputs from WaterCycle are significantly different from those of already existing integrated urban water models.

6.5.2.1 Mains water use

WaterCycle provides a mains water use hydrograph (in figure D.1a) that displays a stochastic mains water use behaviour. The random behaviour of the mains water use is attributed to the probabilistic representation of the water end-use which aggregates to the mains water use. This kind of simulation though does not put into consideration the weekly or seasonal mains water use patterns.
Integrated modelling of an urban water system of the developing world

The use of a probabilistic stochastic modelling algorithm though allows WaterCycle to simulate the mains water use peak flows easily. This, is the major addition WaterCycle provides to the integrated urban water modelling body of knowledge. The existing integrated urban water models, all employ an averaged-based water end-use algorithm, that does not allow for the simulation of these mains water use peaks.

6.5.2.2 Stormwater flow quantity

Figure D.1b shows the stormwater flow output generated by WaterCycle. The output though from WaterCycle in comparison to the existing integrated urban water models, provides a more realistic hydrograph. On a daily scale, WaterCycle reproduces the stormwater flow hydrograph that reproduces the stormwater flow peaks that are experienced across this urban water catchment.

The addition of the Muskingum stormwater flow algorithm and the Soil water accounting algorithm to the integrated urban water system improves and transforms WaterCycle into a fully-grown urban watershed modelling system. Though, some integrated urban water models, had provided a soil water accounting algorithm, in addition to the detailed household landscape schematisation, most did not give a lot of emphasis to the improved watershed modelling. WaterCycle however does provide this addition.

6.5.2.3 Stormwater flow quality

Figure 6.3 shows the stormwater flow quality output from WaterCycle. This output in essence shows the pollutant flow effluent from the urban water catchment to the receiving waters. This output, just like the mains water use and or the stormwater flow quantity, is also generated from by other integrated urban water models, except that the one generated by WaterCycle is different from the others.

The pollutograph generated by WaterCycle contains contaminant flow peaks that are not reflected in pollutographs simulated by the other integrated urban water models. These contaminant flow peaks are thought to originate from the aggregation of the mains water use (or wastewater generation) flow peaks and the stormwater flow peaks. The stochastic nature of the mains water use (which is also represents the source of the pollutants) generates various peaks within the stormwater flow mass. Each instance of stormwater flow generates at least one major peak, a phenomena that is observed across urban wastewater systems, but
hardly ever simulated through an integrated urban water modelling system.

Secondly, Mitchell et al. (2007), stated that another major gap in existing integrated models, is their representation of water use behaviour. Most systems employ mean values to represent what end-use which tends over-estimate water use. In WaterCycle, this gap was alleviated by representing mains water as a stochastic or probabilistic distribution model. This addition coupled with the Muskingum flow routing algorithm, allowed WaterCycle to simulate the flow and contaminant peaks observed by most urban water systems. This observation was first modelled by Rauch et al. (2003) in illustrating its importance in urban wastewater management, however no integrated modelling system has been able to simulate it yet till WaterCycle.

It presents a pollutograph of the stormwater output from the urban water system. Most integrated modelling systems do not provide such an output. This output is of much relevance to an urban water system as it demonstrates role the urban water sanitation subsystem in the sustainable behaviour of the whole urban water system.

6.5.3 Urban water management

In terms of the global urban water management body of knowledge, this study has just demonstrated that it is possible to develop and generate an integrated urban water modelling system for a a city of the developing world. Previous studies had always recommended the need for an integrated urban water modelling of a city of the developing world, but none however extended the existing integrated urban water modelling to the developing world context. This study therefore extended integrated urban water modelling to fill that knowledge gap.

The major novelty of WaterCycle is the ability to model and represent urban water system of the developing world, especially one from a sub-Saharan country. In integrated modelling literature, only Poustie & Deletic (2014) employing UVQ managed to model and represent urban water system of the developing world, a city from a South Pacific country. The urban water behaviour of a sub-Saharan city of the city of the developing world is yet to be carried out. This paper and WaterCycle provided insight into this behaviour.

The sensitivity analysis of the WaterCycle also revealed that for an urban catchment of the developing world, the pollutant contaminant into the receiving water is most sensitive to the pervious hydrology of the urban catchment. In other words, due to the high penetration rate of the on-site sanitation usage, the strategy for effective environmental protection of the
receiving waters, should focus on interventions that reduce on the pollutant seepage from the on-site sanitation systems.

In addition, the complexity of integrated urban water modelling introduced by WaterCycle, revealed that the pollutograph from an urban water catchment of the developing world, involves numerous of pollutant loading peaks to the receiving waters. This kind of simulation in an urban catchment is novel revelation and could help describe the origin of various algal blooms across various receiving water bodies.

6.6 Conclusion

This study has described a methodology (encapsulated in modelling system WaterCycle), developed from scratch in this study, of mathematically describing the hydrology of mains water use, stormwater and wastewater flow within an urban community of the developing country, extending from household scale to the whole city. In addition, the methodology also adds novel approaches (of stochastic mains water use, and of gravity-dominated stormwater flow routing) to the existing integrated modelling paradigms. This addition then enables the modelling system to replicate the high nutrient load peaks that affect the performance of the urban water system’s waste water treatment capability, in addition to being able to successfully model a city of the developing world.

With these additions, the modelling system is able to provide revelations of an urban water system by providing a water use hydrograph output, a stormwater flow hydrograph output, and a pollutant concentration pollutograph. Generating these outputs simultaneously from an integrated urban water modelling system represents a significant advance in the description of urban water hydrology. This integration coupled with stochastic mains water demand estimation, a low-income-specific spatial delineation scale, and a more advanced rainfall-runoff algorithm provides an algorithm for the exploration of various urban water management options (that can be extended also to the developed world). With such an integrated modelling system, it is possible to assess numerous urban water system options, at citywide scale, at subcatchment scale, at household scale, and at subsystem scale to generate a more detailed integrated understanding of the response of a given urban water system.
Chapter 7

Integrated assessment of urban water systems

7.1 Introduction

In section 1.5 of this thesis, it was introduced that one of the objectives of this study, is to increase the understanding of its unique urban water behaviour of a city of the developing world. As such, one of the critical objectives is to provide understanding of how such a city responds to urban water interventions designed to boost its sustainability performance.

Section 3.1 of this thesis discusses that conventional urban water systems across both the developing and developed world comprise of significant weaknesses that prohibit sustainable performance of these urban water systems. Section 3.2 then extended the discussion and suggested that alternative urban water strategies have been introduced and recommended to be applied to existing conventional urban water systems, in order to return them to the path of sustainable performance. The alternative strategies recommended are presented as a combination of both technology and paradigm options.

Sections 3.3 discussed the unique nature of urban water practice in the developing world verses the developed world. First, that cities in the developing world compared to the developed world have been observed to experience poor urban water performance across all their subsystems, and as such, they require both a holistic assessment and holistic form of interventions. Second, that due to the unique nature of the urban water landscape of urban water systems in the developing world, a tailor-made integrated modelling tool was required to study the behaviour of urban water systems in the developing world. In chapter 6.0 of this thesis,
Integrated assessment of urban water systems

this integrated modelling system (that was developed in this study) is discussed and presented.

This chapter, therefore, builds on the platform set by the previous chapters to address how an appropriate integrated urban water systems performance assessment should be carried out. This part of the study is based on the premise that the existing methodologies of assessing the sustainable performance of urban water systems, do not reveal enough detail about the system, to support the appropriate decision making required to boost their sustainable performance. The chapter presents the work carried out in this study to investigate the integrated performance of various conventional and alternative water strategies when applied to an urban water system of the developing world.

Part of the work in this chapter was submitted as an international journal paper as shown in appendix D.

7.2 Background

7.2.1 Introduction

As introduced in section 1.1 and described in section 2.2 of this thesis, the vulnerability of the conventional urban water systems led to the development of alternative urban water systems, as an option to improve the sustainable performance of urban water systems. The primary strategy employed by the alternative urban water management model is the application of alternative urban water technologies (strategies and interventions) across the boundaries of the individual urban water subsystems, to generate a total urban water solution that is sustainable holistically across the whole system and across each of the individual subsystems. This integration within the alternative urban water management systems is what leads to an integrated management of the urban water system.

Integrated management of urban water systems, in this case, implies the exploitation of the interactions (that is, the integration) between the different urban water subsystems to generate a sustainable performance of the urban water (Makropoulos et al., 2008). To understand, precisely how the different urban subsystems can be adequately managed, an appropriate urban water systems assessment procedure is required.
7.2 Background

7.2.2 Justification

In urban water practice, to enhance the sustainable performance of an urban water system, usually, an ‘appropriate’ urban water intervention (or technology) is chosen for the system. The appropriateness of an intervention for a given urban water system, inherently implies a certain level of sustainable performance score has been attached to that intervention (as applied to that urban water system), and it is believed that that score is beyond the threshold required for sustainable behaviour required of that system. However, if for one reason or another that sustainable performance score of an urban water system does not reveal all the sustainable management attributes attributed towards that intervention, then it misleads in the choice of an adequate intervention required for a given urban water system to generate its sustainable performance.

Both the conventional and alternative urban water systems are limited in this area, that is, in providing adequate historical sustainable performance information of each of the interventions’ options they provide. Conventional urban water interventions as well as alternative urban water interventions, are both traditionally prescribed to target a particular urban water subsystem at a time. Figure 7.1 illustrates this weakness, showing the specific urban water subsystems to targeted for performance improvement by specific urban water technologies.

As an illustration, figure 7.1 shows 28 possible urban water technological options for one to consider when attempting to boost sustainable performance of an urban water system. Of these, 32% are designed to target an improvement of the water supply subsystem (here denoted as Water Supply Interventions), 39% to target the stormwater subsystem (here denoted as Stormwater Interventions), and 28% the sanitation system (here denoted as Sanitation Interventions). In addition, of these interventions, 53% are applied at centralised scales, while 47% at decentralised scales. None of these interventions is designed to target the whole urban water system as a whole.

This bias is one of the major limitations of any attempts to generate sustainable urban water systems. It is extended beyond just the interventions to their performance assessment as well. For example, urban water sustainable management studies by Burns et al. (2012); Butler (2007); Dixon et al. (1999); Fewkes & Wam (2000); Hunt et al. (2006) employed water supply interventions and evaluated them solely for water supply subsystem performance only, and not for the stormwater system performance, nor for the sanitation subsystem performance. These studies, in addition, did not evaluate whether the whole urban water subsystem...
Integrated assessment of urban water systems

Fig. 7.1 Urban water interventions (conventional and alternative), with their target urban water subsystem, and also their scale of application (mentioned in Scientific Literature), as sufficient options for an urban water system to return to sustainable performance.

generates the required boost in sustainable performance.

Therefore, the lack of adequate integrated assessments of urban water interventions limits the development of total systems solutions for urban water systems (Mitchell, 2006; Sitzenfrei & Rauch, 2014). Not only is information required for the performance of every possible intervention across every subsystem required for a complete integrated assessment, but also information on the comparative performance of one intervention against one another.

7.3 Review of the methods employed

As a pre-requisite to carry out an integrated assessment of the performance of an urban water intervention, information should be generated of the integrated urban water behaviour of this urban water system relative to the baseline (of a city of the developing world in this case). This comes against the background that integrated urban water modelling tool employed has the ability to simulate both the baseline conditions of the city as well as its corresponding
7.3 Review of the methods employed

'intervention' conditions.

For a given intervention once this characteristic urban water behaviour is defined, then 'performance' of this urban water intervention can be computed.

7.3.1 Integrated urban water modelling

To generate an integrated urban water behaviour simulation of this city of the developing world under both 'baseline' and 'interventions' conditions, the integrated urban water system WaterCycle, developed in this study was employed. The description of this urban water modelling tool is provided in section 3.4 and chapter 6.0 of this thesis.

However, the WaterCycle methodologies described in the sections of the thesis above, employ only baseline conditions, there was need to extend WaterCycle's methodologies to simulate the urban water behaviour of a developing world when intervened with numerous urban water interventions, both conventional and alternative, and whether applied individually or in combination.

7.3.2 Urban water interventions

Numerous urban water interventions were modelled and added to WaterCycle. The interventions studied included a spectrum of conventional, alternative, that is water-supply-related, or stormwater-related, and or sanitation-related interventions (as shown in figure 7.1). The approaches taken to represent and model each of the urban water interventions within WaterCycle are illustrated in table 3.9 and described in detail in section 3.5 of this thesis.

In traditional urban water practice, urban water interventions are usually applied and studied individually for a given urban water intervention. In this PhD study, this line of thought was further extended to test the hypothesis of applying urban water interventions in combination to given urban water system.

Therefore, the urban water interventions studied in this chapter included both the individually applied interventions as well as the sets (or combinations) of the individually applied interventions.
7.3.3 Sustainability performance assessment

Once the integrated urban water modelling tool was able to simulate both the 'baseline' and 'interventions' cases of the developing world, then a performance measurement regime of an urban water intervention and consequently the urban water system had to be introduced.

The performance assessment of an intervention was designed to relate to the main objective of an urban water system, which is to boost its sustainable performance. In this study, originality was added by designing a performance index for each of the urban water subsystem (for an given urban water interventions case relative to the baseline). In all, a given urban water interventions case will generate three performance indices to represent the aggregate performance of such an urban water system intervention.

For the urban water supply subsystem, the mains water savings indicator was employed, and it was presumed that an increase of mains water use would reflect a less sustainable urban water supply subsystem, since an increased mains water use is attributed to increased environmental degradation. For the urban stormwater subsystem, a sustainable performance was reflected through the total volume of stormwater runoff discharged from the urban water system. And for the urban sanitation subsystem, this was assessed through the total mass of contaminant (total nitrogen in this case) discharged from the urban water system.

The precise details of the methods and methodologies applied in this study to assess the integrated assessment of urban water systems is provided in section 3.4 of this thesis.

7.4 Results I - Performance of individually-applied interventions

7.4.1 Water supply interventions

The detailed hydraulic behaviour of each of the water supply interventions is appended (in appendix D). It is against this hydraulic behaviour that the sustainable performance of the interventions (figure 7.2a, figure 7.2b, and figure 7.2c) across the simulation period was generated. These figures show the summarised sustainable performance behaviour of the interventions over the simulation period. Then figure 7.3 shows their combined integrated performance for relative comparison.
7.4 Results I - Performance of individually-applied interventions

Fig. 7.2 Detailed relative performance (median + 95% CI) of water supply interventions
Rain Water - Rainwater Harvesting, Storm Water - Stormwater Harvesting, Grey Water - Greywater Harvesting, DM* - Demand Management, Conv** - Conventional Water Supply
7.4.1.1 Water supply subsystem performance

Of the water supply interventions investigated, only the conventional water supply intervention led to an increase in mains water use (implying a negative \(-14\%\) water supply subsystem performance), all the other interventions led to a reduction in mains water use (hence a positive water supply subsystem performance). This is reflected in figure 7.2a.

The rainfall dependent interventions of RWH and SWH provided the highest reduction in mains water consumption (a median water supply subsystem performance of 37\%, 36\% respectively) followed by the greywater recycling harvesting and demand management taps (each with a median water supply subsystem performance of 24\%). The demand management interventions of toilets and showers retribution led to the smallest reduction in water mains reduction (a median water supply subsystem performance of 2\% and 5\% respectively).

The negative/positive performance range of demand management with toilets or showers shows a characteristic that is typical of developing countries. In certain instances when the system is intervened with retrofitting toilets or showers, the water mains demand is so high that even a reduction in toilet water use or shower water use will not provide a positive impact. This could be explained the low penetration of toilet water or shower water use in the community under conditions of water scarcity.

On comparison with other studies in literature, localised RWH in led to system-wide performances in the range of 0.3 – 0.5 (Schuetze & Santiago-Fandino, 2013) and 0.15 – 0.8 (Rygaard et al., 2011), while demand management programs generated performances of 0.2 – 0.5 (Global Water Partnership Plan, 2012). The comparison revealed that due to the significant changes in climate between the regions, rainwater harvesting in tropical climates of the developing world generates lower ranges than that in the temperate environment. In addition, the demand management interventions despite their independence from climate, show wide variations due to the different urban landscapes in both regions. Demand Management interventions are entirely positive in the developed world, but ineffective at times within the developing world.

The poor performance of demand management interventions (use of low capacity appliances) is related to the low number of appliances users compared to the overall population of the town in a city of the developing world. Therefore, any savings these strategies provide are not adequate enough to get reflected in the overall urban water system performance. Though, at
7.4 Results I - Performance of individually-applied interventions

Fig. 7.3 Overall performance of water supply interventions (abbreviations as defined in figure 7.2)

an individual scale, demand management interventions are expected to generate considerable savings.

7.4.1.2 Stormwater subsystem performance

On the stormwater scale, all the water supply interventions provided a generally linear positive response - a reduction in the stormwater runoff downstream of the urban centre except for conventional water supply which actually delivers more water into the urban water system. The recycling-dependent interventions generally led to a reduction in downstream storm water flow that is a performance of 0.17 for RWH, of 0.18 – 0.19 for SWH, and 0.15 – 0.17 for GrWH. The demand management interventions led to marginal reductions in stormwater flow downstream of 0.026 – 0.033 for toilets retrification, 0.04 – 0.05 for showers retrification, and 0.17 – 0.02 for taps retrification. This is reflected in figure 7.2b.

As mentioned earlier, the lack of a significant number of in-house water appliances within the community limits any significant performance from demand management interventions. Though, no literature was found that provided an assessment of water supply interventions for their impact on the stormwater systems, hence it was not possible to assess the relative performance of water supply interventions. The rainwater and stormwater harvesting inter-
ventions lead to a direct reduction in rainwater and or stormwater flow since they employ part of it for water supply use.

7.4.1.3 Sanitation subsystem performance

On the sanitation subsystem behaviour, the water supply interventions appear to respond non-linearly to the sanitation subsystem (as shown in figure D.1c). Demand management and conventional water supply interventions generated a minimal impact on the sanitation system as shown in figure 7.2c.

The rain water harvesting, stormwater harvesting and greywater harvesting, however, led to significant changes in the concentration of the stormwater effluent from the urban centre. All these systems led to an increase in the stormwater concentration effluent, which in turn led to negative sanitation system performance as shown in figure 7.2c. This observation represents another characteristic that is particular to developing country urban systems. Due to the majority of urban residents employing on-site sanitation systems, that occasionally infiltrate their effluent to the subsurface runoff. Any reduction in the stormwater flow downstream leads to a higher concentration of stormwater effluent out of the city.

As observed with the stormwater system performance, there were no studies in the scientific literature that assessed water supply interventions on a sanitation subsystem scale. Among urban water system interventions studied in the scientific literature, urban water supply interventions were the most popular. However, despite their popularity (which can also be translated as popularity in application across the world), urban water supply interventions have a negative impact on the sanitation system.

7.4.1.4 Integrated performance

Figure 7.3 summarises the performance of the water supply interventions across all the three subsystems in the urban water system of a developing world. The figure shows that water harvesting systems (roof rain water, storm water, or grey water) display the same general trend. They generally lead to positive impact on both the water supply and stormwater subsystems, but a negative impact on the sanitation subsystem. This observation is attributed to the high distribution of on-site sanitation subsystems across the cities of the developing world.

The demand management systems, on the other hand, display a generally minimal positive impact across all urban water subsystems, except that Demand Management (Taps) pro-
7.4 Results I - Performance of individually-applied interventions

(a) Water supply subsystem performance

(b) Stormwater subsystem performance

(c) Sanitation subsystem performance

Fig. 7.4 Detailed relative performance (median + 95% CI) of stormwater interventions

Box* - Infiltration boxes with recycling
vide higher water supply system performance than demand management toilets or showers. Finally, conventional water supply systems provide a generally negative impact (on water supply and stormwater subsystems) but a minimal impact on the sanitation subsystem.

In summary, the integrated performance of water supply interventions shows that:

- interventions that have a high penetration rate across the household population generate the greatest impact across either of the subsystems
- the sanitation system is sensitive to interventions that have a direct impact on stormwater flow

### 7.4.2 Stormwater interventions

The hydraulic behaviour of each of the stormwater interventions is provided in Appendix D and its relative performance behaviour in figure 7.4a, figure 7.4b, and in figure 7.4c. in figure 7.5 then performance of all the stormwater interventions is combined.

#### 7.4.2.1 Water supply subsystem performance

Stormwater interventions do not provide a significant impact on the upstream water supply subsystem (as shown in figure 7.4a) except for the regional storm water harvesting and or infiltration boxes (which involve recycling) interventions.

#### 7.4.2.2 Stormwater subsystem performance

The stormwater interventions all lead to a significant reduction in the volume of stormwater exiting the urban water system (as shown in figure 7.4b), hence leading to significantly high stormwater performance. It should also be noted, as was observed with the water supply interventions, the uncertainty in upstream water use, does not affect the stormwater performance.

#### 7.4.2.3 Sanitation subsystem performance

However, in the sanitation subsystem due to the increased use of the natural stormwater system, these systems lead to a positive performance in the sanitation subsystem (relatively marginal positive performance) as shown in figure D.2c and figure 7.4c. The increase in stormwater flow through the natural subsystem, leads to a reduction in stormwater effluent concentration, hence leading to a positive sanitation performance.
7.4 Results I - Performance of individually-applied interventions

Fig. 7.5 Overall performance of stormwater interventions (abbreviations as defined in figure 7.4)

7.4.2.4 Integrated performance

The integrated relative performance of storm water interventions, shown in figure 7.5. It shows that stormwater interventions generated a relatively high performance across the stormwater system, but generally minimal impact across all the other subsystems (except for storm water harvesting and infiltration boxes [with recycling]). The stormwater recycling (with regional stormwater harvesting or infiltration boxes) leads to a significant positive impact to the water supply subsystem in addition to the high stormwater and marginal sanitation.

The integrated performance of stormwater interventions, in summary, show that:

- the water supply subsystem is affected only by the interventions that involve recycling
- the stormwater interventions (apart from conventional stormwater sewerage - not shown in figure) all provide highly positive stormwater performance
- the sanitation subsystem is still affected, though positively
- stormwater interventions provide positive performance across all the three subsystems
Integrated assessment of urban water systems

(a) Water supply subsystem performance

(b) Stormwater subsystem performance

(c) Sanitation subsystem performance

Fig. 7.6 Detailed relative performance (median + 95% CI) of sanitation interventions

Conv*** - Conventional sanitation, GrWH - Greywater Harvesting
7.4 Results I - Performance of individually-applied interventions

7.4.3 Sanitation interventions

The hydraulic behaviour of each of the sanitation interventions is shown in appendix D and their integrated performance in figure 7.6a, in figure 7.6b, in figure 7.6c, and in figure 7.7.

7.4.3.1 Water supply subsystem performance

The water supply subsystem performance behaviour (in figure 7.6a) shows that (1) the greywater recycling interventions have significant impact on the water supply system, (2) the reuse (solids only, urine, solids and reuse) interventions lead to a minimal impact on the water supply system, and (3) the conventional systems have minimal or insignificant impact.

7.4.3.2 Stormwater subsystem performance

The stormwater subsystem also displays a generally linear response of the urban water system to sanitation interventions (in figure 7.6b). The conventional interventions lead to a linear increase in the stormwater runoff output (in case of combined sewerage), hence leading to a negative impact on the stormwater subsystem.

The greywater recycling interventions still lead to a significantly positive impact on the stormwater subsystem because of their direct reduction in the stormwater effluent from the city. Urine diversion has no significant impact while the solids reuse systems also lead to a positive stormwater performance.

7.4.3.3 Sanitation subsystem performance

The sanitation interventions, on average lead to a linear response in the sanitation subsystem (in figure 7.6c). The conventional sanitation system (especially one connecting all the households) leads to a significant negative performance in sanitation system. The conventional systems lead to a higher wastewater flow output from the urban water system, hence leading to significant negative performance.

The greywater interventions now lead to varied response in the sanitation system. Regional greywater recycling leads to a minimal positive impact while local greywater recycling leads to a negative response. This was a surprising result. It could be attributed to balancing out effect (that is only HC households supply water supply to all other HHs) regional greywater harvesting presents in comparison to the local greywater harvesting (only HC HHs supply
Integrated assessment of urban water systems

Fig. 7.7 Overall performance of sanitation interventions (abbreviations defined in figure 7.6)

water to only HC HHs).

The reuse interventions of urine reuse, solids reuse, or solids and liquids reuse however lead to a positive impact on the sanitation system, as expected. It should noted that these interventions provide the highest sanitation system performance of all the interventions tested.

7.4.3.4 Integrated performance

The integrated assessment (in figure 7.7) of sanitation interventions reveals that all conventional sanitation systems (whether with slums consideration or not) have a negative impact on both the stormwater and sanitation subsystems. The conventional sewerage systems concentrate the blackwater through the pipes, through which they infiltrate to the stormwater systems through sewer infiltration, hence affecting the stormwater system performance. They affect the sanitation system through their conveyance of the blackwater to the wastewater treatment plant, and then finally to the receiving waters.

The grey water recycling interventions have a positive impact on both the water supply and stormwater subsystems, but minimal impact (positive for the regional intervention, negative
7.4 Results I - Performance of individually-applied interventions

for local intervention) on the sanitation subsystem.

The reuse interventions generally had a positive impact on the urban water system. Urine diversion or reuse had minimal impact on all interventions, while the solids reuse interventions provided a relatively more than marginal performance.

In summary, the integrated performance of sanitation interventions reveals that:

- the upstream subsystems (water supply and stormwater) are affected by interventions that involve recycling
- sanitation interventions, surprisingly, do not provide significant positive sanitation subsystem performance

7.4.4 Cross-sectional analysis of the performance

The previous section described in detail the performance of various individually applied interventions to an urban water system of the developing world. This section builds on this analysis and provides a cross-sectional view of the integrated performance of these interventions from the perspective of their attributes.

The attributes of concern when dealing with urban water systems include (1) their intended target subsystem, (2) their scale of application, (3) their use of recycling, or reuse of waste streams.

7.4.4.1 According to their target subsystem

The interventions considered in this study were grouped according to the nature of their target subsystem, that is, either water supply interventions, stormwater interventions, or sanitation interventions. This grouping was employed to explore the individual performance of each intervention.

According to this categorisation, the average integrated performance of water supply interventions is shown in figure 7.8. It is the water supply and sanitation interventions that generate a relatively higher positive impact on the water supply system than the stormwater interventions. This can be attributed to the user interfaces (toilets, showers, etc.) that both the water supply and sanitation interventions target. Note, the sanitation systems generate

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Integrated assessment of urban water systems

Fig. 7.8 Cross comparison of interventions performance according to interventions-type

relatively higher performance than the water supply interventions.

The stormwater interventions generate a minimal impact on the water supply subsystem. The stormwater interventions do not employ any interfaces that either water or sanitation interventions employ.

In the stormwater subsystem, stormwater interventions appear to stand out relative to the other interventions to provide a very high (> 0.5) stormwater subsystem performance. The sanitation and water supply interventions, led to a relatively marginal stormwater performance.

The sanitation subsystem led to relatively surprising results. All the interventions on-average led to minimal sanitation subsystem impact. While the water supply interventions led to a negative impact on average compared to the stormwater and sanitation interventions. The sanitation system in a low-income city is dominated by on-site sanitation system, any intervention that reduces the flow of stormwater significantly affects the sanitation subsystem performance. In this case, water supply interventions do reduce the volume of stormwater flowing downstream.
7.4 Results I - Performance of individually-applied interventions

![Graph showing performance of different subsystems at local and centralised scales.](image)

Fig. 7.9 Cross comparison of interventions performance according to their scale of application

### 7.4.4.2 According to their scale of application

The modelling system also revealed that if the interventions are categorised according to their scale of application - that is local or centralised (in figure 7.9). In the water supply subsystem, locally applied interventions appeared to lead to more positive impact than centrally applied interventions. In the stormwater subsystem, centralised interventions provided much higher impact. In the sanitation subsystem, the localised interventions led a minimal negative impact compared to centralised interventions.

The distributed nature of stormwater interface with users makes it sensitive to any intervention that is centralised, while the localised nature of water supply or sanitation interfaces makes it more suitable to localised solutions.

### 7.4.4.3 According to their use of recycling or reuse of waste streams

Interventions that employed waste water recycling had significant positive impact on the water supply and stormwater subsystems, and a significant negative impact on the sanitation subsystem, as shown in figure 7.10. While interventions without any recycling or reuse had only a significant impact on the stormwater subsystem. This can be attributed to the fact
Integrated assessment of urban water systems

Fig. 7.10 Cross comparison of interventions performance according to the recycle or reuse of waste streams that recycling reduces wastewater flow effluent into the stormwater system, which in turn increases the concentration of stormwater flows.

On the other hand, interventions that employed the reuse of waste streams (like urine or solids) had a minimal impact on the water supply subsystem, significant impact on the stormwater subsystem, but a significantly positive impact on the sanitation system.

7.4.5 Relationship between the subsystems

Figure 7.11 shows a novel relationship between the performances of the urban water subsystems for all the interventions. The figure shows that there is a moderate negative relationship between the urban water supply subsystem performance and the urban sanitation subsystem performance. This, in essence, implies that interventions that generally lead to a positive water supply subsystem performance, in turn, tend to lead to a negative sanitation subsystems performance and vice versa.

The relationship between the water supply subsystem performance and the stormwater subsystem performance showed a weak positive relationship in a similar way as the relationship between the stormwater subsystem performance and the sanitation subsystem performance.
7.4 Results I - Performance of individually-applied interventions

![Graphs showing relationships between urban water subsystems](image)

Fig. 7.11 Relationship between different urban water subsystems

This relationship implies that the interventions that lead to positive water supply subsystem performance (or positive sanitation subsystem performance) have no performance relationship with those that lead to positive stormwater subsystem performance. In other words, the interventions that lead to positive stormwater subsystem performance appear unrelated or independent from all the other interventions.

This confirms the deductions that have been observed throughout the other sections of this chapter. It appears that there is a serial relationship between water supply and sanitation interventions that should not be avoided, while it also appears that there is no significant relationship between stormwater interventions and the water supply or sanitation interventions. However, since the environmental performance of the urban water system driven by the nature of the stormwater subsystem, which in turn drives the sanitation subsystem, then it is imperative that in the design of urban water interventions the order in which stormwater, water supply, and sanitation interventions are implemented is given the emphasis it deserves.
7.5 Results II - Performance of combined-interventions

7.5.1 Introduction

As shown in section 7.4, none of the individually applied interventions could provide an all-positive sustainable performance across all the three urban water subsystems. This section however shows the integrated performance of an urban water system, when combined interventions are applied.

This section of the thesis therefore provides results of this activity of the study.

7.5.2 Results

Combining different interventions provided an increased number of options, from the 27 number individually applied interventions, to about 60 number possible combinations of urban water interventions. Table 7.1 shows the performance of each of the possible combination tested.

Of all the tested combinations, it was observed that sanitation performance remained the 'weakest' link of the tested combo interventions. Sanitation performance still varied between negative and marginal (<0.2) performance compared to the other subsystems. Nevertheless, of all the 60 number tested combo interventions, only 5 number interventions generated positive performance across all the three urban water subsystems. These interventions are highlighted in table 7.1 and included:

- Demand management taps combined with conventional sanitation
- Demand management showers combined with solids/liquids reuse
- Solids/liquids reuse combined with storage ponds
- Solids/Liquids reuse combined with storage wetlands
- Solids only reuse combined with storage wetlands

It was observed however that of all the combinations majority came from the sanitation interventions, confirming the importance and relevance of sanitation interventions in driving the sustainable performance of urban water systems.
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7.5.3 In comparison to individually-applied interventions

When the performance of individually applied interventions is compared to the intervention-combinations, there is general observed improvement in subsystem performances.

As shown in figure 7.12a, the water supply subsystem performance shows an improved performance for both the stormwater and sanitation interventions when intervened with combined interventions. The water supply subsystem performance for water supply interventions provided a mixed performance for the original individually applied interventions verses the combined interventions. There was no observed general improved performance of one group verses another.

In figure 7.12b, the stormwater subsystem performance of the combined interventions in general improved for both the sanitation and water supply interventions. The stormwater interventions, given their high performance of their individual systems, generated lower combined stormwater subsystem performance.

In figure 7.12c, the sanitation subsystem performance stormwater interventions gave an improvement when combined with other interventions. However, the water supply and sanitation interventions generated mixed and lower than expected sanitation subsystem performance. This performance of sanitation systems was also observed through the assessment of individually-applied interventions, sanitation interventions and sanitation subsystem performance is quite uncertain.

In summary, it can be said that combined different interventions significantly improves the urban water subsystem performance of the other subsystems. For example, water supply interventions provided better stormwater system performance than their individually applied counterparts. Also, stormwater interventions provided a better water supply subsystem performance than their individually-applied counterparts. And the sanitation interventions provided an improved water supply and stormwater subsystems performance than their individually applied counterparts.

This trend in performance is confirmed when the performance of all the individually-applied interventions are compared in uniformly with the combined interventions as shown in figure 7.13. The combined interventions provided a better performance for both the stormwater and water supply subsystems. However, the sanitation interventions did not provide an improvement.
7.5 Results II - Performance of combined-interventions

(a) Water supply subsystem

(b) Stormwater subsystem

(c) Sanitation subsystem

Fig. 7.12 Detailed performance of combined interventions in comparison to individually applied interventions
Integated assessment of urban water systems

Fig. 7.13 Overall performance of combined interventions in comparison to individually - applied interventions

7.6 Discussions

7.6.1 Background

In section 2.6 of this study, it has been shown that there are hardly any studies in the scientific literature that provide an assessment of the performance of urban water interventions across all the three major urban water subsystems, that is, the water supply subsystem, the stormwater subsystem, and or sanitation subsystem. Most studies assess urban water systems across a single subsystem of interest (for example in Burns et al. (2012); Butler (2007); Dixon et al. (1999); Fewkes & Wam (2000); Hunt et al. (2006), etc.), ignoring the impact on the other subsystems. Sharma et al. (2008) was the only study that attempted to assess urban water interventions across all the three subsystems. However, this study considered only a limited number of interventions.

Second, as much as there are few studies such as Achleitner et al. (2007); Friedrich (2006); Sharma et al. (2008); Wong et al. (2002) that assess an urban water intervention across the whole urban catchment. The majority of the studies discussed in the scientific literature focus their performance assessment of urban water interventions across localised households. In

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as much as the households might have positive urban water performance, it is not a direct indicator that the whole urban water system will be impacted positively. That is why the performance across the whole urban water system, is required. The study (in this thesis) however placed emphasis on the assessment of urban water interventions across the across the whole urban water system - that kind of study is novel.

In addition, it has been shown in scientific literature that though the strategies adopted for the improved performance of urban water systems push for a consideration of all possible interventions as well as for integrated urban water approaches, the focus of these strategies is on urban water systems of the developed world. The performance of urban water systems in the developing world is largely unknown.

It is these gaps in scientific knowledge that that this chapter sought to fill.

### 7.6.2 Performance of urban water interventions

In scientific literature, there are not many urban water interventions are studied for their performance assessment. Table 7.2 shows the performance of some of the interventions tested in this study verses that could not be found in literature.

#### 7.6.2.1 Water supply interventions

Of the water supply interventions found in literature, rain water harvesting systems were the most studied. They were studied for both water supply subsystem and the stormwater subsystem performances. In literature, rainwater harvesting systems were found to generate an urban water supply subsystem performances in the range 0.3 – 0.6 (see table 7.2) which was in general comparable to urban water subsystem performance generated through this thesis.

Demand Management interventions, on the other hand, displayed urban water supply system performance of 0.11 – 0.24 (in scientific literature, see table 7.2). In this thesis, the demand management interventions generated an urban water subsystem performance of 0.02 – 0.2, again which is comparable. Localised greywater recycling generated an urban water systems performance of 0.12 – 0.3 which is also very similar to the performance generated in this thesis of 0.13 – 0.33. The stormwater system performance also led to relatively results with a performance of 0.14 – 0.20 in literature, compared to a 0.15 – 0.17 in this thesis.

In summary, it can be concluded that the performance of most urban water supply interventions across the urban water supply and stormwater subsystems, is comparable for both the developing and the developed world. This observation can be used to confirm and validate the accuracy of the integrated modelling and performance assessment of methodologies and revelations generated from this thesis.

### 7.6.2.2 Stormwater interventions

Despite the popularity of stormwater interventions, among the alternative urban water interventions, they presented the least studied or documented studies in literature (from an integrated urban water management perspective). In the scientific literature, only green roofs in Li & Babcock (2014), urban wetlands in Wong et al. (2002), and stormwater harvesting in Hunt et al. (2006) were found, and they were all assessed across the stormwater subsystem only.

In table 7.2, green roofs and stormwater harvesting systems generated stormwater subsystem performance that is comparable for both those found in literature verses those generated in this study. The stormwater wetlands were a surprise, but this variation could be attributed to the impact of different urban landscape on the performance of stormwater systems.

### 7.6.2.3 Sanitation interventions

Urine separation or reuse was found to generate a sanitation subsystem performance of 0.1 – 0.25, while solids reuse despite the mention was not assessed precisely but as one that leads to a positive sanitation performance. In this thesis, urine reuse generated a sanitation system performance of 0.04 – 0.13, while solids reuse a performance of 0.07 – 0.14. These performance demonstrate a similarity in general performance trend despite the significantly different urban landscapes.

All in all, the subsystem performances of interventions found in literature verses similar interventions assessed in this thesis, reveals a generally comparable performance, despite the change in urban landscapes between both scenarios. This revelation not only confirms the accuracy of the urban water subsystems performances carried out in this study, but also appears to suggest that the performance of urban water systems is comparable across different urban landscapes.
7.6.3 Urban water management

7.6.3.1 Introduction

In chapter 3.0 of this study, the scientific literature on urban water practice revealed that the process of improving the sustainable performance of an urban water system involves the selection and application of an appropriate intervention (or urban water systems technology) to urban water system to boost its sustainable performance. The selection of the urban water intervention required is usually limited to: (1) the urban water paradigm employed, and (2) the urban water subsystem whose performance is targeted for improvement. Most studies (such as those by Burns et al. (2012); Butler (2007); Dixon et al. (1999); Fewkes & Wam (2000); Hunt et al. (2006), etc.) assess urban water systems across a single subsystem of interest, ignoring the impact the interventions have on the other subsystems. The studies, however, that provide an integrated assessment similar to the one in this paper (such as Achleitner et al. (2007); Erni et al. (2010); Friedrich (2006); Mah et al. (2009); Mitchell (2006); Sharma et al. (2008); Wong et al. (2002)) were carried out on a limited number of interventions (and also did not assess the interventions across all three subsystems).

This chapter has therefore attempted to fill this gap in scientific knowledge by suggesting and testing an approach to assessing numerous urban water interventions across all the three urban water subsystems. The approach was tested on 28 possible urban water interventions to illustrate the relevance of this kind of assessment to modern urban water management, both individually and in combination.

7.6.3.2 Revelations

7.6.3.2.1 Individually - applied interventions

Of the 28 individually - applied interventions, none of them generated a significant positive urban water subsystem performance across all the three urban water subsystems. This was taken to imply that no single individually applied urban water intervention has the capability to boost improved sustainable performance of an urban water system across the three subsystems. And that the usual urban water practice of considering only one intervention at a time to an urban water system is flawed and misleading.

The performance of all the alternative urban water interventions showed considerable variation. The study has revealed that these interventions are still designed to target a single urban water subsystem and as such, no single intervention provided an all-round positive performance across all the three urban water subsystems. It can be said this is because the
urban water interventions are designed to target only one of the three subsystems, and hence the intervention would not be expected to boost all the three subsystems.

The study further revealed that the interventions that lead to positive water supply subsystem performance in turn generally lead to significant negative sanitation subsystem performance. The interventions that lead to positive stormwater subsystem performance though are are generally independent of all the other interventions (except for recycling-based interventions).

In summary, this study has revealed that to achieve an all-round sustainable performance of an urban water system, that is sustainable across the whole urban water system and across each of the individual subsystems (as advocated by Closas et al. (2012); Loftus (2011); Sharma et al. (2008)), the process of choosing the most appropriate ‘intervention’ should allow for the consideration of a mix of interventions, instead of the usual procedure of considering only a single intervention. The chapter goes further to give an indication of how this choice should be made. The chapter concludes that stormwater interventions should be considered in due consideration of how they affect the sanitation subsystem, while water supply interventions and the sanitation interventions should be considered as a package.

7.6.3.2.2 Combined interventions

To further test the hypothesis that applied a mix of interventions can lead to better urban water performance than individually - applied interventions, this study investigated the performance of mixed interventions on an urban water system. The study revealed that the use of combined interventions doubled the possible number of interventions options available for a given urban water system, that is from the possible 28 number with individually applied interventions to the 60 number with mixed interventions.

The testing of numerous mixed interventions revealed an improved urban water performance in comparison to individually - applied interventions. In addition, the mixed interventions generated 5 number interventions that generated all-positive urban water subsystem performance across all the three urban water subsystems.

7.6.3.2.3 Conclusions

Given that the accuracy of the modelling system employed in this study has been confirmed, in the generation of realistic urban water subsystem performance values. It can be deduced from this study that
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- the practice of improving the sustainable performance of an urban water system through the application of only a single urban water intervention is flawed and misleading
- this practice can be improved by considering the application of a mix of interventions instead of a single intervention
- the appropriate mix of interventions to be applied to a given urban water system, will have to be tested through an integrated urban water assessment simulation.

7.6.3.2.4 Limitations and further research
The study of the performance of urban water interventions in this study has the following limitations:

- the study focused its view of urban water sustainable performance to the only the physical water environment parameters.
- the study does not put into consideration the economic cost of the various interventions, which can have an impact the choice of the most appropriate interventions
- the study also assumed that each of these interventions will have 100% social acceptance rate across the whole community.

It is not possible to ascertain the impact of these limitations on the conclusions this study has generated on the scientific body of knowledge. It is therefore befitting to recommend a further study on how the impact of these limitations have on the impact of urban water interventions on the urban water subsystems performance.

7.7 Summary

This chapter of the thesis has presented a methodology for the assessment of an urban water systems that considers the integrated performance of urban water interventions, verses the usual single subsystem performance. This integrated assessment approach illustrates that the current practice of urban water assessments, that considers each intervention according to the urban water subsystem it targets, is misleading in terms of the sustainable performance of these interventions. The integrated assessment of interventions is novel because it summarises the performance of numerous interventions (both conventional and alternative) across all the urban water subsystems. No previous studies have reported a similar methodology of form of assessment.
It also proposes that this assessment is of relevance to modern urban water management in that it reveals information about the system that cannot be generated by current isolated urban water assessment methods. The study has shown that of all the 28 urban water interventions studied, none of them provided a significant positive performance across all the three urban water subsystems. It showed that most interventions provide a performance that is strong in one or two of the subsystems but poor or negative in the third subsystem. This implies then that for an optimal and sustainable performance of an urban water system, it is inevitable that two or three interventions will have to be combined in a single urban water system.

Hence, as an overall conclusion, this study reveals that it is not prudent to assume or presume that one kind of urban water intervention will generate all the required subsystem performances required of a sustainable urban water system. This study, therefore, recommends that the urban water procedure for selecting the most optimal intervention(s) for a given urban water system should consider an optimisation procedure that tests the urban water subsystem performance(s) of each of the interventions.

Finally, it should be mentioned that this study was conducted under limited resources (data, funding), but despite these challenges, it has generated unique insights and guides for future studies.
Chapter 8

General Discussions and Conclusions

This chapter of the thesis correlates study objectives, methodologies and findings to highlight and discuss the scientific relevance of the study. It then summaries all the findings as conclusions, lessons learnt as well as presenting proposals for future studies.

8.1 Research Summary

8.1.1 Introduction

The study described in this thesis focuses on the practice of urban water management in a city of the developing world. It is premised on the possibility of generating an in-depth understanding modern urban water management across cities in the developing world. Since it is the urban water systems of the developed world that are more documented and studied in the scientific literature than those of the developing world, this study focuses on the developing world systems, to contribute valuable scientific knowledge about their sustainable behaviour.

In spite the absence of urban water management studies on cities of the developing world, this study was also premised on the presumption that the cities of the developing world, are different in landscape and urban water behaviour from those of the developed world. Because of these differences, it also presumed that urban water systems of the developing world will behave and respond differently to any interventions applied to boost its sustainable performance.

However, to study the sustainable performance of urban water systems of the developing world, the study quickly noticed the absence of background information (and tools) to support this line of study. Therefore to bridge these knowledge gaps, this study then, had to generate
General Discussions and Conclusions

novel analysis and modelling tools or methodologies to allow for the study of the sustainable behaviour of urban water systems in the developing world.

The following sections summarise the key research outputs of this thesis:

8.1.2 System analysis of longitudinal dynamics of urban water systems

Chapter 4.0 of the thesis provided an innovative and novel methodology of analysing urban water supply systems to generate fundamental knowledge of their behaviour, employing and extending the limited data, usually available in cities in the developing world. Even if, the method focuses on urban water supply systems, it can be extended to downstream subsystems if their elementary data is available.

The chapter employed an approach to generate fundamental dynamics of an urban water supply system. This approach (time series analysis from a systems perspective) has found applications within mainly water resources applications, but hardly in urban water resources applications. With urban water systems in the developing that lack adequate data (but rainfall and monthly billings), this data can be employed to deduce various originally unknown fundamental dynamics about the system.

This approach revealed that part of the longitudinal dynamics of mains water consumption is driven by the dynamics of the input rainfall despite the presence of storage with the system. However, those dynamics reflect an inverse relationship between the rainfall and the mains water consumption due to the presence of rain water harvesting with the town. Hence, in the design of conventional urban water systems, in the developing world, the influence of local rain water harvesting should not be neglected, if an optimal design is required.

Finally, the study also revealed that the urban water system behaves linearly at a variety of time steps such as monthly, bi-monthly, every 3 months, and every 6 months, which can be extrapolated to daily, weekly time-steps. This conclusion implies that any modelling assignment that involves or assumes a linear behaviour of the system should be applied at only these time steps. Any other time steps will lead to inconsistent results.

In terms of urban water philosophy, this chapter of the thesis introduced a new methodology for assessing urban water systems, that is novel to the conventional assessment of urban water systems. This method provides detailed holistic knowledge of the system, knowledge which is fundamental to the assessment of the basic sustainable performance of the system. This
methodology is of relevance, as pre-requisite knowledge, to justify the need for intervening in the system.

In terms of new knowledge, this chapter revealed that utilising this methodology has the ability to generate information about an urban water supply system - information that was not originally available through other approaches. Time series analysis revealed that the case urban water system requires a storage time of 4 – 9 days for the system to perform efficiently.

8.1.3 Water end-use modelling

In chapter 5.0 of the thesis, again due to the absence of knowledge and data within urban water systems of the developing world, the thesis provided an innovative and novel methodology for evaluating the water end-use volumes of the community. The chapter demonstrated a novel approach for simulating and evaluating of water end-use volumes in an urban community of a developing country, by improving the accuracy of the collected household survey end-use data, through a stochastic modelling simulation. This approach was carried out on the premise that the existing water end-use modelling approaches, which were developed for systems of the developed world, are not adequate and/or appropriate for the developing world.

The simulated end-use volumes of house-connected users (who were assumed to be relatively comparable to developed country communities) were found to be relatively lower than comparable communities in the developed world. At the same time, the yard-tap users (who were assumed to be relatively comparable to rural communities) were found to have higher end-use volumes than rural communities. The principal differences in this water end-use behaviour was found to be hidden in (1) the presence or absence of certain end-uses in this community versus the developed country communities, (2) and even within the similar end-uses, some of the end-use parameters were significantly different, reflecting a difference in water use culture of both communities. This study, therefore, concludes with a caution that water end-use characteristics of one community should be employed sparingly to assess or design decentralised systems of another community, otherwise they might lead to misleading results.

The study also showed that showering (or bathing) water end-use is, on average, the largest household water use for both house-connected users and yard-tap connected households, but it was not the most uncertain. In yard-tap customers, hand-washing was the most uncertain household water end-use, while showering was again the most uncertain water end-use in the
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house-connected water users.

Finally, in terms of new knowledge, this chapter provided detailed estimates of the water end-use information of a city of the developing world. Such information is not available to this detail in scientific literature. The end-use volumes characteristics could then be employed in the design of appropriate urban water interventions to boost the sustainable performance of urban water systems of the developing country city.

8.1.4 Integrated urban water modelling

This chapter 6.0 of the thesis described a methodology of mathematically describing the hydrology of water, stormwater and wastewater flow within an urban community of the developing country. Fletcher et al. (2013) reviewed this phenomenon and concluded that generating reliable modelling tools to quantify the hydrology of an urban catchment, was one of the greatest challenges of the last 20 years. In the last 10 years, this gap has been getting filled up with tools like Aquacycle, UWOT, CWB, and now WaterMet, however, all these tools focused on urban catchments in the developed world.

In these modelling systems, the urban catchment landscape of the developing world was not given priority, their representation of an urban water system. This chapter proposed a contribution by designing an urban water system representation of the specific urban water hydrology of water and wastewater of a developing world system flow right from household to the whole town-wide scale.

In addition, it was observed that within the existing integrated modelling systems, the water end-use representation is not suitable for an urban water behaviour of the developing world. Using the research output from chapter 5.0, this thesis then added a more realistic water end-use representation to the integrated modelling systems (that is a stochastic variation of the mains water use (and or stochastic generation of wastewater)). This addition then improves the way an integrated modelling system represents a city of the developing world.

The modelling system computes the water use hydrograph, the stormwater flow hydrograph and the pollutant concentration pollutograph as its major results. These results together being generated from a single integrated urban water modelling system represents a great and novel achievement in the urban water hydrology. This modelling system can now be applied to study the impact different interventions will have on the sustainable performance of an urban water system.
8.1.5 Integrated assessment of urban water systems

Chapter 8.0 of the thesis then, presented and illustrated a methodology of assessing an urban water system for its integrated performance and consequently sustainability. This integrated assessment approach illustrates that the current practice of urban water assessments, that considers each intervention according to the urban water subsystem it targets, is misleading in terms revealing accurately the sustainable performance of an urban water system. The integrated assessment of interventions (that is an urban water system with interventions applied to it) is novel because it summarises the performance of numerous interventions (both conventional and alternative) across all the three urban water subsystems. Existing integrated urban water system performance assessments do not consider this kind of assessment.

This study revealed that (1) none of tested interventions could generate an all-round significant positive urban water subsystem performance across all the three urban water subsystems when applied individually to an urban water system. In other words, no single individually applied urban water intervention has the capability to boost improved sustainable performance of an urban water system across the three subsystems. And that the usual urban water practice of considering only one intervention at a time to an urban water system is flawed and misleading.

In summary, this study has revealed that to achieve an all-round sustainable performance of an urban water system, that is sustainable across the whole urban water system and across each of the individual subsystems (as advocated by Closas et al. (2012), Sharma et al. (2008), and Loftus (2011)), the process of choosing the most appropriate 'intervention' should allow for the consideration of a mix of interventions, instead of the usual procedure of considering only a single intervention. This hypothesis was tested further in this study.

On testing with mix interventions, this study concluded revealed that the application of combined interventions doubled the possible number of interventions options available for a given urban water system, that is from the possible 28 number with individually applied interventions to the 60 number with mixed interventions. And also, confirmed the hypothesis that mixed interventions generated a better urban water performance (across the three subsystems) relative to the individually-applied interventions.

In addition, the mixed interventions managed to provide 5 number mix-interventions that generated all-positive urban water subsystem performance across all the three urban water
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subsystems.

In terms of new knowledge, this chapter revealed that in terms of urban water system performance, water supply subsystem performance is inversely related to the performance of the sanitation subsystem. Also, the study also revealed that if (1) DM Taps is combined with conventional sanitation, or (2) DM showers with Solids and Liquids reuse, and (3) Solids and Liquids reuse with stormwater Ponds or Wetlands; an all-round significant positive sustainable performance across the three subsystems.

The chapter then concludes that this assessment is of relevance to modern urban water management in that it reveals information about the system that cannot be generated by current isolated urban water assessment methods. And as such recommends that it is not prudent to assume or presume that one kind of urban water intervention will generate all the required subsystem performances for a sustainable urban water system. Hence, the urban water procedure for selecting the most optimal intervention(s) for a given urban water system should consider an optimisation procedure that tests the urban water subsystem performance(s) of each of the interventions.

8.2 Discussion

In general, within the scientific literature, there is a limited presence of knowledge, tools and information on the behaviour of urban water systems of the developing world. The majority of research and knowledge documented of the behaviour of urban water systems, is for systems from the developed world. The behaviour developing world systems is therefore usually inferred from what has is known of the developed world systems. This study argued that inferring developing world systems from the developed world is a misleading presumption that can generate unrealistic conclusions and deductions about systems in the developing world. This study, therefore, pursued a path to fill some of these voids in the scientific knowledge of systems of the developing world.

The existing discussions on urban water management in the developing world (such as Porto et al. (2007b), Mara (2006), Montgomery & Elimelech (2007), Bell et al. (1993), Lee & Schwab (2005), Jacobsen et al. (2013)) place emphasis providing the basic urban water services such as adequate water supply and sanitation. In the developed world discussions (numerous references) however, the emphasis is placed on optimising the sustainable performance of the urban water systems. This suggests that the urban water systems knowledge
levels are different. Chapter 2.0 of the thesis illustrated this argument by suggesting developed world systems are a step higher than developing world systems in terms of development evolution. These divergent views between both systems is what led to the major research question of this thesis, that do the systems of the developing world have to follow the same path to sustainable development as the developed world systems.

Against this background, this thesis generates findings and revelations to bridge between these two divergent views for developing world systems. The study provides avenues through which an urban water system of the developing world can follow to generate the required urban water services sustainably. For a developed world system, these avenues have already been defined in the scientific literature, this thesis argues then that these avenues may not be applicable to developing world systems.

The research output (in chapter 4.0), provided the first novel avenue, by introducing time series approach as a novel approach for the hydrodynamic assessment of urban water supply systems with limited data availability or with mixed water supply systems usage. The novelty of this tool to modern urban water management is that it provides an alternative approach to the generating fundamental insights into the performance and operation of the urban water system, insights that are not necessarily available through the traditional longitudinal dynamics urban water accounting approaches. This chapter introduces this methodology and illustrates its application to systems of the developing world.

The research output (in chapter 5.0), on the other hand, generates both an approach and information on urban water systems of the developing world. The chapter generated a novel approach for simulating and evaluating water end-use volumes in an urban community of a developing country. It involved the improvement of the accuracy of the household survey end-use data, through a stochastic modelling simulation. In addition, this chapter of the thesis, provided unit water end-use information (that is always lacking in scientific literature) to quantify the urban water behaviour of a city of the developing world, which can be employed as grey data any future urban studies.

The research output (in chapter 6.0), generated an integrated urban water modelling approach applicable to cities of the developing world. In urban water systems of the developed world, integrated modelling is still an infant and growing body of scientific knowledge (Mitchell et al. (2007), Urich & Rauch (2014), and Behzadian & Kapelan (2015)). And as such, it does not have documented applications of integrated urban water modelling of cities of
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the developing world. This thesis, therefore, in a bid to fill this void, built and extended already existing approaches of integrated modelling to develop insights and methodologies to generate an integrated modelling algorithm for cities of the developing world. In conclusion, this chapter of the thesis makes a scientific contribution of the bridging the gap of generating an integrated urban water modelling appropriate for a city of the developing world.

The climax of the research output (in chapter 7.0), generated a novel approach to an integrated assessment of an urban water system. The chapter proposes that this assessment is of relevance to modern urban water management in that it reveals information about the system that cannot be generated by traditional urban water assessment methods. In traditional integrated urban water management (even for studies of cities (even in developing world cities like Poustie & Deletic (2014), Closas et al. (2012)) integrated urban water management is carried out without consideration of the contribution to each subsystem. The novelty of integrated assessment introduced by this chapter extends beyond developing world urban water systems.

The scientific contribution of this research illustrated by Sitzenfrei & Rauch (2014). Sitzenfrei & Rauch (2014) stated that there is a general lack of integrated modelling studies, that assess comprehensively a large number of studies, modelling real-world case studies. This research output provides a comprehensive assessment of 28 No. urban water interventions (under a stochastic scenario assessment of 1000 instances each), hence contributing to this body of knowledge, and all these case studies were for systems in the developing world.

In addition, this thesis makes significant scientific contributions, by providing insights into the urban water behaviour of developing world systems. The thesis introduces a number of novel tools that fill the void left by the inadequacies of the existing traditional urban water assessment approaches (and or the unavailability of data). But in a bid to generate novel approaches to improving the sustainable behaviour of systems of the developing world, this thesis then generates an innovative approach to the integrated assessment of urban water systems performance. This integrated assessment then generated insights about urban water systems that are applicable to all types of urban water systems.

8.3 Recommendations

The major challenge (and critique) to the research output (in chapter 4.0), of introducing time series methods as an alternative to urban water accounting methods, is that the applications
were built on data of a coarse time-step (monthly). In as much as time series analysis, provides an alternative to the traditional hydrologic assessment of data-limited urban water systems, its insights and approaches are best demonstrated if a dataset of finer time-steps is employed. It is therefore recommended that this approach is confirmed through an urban water system that has a data-rich system. In addition, the study did not validate the time series analysis through a comparative hydrological modelling of the urban water system. It also, therefore, recommended that this approach is validated through comparative hydrological modelling assessment.

The integrated modelling system developed through this thesis (in chapter 5.0) added a more precise description of the urban water landscape (as well as urban water use population) to generate an integrated simulation of the urban water behaviour of a developing world urban water system. In the thesis, the development of the integrated urban modelling system is developed through an improvement of the description of the urban landscape (and urban water use hydrology) of an urban water system. However, in this thesis, due to the absence of measurement data, it was not possible to fully calibrate the hydrological computation of integrated modelling system. It is therefore recommended that this integrated modelling system is confirmed through a developing world urban water system, with a more elaborate calibration and validation dataset.

The integrated assessment of urban water systems (in chapter 6.0) developed a novel methodology of assessing urban water systems. The study concluded that it is not prudent to assume or presume that one kind of urban water intervention will generate all the required subsystem performances to ensure a sustainable urban water system. It is therefore recommended that this approach is tested in a study to illustrate the appropriate interventions permutations to boost sustainable performance across an urban water system.
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Appendix A

Paper I

This section of the thesis displays the contents of the journal paper (denoted as Paper 1) that was submitted to an international journal. This paper has been submitted to Urban Water Journal.

In general, the reviewers agreed that the application of time series analysis appears to be technically correct, but the representation of the journal paper required more work. The authors all gave the same similar comment that the paper required more justification or illustration into the weaknesses of the traditional methods, as a way to improve or illustrate the precise novelty of the time series analysis approach is introducing.

Some of the reviewer’s comments were addressed as part of the revision of chapter 6.0 of this thesis, however, it was felt that the justification required by the authors involved more data collection, and more data analysis. This justification and data analysis was out of the scope of this thesis, and hence was not pursued at this time.

A.1 The paper as submitted to Urban Water Journal (UWJ)
Introducing Time Series Analysis as alternative and novel approach to characterise the fundamental hydrodynamics of an urban water supply system

Kenneth Muniina, Cedo Maksimovic, Nigel Graham
Imperial College London
k.muniina11@imperial.ac.uk

Abstract

This paper introduces and illustrates the application of time series analysis as a tool to supplement traditional urban water hydrological modelling approaches. In this paper, the tool was applied to understand the relationship between the rainfall input to an urban water supply system and its associated mains water consumption, in an essentially rainfall-fed urban water supply system of a developing country. Time series analysis systems analysis provided insights into the behaviour of the urban water system that are not necessarily available through the traditional urban water hydrological modelling approaches, but however cannot replace the information generated by the traditional hydrological modelling approaches.

1. INTRODUCTION

1.1. The need for appropriate urban water accounting

Many centralized urban water supply systems across the developing and developed world are struggling to sustain the provision of water to their users (Al-Jayyoussi, 2003; Sharma et al., 2013). The reasons for this failure of centralized water supply systems are varied but most point to the inherent weaknesses within the centralized urban water management approach, as illustrated in Khatri, K. and Vairavanmoorthy (2007); Bdour et al. (2009); Blackmore and Plant (2008); Fidar et al. (2010); Memon et al. (2005); Sharma et al. (2010); Zhang et al. (2007). One of the approaches that has been advocated for, to improve the sustainable performance of urban water supply systems, involves the use of adequate water accounting systems (Kayaga and Smout, 2011; Mutikanga, 2012), as a tool to assess and monitor the performance of the urban water systems. Urban water accounting in this case implies the process of describing the mathematical relationship between the urban water system’s input water volume with the system’s water losses, the system’s storage dynamics, and the water consumption (Mutikanga, 2012).

In urban water systems, water budgeting is often referred to as hydrological modelling, which involves the process of accounting of the water input volume to the urban water supply system as the sum of the water consumed, and the change in internal storage (within any physical tanks and pipelines), and to any water lost from the system through leakage (Mutikanga, 2012). Despite, the preference this methodology gets for application across various urban water systems (Cook et al., 2009; Chan et al., 2010; Mitchell and Cleugh, 2008), it has varied applications, and hence varied interpretations.

In conventional urban water supply systems, water accounting is usually practised through either the IWA/AWWA water balance approach and or hydrological water balance modelling. The IWA/AWWA water balance approach, focused on the water input and water output to the water distribution system Mutikanga (2012), in order to estimate the system’s water loss components. In hydrological modelling approach (for example the the double mass curve approach), the focus is on the water input and water output to the water supply system right from the raw water input to the consumption output, as illustrated
in Mutesi et al. (2006); Raghunath (2006). The objective of this approach is usually on quantifying the volume storage required to balance the divergence between input and output variabilities. Therefore, despite the similarity in these methods, there focus and urban water supply system schematisation is different. Hence, the information they generate is subjective.

In addition, these methods have a high data requirement for their successful application. Mutikanga (2012) mentioned that the absence of data in certain components of the water balance leads to misleading or subjective water budget assessments. Hence, making these methods inappropriate for urban water systems with limited data availability, such as those in the developing world. Further, in both approaches, the urban water system is rarely schematised to include the rainfall input as a component, even if most of the urban water systems across both the developing and developed world, are rainfall-dependent.

Therefore, with the limitation of these conventional approaches in characterising the hydrodynamics of an urban water supply system (especially systems with limited data availability), there is need for novel approaches to reveal the hydrodynamic performance of such systems. This paper therefore attempts to provide an alternative approach of characterising the fundamental hydrodynamics of an urban water system with aid of time series analysis.

2. Methods

2.1. The case of urban water systems in the developing world

Many urban water supply systems in the developing world, are usually characterised by a rain-fed supply (that is, their water source is directly or indirectly fed by rain falling on the catchment), a limited and mostly inaccurate data description of their internal pipeline structures, and an almost wholly metered customer base. The water supply system’s major input, rainfall, is usually monitored regularly (from a national weather station), and the mains water consumption (water exiting the system) is also monitored for billing purposes. Hence, for most of these urban water systems, the input (rainfall) and output (mains water consumption) time series are the most reliable and available data series they have or have access to. In these kind of urban water systems, application of the IWA or the Double Mass Curve methodologies will certainly lead to highly misleading results and interpretations. However, since the systems are all rain-fed, the relationship between the rainfall-input and the water consumption output, is of ultimate relevance to the strategic management of these urban water systems.

These urban water systems are in a way synonymous to many complex natural water systems, for which have only input-output data series as the most reliable data to deduce the hydrological and hydraulic functioning of the system. For example, in complex ground water systems (Bailly-Comte et al., 2008; Gelhar, 1974; Jencov and Petrie, 2010; Mathew et al., 2004) or in complex river catchments (Bourodimos, Elstathious and Oguntunase, Abiase, 1974; Chow, 1969; Lafreniere and Sharp, 2003), the input rainfall and output (catchment river flow) data was assessed through time series analysis methodology to deduce the systems fundamental hydrological and hydraulic behaviour of these systems - information that is of relevance to the systems future development intervention. Because of this analogy in circumstances intervention between these natural water systems and urban water systems in the developing world, time series analysis methodology was employed to assess the hydrologic and hydraulic functioning of the urban water system in a small town of the developing world.
2.2. Time Series Analysis for Systems Assessment

2.2.1 Introduction

The methodology schematizes an urban water supply system as a "black box system" (with a single water input, through the system, leading to a single water output) that filters or modulates the input stochastic signal (or time series) to generate an output stochastic signal (Mathevet et al., 2004). This is illustrated in figure 1. Then analysis of this modulation effect provides an understanding of the fundamental longitudinal hydrological functioning of the water system. The modulation effect is viewed through the revelations provided by statistical methods of auto-correlation and cross-correlation of the input/output stochastic time processes (Labat et al., 2000; Bailly-Comte et al., 2008).

Essentially and analytically, the mains water consumed from the urban water system is considered to be an integral sum of (1) the system input rainfall, (2) the system storage, and (3) any significant water losses (Chow, 1969). Then this mathematical relationship is assessed through time series techniques of autocorrelation, cross correlation, autospectral analysis, and cross-spectral analysis. The details of the mathematical description are provided in appendix A. In this section, a skeleton brief of the methods and their relevance to water supply systems is described.

2.2.2 Correlation Analysis

The autocorrelation assessment of each of the input and output time series is used to quantify any linear dependency of successive values in either of the input or output series. This individual assessment of each series, characterises the nature and structure of each of the input or output time series, which then gives an indication of how the output series is transformed relative to the input, and in so doing outline the effect of water supply system memory on the output series (Mathevet et al., 2004). That is, if an event has a long term influence on any of the time series, its output auto-correlogram slope is expected to decrease gradually as a function of the lag time. In summary, the auto-correlation analysis provides an insight into the individual stochastic structure of each of the input and output time series, and their linear inter-dependency over a given time period.

The cross correlation assessment of the input series against the output series was used to show which of the two series dominates (or leads) the other, through the water supply system. If there is a lead, an estimate of that lead or delay time, was estimated as the lag time difference between the initial (lag time = 0) and the point of maximum cross-correlation. This lead or delay time estimation is usually taken to represent the peak impulse response time of the system. Hence, the cross correlation function can be used to estimate the approximate time lags at which the two series are well-correlated. This also, is a guide for estimation of the impulse response time of the system.

The autocorrelation and cross correlation analyses, however, are carried out in the time domain. In the frequency domain, further analysis of the impulse response (now called frequency response) of the system is represented by the auto-spectral and cross spectral analyses. For the auto-spectral density function of each of the series, a large value (usually spike) of the spectral density is taken to respond to the frequency that is strongly represented in the series (Molenat et al., 2000; Mathevet et al., 2004). In summary, a comparison of the input series against output spectral densities will reveal which periodicities in the input series are still prevalent in the output series, which is a further indication of the impulse response of the system.

2.2.3 Spectral Analysis

The cross-spectral density analysis of the input against the output series was interpreted as a measure of the covariance between the respective fre-
quency components in the two series, in a way showing how the input signal is modified by the system to produce the output signal. However, the frequency response of the system (which is equivalent to the systems impulse response in the time domain) is characterised fundamentally by the Cross Gain and Cross Phase Functions, which are all indirectly further modules of the cross spectral analysis.

The Cross Gain Function (GGF) expresses whether, at each frequency, the output series is amplified (\(>1\)) or attenuated (\(<1\)) relative to the input series by the system. The Cross Phase Function (CPF) estimates the extent to which, at each frequency component, one series leads or lags the other (i.e. the delay of output with respect to input). The time equivalent of this lead or lag is estimated through the slope of the phase function at a given frequency, assuming the phase function is linear at that frequency. Hause, John (1971) recommends the interpretation of this time lag as a system characteristic time. For the case of a water supply scheme, this characteristic time was taken to represent the time measure of a time representation of the storage capacity of the system - that is the mean transfer time of water through the system.

The final module of the cross spectral analysis computed for comparison of the input against the output is the cross coherency function (COF), which is used to show the linear correlation between the frequency components of the two series. It shows whether variations in the output series respond to the same type of variations in the input series, and thereby indicates the presence or absence of any linearity in the input-output relationship (Tam et al., 2005). A system is linear if \(COF \approx 1\), and implies that a change in the input series creates a proportional change within the output series. If the COF shows a very chaotic pattern with values much greater than unity, that is \(COF > 1\), non-linearity very likely exists in the system and other input factors should be considered in the description of the system. However, the COF should not be interpreted by itself, but in conjunction with other functions.

A more mathematically description of this approach is provided in appendix A.

2.3. Case Study - Mbarara Town

The urban water supply service system of a town in South West Uganda (a developing country) was employed as the case study to illustrate the application this approach. Mbarara is a medium-size town (relative to other towns in the country) with an estimated population of 195,000 in the national census of 2014. The water supply infrastructure in the town consists of a centralised water mains network, sourcing water from River Rwiizi that traverses the town. The water pipe network reaches and supplies mains water to approximately 82% of the households and institutions resident within the town. The remaining water users employ mainly decentralised sources like protected springs, boreholes but mainly localised rain water harvesting. However, decentralised water sources (especially localised rain water harvesting) are not only employed by the non-mains water users, but also by the mains water users as a secondary source to complement the unreliable centralised mains water. A recent study carried out in the area, by the author, showed that over 47% of the mains water users in the area employ rain water harvesting as their primary or secondary household water supply source. Therefore, as a water usage service model in the area, it can be concluded that residents in this town employ a mixture of centralised and decentralised urban water supply systems and that the system is rain-fed.

The town experiences a tropical climate with two rainy seasons separated by two dry seasons, with an annual monthly average rainfall of 97.5mm. This availability of rainfall could explain the widespread use of rain water harvesting in the town to complement the centralised water supply (Howard and Bartram, 2005). The rainfall that the small town catchment receives, is recorded on a daily scale at a
national weather monitoring station situated within the town. The mains water use at every water user’s premises in the system is monitored through a meter, on a monthly basis - mainly for billing purposes. The volume of localised rain water usage relative to the mains water at a given user location is not monitored or assessed.

2.4 Systems Representation of the Urban Water System

As mentioned earlier, the first step in this approach is to represent the urban water supply system as a Single-In-Single-Out black box system (SISO). In the representation of Mbarara town urban water supply system, the rainfall was considered as the single input with the mains water consumption as the single output, as illustrated in figure 1. This choice was dictated by the availability of these two datasets, and because the water supply system in this town is rain-fed.

Since the mains water consumption data was of monthly scale, for the time series analysis, monthly rainfall data was computed from daily rainfall measurements at a national weather station in Mbarara (for period 2008 – 2012). Since it is essentially an independent analysis of each time series is carried out, there was no need for change of units (of the rainfall depth to volume).

3. Results

3.1 Temporal Domain Analysis

3.1.1 Auto Correlation

The rainfall correlogram in figure 2a reveals that the input rainfall system consists of periodic oscillations of period of approximately 3 months, with minimal damping. The mains water consumption correlogram (in figure 2a) reveals that the mains water consumption does not contain significant oscillations despite of significantly periodic input. The output correlogram is though slowly descending, with minimal oscillations.

The gradual descent of the output correlogram is usually taken as indication of the influence of a system’s memory on the input to produce the output. The system’s memory in this case could represent an effect of the water supply internal structure (representing mainly the storage). This result demonstrates the impact of the water supply system’s storage structure on the mains water consumption. However, recomputing the output correlogram without the effect of the long-term [as a way to magnify the oscillations in the output], as shown in figure 2b, reveals that the mains water consumption is also comprised of significant oscillations, oscillating around a longitudinal average mains water consumption. The oscillations in the mains water, appear not to correspond directly corresponding in lag time to the oscillations in the input. This is a preliminary indicator that the periodicity of mains water consumption is not a result of the rainfall variations only.

Following the trend of the mains water consumption correlogram (in figure 2b) with that of the sequential rainfall, can generate further insights into the possible drivers of the oscillations in the water mains consumption. The mains water changes gradient (from a high descent gradient to gradual descent gradient) at time lag 1, while the rainfall, though still descending, changes gradient to a gradual descent at the same time lag. The rainfall then changes gradient further at lag 3 to start increasing, while the mains water consumption changes to a slower descent gradient but still descending. The mains water consumption continues the descent till lag 6, at which point the rainfall peaks. The rainfall starts to decrease again at lag 6, while the mains consumption is still rising for a further one lag the starts decreasing. This trend appears to suggest that there could be an inverse relationship between the input (rainfall) and the output (mains water consumption).

This inverse relationship raises key fundamental questions when it comes to the behaviour of mains
water consumption in an urban centre, with a rain-fed urban water supply system. Usually, mains water consumption is assumed to be independent (that is, its variation does not depend on any external factors like rainfall), but this analysis is showing that presumption is not necessarily accurate for urban water supply systems of the developing world. For the mains water to have an inverse relationship with the rainfall input, then possibility the household water consumption structure should include another silent driver (like localised rainwater harvesting) that is responsible for this behaviour. In this way, for a constant total household consumption, the mains water use in a household should vary interchangeably with the use of locally harvesting rain water (which is also depends on the availability of rainfall).

3.1.2 Cross Correlation

The figure 2c and 2d of cross correlation illustrates further the complex relationship between the rainfall and the mains water consumption. Cross Correlation analysis confirms that the periodicity of the rainfall contributes to the periodicity in the mains water consumed. These oscillations in the mains water consumption are amplified with the elimination of the long term trend from the mains water series (in figure 2d).

Further comparison of the cross correlogram with the rainfall input (in figure 2d), the effect of a combined household water consumption model described in section 3.1.1 is illustrated further. The cross correlation starts increasing while the rainfall is still decreasing at lag 2, the mains water consumption starts reducing while the rainfall is still increasing at lag 5. The rainfall starts increasing again at lag 7 while the rain is still decreasing, only to peak at the same time as the rain approaches its minimum lag time. This observation goes on to reaffirm that in a given household, both mains water and rain water harvesting are employed concurrently, one to supplement the other. And that the peak mains water use occurs when rainfall is at its minimum, and vice versa.

3.1.3 Temporal Domain Analysis - Conclusion

The temporal domain analysis reveals that the input rainfall is periodic with a 3 months period. The output mains water consumption however is not as periodic as the input but has an additional set of oscillations that do not correspond (in timing and amplitude) to the input. This behaviour could be attributed to the presence of an additional driver in the water supply system, that is not specified system schematic, and is responsible for additional oscillations in the output. This was attributed to the widespread use of localized rain water harvesting across the community.

The temporal analysis further illustrated that the input rainfall has an inverse relationship with the mains water consumption, in that when the rainfall is at its minimum, the mains water consumption is at its maximum, and vice versa. This inverse relationship was also attributed to the widespread use of localised rainwater harvesting in the community, that it affects the mains water consumption trends.

From a water supply perspective, time series analysis has demonstrated that localised rain water harvesting has an sequential impact on the mains water consumption, at least in an urban water system of the developing. This revelation reveals that in a community with centralised urban water supply system, the effect of localised rain water harvesting should not be underestimated during the interventions design process of the system. Therefore, this effect should be compensated for in any water demand estimations (especially if the estimations are based on mains water consumption measurements).

3.2 Frequency Domain Analysis

3.2.1 Auto Spectral Analysis

The rainfall input spectrogram (figure 3a) of the series reveals that the rainfall (input) consists of
two major frequencies (of periods 6, 3 months) as well as some minor oscillations. The mains water consumption output spectrogram (figure 3a) reveals that the mains water consumption consists of one primary frequency (of period 6 month), with two secondary frequencies (of periods 3, and 12 months), and numerous minor frequencies. The spectral analysis, therefore confirms that the rainfall input still exerts a certain level of dominance over mains water consumption, but is not its main driver.

The change of the major frequencies in the mains water consumption, from the one originating from the input (of period 6 months), to the one observed in the output (of period 3 months). That coupled with numerous minor frequencies (of periods of approximately 3, 2, 1 months) in the output, signifies the presence of another driver in the system. This confirms the impact localised rain water harvesting has on the mains water consumption - which was first observed in the cross-correlation.

3.2.2 Cross Spectral Analysis

The cross amplitude function (figure 3b) shows that the major oscillations observed in the mains water are a result of the rainfall input into the system. Though, not all the oscillations in the cross amplitude function correspond to the major and minor frequencies in the input.

With this correspondence in frequencies between the input and the output, it is expected that the water supply system will exhibit linear behaviour at these frequencies. The linear behaviour implies that, at this frequency the input just traverses through the system with minimum delay. This is illustrated in the coherence plot in figure 3c. The coherence plot shows that the system is linear (when r ≥ 0.5) at frequencies 5/24, 7.5/24, 14/24, 20/24 which correspond to periodicities of wavelengths 6, 3, 1.7, 1.2 months. All these periodicities appear to originate from known system drivers, some from input system like the rainfall (6 months, 3 months), and the others (1.7 months, 1.2 months which can approximated to 2 and 1 monthly periods) from the household water consumption behaviour (daily, weekly, monthly). However, the system behaves linearly highest (at frequency correlation r ≥ 0.8) which corresponds the monthly periodicity.

Though, on the other hand, from a water supply systems perspective a linear behaviour an urban water supply system could be taken as a representation of poor internal structure (for example its storage requirement) of the system. This further affirms that time series analysis as an approach can be employed to provide an indicative assessment of an urban water supply system.

The phase function shows a dome-like or trough-like shape at each of the linear frequencies except the 6 month period as shown in figure 3d. The dome-like shape can be interpreted as two lines that change gradient within and around that frequency. This change in gradient from positive to negative can be interpreted as a mixture of two processes during that cycle. At one time, the water is draining through the system (that is the mains water is leading), and at another time the system is filling up with water (so the rainfall input is leading). Using the phase function, characteristic times were computed for the system, which correspond to the response times of the system (hence the time it takes the system to drain or the system to fill up). These times are detailed in table 1.

The time series analysis reveals that water supply system has a characteristic filling time that varies from 2.0 days to 8.5 days with an average of 5.78 days. While the systems characteristic draining times range from 4.5 days to 7.5 days with an average of 5.43 days. The draining and filling times could be corresponding to the amount of internal storage that the system requires to stabilise.
3.2.3 Frequency Domain Analysis - Conclusion

The frequency analysis of the system shows that the system is driven partly by the rainfall (input) and partly by the household water consumption behaviours, which is an indication of the system's instability. The coherence frequency plot shows that the system behaves linearly (highest) at monthly periodicities, which can be down-scaled to daily time steps. The phase function plot shows that the system water has an average transfer time of about 5.8 days for filling, and 5.4 days for draining. This time scale could be taken to represent the amount of internal storage the system requires to stabilise.

4. DISCUSSION

4.1. Relevance of Time Series Analysis in Urban Water Systems Assessment

This paper describes a time series approach as a novel method to the hydrodynamic assessment of urban water supply systems. The approach provides fundamental insights into the performance and operation of the urban water system, insights that are not necessarily available through the conventional urban water balance approaches.

In rain-fed water supply systems for which the overall water source is the catchment rainfall, the traditional water supply assessment approaches would require a tremendous amount of computational effort to generate a dynamic relationship between the rainfall falling on the catchment and the water consumption in the system. These weaknesses of the traditional water supply systems assessment are what make this method of time series analysis relevant for modern urban water supply performance assessment.

4.2. The novelty of time series systems

The Temporal domain analysis revealed the mains water consumption has an inverse relationship with the input rainfall as a consequence of localised rain water harvesting use within the area. This relationship cannot be generated through conventional IWA/AWWA or Double Mass Curve methodology.

The Frequency Domain analysis of the system revealed that the urban water system is driven partly by the rainfall input, not by the pumped water system input as the IWA/AWWA approaches appear to suggest. In addition, the analysis also generated some indications on the appropriate storage required to stabilise the system.

These findings reveal that time series analysis as a method applicable to urban water supply systems, provides insights about the water supply system that are not only of relevance to traditional urban water system design, but also insights that cannot be easily generated by the traditional methods.

4.3. Weakness of the Time Series Analysis approach

The time series systems analysis methodology despite its major strengths does exhibit some weakness. For a successful volume of insights, a large volume of time series data is required (preferably at smaller time series). In this study, monthly data was employed, implying that certain insights that occur at daily or smaller time series, could not be generated.

Also, it must be mentioned that this approach, provides only indicative insights into the hydrodynamic behaviour of an urban water system. Insights, which inspite of being unique to the traditional hydrological methods, they cannot replace the information provided by the existing traditional methods. Therefore, this approach can only be employed to supplement the existing traditional urban water assessments.

5. CONCLUSION

This paper has introduced and illustrated a method of time series analysis that provides fundamental in-
sights into the interaction of an urban water system’s major processes (that is rainfall and mains water consumption). Though, this type of analysis does not aim to describe the detailed urban hydrology of the urban water supply system, it captures the mean hydrological behaviour of the urban water supply system, as well as estimate some of the system’s characteristic time scales. Hence, this method can be employed as the first diagnostic tool for the analysis of the urban water supply system especially in the preparation of any centralised or decentralised interventions, or in performance assessment of an urban water system.

The paper also shows that time series analysis provides insights about a water supply system, that require considerable effort to estimate using traditional hydraulic or hydrologic modelling assessments. Therefore, this approach is relevant to modern urban water management, and will be of significant importance as a first diagnostic tool to complement traditional modelling approaches.

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List of figures

**Figure 1.** How Time Series Analysis amplifies hydrodynamic behaviour of a Water Supply System

**Figure 2.** Auto and Cross Correlation OUTPUT between rainfall and mains water consumption

**Figure 3.** Auto and Cross Spectral analysis output between rainfall and mains water consumption
River Rwizi
(Rainfall)

Mbarara Town Water Supply System

Q_{in}

Q_{out}
(Mains Water)

System Modulation Effect

Autocorrelation

Cross Correlation

The fundamental hydrodynamics of the water supply system

Auto-Spectral Frequency Analysis

Cross-Spectral Frequency Analysis

**Figure 1:** How Time Series Analysis amplifies hydrodynamic behaviour of a Water Supply System
Figure 2: Auto and Cross Correlation OUTPUT between rainfall and mains water consumption
Figure 3: Auto and Cross Spectral analysis output between rainfall and mains water consumption
Table 1: The Water Supply System Residence Times at various frequencies (with their associated drivers)

<table>
<thead>
<tr>
<th>Periodicity</th>
<th>Slope (Ph)</th>
<th>RT (Months)</th>
<th>RT (Days)</th>
<th>System Driver</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual</td>
<td>0.95 / -0.92</td>
<td>0.15 / -0.15</td>
<td>4.5 / 4.4</td>
<td>Rainfall / HH Consumption</td>
</tr>
<tr>
<td>Bi-annual</td>
<td>-1.43</td>
<td>-0.23</td>
<td>-6.8</td>
<td>HH Consumption</td>
</tr>
<tr>
<td>Quarterly</td>
<td>1.57 / -1.78</td>
<td>0.25 / -0.28</td>
<td>7.5 / 8.5</td>
<td>Rainfall / HH Consumption</td>
</tr>
<tr>
<td>Every 2 Months</td>
<td>-0.42 / 1.12</td>
<td>-0.07 / 0.18</td>
<td>-2.0 / 5.3</td>
<td>HH Consumption / Rainfall</td>
</tr>
</tbody>
</table>

A. APPENDIX A

A MORE MATHEMATICAL DESCRIPTION OF THE TIME SERIES ANALYSIS CONCEPTS

In conventional time series analysis, a system is considered to be a Single-In-Single-Out (SISO) black box system that filters or modulates an input stochastic signal (or time series) to produce an output stochastic signal (time series) (Mathevet et al., 2004). Then analysis of this modulation effect provides an understanding of the fundamental temporal hydrological functioning of the system. The modulation effect is viewed through the lens of autocorrelation and cross-correlation of the input/output stochastic time processes, and also through their auto and cross spectral correlation (Labat et al., 2000; Bailly-Comte et al., 2008).

For mathematical representation of an urban water system as a SISO, its system input is discretised time series as $x_{n}$ and the system output as $y_{n}$, where $n$ is the total number of data pairs available. Using this naming convention, the autocorrelation functions or correlograms of both the input ($r_{x}(k)$) and output ($r_{y}(k)$) series are mathematically described as:

$$r_{x}(k) = \frac{C_{x}(k)}{C_{x}(0)}$$  \hspace{1cm} (1)

$$r_{y}(k) = \frac{C_{y}(k)}{C_{y}(0)}$$  \hspace{1cm} (2)

where $k$ is the time lag ($k = 0, m$), with $m$ representing the system memory. $C_{x}(k)$, $C_{y}(k)$ are the auto-covariances of the input and output series which are described as:

$$C_{x}(k) = \frac{1}{n} \sum_{n=k}^{n-k} (x_{i} - \bar{x})(x_{i+k} - \bar{x})$$  \hspace{1cm} (3)

$$C_{y}(k) = \frac{1}{n} \sum_{n=k}^{n-k} (y_{i} - \bar{y})(y_{i+k} - \bar{y})$$  \hspace{1cm} (4)

The auto-correlograms quantify any linear dependency of successive values in either of the input or output series, and in so doing they outline the memory of the system as represented separately by the input and output (Mathevet et al., 2004). That is, if an event has a long term influence on the time series, the slope of the autocorrelation function decreases slowly as a function of the time lag $k$. In short, the correlation analysis provides an insight into the individual stochastic structure of each of the input and output time series, and their linear dependency over a time period.
The cross correlation function (CCF) between the input and output series is mathematically described as:

\[ r_{xy} = \frac{C_{xy}(k)}{\sigma_x \sigma_y} \]  \hspace{1cm} (5)

\[ r_{yx} = \frac{C_{yx}(k)}{\sigma_x \sigma_y} \]  \hspace{1cm} (6)

where

\[ C_{xy}(k) = \frac{1}{n} \sum_{i=1}^{n-k} (x_i - \bar{x})(y_{i+k} - \bar{y}) \]  \hspace{1cm} (7)

\[ C_{yx}(k) = \frac{1}{n} \sum_{i=1}^{n-k} (y_i - \bar{y})(x_{i+k} - \bar{x}) \]  \hspace{1cm} (8)

The cross correlation function is not symmetrical: \( r_{xy} \neq r_{yx} \). That is, if \( r_{xy} > 0 \) for \( k > 0 \), the input series \( x_i \) influences (or leads) the output series \( y_i \), while if \( r_{xy} > 0 \) for \( k < 0 \) the output series \( y_i \) influences (or leads) the input series \( x_i \). And if it is leading, the delay time, is estimated as the lag time between \( k = 0 \) and the point of maximum \( (r_{xy}(k)) \): - this estimation represents the peak impulse response time of the system. Hence, the cross correlation function can be used to estimate the approximate time lags at which the two series are well-correlated - this is a guide for estimation of the impulse response time of the system.

The autocorrelation and cross correlation functions analyses are carried out in the time domain. In the frequency domain, further analysis of the impulse response (now called frequency response) of the system is represented by the **Spectral Density** and **Cross Spectral Density** functions. The spectral density function \( S_x(f) \) of the input time series \( x_i \) corresponds to the discrete-time Fourier Transform of the input's autocorrelation function \( r_x(k) \), and correspondingly for the output series as shown in the equation below:

\[ S_x(f) = \int_{-\infty}^{\infty} r_x(\tau) e^{-2\pi ft} d\tau \]  \hspace{1cm} (9)

\[ S_y(f) = \int_{-\infty}^{\infty} r_y(\tau) e^{-2\pi ft} d\tau \]  \hspace{1cm} (10)

A large value of the spectral density of either series corresponds to the frequency that is strongly represented in the time series (that is - strong periodicities) (Molen et al., 2000; Mathevet et al., 2004). Therefore, the \( S_x \) and the \( S_y \) will show which periodicities in the input series are still prevalent in the output series - further indication of the impulse response of the system.

In the same way, the cross-spectral density function \( S_{xy} \) the discrete-time Fourier Transform of the cross correlation function \( r_{xy}(k) \) of the input/output series. The magnitude of the cross spectral density is the called the cross-amplitude function (CAF):

\[ S_{xy}(f) = \int_{-\infty}^{\infty} r_{xy}(\tau) e^{-2\pi ft} d\tau \]  \hspace{1cm} (11)

\[ \text{CAF}_{xy}(f) = |S_{xy}(f)| \]  \hspace{1cm} (12)

The CAF can be interpreted as a measure of the covariance between the respective frequency components in the two series, showing a way in which the input signal has been modified by the system to produce the output signal. However, the frequency response of the system (which is equivalent to the systems impulse response
in the time domain) is characterised fundamentally by the Cross Gain $G_{sy}$ and Cross Phase Functions $\phi_{sy}$, which are all indirectly modules of the CAF. They are defined directly through a new function, the Transfer Function $H_{sy}$ of the system (ratio of the spectral densities of the output and input), whose relationship to CAF is described below:

\[
S_y(f) = H_{sy} S_x(f) \tag{13}
\]

\[
H_{sy} = G_{sy} e^{-j\phi(f)} \tag{14}
\]

\[
G_{sy} = |H_{sy}(f)| = \frac{|\text{CAF}_{sy}(f)|}{|S_y(f)|} \tag{15}
\]

\[
\phi_{sy} = \arg[H_{sy}(f)] = \arg[|\text{CAF}_{sy}(f)|] \tag{16}
\]

The Cross Gain Function (GGF) expresses whether, at each frequency, the output series is amplified (> 1) or attenuated (< 1) relative to the input series by the system. The Cross Phase Function (CPF) estimates the extent to which, at each frequency component, one series leads or lags the other (i.e. the delay of output with respect to input). The time equivalent of this lead or lag is estimated through the slope of the phase function at a given frequency, assuming the phase function is linear at that frequency. Though, (Hauge, John. 1971) cautions that the interpretation of this phase statistic should depend upon the system model or class of models that has been assumed to govern the relationship between the input and output series. If the system is a distributed linear system (like a SISO), and for a given frequency $f_x$, its output leads the input if $\phi$ is positive, and that its output lags the input if $\phi$ is negative. Then time delay $t_0$ for this kind of system is represented as:

\[
t_0 = \frac{\phi_{slope}}{-2\pi f_x} \tag{17}
\]

where $\phi_{slope}$ is the estimated slope of the line of best fit of the phase function at frequency $f_x$. Since the phase function is not always linear for most systems, (Molénat et al., 1999) suggests that the phase function analysis should be carried out in partnership with the cross-coherency function (COF) - described later in the section. The COF should be used first to indicate at which frequencies, the system behaves linearly, and it is at these frequencies that the time delay $t_0$ should be computed according to equation 17.

However, the system's time delay $t_0$ represents to the system much more than a pure delay, it is prudent to consider it a characteristic time scale of the system (Manga, 1999). This is because, different authors have computed it for their systems, and categorically ascribed it different descriptions, descriptions that are appropriate for the system being investigated. For example; (Molénat et al., 1999) described $t_0$ as a system response time, (Manga, 1999) described it as a hydraulic response time, (Molenat et al., 2000) as a system's residence time, (Bailly-Comte et al., 2008) as a mean transfer time which can be used to show how well drained the system is (Mathevet et al., 2004), and consequently its storage capacity.

The Cross Coherency Function (COF) $\text{COF}_{sy}(f)$ is described mathematically as:

\[
\text{COF}_{sy}(f) = \frac{\text{CAF}_{sy}(f)}{\sqrt{S_x(f) S_y(f)}} \tag{18}
\]

$\text{COF}_{sy}$ can be interpreted as the linear correlation between the frequency components of the two series. It shows whether variations in the output series respond to the same type of variations in the input series, and thereby indicates the linearity between the input-output relationship (Tan et al., 2005). A system is linear if $\text{COF}_{sy} \approx 1$, and implies that a change in the input series creates a proportional change in the output series. If
the COF shows a very chaotic pattern with values much greater than unity, that is $COF_y > 1$, non-linearity very likely exists in the system and that other input factors should be considered in the description of the system. However, the COF should not be interpreted by itself, but in conjunction with other functions.
Appendix B

Paper II

B.1 The paper as submitted to Urban Water Journal (UWJ)
A novel approach for estimating urban water end use characteristics of cities in the developing world

Kenneth Muniina, Cedo Maksimovic & Nigel Graham

To cite this article: Kenneth Muniina, Cedo Maksimovic & Nigel Graham (2017) A novel approach for estimating urban water end use characteristics of cities in the developing world, Urban Water Journal, 14:7, 750-757, DOI: 10.1080/1573062X.2016.1254253

To link to this article: http://dx.doi.org/10.1080/1573062X.2016.1254253
A novel approach for estimating urban water end use characteristics of cities in the developing world

Kenneth Munjua, Cedro Maksimovic and Nigel Graham
Department of Civil and Environmental Engineering, Imperial College, London

ABSTRACT
The design of alternative urban water supply interventions for a community located in a low-income country requires detailed and precise knowledge of the nature, frequency and intensity of various characteristic water end-uses in the community. Without the availability of this characteristic water use information, high resolution metering experiments are the usually preferred methods to measure the water use volumes. However, in the developing world, these high resolution experiments are not an affordable option. Leaving the imprecise household interviewing process of data collection as the only option. This paper presents a novel methodology that improves and expands on the socially collected water uses data, through the use of a stochastic modelling process of the water use volumes to estimate the total monthly water use of the community. The methodology not only improves the estimates of water use volumes but also provides a mathematical description of the household water uses in the community.

1. Introduction
It is becoming accepted that conventional urban water supply systems across both the developing and developed world are struggling to sustain provision of appropriate water services to their users. The unsustainable behaviour of these systems is related to their inherent weaknesses such as delivering high quality potable water to all the users who require only a small fraction of the water for potable end uses like drinking or cooking (Sharma et al. 2013). As a result of this unsustainable behaviour, the centralised (or conventional) urban water service model is being ruled out as the most appropriate solution for urban water supply (Zhang et al. 2007, Sharma et al. 2010, 2013) in either the developing or the developed world.

This failure of the conventional urban water supply service model has led many authors, such as Porto et al. (2007), Bdour et al. (2009), Blackmore and Plant (2008), Ficar et al. (2010), Memen et al. (2005), Sharma et al. (2010), Zhang et al. (2007) to advocate for alternative urban water supply service models to improve sustainability. Such alternative urban water system service models are centred on a fit-for-purpose water distribution principle (Cook et al. 2009, Sharma et al. 2013) that requires the supply of water to be driven by the quality requirements of each specific end-use the water is intended for (Sharma et al. 2010). Such design of an urban water intervention requires the total water use in the community to be broken into a series of streams of the various water end-uses (Philip 2011).

In urban communities of low-income countries, this kind of design is challenging due to the unavailability of water end-use information that is specific to these communities. However, in urban communities of the developed world, water end-use information is collected through high resolution metering experiments, as demonstrated in Al Amin et al. (2011), Athuraliya et al. (2008, 2012b), Beal and Stewart (2011), Dziegielewski et al. (2000), Heinrich (2007), Heinrich and Isaacs (2008), Jethoo and Poonia (2011), Keshavari et al. (2006), Lu and Smout (2010). In the developing world, high resolution metering of end-uses would be inappropriate and impractical owing to its relatively large resource requirements. Hence, social survey methods are the only feasible approach to estimate water end use volumes in these communities.

Employing social survey methods to estimate volumes of water end use generates imprecise and uncertain data on water use, despite its ease. The method involves asking residents to recall their water use instead of physical measurement leading to inaccurate results (Athuraliya et al. 2008, Otaki et al. 2008). This paper therefore, provides a methodology that attempts to improve the accuracy of socially-generated water end-use data to generate a more representative and expanded quantification of water end-uses in a low-income urban water community.

2. Methods
2.1. Introduction
The methodology being suggested in this paper involves (1) the collection of representative water use data (both water end-use and billing data) from a low-income community, (2) then using this data to generate and calibrate a stochastic water end-use demand model of the community.

2.2. The water use community
An urban community from south-west Uganda (Mbarara town), which has an urban resident population of 192,000 was
employed as the case for this study. The town is supplied with piped water, sourced from a river traversing the town, with a supply coverage rate of about 82% (that is the percentage of mains water users against the total town population). Of the mains water users, the study however focused on the resident water user population (who represent about 80% of the mains water using population).

The community, like most urban centres in the developing world, consists of a heterogeneous resident population. The heterogeneity (related to their water use behaviour) was schematised by categorising the user population into two main groups: house-connected water users and yard-tap-connected water users. House-connected water users, who are 33% of the mains supplied resident population, represent households that receive water directly in to the house, and thus employ in-door water appliances like flushing toilets, showers, and hand-wash basins. Yard-tap water users, who are 67% of the mains supplied water users, represent households that receive water by means of an outdoor tap, and thus use the water through hand-held containers. Such water users also employ on-site sanitation facilities like pit latrines implying that they do not employ any in-house water appliances. This heterogeneity is shown diagrammatically in Figure 1.

The community is located in a tropical climate zone, which receives both a rainy and a dry season. In the dry season, it is expected that the water use intensity is greater in the community compared to the rainy season. Therefore, in this study, the water use data was collected during the dry season, but the analysis was carried out for each of the wet and dry season independently. The water use in the wet season is assumed to reduce within the mains water use but increase through localised household rain water harvesting.

2.3. Data collection

Two forms of data were employed in this study: (1) socially collected water end-use data, (2) and the measured household monthly water consumption accessed from the local water utility operator operating the piped water supply system in the community.

The water end-use data was collected by means of household interviews from a sample of randomly selected household water users (a sample size of 423) during the dry season. The nature of the end-uses for each group was defined with the aid of local socio-economic experts and are shown in Figure 1. For each end-use, data was collected (1) of its water use intensity (or volume), and (2) of its frequency.

Secondly, to ease the measurement of the volume or intensity of water used, water users were asked to estimate their usage intensity in units of jerry cans (or in terms of cans or basins employed in the area). The local water users in the area have a better sense of the number of cans they employ than in terms of litres or cubic metres. For end-uses like toilet use (for house connections), hand washing (both yard tap and house connections), showering (for house connections) that require further parameters to complete the end-use computation, data from the high-resolution metering study by Athuraliya et al. (2008) in Australia was employed. This data was chosen because it was a reasonable match for this community, given that both communities experience similar day temperatures. Further, as an assumption, all the end-uses were assumed to have a penetration rate of 1.0, with all the water users employing them on a daily or weekly scale.

The other set of data employed in the study, the measured monthly consumption (or utility billing data) was accessed from the national utility, the National Water and Sewerage Corporation. In this community, like many other urban communities in the developing countries, all mains supplied water users are metered and hence their monthly consumption is regularly monitored by the utility.

2.4. Stochastic modelling

The water use modelling is similar in principle to the pulse demand modelling work in Buchberger and Wu (1995), Buchberger and Wells (1996), Rauch et al. (2003), Memon et al.
The same group of inhabitants - their measured monthly water consumption on record, (m³/month)

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(c) Measured Monthly consumption (billing)

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(a) Social Surveying

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(b) Stochastic Modelling

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(d) Model Calibration

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Simulated Monthly Consumption

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Measured Monthly Consumption

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A group of randomly selected town inhabitants are assessed socially on the amount of end water they consume per end use (litre/day)

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Figure 2. The modelling methodology approach applied.

(2005), Haashoff (2006), Blokker et al. (2010), Creaco et al. (2016), but closer in detail to works by Haashoff (2006), Blokker et al. (2010). In general the modelling involves the generation of water use volumes, through the aggregation of respective water end-uses (across different households) to generate the overall water demand of the community. In this study though, socially collected water use data is used as an input to the stochastic model, and also the study is applied to a low-income community. The pulse demand models mentioned earlier (as summarised in Rathnayaka et al. (2011), Creaco et al. (2016)) focus on applications in high-income communities.

The methodology employed to model and calibrate the water end-use volumes for each group in the community is schematised in Figure 2. The components (that is the frequency and or the intensity) of each end-use were represented as a probability distribution model. Since data collected through household interviews is susceptible to human errors (or is uncertain), the probability distribution model of each water end-use component was considered to represent its uncertainty or statistical spread. However, the position and spread parameters of the probability distribution model adopted for each water end-use component was calibrated to improve the predictability of the overall water end-use model in estimating the overall monthly water use of the community. Thus, the calibrated end-use stochastic models are taken to represent the actual end-use volume distribution of the water users in that town.

A more elaborate description of the water end-use model employed in this study, including its mathematical details, calibration and validation methods are provided in the supplementary material.

3. Results

3.1. Model calibration and validation

The results of the calibration procedure are shown in Figure 3 for both yard-tap water users and for house-connected water users, in the dry season. The aim of the calibration exercise was to use the water end-use model to predict the monthly water consumption for each of the yard-tap and the house-connected water users in the community. Hence, confirming the appropriateness of the developed water end-use model in representing overall water consumption in the community.

For all the months simulated, the measured monthly water consumption values were within the interquartile range of the model simulations as shown in Figure 3(a) for yard tap water users and Figure 3(b) for house-connected water users. The cumulative frequency distributions were also compared graphically as shown in Figure 3(c) and in Figure 3(d), and analytically using the Kolmogorov-Smirnov test. The figures show that both the simulations and the measured consumption data are comparable numerically and statistically (with Kolmogorov-Smirnov test h = 0 at 5% significant level) for all the groups. Hence, it can be concluded that fitted probability distributions of the water end-use components are an optimal representation of the water end-use in the community.

3.2. Characteristics of the community water end-use

3.2.1. Global distribution of the community water uses

Supplementary material figures A3, A4 and A5 show the results of the probability fitting process of the socially collected water consumption end-use data of the community, as well as the parameters of their respective distributions. The strength of the fit was measured with aid of the correlation coefficient (not reported in the figures) which was moderately high (> 0.8) for most of the end-uses, and hence showed good model representation of the end-uses by the probability distributions.

The results showed that the majority of the communities' water end-use frequencies and volumes or intensities required highly-skewed probability distributions such as log-normal or gamma, and in a few scattered cases with Normal and Weibull probability distributions. This implied that the highest proportion of the residential water users in the community consists of lower-end water users, with very small proportions of very large water-users.
3.2.2. Distribution of household size
The number of adults per household, in this study, was fitted to a log-normal distribution (in figure A3(a) for yard tap users, and in figure A4(a) for house connected users), with a geometric mean of 4.1 persons per household (for yard-tap connected users) and of 4.8 persons per household (for house-connected users). This study also showed that house connected water households contain relatively higher number of adults than yard tap connected water users.

3.2.3. Distribution of bathing (or showering)
Bathing (and or showering) frequency was modelled with a Weibull distribution in yard tap households (in figure A3b) and as Log-normal in house connected households (in figure A4e). The average frequency of bathing or showering in both groups was observed at about 2.0 times per day, which is higher than the average frequency of 0.7 recorded for a Dutch community in Blokker et al. (2010) or 0.73 per person per day in Athuraliya et al. (2021a). This is one of the major cultural (and may be due to climate) differences between communities in Sub-Saharan Africa and those of the developed world. The volume of bathing, on the other hand, used in the yard tap connected water users was estimated at an average of about 27 litres per person per day which is comparable to studies carried out in other African countries as reported in Thompson et al. (2001), Otaki et al. (2008), Nyong and Kanaroglou (1999).

3.2.4. Distribution of dish washing
The frequency of washing dishes (shown in Figure A3c and Figure A4c) for both yard tap and house connection water users was approximated with a geometric mean of 2.0 per household per day (and 2.5 for yard connected households). This frequency rate is relatively higher than that observed in developed communities in Athuraliya et al. (2008) and Blokker et al. (2010), of about 0.3–0.5 per household per day. This significant difference could be because of the use of dish washing machines in the developed world versus typical hand-dish washing in this community. Dishes are washed more frequently in the developing world but at lower volumes than in the developed world. The volume of dish washing, on the other hand, for yard tap users was measured at approximately 24.4 litres per household which is moderately higher than other studies in the developing world recorded in Thompson et al. (2001), Otaki et al. (2008), Nyong and Kanaroglou (1999).

3.2.5. Distribution of other water end-uses
The frequency of laundry events in the community was comparable to other countries, the laundry water use in developed
countries had a geometric mean of 0.3 times per day (and 0.4–0.7 times per day for the developed world as reported in Athuraliya et al. (2008) and Blokker et al. (2010)). The laundry use volume or intensity of water end-use in this study generated a geometric mean of 34.0 litres per capita for house-connected water users while in the developed world the corresponding value is 50.3–53.0 litres per capita per day. Both external water use and general cleaning end-uses could not be compared to documented enduses of the developed world. However, it should be noted that the external water end-use data could not be fitted to a model and, in addition, the external water end-use required a negative binomial distribution (not shown in figures) to cater for a 42% penetration rate in the usage of external water services.

3.3. Improved estimation of water end-uses

The final calibrated end-use volumes are detailed in Table 1 showing the spread and median of the simulated end-use volumes for both yard-tap connected water users and house-connected users. The house connected households were evaluated to have a median total consumption of approximately 586.2 L/household.day (109.2 L/capita.day) while yard tap households have a median consumption of 347.9 L/household.day (60.2 L/capita.day). These consumption values are comparable to other end-use studies documented in the literature as shown in Figure 4. For house connections, small to medium cities in comparable tropical climate were measured to have total household water consumption in the range 77–130 L/capita.day as described in Nyong and Kanaroglou (1999), Keshavarzi et al. (2006), Athuraliya et al. (2008), Liu and Smout (2010). For yard tap consumers, the studies concentrate on water users in rural settings of low to medium developing countries in Fan et al. (2013), Nyong and Kanaroglou (1999), Keshavarzi et al. (2006), Jethoo and Poonia (2011), were measured to have end-use consumption of 68–123.5 litres per person per day. However, these household end-use consumptions should be compared with caution.

For both house-connected water users and yard-tap users, showering or bathing was evaluated as the largest household end-use (45.5% in the house-connection users, and 43.8% in yard tap-connected users as illustrated in Table 1 and Figure 5). This was followed by toilet use in house-connected users and hand-washing in yard-tap users. Also, it can be inferred from Table 1 that the proportions of non-potable water end-uses were 82.8% in yard-tap and 77.7% in house-connected users. In other words, a significant proportion of the total household water use in this community is of non-potable nature.

Finally, this study also revealed that the hand-washing in yard-tap water users, and showering (as well as hand-washing) in house-connected water users were the most uncertain (in terms of variability) water end-uses. This high level of variability is therefore expected to sequentially the reliability of any grey water harvesting interventions.

4. Discussion

4.1. Water end-use estimation methodology

White et al. (1999) states that one of the limitations of characterising the end-use behaviours and volumes of a community is the lack of reliable data on how and where water is being used. Survey data of a sample of the end-uses employed in the community can in general be collected for a community with relative ease and with lower resources compared to high-resolution metering exercises. Survey data collection, therefore, would be a suitable approach for estimating water end-use characteristics of a low-income community. However, since water end-use survey data is imprecise, and cannot accurately measure all community water end uses (Athuraliya et al. 2008, Otaki et al. 2008), then such end-use data collected through survey exercises should be applied in urban water design assessments with caution. This is particularly true for low-income communities, and this paper therefore has presented a novel methodology to compensate for this limitation. The methodology improves on the accuracy of end-use data collected by social surveys by describing the end-use data through calibrated probability distribution models that describe the statistical spread of water end-use in the community.

In a community of the developing world, monthly metering of all water utility water users is a common practice, which makes available a representative dataset of monthly consumption of the community. This study has illustrated how this readily available dataset can be utilised to improve the estimation of water end-use approximations within a community. Monthly consumption billing data is hardly ever employed in end-use volume estimations, due to the limitations of accurately describing the temporal evolution of daily consumption to monthly values, as observed by Rathnayaka et al. (2011), Mayer et al. (1999).
Table 2: Calibration Parameters.

<table>
<thead>
<tr>
<th>Category</th>
<th>Water end-use</th>
<th>Factor</th>
<th>Remark (Target Parameter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yard Taps</td>
<td>Bathing</td>
<td>0.7</td>
<td>No. of Jerry cans</td>
</tr>
<tr>
<td></td>
<td>Washing</td>
<td>1.4</td>
<td>No. of Jerry cans</td>
</tr>
<tr>
<td></td>
<td>Household Size</td>
<td>1.78</td>
<td>General Increase</td>
</tr>
<tr>
<td></td>
<td>Metering Error</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>House Connections</td>
<td>Toilet</td>
<td>0.5</td>
<td>No. of flushes</td>
</tr>
<tr>
<td></td>
<td>Shaving</td>
<td>0.5</td>
<td>Intensity Volume</td>
</tr>
<tr>
<td></td>
<td>Washing</td>
<td>0.5</td>
<td>Flow Rate</td>
</tr>
<tr>
<td></td>
<td>Household Size</td>
<td>1.33</td>
<td>General Increase</td>
</tr>
<tr>
<td></td>
<td>Metering Error</td>
<td>0.1–0.2</td>
<td>Uniform Distribution</td>
</tr>
<tr>
<td>General</td>
<td>Rain Water Use (Dry)</td>
<td>0.15–0.25</td>
<td>Uniform Distribution</td>
</tr>
<tr>
<td></td>
<td>Rain Water Use (Wet)</td>
<td>0.23–0.50</td>
<td>Uniform Distribution</td>
</tr>
<tr>
<td></td>
<td>Temporal Evaluation factor</td>
<td>1.0</td>
<td>—</td>
</tr>
</tbody>
</table>

Figure 5: Relative comparisons between the water use volumes in a typical household of a yard-tap user against one of a house-connected water user.

Hence, its employment in this study to calibrate the aggregation of end-use models is a novel approach.

4.2. Mathematical modelling of water end-use in a low-income community

In general, the mathematical model concept employed in this study to represent water end-use (as a building block for overall water demand) is not novel. In scientific literature, models of a similar nature were employed in Rauch et al. (2003), Haarhoff (2006), Jacobs and Haarhoff (2002), Jacobs and Haarhoff (2007), Jacobs (2007), Blokker et al. (2010) and reviewed in White et al. (1999), Rathnayaka et al. (2011). However, these models were applied to high income communities that are socially different from low income communities studied in this paper. Therefore, to adopt this concept to a low-income community these models had to be tailor-made by aggregating water end-uses that are specific to the low-income community.

Nonetheless, due to the high volume of data required for the development of water end-use models, and also due to the limited availability of community data in low-income communities. A novelty is introduced by this study relating to how the study overcomes these challenges of data limitations to develop and calibrate a water end-use model of a community in the developing world.

4.3. Water end-use estimations

The results of the analysis of end-use water consumption evaluated in this study are comparable to other studies as shown in Figure 4, although these comparisons should be interpreted cautiously. Firstly, it is recognised that house-connected households in Uganda significantly differ to typical households in the developed world, the nature of their end-uses are not entirely the same. In the Ugandan community studied here, house connected households employ water for general household cleaning which is not represented in the end use structure of the developed world household communities.

Further, in the developed world communities, the households employ significant amounts of water for out-door irrigation (during the summer) which contributes the majority of outdoor water usage. While in this Ugandan community, (1) external water use is limited, and (2) where it is employed, it is used mainly for car washing instead of irrigation. The yard tap connected users, on the other hand, in this community, do not employ water for toilet flushing which is the major difference from house-connected users. Even for similar end-uses like the indoor water uses, this study has shown that there are still significant differences in the water consumption end-use parameters.

The differences in water end-use parameters drive the major differences between the household end-use proportions of both communities, as shown in Figure 4. In this community, due to the high frequency of showering, this is the largest proportion of the overall household water use (43.8% in yard-tap users, and 45.5% in house-connected users) compared to only 24% in most developed world communities. This implies that integrated urban water interventions that target showering or bathing or hand-washing will most likely lead to a more significant impact on the performance of urban water systems in the developing world than in the developed world.
In addition, the developed methodology provides a way of describing water use in a community of the developing world, a more holistic description of water use in the community than what the socially collected end-use data can provide. The water end-use mathematical model and the methodology suggested by this study can be employed or extended in the design and assessment of urban water systems, especially in uncertainty or sensitivity analysis, and/or, in studies that require a breakdown of water use for different water uses.

5. Conclusion

This paper has demonstrated a novel approach for simulating and evaluating water end-use volumes in an urban community of a developing country by improving the accuracy of the household surveyed end-use data, through a stochastic modelling simulation. The modelling approach involved grouping the community into two heterogeneous subgroups (house-connected users and yard-taps users). Then, for each subgroup, probabilistic regression models were developed for each category of water end-uses. The probability models for all the end-uses were then aggregated to generate the monthly consumption of the group, which was then calibrated - using the group’s measured monthly billing as the ‘true’ consumption, to generate representative end-uses volumes and distributions for the community.

The evaluated water end-use volumes of the community revealed that, most of the end-uses (their components of frequency and intensity) displayed highly-skewed distributions (log-normal) characteristics. This implied that: the majority of water users in the community are low-capacity water users. The approach also showed that a typical household in the community has consumption volumes of 109.2 L/cap/day for house connected users and 60.2 for yard connected users.

The simulated end-use volumes of house-connected users (who were assumed to be comparable to developed country communities) were found to be relatively lower than comparable communities in the developed world. At the same time, the yard-tap users (who were assumed to be relatively comparable to rural communities) were found to have higher end-use volumes than rural communities. The principal differences in the water end-use behaviour were found to be hidden in (1) the presence or absence of certain end-uses in this community versus developed country communities, (2) within similar end-uses, some of the end-use parameters were significantly different, reflecting a difference in the water use culture of both communities. This study therefore concludes with a caution that water end-use characteristics of one community should be employed carefully in the assessment or design of decentralised systems of another community, otherwise misleading results will be generated.

The study has shown that showering (or bathing) water end-use is, on average, the largest household water use for both house-connected users and yard-tap connected households, but it was not the most uncertain. In yard-tap customers, hand-washing was the most uncertain household water end-use, while showering was the most uncertain water end-use in the house-connected water users.

Funding

This work was supported by Commonwealth Scholarship Commission (grant number UGCS-2011-538).

References


A. STOCHASTIC MODELLING OF WATER END USE

A.1. Mathematical Representation of the Community Water end-use

For purposes of predicting water demand or water use in a community, Creaco et al. (2016) stated that there is a high volume of scientific studies that has been carried out in the development of water use or water demand models. These models can be classified into those that break the water use into micro-components (or water end-uses) and those that lump the water use as one. This study focuses on the former. Models that break the water use into micro-components, spatially and temporally cascade the water component pulses (across different households) through a bottom-up approach to generate the overall demand.

A.1.1 The community

In this study, the community was schematised spatially and temporally to build its water end-use model in shown in figure A.1. The residential mains water users in the community were categorised into two groups - the house connected users (group 1) and the yard-tap connected users (group 2). It was noted that there were significant differences in the water end-use behaviours between these two groups, as explained in section 2.2 of this paper, that warranted their separation. And within each group, the constituent households were considered to be homogeneous.

Rathnayaka et al. (2011) observed that the concept of representing the spatial heterogeneity of a community across different household types is common in various water end-use models. This concept has been applied in Haarhoff (2006); Blokker et al. (2010). This study extended this concept to a community of a low-income country - hence introducing new set of heterogeneous household groups.

A.1.2 The Household

At household level, the general principles used in the generation of the total household water use are similar in principle to works by Buchberger and Wu (1995); Buchberger and Wells (1996); Rauch et al. (2003); Memon et al. (2005); Haarhoff (2006); Blokker et al. (2010); Creaco et al. (2016) but closer in the modelled water end-use details to works by Haarhoff (2006); Blokker et al. (2010). In all these works, each water end-use pulse was generated as a product of two independent pulses: the intensity of the water end-use and its frequency. Though, Creaco et al. (2015, 2016) recommend that the duration and its corresponding intensity of an end-use should be modelled as dependent variables, in this study they were maintained as independent variables.

The intensity of the water end-use represents the volume of water used for that end-use event per unit time (which was days or weeks in this study) while the frequency of the end-use represents the number of end-use events per unit time. A product of these two quantities yielded the amount of end-use water used per person in a given time unit (day). The per-capita water quantity was then further multiplied by the household population (no of adults per household) to yield the total end-use volume of water used per day in that household. Water end-use events showering and dish washing of the house-connected users group had their intensity broken down further as a product of the event duration (in minutes) and the event flow rate (litres per min).

In Memon et al. (2005); Jacobs and Haarhoff (2006); Haarhoff (2006), the end-use volume parameters of intensity and frequency were generated from community averaged intensities and frequencies of end-uses.
of all the households in the community. Statistically, the use of community averaged position and spread parameters presumes that the household population water uses follow a symmetric distribution like normal distribution. In this community however, this presumption would be a misrepresentation of the community water use, since the socially collected data of this community showed that most of the water use distributions across the community were skewed, and hence not symmetric. Therefore, the approach employed in Blokker et al. (2010); Rauch et al. (2003) that involves the probabilistic distribution of each water end-use parameter was also applied in this study. This approach was preferred for this study because it does not prescribe any pre-requisite distributions to any parameters, and is also well-suited for studies involving relatively small sample sizes.

All in all, mathematically the overall water use in a household (and then across all households of a group) was represented as:

$$Q = \sum_j \sum_i (a_{i,j} \times b_{i,j} \times n_j)$$

where \(a_{i,j}\) represents the volume (or intensity) of water consumed per end-use \(i\) per person in a household \(j\), \(b_{i,j}\) represents the frequency of use events of end-use \(i\) per person in a day in household \(j\), and \(n_j\) is the number of adults in household \(j\). The summation is done for all end uses considered, and for all the households in the group.

The parameters \((a_{i,j}, b_{i,j}, n_j)\) are instances of probability density distribution models. For each consumer group and for each constituent water end-use parameter (that is its intensity and its frequency), their statistical position and statistical spread values were estimated from the socially surveyed data of the community. The histogram of each water end-use parameter was then fitted to each of the native probability density distributions (like Normal, Lognormal, Gamma, Weibull, Exponential, Rayleigh, and Chi-Squared), from which the probability distribution with the closest fit (as measured by a correlation coefficient) was taken as the most appropriate probability distribution model of that end-use parameter. The details of the appropriate probability distributions chosen for each water end-use parameter is represented in figure A.3, figure A.4 and figure A.5.

A.2. Temporal Resolution

The product \((a_{i,j} \times b_{i,j} \times n_j)\) in equation 1 represented the total water volume consumed in a single day (for toilet use, showering, hand washing) or in a single week (for laundry, for general cleaning). To simulate the water consumed over a month, the daily flow water end-uses were multiplied by 30, while the weekly flows were multiplied by 4.3. In other words, the time space was modelled as a deterministic variable in this study.

In Blokker et al. (2010), a methodology that originated from Buchberger and Wells (1996) and extended by Creaco et al. (2016) is used to describe the time space. This method considers each time ordinate as an output of a Poisson probability distribution model. Therefore, in a modelling system with small time steps for example one second simulating up to one hour (or to a day), this would create a large enough sample space to allow for statistical consistency in applying this probability distribution model.

In this study, the time evolves from a single day to one month (30 time ordiinates) for toilet, showering and handwashing water end-uses and from a single week to a month (4.3 ordinates) for laundry and general
cleaning water end-uses. These time space sample sizes are not adequate to ensure statistical consistency of the outputs, justifying the need for a simplified representation of the time space.

A.3. Making the water end-use model more realistic

In general, the purpose of the water end-use model development was to provide a platform upon which the surveyed or measured water end-use volumes can be justified as representative of the water used in the community. Therefore, the water end-use model also had to be modified further to make it more representative of the water consumed in the community, and also more representative of the monthly billing measurements.

In the measurement of household water use (for the billing process), household metering errors are experienced. Two, it was revealed from the analysis of the socially collected data that a significant proportion of the community mains water users employ rainwater harvesting. The model was therefore updated to include: a parameter for household metering errors, a parameter for the effect of rainwater harvesting on the household, and finally a parameter to allow for temporal summation of the end-use volumes for all the days of the month (that is 30 for daily end-uses, and 43 for weekly end-uses). The temporal evolution parameter was introduced because it is expected there could be a temporal evolution trend with the water consumption that was not considered in the model development.

The final updated stochastic water end-use for the community model that estimates the total amount of mains water consumed by a group of households in a month was represented as:

\[ Q_t = \sum_{i=1}^{n} \sum_{j=1}^{m_i} [m_j \times rW_j] \times [a_{i,j} \times b_{i,j} \times n_j] \times [t_t] \]  

where \( n \) and \( m \) represent the total number of households and end-uses considered respectively. The parameters are still represented the same way as in equation 1, except for the rain water harvesting parameter \( rW_j \), the temporal frequency parameter \( t_{t} \), and the metering error parameter \( m_j \) that were added.

In addition, the monthly water consumption data for the community shows that the number of households is not a constant from month to month, it varies randomly. Because of this, the water end-use model was therefore modified to compute the total monthly consumption of each month independently for each month, in that the number of households billed in that month was used as an input into the stochastic model (for the number of households simulated).

Further, since this was a stochastic simulation, each month was simulated for a thousand 1000 times (under a Monte Carlo simulation) to provide a distribution of monthly consumptions, from which a monthly consumption distribution was generated.

A.4. Calibration and Validation

In summary, the water end-use model in equation 2 generates instances of the monthly consumption of the community - which should statistically and numerically be equivalent to the measured monthly (and billed) water consumption of the community. And if the two datasets (the computed and the measured water...
consumptions) are both statistically and numerically equivalent, then their statistical centralised values (mean or median) and their cumulative density functions (a representation of their statistical frequency distribution) should converge. Therefore, the comparison of these datasets is not one of comparing statistical moments like mean or median, but also of their cumulative frequency distributions.

This calibration approach for stochastic models has been applied in similar works by Blokker et al. (2010); Creaco et al. (2016). In both works, the authors agree that total monthly water consumptions can be generated by summing up the individual ordinate consumptions, confirming the procedures applied in this model. Again, both authors employ cumulative density functions are a calibration procedure to confirm the statistical consistency between the simulated and measured observations. Therefore, the objective of the calibration was to ensure that the measured (billed) monthly total water consumption falls within the 95% confidence interval bounds of the monthly total water consumption simulations, and that the both cumulative density functions are similar in shape. Mathematically, this is illustrated as:

\[
\text{Minimise } |Q_r - Q_m| \quad (3)
\]

\[
\text{Minimise } |CDF_r - CDF_m| \quad (4)
\]

BY: adjusting various water intensity end-use and household size parameters

\(Q_r\) represents the median of the simulated total monthly water end-use volumes, while \(Q_m\) represents the measured or billed total monthly water consumption in the community. \(CDF_r\) is the cumulative distribution function of the simulated median total water use volume, while \(CDF_m\) is the cumulative distribution function of the measured or billed water volumes. Objective one (1) was not necessarily focussed on ensuring that the median simulated water volume is comparable to the measured volumes, but on ensuring that the measured volumes like within the simulated 95% confidence interval boundaries.

One of the major weaknesses of the social surveying of water end-use investigation was the estimation of the water use volumes, that is, the water end-use intensities. The calibration procedure therefore focused on the adjustment of the water end-use intensities. Each water use intensity parameter (the position and or spread) of interest was increased or decreased incrementally with a factor, till both calibration objectives above were satisfied. The final factors employed in the calibration are shown in table A.1. In addition, the household size was another parameter that was calibrated. According to the recently released national census details of household size, the survey data collected in this community showed minor variations with those shown in the national census. This difference warranted a modification of the household size as a calibration parameter. The calibration results are shown in figure A.6.

The calibration procedure was carried out on the months during the dry season, and the wet season months were employed to validate the calibration. In this, it was assumed that the only difference between the wet and dry seasons, was the rate of rain water harvesting taking place between both periods. So, in the validation period, only the rain water harvesting parameter was adjusted all the other parameters were not adjusted any further. The validation comparisons between the measured and the simulated total monthly consumptions were comparable, as shown in figure A.8.
REFERENCES


A group of randomly selected town inhabitants are assessed socially on the amount of end water they consume per end use (litres/day).

The same group of inhabitants – their measured monthly water consumption on record, (m$^3$/month)

(c) Measured Monthly consumption (billing)

(d) Model Calibration

(b) Stochastic Modelling

(a) Social Surveying

**Figure A.1:** A schematisation of the water user groups in the community

**Figure A.2:** The Modelling methodology approach applied
Figure A.3: Probability fit models (continuous line) used to represent frequency distribution data (black dots) of (a) household size and water use of (b) bathing, (c) dish washing, (d) laundry, (e) external use, and (f) general cleaning across yard-tap water users.
(a) HOUSEHOLD (HH) SIZE

(b) LAUNDRY

(c) WASHING DISHES

(d) GENERAL CLEANING

Figure A.4: Probability fit models (continuous line) used to represent frequency distribution data (black dots) of (a) household size and water use of (b) Laundry, (c) dish washing, and (c) general cleaning across house-connected water users.
Figure A.5: Probability fit models (continuous line) used to represent frequency distribution data (black dots) of more water users (a) showers, (b) toilet use, and (c) hand-washing) across house-connected water users in the community.
Table A.1: Calibration Parameters

<table>
<thead>
<tr>
<th>Category</th>
<th>Water end-use</th>
<th>Factor</th>
<th>Remark [Target Parameter]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yard Taps</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bathing</td>
<td>0.7</td>
<td>No. of Jerry cans</td>
</tr>
<tr>
<td></td>
<td>Washing Dishes</td>
<td>1.4</td>
<td>No. of Jerry cans</td>
</tr>
<tr>
<td></td>
<td>Household Size</td>
<td>1.18</td>
<td>General Increase</td>
</tr>
<tr>
<td></td>
<td>Metering Error</td>
<td>0</td>
<td>–</td>
</tr>
<tr>
<td>House Connections</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Toilet Use</td>
<td>0.5</td>
<td>No. of flushes</td>
</tr>
<tr>
<td></td>
<td>Showering</td>
<td>0.5</td>
<td>Intensity Volume</td>
</tr>
<tr>
<td></td>
<td>Washing Dishes</td>
<td>0.5</td>
<td>Flow Rate</td>
</tr>
<tr>
<td></td>
<td>Household Size</td>
<td>1.35</td>
<td>General Increase</td>
</tr>
<tr>
<td></td>
<td>Metering Error</td>
<td>0.1 - 0.2</td>
<td>Uniform Distribution</td>
</tr>
<tr>
<td>General</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rain Water Use [Dry]</td>
<td>0.15 - 0.25</td>
<td>Uniform Distribution</td>
</tr>
<tr>
<td></td>
<td>Rain Water Use [Wet]</td>
<td>0.23 - 0.50</td>
<td>Uniform Distribution</td>
</tr>
<tr>
<td></td>
<td>Temporal Evolution factor</td>
<td>1.0</td>
<td>–</td>
</tr>
</tbody>
</table>
Figure A.6: Overall calibration process results for total monthly water consumption of yard-tap water users shown in (a) and (c), and also for house-connected water users shown in (c) and (d).

[*] The order or nature of the month was not a subject of the research apart from the number of households measured in that month. Each month was simulated independently. That is why the months are not labelled on the x-axis. [**] Total Water Use represents the total water used up by all the households in a given group in a given month.
[**] The order or nature of the month was not a subject of the research apart from the number of households measured in that month, each month was simulated independently. That is why the months are not labelled on the x-axis.  

**Figure A.7:** Overall calibration process results for total monthly water consumption for house-connected water users during (a) dry season and (b) wet season, and also for their respective cumulative distribution functions in (c) and (d).
Figure A.8: Validation process results for total monthly water consumption of yard-tap water users shown in (a) and (c), and also for house-connected water users shown in (c) and (d).
B.2 Data Collection Tools - Questionnaires
B.2 Data Collection Tools - Questionnaires

B.2.1 Water users’ questionnaire (Households)
Questionnaire to assess the Social Behaviour of NWSC Customers  
[Household Questionnaire]

This questionnaire assesses the level of satisfaction of NWSC customers towards the water and sanitation service levels provided by NWSC. It then goes ahead to assess the attitudes of the customers towards the possible decentralised solutions.

**Interviewer** - Introduce yourself to the customer, stating the reasons for the interview, and how the interview is going to be conducted.

**Pre-Interview Information**

Enumerator's Name:........................................ Date:................................ Division:.............
Ward:........................................ Cell/Village:........................................

*Note: Only the head of the household or his / her spouse should be interviewed.*

**About the Customer**

*The Nature of the Property*

1. The reference numbers of the property: (i) Customer Reference (CR): (ii) Property Reference(PR):

**Interviewer** - Kindly ask the customer for their recent NWSC bill, and copy the CR and PR from it.

2. Which kind of water connection is employed at this property?
   (i) House Connection    (ii) Yard Connection    (iii) No water connection - where does the HH get its water from:...........................................................

3. What about the sanitation system - which kind of sanitation (toilet) system is employed at this property?
   (i) Connected to NWSC Sewer    (ii) Use a Septic Tank    (iii) 2 Use a Pit Latrine
   (iv) Do not own a Toilet. State which options you use:........................................

**Interviewer** - kindly explain to the customer what you mean by a sanitation system, and why you need information of its nature

4. House Ownership:    (i) Owned    (ii) Rented    (iii) Other Specify

5. Type of Housing:    (i) Temporary    (ii) Semi-Permanent    (iii) Permanent

6. Type of Roof Materials:    (i) Grass Thatch    (ii) Corrugated Iron Sheets    (iii) Banana Fibres
   (iv) Plastic Sheet or Tarpaulin    (v) Concrete/Clay Tiles    (vi) Concrete slab    (vii) Other - Specify:............

**Demography of the Household (HH)**

7. Sex of the HH head:    (i) Male    (ii) Female

8. Religion of the HH head:    (i) Christianity    (ii) Islam    (iii) Traditional    (iv) Other. Specify:.........................
9. How many individuals reside at this property? (i) Adults(>10yrs): (ii) Children(<10yrs):

10. Household head’s highest level of Education:
(i) Uneducated (ii) Primary Level (iii) Secondary Level (iv) University Level (v) Other - Specify:

**Water Supply Service in the Area**

11. What is the **primary** source of water for the household?
(i) National Water and Sewerage Corporation(NWSC) (ii) Borehole (iii) Spring (iv) River
(v) Lake or Pond (vi) Rain water Harvesting (vii) Other - Specify:

12. What is the **secondary** source of water for the household?
(i) National Water and Sewerage Corporation(NWSC) (ii) Borehole (iii) Spring (iv) River
(v) Lake or Pond (vi) Rain water Harvesting (vii) Other - Specify:

13. When do you use the **secondary** source? (i) In the Dry Season (ii) In the Wet Season
(iii) When the **primary** source is out

14. What happens to the **primary** water source during severe dry spells?
(i) No water (ii) Reduced Flow but Reliable (iii) Reduced Flow but not Reliable

15. If the **primary** source is NWSC, how many times a **month** on average do you experience **no water** or **low water pressure** supply from NWSC on this property?
(i) 0 - 10 times (ii) 11 - 20 times (iii) 1 - 30 times (iv) Greater than 30 times

16. What level of satisfaction would you assign to NWSC service in terms of water and sanitation?
(i) Poor (ii) Fair (iii) Good (iv) Very Good

**Household Income**

17. What is the major occupation of the household head? (i) Owns a Business (Businessman)
(ii) Does Commercial Farming (iii) Is employed in a Private Business Organisation (non-government)
(iv) Is employed by a Government Department (v) Is a Casual Labourer (vi) Is a student (post-secondary education) (vii) Is not employed

18. How many Income Earners are there in your Household:

19. House ownership? (i) Owned (ii) Rented (iii) Other - Specify:

20. Number of people residing on the property:

21. Number of dwelling rooms in the house:

22. If rented, how much do you pay monthly in rent:
23. If connected to NWSC, how much, on average, do you pay in water bills?
   (i) UGX 0 - UGX 50,000  (ii) UGX 50,001 - UGX 100,000  (iii) UGX 100,001 - UGX 150,000
   (iv) Above UGX 150,000

**Water Component Use**

**Interviewer** - Please introduce this section to the customer. In this section, the questionnaire attempts to assess on the composition and quantity of the customer’s component of water use. Use section A for properties with House connections and section B for properties with Yard Connections. What do you think of those who buy from either tapstands, kiosks or vendors?

**A. House Connections - Properties with in-house water appliances**

*Toilet*

24a. How many flush toilets do you have on the property:

24b. Are any of the toilets on the property dual flush?  (i) Yes  (ii) No

**Interviewer** - explain to the customer the meaning of dual flush toilets

24c. **Interviewer** - estimate the volume of the each of the toilets, using the measuring tape L x W x D (cm) State the dimensions of each toilet separated by a comma.

*Bathroom*

25a. How many showers do you have in your household

25b. Now, am going to measure the volumetric capacity of the showers in your household

25c. How many times a day, on average, do people in the household use the showers to have a bath?

25e. How many hand basins do you have in your bathrooms?

**Interviewer** - clarify to the customer the difference between a hand basin and a trough

25f. How many bath tubs do you have in your household?

25g. **Interviewer** - estimate the capacity of the bath tub: L x W x D (cm)

25h. How many times a day is the bath tub used for a bath?

**Interviewer** - Please clarify to the customer the difference between bathing and having a shower in the bath tub. We are interested in bathing since showering has already been covered.

*Laundry*

26a. How do you do your laundry (wash your clothes) in this household?

   (i) Using Washing Machine  (ii) Hand Washing

26b. If Washing Machine, how many times a week do you carry out your laundry? What is the volumetric capacity rating of the washing machine per wash?
**Interviewer - please check for the volumetric rating of the washing machine.**

26c. If Hand washing, how many times a week do you do laundry (wash clothes)?

26d. How many basins-full or buckets-full of water do you usually use for the wash?

(i) Basin or Bucket Volume (Litres):........(ii) No of Basins or Buckets:...........

**Interviewer - take the customer through a typical clothes-washing process for him or her to estimate the amount of water used. Do not forget to estimate the volume of basins or buckets they use.**

**Kitchen**

27a. How many sinks do you have in your kitchen?.......**Interviewer - please count the double sinks as one.**

27b. How many times a day do you approximately use the sink to wash dishes?

27c. How long approximately does it take to wash a large volume of dishes?

27d. Do you have a dish-washing machine in your kitchen?  (i) Yes   (ii) No

27e. If Yes, how many times a day do you use this machine to wash dishes?....... **Interviewer - estimate the volume rating (amount of water used per wash) of the machine?**

**B. Yard Connections - properties without in-house water appliances**

**Bathroom**

28a. How many times a day, do the household members take a bath?....**Interviewer - in short how many times a day is the bath room visited in a given day for a bath**

28b. How many basin-fulls or bucket-fulls of water are usually used during each bath?.........................

**Kitchen**

29a. How many times a day does your household wash dishes?

29b. Estimate the volume of water used in washing dishes (the number of pans or jerry cans used, and their quantity):

(i) Pans - size (diameter) of each of the pans   (ii) Pans - the number of times each pan is filled

**Interviewer - please guide the customer in revealing this information**

**Laundry**

30a. How many times laundry (washing clothes) done in your Household?

30b. Estimate the volume of water used in washing clothes:

(i) Basins or Buckets - size (diameter) of each of them   (ii) 2 Basins or Buckets - the number of times each is filled. **Interviewer - please guide the customer in revealing this information**
External Water Use

31a. Do you have any external uses of the water outside the house? (i) Yes (ii) No

31b. If Yes, what do you use the water for externally?

(i) Car Washing (ii) Garden Irrigation (iii) Both - Car Washing and Garden Irrigation
(iv) Other - Specify:........................................................................................................

31c. How many times a month do you use the water externally:

31d. How long does it take you to carry out an external use session:........Interviewer - for multiple external uses add the times for both uses.

Decentralised Interventions

Interviewer to the Customer - The logic behind decentralised interventions is to provide another source of water to the customer to supplement the mains supply (NWSC supply). However, the source of water is UNUSUAL - therefore we have to study your attitude towards these unusual sources.

General

32a. As a customer of NWSC, do you think the water from NWSC requires supplement or is it enough to meet all your requirements, all the time? (i) Yes (ii) No

32b. If Yes, usually when the water from NWSC is not flowing, where do you get your supply from?

(i) Buy from Vendors (ii) Buy Bottled (Mineral) Water (iii) Collect from a Ground Water Source (Spring, Borehole) (iv) Collect from a Surface Water Source (Pond, River) (v) Do nothing, wait for NWSC water to return Interviewer - please tick all the options the customer provides

Rain Water Harvesting

Interviewer to the Customer - An intelligent RWH harvesting system is one where the whole Household supply is entwined with the mains supply (through a tank) - show the customer a diagram. When the Household receives rain water, it replaces the mains supply in the system, however, when there is no rainwater, the system uses mains water. Though, RW has the disadvantage that it is not continuous, only appears in the wet season, so it is not easy to plan for it.

33a. If you were given rain water in your taps to use in your household, would you use it to meet any of your household needs? (i) Yes (ii) No

33b. Which Household needs would you apply rain water to:

(i) Cooking (ii) Laundry(Washing Clothes) (iii) Toilet Flushing (iv) Kitchen Use (Dish washing,
Food washing) (v) External Use(Garden Irrigation, Car washing, etc)  

Interviewer - mark the ones the customer chooses

33c. Interviewer - estimate the possible collection area of the possible rain water harvesting system:

(i) Roof Collection Area L x W (m) (ii) Whole Household Area L x W (m)  

Interviewer - please approximately measure the areas.

Grey Water Recycling

Interviewer to the Customer - Grey water is waste water from laundry use, bathing, kitchen use, cooking, but does not include toilet use water. A grey water recycling system consists of a system that collects grey water from the household, treats it, then returns it to the house for additional use. Please show the customer the diagram.

34a. If recycled grey water was supplied to your household through some of the taps, would you be comfortable to use it to meet any of your HH water needs? (i) Yes (ii) No

34b. Which Household needs would you apply recycled grey water to:

(i) Cooking (ii) Laundry(Washing Clothes) (iii) Toilet Flushing (iv) Kitchen Use (Dish washing, Food washing) (v) External Use(Garden Irrigation, Car washing, etc)  

Interviewer - mark the ones the customer chooses

Recycled Waste Water

Interviewer to the Customer - Sometimes all the waste water (including toilet water) from the household is collected, treated, diluted with storm water (rain water) then returned to the household to be reused.

35a. What about recycled waste water, would you be comfortable to use recycled waste water to meet your needs if the recycled waste water was provided through one of your taps?

(i) Yes (ii) No

35b. Which Household needs would you apply recycled waste water to:

(i) Cooking (ii) Laundry(Washing Clothes) (iii) Toilet Flushing (iv) Kitchen Use (Dish washing, Food washing) (v) External Use(Garden Irrigation, Car washing, etc)  

Interviewer - mark the ones the customer chooses

Waste Solids Reuse or Liquids Waste Reuse

Interviewer to the Customer - the solids (faeces) or liquids (urine) from human waste, after some preliminary treatment, can be used as manure or fertiliser in agriculture. However, for application of either of these two systems, the customer will have to employ a toilet that separates the liquid from the solid. And to apply the solids or liquids to the gardens, the customer may have to handle the faeces or the urine directly. In terms of water conservation though, this intervention reduces eliminates the need for toilet water use, hence reducing on the mains water requirement.

36a. Do you practice any agriculture in your household or at another location?
(i) Yes (ii) No  
**Interviewer** - inform the customer that in case they do not have a garden, the waste can be sold to farmers who have.

36b. In case this system is installed on your property, are you comfortable with handling solid waste or liquid waste directly to transfer it to the garden? (i) Yes (ii) No

**Interviewer** - please inform the customer about the methods of transferring the solids and liquids - using buckets and jerry cans.

**Demand Management Interventions**

**Interviewer to the Customer** - Demand Management Interventions are Interventions targeting, you the user of water, trying to convince you the user to change the volume of water used.

37a. Would you reduce on the amount of water you use, say for bathing, cooking, toilet use, if the water tariff was increased? (i) Yes (ii) No

37b. For customers using water flushing toilets - would you be comfortable with changing the high-volume toilets in your house to low-volume toilets (assuming they will be supplied free) to save water used during toilet use?

(i) Yes (ii) No

37c. If no, please state the reasons why?

…………………………………………………………………………………………………………………………………………………………………………………………
…………………………………………………………………………………………………………………………………………………………………………………………
…………………………………………………………………………………………………………………………………………………………………………………………
…………………………………………………………………………………………………………………………………………………………………………………………

..

End
B.2.2 Water users’ questionnaire (Water Managers)
Questionnaire to assess the Social Behaviour of NWSC Customers [Leaders and Managers Questionnaire]

This questionnaire assesses the level of satisfaction of the community leaders towards the water and sanitation service levels provided by NWSC to their customers. It then goes ahead to assess the attitudes of the community leaders towards the possible decentralised or regional solutions.

**Interviewer** - Introduce yourself to the community leader, stating the reasons for the interview, and how the interview is going to be conducted.

**Pre-Interview Information**

Enumerator's Name:.................................. Date of the Interview:................................Division:......................

Ward:............................................................... Cell/Village:......................................................................

**Characteristics of the people in your area**

1. How many households are in your area of jurisdiction?.................................................................

2. What is the overall population of the people in your area?...........................................................

3. What is the religious composition of the people in your area?.........................................................

4. What is the main form of activity of residents in your area?
   (i) Farming – Cultivation  (ii) Farming - Livestock Rearing  (iii) Farming – Crop growing  (iv) Local Trading  (v) Government - Public Service  (vi) Private - Skilled Service  (vii) Other (Specify):..................

**Interviewer** - ask for percentage volumes of persons carrying out a specific activity

**Economic Activities in the Area**

5. Please RANK, which is the major problem in the area?

   Water Supply  ( ) Sanitation  ( ) Diseases  ( ) Education  ( ) Unemployment  ( ) Transport and Communication

6. Please RANK, which one of them would you like to solve first?

   Water Supply  ( ) Sanitation  ( ) Diseases  ( ) Education  ( ) Unemployment  ( ) Transport and Communication

7. What are the community attitudes towards involvement in development projects?

   (i) Positive  (ii) Negative  (iii) Neutral

8. Do communities willingly participate in development projects?  (i) Yes  (ii) No
Water and Sanitation in the Area

9. What is the primary source of water in your area?
   (i) National Water & Sewerage Corporation (NWSC)   (ii) Borehole   (iii) Spring   (iv) River   (v) Lake or Pond   (vi) Rain water Harvesting   (vii) Other - Specify: .................................................................

10. What is the secondary source of water in your area?
   (i) National Water & Sewerage Corporation (NWSC)   (ii) Borehole   (iii) Spring   (iv) River   (v) Lake or Pond   (vi) Rain water Harvesting   (vii) Other - Specify: .................................................................

11. What about sanitation - what is the major form of sanitation system employed in your area?
   (i) Connected to NWSC sewerage system   (ii) Septic Tanks   (iii) Pit Latrines   (iv) Public Toilets   (v) No Toilets

   Interviewer - ask for approximate percentages of each type

Decentralised Interventions

   Interviewer to the Community Leader - The logic behind decentralised interventions is to provide another source of water to the customer to supplement the mains supply (NWSC supply). However, the source of water is UNUSUAL - therefore we have to study your attitude towards these unusual sources.

Rain Water Harvesting

12. What percentage of households in the area practice rain water harvesting? ...........................................

13. If the government was to promote rain water harvesting as an option to alleviate water supply issues in the area, do you think more people would be convinced to install rain water harvesting systems in their compounds?
   (i) Yes, by how many percentage points: .........................   (ii) No

Grey Water Recycling

14. What about grey water recycling - if the government advocated for the use of recycled grey water in the households as a way to improve the water supply levels in the community? Do you think the residents would embrace this technology?   (i) Yes   (ii) No

15. What percentage of households do you think would embrace the use of recycled grey water in their homes? ...........................

16. What hindrances do you think some residents would have in the use of recycled grey water in their homes?

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Waste water Reuse

17. What about waste water recycling - if the government advocated for the use of recycled waste water (the waste water is mixed with storm water treated and returned to the HHs in a different tap) in the households as a way to improve the water supply levels in the community. Do you think the residents would embrace the use of recycled waste water in their homes? (i) Yes (ii) No

18. What percentage of households do you think would embrace the use of recycled waste water in their homes?..............................

19. What hindrances do you think some residents would have in the use of recycled waste water in their homes?..............................

Waste Solids Reuse or Waste Liquid Reuse

20. We understand a great proportion of your residents practice livestock agriculture. What percentage of them uses the cattle excreta (aka cow dung) as mature for their gardens?..............................................................

21. Similarly, if the residents were introduced to the use of human excreta or human urine as a form of manure for use in their gardens. Do you think these residents involved in agriculture would embrace this technology? (i) Yes (ii) No

22. What about the other residents - do you think they will be comfortable with collecting human excreta or human urine from their homes for use in agriculture or to sell to those who have gardens or practice commercial farming? (i) Yes (ii) No

23. What percentage of households do you think would allow the use of human excreta and or human urine collecting toilets, if they were provided free of charge?.................................................................

24. What hindrances do you think some residents would have in the use of human excreta or human urine for agriculture in their gardens?

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Demand Management Interventions

25. What percentage of your residents use pour flush toilets?.................................................................

26. Sometimes to save on water use in a given HH, residents are advised to replace the high capacity pour flush toilets with lower capacity toilets - in terms of volume of water used during the flushing process. Do you think your residents would consider changing the high capacity toilets in their HHs with low capacity toilets, even if they were provided free? (i) Yes (ii) No

27. By what percentage points, do you think residents with pour flush toilets would consider replacing their toilets?........................................................................................................................................

28. What hindrances do you think some residents would have with getting them to replace their high capacity toilets with low capacity ones?

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End
Appendix C

Paper III

This section of the thesis displays the contents of the journal paper (denoted as Paper 3) that was submitted and published to an international journal - Environmental Modelling and Software.

C.1 The paper as submitted to Elsevier’s Environmental Modelling and Software
An Integrated Urban Water Modelling Approach for Cities in the Developing World

K. Munina\textsuperscript{a,b,*}, C. Maksimovic\textsuperscript{a}, N. Graham\textsuperscript{a}

\textsuperscript{a}Imperial College London, South Kensington, SW7 2AZ, UK
\textsuperscript{b}Uganda National Roads Authority

Abstract

It is becoming accepted that existing urban water systems across both the developing and developed world require an integrated management paradigm that exploits the interaction between different urban water subsystems. This interaction though can only be illustrated with aid of an integrated urban water modelling tool. Existing integrated modelling tools such as Aquacyle, UWOT, City Water Balance, are designed specifically for application in developed world cities, making them inappropriate to represent the major urban water features of a developing world city. This paper provides a novel approach that extends existing integrated urban water modelling to cities of the developing world. It characteristically describes the fundamental urban water features of developing world cities that are prerequisites for their analysis and modelling. In so doing, the paper then demonstrates the value these novel additions provide to modern urban water management.

Keywords: Integrated urban water systems, Integrated urban water modelling tools, Developing countries, Aquacyle, UWOT, City Water Balance, WaterMet

Software availability

Name of the software: WaterCycle
Contact Address: Kenneth Munina, Cedo Maksimovic, Department of Civil and Environmental Engineering, Imperial College London, South Kensington, SW7 2AZ, London, United Kingdom. Tel.: +44 (0) 20 7594 6013; Email: muninan kenneth@yahoo.co.uk, c.maksimovic@imperial.ac.uk
Year first available: 2015
Software requirements: MATLAB Release 14
Program Language: Matlab/Simulink
Program Size: 100 MB
Availability: Freeware, contact developer

1. Background

1.1. The need for Integrated Management and Assessment of Urban Water Systems

It is becoming accepted that conventional urban water systems across both the developing and developed world are struggling to sustain the provision of appropriate water services to their users or to sustain the prevention of environmental degradation. The unsustainable behaviour of these systems is related to their inherent weaknesses that are centred on the lack of integration of between the urban water subsystems. In conventional systems, the urban water subsystems are managed, analysed, and assessed in isolation from one another (Sharma et al., 2013) which in turn makes the urban water system vulnerable to any external pressures (Philip, 2011). As a result of this unsustainable behaviour, the conventional urban water management paradigm or model is being ruled out as the most appropriate system for sustainable urban water systems management (Zhang et al., 2007; Sharma et al., 2010, 2013; Philip, 2011) in cities of both the developing and the developed world.

This failure of the conventional urban water management model has led many authors, such as Porto et al. (2007); Bihour et al. (2009); Blackmore and Plant (2008); Fidjar et al. (2010); Memmo et al. (2005); Sharma et al. (2010); Zhang et al. (2007); Closas et al. (2012); Philip (2011) to advocate for an alternative urban water systems management model to improve sustainability. An alternative urban water management system should be centred on the application of alternative urban water interventions across the boundaries of the individual urban water subsystems, to generate a total urban water solution that is sustainable holistically across the whole system and across each of the individual subsystems (Closas et al., 2012; Sharma et al., 2008; Philip, 2011). Thus, the alternative urban water management system enables an integrated management of the urban water system.

Integrated management of urban water systems places emphasis on the need for exploitation of the interactions (or the integration) between the different urban water subsystems to yield a sustainable urban water system performance (Makropoulos et al., 2008). This management system depends on the synergy the subsystems' interaction contributes to the successful behaviour of the urban water system and also amplifies the poor performance, which in the end allows for the revelation of hidden insights driving the poor performance.

\textsuperscript{*}Principal corresponding author
Email address: muninan kenneth@yahoo.co.uk (K. Munina)

Preprint submitted to Environmental Modelling & Software

March 1, 2017
1.2. Integrated assessment and Integrated Modelling of urban water systems

The design and assessment of conventional urban water management ignore the importance of interactions between different urban water subsystems, their inter-subsystem non-linearities, nor the time delays between their feedback mechanisms (Pahl-Wostl (2007)). This kind of assessment or planning generates problematic designs which despite the short-term successes they provide in the end lead the system to unforeseen side-effects in the long term ((Urich and Rauch, 2014), (Pahl-Wostl, 2007)). That deficiency in conventional planning illustrated the relevance of following the interactions (that is, the integration) between the different urban water subsystems (Makropoulos et al., 2008) in a given urban water system. However, these interactions need to be investigated and quantified in order to identify the future possibilities and/or limitations of different water development options within the context of sustainable water management (Makropoulos et al., 2008). Hence, the need for an integrated modelling of an urban water system.

Integrated modelling of an urban water system, in essence, refers to the development of a system that allows for the integration of the different constituent urban water subsystems within an urban area (city). That is the integration of the urban water supply subsystem, to the storm water system, to the sanitation subsystem (Bach et al., 2014b), and vice versa. It is presumed that the hydrological processes within each of these subsystems have an influence and an effect on the global hydrological behaviour of the urban water system. The integrated modelling approach then allows for the revelation of these influences and/or effects. Mitchell et al. (2001) and Mitchell et al. (2007) advocates that such kind of urban water modelling should be at the centre of the development of any urban water strategy especially one that involves the employment of urban water interventions that spread across both decentralised and centralised spatial scales.

Currently, tools developed specifically to allow for integrated urban water modelling of urban water systems are few and many still in their infancy (Bach et al., 2014b; Mitchell et al., 2001). In the scientific literature, such integrated modelling systems included the Aquacycle system (Mitchell et al. (2001) and Mitchell et al. (2007)), the UWOT system (Makropoulos et al. (2008)), the UrbanCycle system (Hardy et al. (2005)), City Water Balance system (Last (2010)), and the WaterMet system (Behzadian and Kapelan (2015)). These tools were found to be highly site specific in their representation of an urban water system, in that their representation places a high level of emphasis on urban water characteristics specific only to developed world cities. For cities in the developing world particularly sub-Saharan Africa, no integrated urban water modelling tool to describe them was found in scientific literature.

An integrated urban water modelling tool suitable for a city in the developing world must, as part of its basic foundation, appropriately describe the specific and unique urban landscape of the developing world. In these cities (compared to the developed world), the water use heterogeneity is much more, the storm water flow is dominated by a larger percentage of natural unpaved surfaces, and the sanitation practices are dominated by the use of on-site systems (that is pit latrines and/or septic tanks). These characteristics and practices of this city the urban water hydrology of this city to generate a behaviour that is different from that of a developed country city.

This unique behaviour of urban water systems of the developing world is illustrated through their observed behaviour. Porto et al. (2009) observed that the weaknesses within the water supply subsystem in these cities are related to the deficiencies within the sanitation subsystem, which in turn affect the performance of the storm water subsystem. In other words, the performance of the water supply subsystem is influenced by the performance of the sanitation subsystem, which in turn influences the performance of the storm water subsystem. Therefore, despite the lack of integrated modelling systems for cities of the developed world, there is no doubt that their urban water systems also require a holistic and integrated form of assessment in order to assess and optimise their performance.

1.3. Paper Objective

It can be concluded that cities of the developing world, in the same way as those of the developed world, also require an integrated assessment of their urban water systems to achieve sustainable performance. However, existing integrating modelling algorithms have been designed for cities of the developed world, and do not consider the requirements of cities in the developing world. This paper attempts to fill this knowledge gap by describing and developing an integrated water modelling system that is more applicable to cities of the developing world.

2. Current Approaches to Integrated Urban Water Modelling

2.1. Global Approach

Mitchell et al. (2001) and Bach et al. (2014b) stated that the number of integrated urban water modelling tools developed is still low and that some of their fundamental theories are still in their infancy. In the scientific literature, such integrated modelling tools include Aquacycle (Mitchell et al. (2001) and Mitchell et al. (2007)), UWOT (Makropoulos et al. (2008)), UrbanCycle (Hardy et al. (2005)), City Water Balance (Last (2010) and Mackay and Last (2010)), and WaterMet (Behzadian and Kapelan (2015)). Other designated integrated urban water modelling tools were employed in Fagan et al. (2010); in Soares et al. (2005); in Hochstrat et al. (2005); and in Paton et al. (2014). In table 1 these modelling tools are summarised.

In general, these modelling systems employ a mass balance approach (for both water and contaminants where applied) to provide a complex modelling of all the processes that drive the
urban hydrological cycle (that is water supply, waste water disposal and storm water runoff) in a city. All the modelling systems except that described in Fagan et al. (2010), employ a discrete water budgeting approach across different temporal and spatial scales when following the multiple water flow streams across an urban centre.

2.2. Spatial Heterogeneity

In table 1, the main differences in these systems are found in the way they address the spatial scale variability across the entire urban landscape. In most of them, the household scale (which implies a building in the urban centre) is employed as the smallest and lowest spatial unit upon which the whole urban water landscape is developed. The household scale is then cascaded vertically to describe the entire spatial domain of the urban centre (as a network typology), that is from household scale to the largest scale possible (Hardy et al., 2005). In Aquacycle, City Water Balance and WaterMet households are cascaded to clusters (groups of homogeneous households), then to developments or sub-catchments (which represents groups of clusters), and then finally to catchments. In UWOT and the system proposed by Fagan et al. (2010), households are cascaded up to the development scale only. However, it is not clear whether the development scale or sub-catchment scales employed in UWOT, in Aquacycle, or in the Fagan et al. (2010) system represents natural watersheds. In City Water Balance and WaterMet, the natural watersheds of the urban landscape are represented.

2.3. Household Hydrology

As shown in table 1, the urban water hydrology of a city in all the modelling tools is aggregated from the household scale through to the whole urban landscape. In the same way, the storm water and water use hydrology at a household scale is aggregated to the clusters, then clusters to the developments, then to the sub-catchment, and finally to the catchments (whichever is the broadest scale in the system). At household scale, the water use is broken down in micro-components (or end-uses) of the individuals or appliances within a given household. However, the representation of the water use in terms of micro-components assumes a homogeneous form of water end-use with single unit end-use rate defined for a given water end-use, with no provision for variation across different households. In UWOT, micro components are defined in terms of the appliances used, while in Aquacycle average per capita water end-uses are defined.

The stormwater hydrology at the household scale divides the household surface into both pervious and impervious portions, from which the runoff from each surface is aggregated to generate the total surface run off from a given household. The Aquacycle and City Water Balance employ a soil-water accounting model as part of their local and global rainfall-runoff processes, while UWOT does not provide for the soil-water accounting.

However, despite the general similarity in the local household hydrology across the systems, it must be emphasised that this hydrology is dictated by the household type represented in the model. In all the existing tools, only three households types were employed, these being residential or private, commercial, and institutional and in all these households it was assumed that in-house water-use appliances (such as flush toilets, showers, sinks, etc) were employed. Thus, in all these systems there is no consideration for low-cost households which are common in the developing world.

Another significant characteristic of these modelling systems, is in their consideration of the rainfall-runoff processes, that is the flow of stormwater or wastewater from household to household, cluster to cluster, or from catchment to catchment. These systems do not place emphasis on the gravity plays in driving this downstream flow. Of the existing systems, only WaterMet allows for a gravity-dominated flow of stormwater through the use of the Rational Method. However, this also is limited to stormwater flows within sub-catchments, and not for subcatchments-to-subcatchments flow.

In terms of sanitation use, all the systems assume that households that employ the use of indoor flush toilets and as such their wastewater is channelled to a centralised and conventional sewerage system. For City Water Balance and UWOT, the use of septic tanks is included in a conventional sanitation system. However other sanitation systems like the use of pit latrines or open defecation, such as those observed in developing country cities, are not represented in these systems.

2.4. Summary

The global hydrology of existing integrated modelling systems demonstrates the significant progress made in the paradigm of an integrated assessment of urban water systems. Their fundamental processes of cascading the urban water hydrology from the household to a catchment or the whole urban centre, represent one of their major strengths. However, despite the progress in their development, these systems are quite varied in the fundamental processes they utilise to represent a particular urban water system. In summary, it can be said that these systems appear to be directed towards modelling urban water hydrology of a city in the developed world and have significant limitations in accurately modelling a city of the developing world. This conclusion is consistent with the recommendation of Mitchell et al. (2007) in reviewing existing integrated urban water systems, that no integrated modelling tool is suitable for all urban water applications for both the developing and developed world. Hence, there is need to tailor existing tools to the specific needs and circumstances of urban water systems of the developing world.

3. Methods

As summarised in table 1, the existing integrated urban water systems of UWOT, Aquacycle, City Water Balance, and WaterMet lack the capacity to fully address the unique physical features of an urban water system of the developing world. It
is these features which are responsible for driving the unique urban hydrology of this city. Therefore, as a pre-requisite to developing WaterCycle, an integrated urban water system suitable for a low-income city, the unique urban water features of a city of the developing world had to be precisely schematised.

3.1. Mbarara Town - The Case Study

The urban water system in a medium-sized town in south-west Uganda was employed as a case for this study. Its urban water supply subsystem consists of a centralised mains water supply system that sources water from River Rwizi, which traverses the town. The mains water supplied area has a network length of about 204 km that extends to most fringe areas of the town, leading to a supply coverage of 57% in the town area and 43% in the fringe area. The major challenge facing the urban water supply system of the area is the high reliance on a highly fluctuating river, which dries during the dry season leading to severe water shortages.

Mbarara town, like most towns in Uganda, experiences a tropical climate with two rainy seasons separated by two dry seasons in a year with an average annual monthly rainfall of 97.5mm. However, even during the dry season, occasional heavy rains occur, resulting in a relatively uniform (but seasonal) rainfall distribution throughout the year. This could explain the widespread use of rain water harvesting in the town.

For the urban water sanitation subsystem, there are three forms of sanitation: a centralised sewerage (with waste stabilisation ponds for treatment before disposal into the river River Rwizi), septic tanks, and pit latrines. Only 5% of the mains water users utilise the centralised sewerage (across 3 stabilisation ponds due to the highly undulating topography). 28% utilise septic tanks, and 67% pit latrines.

These urban water characteristics of this particular town of the developing world illustrate the significant differences between cities of the developing world and those of the developed world. These characteristics are not provided with due consideration within the existing integrated urban water modelling tools.

3.2. Spatial schematisation of a city in the developing world

It has been observed that in cities of the developing world, it is not only the water behaviour that is different from the developed world, but also the nature of sanitation use, and the stormwater drainage systems in the community. Therefore the objective of the urban water system discretisation is to precisely define the building blocks of the urban water system at small scales, that cascade to form the overall urban water system.

In Mbarara as with many developing world cities, it is important to define precisely the city’s household heterogeneity, in terms of the constituent water end-uses and consequently the waste water generation. In this city, it was assumed that the household water user community could be categorised principally into four major groups these being domestic (80%), institutional (3%), commercial (16%), and government-oriented customers (2%) according to the overall water use quantity. To gain more precision, these principal categories can be further sub-categorised into either house-connected water users or yard-tap water users. House-connected water users, who are 33% of the mains supplied resident population, represent households that receive water directly into the house, and thus employ water appliances like flushing toilets, showers, and hand-wash basins. Yard-tap water users, who are 67% of the mains supplied water users, represent households that receive water by means of an outdoor tap, and thus use the water by hand-held containers. This categorisation leads to eight (8 No.) water user groups of the community, each group with its unique water end-use profile, as shown in figure 1(a) and figure 1(b).

Another unique feature of the urban water usage in this community is the high overall usage of on-site sanitation (in the form of septic tanks and pit latrines) over sewered or piped sanitation. This feature has further influence on the water user community categorisation above. The house-connected water users employ either sewered sanitation or on-site septic tanks, while yard-connected water users employ pit latrines. Further, in the developing world, there is a significant level of low-income unplanned settlements (or slums) among the yard-tap water users. This aspect was also included in the urban water user community categorisation shown above. In this community, a factor defined by Kiggundu (2014) is used to prescribe the proportion of low-income households from the yard-tap water users (that is 60%). This sanitation use and slums categorisation has an influence on the nature of wastewater generation from the mains water use, and consequently on the disposal route of the wastewater into the drainage or stormwater system.

Therefore, in addition to the eight (8 No.) water user groups, an additional low-cost household (that is slums) water user group was added to the domestic mains water users, which employs yard-tap water connections.

Finally, all the households were further categorised according to their different locations across the city terrain, that is into different subcatchments or watersheds. In addition, another level of categorisation was added to the description of households across the city, by subcategorising them further to the subcatchment the household is located. The city was delineated into 16 watersheds or subcatchments, which represent the major stormwater drainage systems in the community. This combination of the 10 water users groups and the 16 subcatchments generated a distribution of the urban water groups of the city as shown in table 2. This detailed representation and distribution of households (each with its own unique and representative water end-use structure) provided a strong foundation upon which the integrated urban water modelling of a city of the developing world could be built, giving a total of 16 No. by 14 No. water user groups.
3.3. Integrated urban water hydrological modelling of the low-income city

3.3.1. Introduction

This urban water use schematisation of the city provided the foundation upon which the integrated urban hydrological modelling system (WaterCycle) was built. In WaterCycle, first the urban water system catchment of the city was delineated into 16 subcatchments (or watersheds) as shown in figure 2(a) following the natural stormwater drainage network of the city. The stormwater network (at global level) was then schematised into a drainage network model as shown in figure 2(b), with the subcatchments as nodes and the stormwater flow paths as segments.

Then within each subcatchment, the constituent urban water hydrology was defined and described further. The constituent household groups or clusters (including their large open spaces) were cascaded from the global network as hydrological components of a given subcatchment, as illustrated in figure 2(c). Within the hydrology components of each household group, the mains water use and the stormwater flow were integrated to generate the overall stormwater (and or wastewater) outflow effluent (see figure 2(d)). In this localized household group, the number of households was the major input, that drove the computation of the volume of mains water use and/or the volume of stormwater outflow from that group. The mains water use, which consequently led to the human wastewater generation was developed from the computation of the various households’ water end-uses (according to the nature of the household group), as illustrated in figure 2(e). The water end-uses considered for each household type was carried out following the household schematisation defined in figure 1. Finally, rainfall input was added to the household group to allow for the development of the stormwater hydrology across the various households. The plan space of the households was broken down into both the impervious stormwater hydrology (in figure 2(f)) and the pervious stormwater hydrology (in figure 2(g)) to generate the overall surface stormwater flow output from the cluster. In essence, the cluster hydrology block (2(d)) represents the heart of the integrated modelling system, it is from its computations that the two major outputs - the human wastewater and or the stormwater runoff, in both quantity and quality are generated for a given subcatchment. It is these outputs that are conveyed to the downstream subcatchment (or recycled where necessary).

3.3.2. Mains water use and wastewater generation

The figure 2(e) represents the module in each households group, that models the mains water used and consequently wastewater generated from that group. This modelling system follows the household water use schematisation illustrated in figure 1 showing that the mains water use is computed following the aggregation of the water end-uses of the households in that group. In WaterCycle, a novel approach introduced by Munii et al. (2016) that employs a stochastic mathematical description of the unique water end-use of a community in the developing world was applied. Instead of characterising only domestic households as done in Munina et al. (2016), the approach was extended to the other water users in the community (that is the commercial, the institutions, and the public institutions). A more elaborate description of the mains water use hydrological computation are provided in supplementary material (appendix A1).

The waste water generated from a group of households was either directed to the pervious surfaces (for households that employ on-site sanitation systems such as pit latrines and septic tanks) or to the sewer (for households that employed off-site sanitation systems). For households employing septic tanks (or pit latrines), all the wastewater is directed to an on-site...
**Figure 2:** The integrated urban water modelling (modularised modelling) procedure

- **(a)** City delineated into watersheds (*SC*).
- **(b)** SCs schematised as drainage flow network.
- **(c)** In each SC, **HH** clusters.
- **(d)** In each HH Cluster,
  - HHs no.
  - Water Use & WW** Generation
  - Rainfall
  - Pervious Hydrology
  - Impervious Hydrology
  - Catchment Area
  - Stormwater flow (output 2)

- **(e)** Each HH, Mains Water end-uses
  - Toilet use
  - General Cleaning
  - Dish Washing
  - Handwashing
  - Laundry Use

- **(f)** Each HH, Impervious Surfaces
  - Paved (Roof)
  - Paved (Compound)
  - Paved (Road)

- **(g)** Each HH, Pervious Hydrology

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3.3.3. Household Stormwater Hydrology

As illustrated in figures 2(d), 2(f), and 2(g) the stormwater hydrology in WaterCycle comprised both impervious and pervious hydrology. The approaches employed in WaterCycle for urban stormwater hydrology were not novel but based on approaches already employed in UWOT (Makropoulos et al. (2008)), Aquacycle (Mitchell et al. (2001)), City Water Balance (Last (2010)) and WaterMet (Behzadian and Kapelan (2015)). Every household or group of households was modelled to receive input from the rainfall and household human wastewater effluent, which together pass through the system, to output as evaporation, stormwater runoff, and/or as sewer wastewater.

Each household space was divided into four surfaces that can generate runoff, that is roof, pavement, open space, and road. At the cluster scale, it assumed that the group of households contains a larger public open space (such as a park, or golf course) that was added to the stormwater space delineation (see 2(c)). These surfaces are grouped as either impervious (road, roof, pavement) or pervious (household open space, and public open space). The runoff running off the impervious surfaces drains to the pervious surface, which in turn drains to the stormwater drainage system (as it exits the subcatchment).

The modelling of flow from impervious surfaces follows the process described in Mitchell et al. (2001), Mitchell (2005) and Last (2010). The runoff from these surfaces is directed to the pervious surfaces. The details of the impervious hydrology are provided in the Supplementary Material (Appendix A2).

Pervious surfaces (illustrated in figure 2(g)) receive runoff from the impervious surfaces and model their runoff generation fol-
lowing a soil-moisture water flow accounting algorithm (Partial Area Model based on the Australian Water Balance Model (AWBM)) described previously by (Mitchell et al., 2001) and utilised also by Last (2010). This algorithm was chosen for this study because it is well suited for areas with high levels of evapotranspiration and intense rains (Last, 2010) - similar to the tropical conditions experienced in Mbarara town. Further details of the previous hydrological modelling in WaterCycle are provided in the Supplementary Material (Appendix A2).

3.3.4. Subcatchment - Subcatchment flow modelling

With existing integrated modelling systems (Aquacyle, City Water Balance, WaterMet), the flow of water from one subcatchment to another follows only a mass balance approach, without allowing for gravity to impact momentum on the flow as is expected in natural waterways (Mitchell et al., 2001). In stormwater drainage systems, gravity alone provides the force to move the liquid downstream (Walski et al., 2007), and hence it is important that gravity is allowed to control the flow of stormwater downstream. Behzadi and Kapelan (2015), however, attempted to address this limitation by introducing the Rational Method, but this was applied only to flows within a given subcatchment, not for flows from one subcatchment to another.

Therefore in WaterCycle, this gap was alleviated by introducing the Modified Muskingum routing approach to model the flow of stormwater downstream from one catchment into another, for the whole urban water system. The Modified Muskingum rainfall-runoff models provide a more realistic gravity-controlled flow of stormwater downstream. The details of the rainfall-runoff-routing approach employed in this study are provided in the Supplementary Material (Appendix A3).

3.3.5. Modelling Contaminant Flow

In integrated modelling, due to the overall complexity of the physical system being modelled, most practitioners recommend that only the dominant processes (and pollutants) should be represented, and described quantitatively (Aichleitner, 2006). In the description of catchment water quality performance, a number of different water quality parameters are usually given emphasis. However, to examine the impact of the urban catchment on its receiving waters usually, Total Phosphorus or Total Nitrogen are recommended as the indicator parameters. In WaterCycle, Total Nitrogen (TN) was chosen as the parameter to represent pollution of the urban water runoff. This parameter was chosen because the focus of urban water systems modelling is usually on studying the impact of the human activities (in the urban centre) on the receiving environment.

The modelling of Total Nitrogen (TN) followed the concepts outlined in UVQ (Mitchell and Diaper, 2005) and in City Water Balance (Last, 2010). The contaminants are modelled conservatively, so no account is taken of their conversion or degradation in transit. Contaminants are input into WaterCycle through the water end-use characteristics. Their flow across the urban water system is then followed in parallel with the water flow. However, when they find a treatment system like a septic tank, wastewater treatment plant (such as waste stabilisation ponds), or pit latrine, the waste water contaminant concentration is reduced according to the treatment efficiency of that waste treatment system. Also, whenever two or more waste water streams combined in the urban water system, their wastewater concentration is aggregated.

3.4. Summary - Urban Water Hydrology

In summary, for each subcatchment, the number, type, and characteristics of the constituent households located within that subcatchment were defined (from the actual field data). Then within each household or households groups, these characteristics (including the water use and physical properties) were transformed into parameters which were utilised in the model to compute the mains water requirement, the household wastewater and the stormwater runoff (both in quantity and quality). These computations were carried out from subcatchment to subcatchment, from time step to time step (daily) across the whole urban water cycle.

The intention of WaterCycle was for strategic planning and preliminary evaluation of sustainable urban water management options rather than as a detailed design tool. Thus, a daily time step was considered to be the most appropriate to reveal such information from an urban water system.

4. Results

WaterCycle generates three major outputs from an urban water system that is the total mains water use or demand, the surface stormwater flow quantity, and the surface stormwater contaminant quality. More outputs could be generated from the system but these were chosen in order to provide a way to account for the role played by each of the subsystems, in generating the sustainable behaviour of an urban water system. In addition, further outputs can be generated from WaterCycle that provide deeper insights into the sustainable behaviour of an urban water system. Such information includes the attribute information that follows each scenario (or intervention) like the three outputs (mains water use, stormwater flow, stormwater concentration) per urban water subsystem, or per subcatchment, per households group, and/or per scale of application of the intervention. In this paper, only the overall outputs from the city are considered.

4.1. Mains Water Use

For all household groups, the mains water use portion of WaterCycle was calibrated against the monthly mains water use measured and billed by the city water utility (see figure 3). The calibration showed a good performance of the mains water use models in estimating the monthly consumption volumes since the measured consumptions were within the boundaries (minimum and maximum) of the estimated consumption volumes. Since WaterCycle mains water use is a stochastic modelling
system, the mains water use was validated through the comparison of the distribution of the computed mains water use volumes to the distribution of the measured mains water use volumes. The distribution validation performed relatively well except for a few scattered groups that had poor data availability. This performance showed the suitability of WaterCycle in representing the mains water use of the community.

4.2. Stormwater Runoff

Figure 4a shows another novel output from the system, the surface stormwater hydrograph of the urban water system and its calibration performance in figure 4b. Since the urban catchment is not gauged for stormwater flow, there was no direct stormwater flow data source to calibrate the stormwater flow computation. However, the river that traverses the city has a gauging station (whose location is shown in figure 2(b)), whose data though does not provide a good representation of the stormwater flow exiting the city, does provide a minor reflection of the expected stormwater flow hydrograph.

The K and X constants in the model were adjusted until the shape of the stormwater runoff hydrograph was as close as possible to that of the observed river flow hydrograph, to confirm the appropriateness of WaterCycle’s stormwater simulation. Though in essence the two flows represent two different catchments and hence different responses, it is presumed that since they belong to the same overall catchment, there should be a positive correlation between them. This relationship is shown in figure 4b, with a positive correlation coefficient of 0.3 ($p<0.05$). It must be emphasised however that since the river flow represents a much larger catchment than the urban stormwater flow simulated by the model, then a positive relationship between both flows can be taken as a realistic representation of the storm water flow in the modelling system.

4.3. Stormwater Concentration - Pollutograph

Figure 5 shows another novel output from the modelling methodology. It shows a longitudinal series of a contaminant (total nitrogen in this case) with time. Most integrated modelling systems do not provide such an output. This output is of much relevance to an urban water system as it demonstrates the role the urban water sanitation subsystem in the sustainable behaviour of the whole urban water system. In addition, the pollutograph confidence intervals (medians of the 5% and 95% signals) were compared to the 95% intervals of the observed effluent exiting the waste water treatment plants in the systems. Both intervals are comparable. However, there was not enough to provide enough water quality data to allow for a linear comparison of the measured and observed pollutographs. Nevertheless, despite the absence of sufficient water quality data, the urban water sanitation system modelling in WaterCycle provided reflection of a relatively sufficient estimation of the urban water sanitation system of the developing world city.

5. Discussions

WaterCycle is a conceptual, simulation type, mass and contaminant balance based model which quantifies the water and contaminant flows across an urban water system (that is across the water supply subsystem, the storm water subsystem, and the sanitation subsystem) of a city of the developing world. This model was developed with an objective of filling the knowledge gaps in integrated urban water modelling described by Mitchell et al. (2007). In terms of typology, WaterCycle can be described by Bach et al. (2014a), to belong to the category of Integrated Water Component Modelling Systems (IWCM).

The review by Mitchell et al. (2007) of existing integrated urban water systems stated that their poor handling of the urban spatial scale as one of the major set-backs in their development. As a consequence of this limitation, these systems provide a poor representation of the urban water infrastructure of a developing world city. WaterCycle attempted to fill this gap. Therefore, WaterCycle placed emphasis on developing an integrated urban water modelling system that precisely represents the major urban water features (such as a unique mains water use structure, a predominantly naturally-based storm water drainage, and a predominantly on-site sanitation system) of a city in the developing world. The integration of these features in an urban hydrological system for such a city is the major novelty WaterCycle adds. This interaction allows WaterCycle to illustrate the impact of any on-site sanitation-based or land-use based urban water interventions on the environmental performance of the urban water system.

WaterCycle alleviates another weakness highlighted in Mitchell et al. (2007) of the current integrated urban water modelling systems. In the existing integrated urban water systems (AquaCycle, UWOT, CWB, WaterMet), mains water use is represented principally through a centralised (with the aid of arithmetic average) water end-use, which consequently represents the wastewater generated in the model. In WaterCycle, a stochastic mains water use algorithm to develop a more-realistic approach to describe the mains water use variability across the whole city was employed instead. This algorithm is of much relevance to integrated urban water management in that it allows WaterCycle to illustrate the impact of mains water use on the environmental performance of an urban water system, a concept that demonstrated by Rauch et al. (2003).

WaterCycle, in addition, relative to existing integrated modelling systems employs an advanced rainfall-runoff stormwater flow routing algorithm to model the flow of stormwater downstream. This new methodology provides this addition by allowing the Muskingum rainfall-runoff approach to dominate the flow from sub-catchment to subcatchment, and finally downstream to the receiving waters. This functionality in the integrated modelling allows WaterCycle to reproduce the flow and contaminant peaks experienced by most urban water systems. This behaviour allows plays a role in illustrating the role played by water supply subsystem and stormwater
Figure 3: Calibration and validation of mains water use computation - the volumes calibration [modelled as dotted line] in (a), (c), (e), (g) and the distribution calibration (in (b), (d), (f), (h))
subsystem in the operation and design of appropriate urban water interventions.

Finally, with the new additions to WaterCycle, it provides an appropriate platform for the design, assessment, and performance testing of integrated urban water design schemes for a city of the developing country. Although, not described in this paper, this modelling system has been extended for the assessment of various decentralised system interventions involving water supply subsystems, storm water subsystems, and sanitation subsystems. The paper has demonstrated that existing integrated modelling systems are highly inappropriate in the design of integrated urban water management schemes for cities of the developing world. Therefore any improvement provided by WaterCycle is novel.

6. Conclusion

This study has described a novel methodology (encapsulated in modelling system WaterCycle) of mathematically describing the hydrology of mains water use, stormwater and wastewater flow within an urban community of the developing country, extending from household scale to the whole city. In addition, the methodology also adds novel approaches (of stochastic mains water use, and of gravity-dominated stormwater flow routing) to the existing integrated modelling paradigms. This additions then enables the modelling system to replicate the high nutrient load peaks that affect the performance of the urban water system’s waste water treatment capability, in addition to being able to successfully model a city of the developing world.

With these additions, the modelling system is able to provide novel revelations of an urban water system by providing a water use hydrograph output, a stormwater flow hydrograph output, and a pollutant concentration pollutograph. Generating these outputs simultaneously from an integrated urban water modelling system represents a significant advance in the description of urban water hydrology. This integration coupled with stochastic mains water demand estimation, a low-income-specific spatial delineation scale, and a more advanced rainfall-runoff algorithm provides a novel algorithm for the exploration of various urban water management options (that can be extended also to the developed world). With such an integrated modelling system, it is possible to assess numerous urban water system options, at citywide scale, at subcatchment scale, at household scale, and at subsystem scale to generate a more detailed integrated understanding of the response of a given urban water system.

References

Achleiter, S., Fuchs, S., Rintalt, T., Rauch, W., 2008. Nowcasting of rainfall and of combined sewage flow in urban drainage systems.


Appendix A. Supplementary Material

Appendix A.1. Modelling in-house water use

Figure 1 shows the discretisation of the community employed in this study that categories households according to the water use category and sanitation type. It also specifies the characteristic end-uses of each water user group. This discretisation of the community was employed to generate a stochastic model of water use regime of the community. The approach used to generate this stochastic model is extended from an approach by Munina et al. (2016). The stochastic model was preferred because preliminary water use data of the community revealed the water use distribution to be highly skewed. Further, this stochastic water use representation provided a platform for describing the urban water use uncertainty or variability in a developing world community. This variability as Rauch et al. (2003) describes, has a significant impact on the behaviour of the urban water system downstream.

Munina et al. (2016) represented the overall water use in a household (and then across all households of a group) as:

\[ Q = \sum_j \sum_i [a_{ij} \times b_{ij} \times n_j] \]  
(A.1)

where \( a_{ij} \) represents the volume (or intensity) of water consumed per end-use \((i)\) per person in a household \((j)\), \( b_{ij} \) represents the frequency of use events of end-use \((i)\) per person in a day in household \((j)\), and \( n_j \) is the number of adults in household \(j\). The summation is done for all end uses considered, and for all the households in the group.

The parameters \((a_{ij}, b_{ij}, n_j)\) are instances of probability density distribution models. For each consumer group and for each constituent water end-use parameter (that is its intensity and its frequency), their statistical position and statistical spread values were estimated from the socially surveyed data of the community. The histogram of each water end-use parameter was then fitted to each of the native probability density distributions (like Normal, Lognormal, Gamma, Weibull, Exponential, Rayleigh, and Chi-Squared), from which the probability distribution with the closest fit (as measured by a correlation coefficient) was taken as the most appropriate probability distribution model of that end-use parameter. The details of the appropriate probability distributions chosen for each water end-use parameter is described in Munina et al. (2016). The approach by Munina et al. (2016) was applied to domestic mains water users only, in this study the approach was extended to other water user groups to model household water use.

Households with similar end-uses were grouped into the same group to generate a total of eight (8) groups (as shown in figure ??), that is: domestic, commercial, general institutional and or large institutions, and also according to nature of sanitation employed at each location. Commercial group users compromise of water consumers like business offices, shops, restaurants, while small institutions compromised of mainly churches, mosques, clinics. Large institutions consisted of users that have a high concentration of adults in a small area for example universities, schools, hospitals that allow for accommodation-related end-uses. The user groups were further sub-divided (in each group) according to the nature of sanitation practice employed, that is house connection or yard tap connection. This kind of grouping provided a way to cater for the heterogeneity of the various users found in the town community.

For domestic water users, the end-use system was modelled with the same parameters as those employed in equation A.1. However, for the other user groups (commercial, small institutions, and large institutions), the equation had to be modified. It is assumed that the per capita end-use volumes of domestic users (for corresponding end-uses), are similar to those of other groups but differ on the number of users (adults) per household or account. That is, the non-domestic user groups were designed as a replicas of the domestic user groups but with different household size parameters, and different component end-use types. For all groups, their representative equation was calibrated against the monthly and measured water consumption for all the household population in the user groups. The calibration performance is shown in figure 3. The same water demand volume computed through this model was then transformed into human waste water volume (assuming no water loss).

Appendix A.2. Impervious Stormwater Hydrology

Figure A.6 provides an alternative view of how stormwater hydrology is modelled across an urban water system in the modelling system. The modelling of flow from impervious surfaces is modelled in the same way as described in Mitchell et al. (2001); Mitchell (2005); and Last (2010). Impervious surfaces (roof, paved, road) are each modelled as single storage runoff saturation excess process. The water retained in the store represents the initial losses due to interception and depression storage.

The runoff from impervious surfaces is diverted either to pervious surfaces (denoted as NEAR in the equation A.2) or contributes directly to overland flow (denoted as IRUN in equation A.3). Assuming no depression storage.

\[ NEAR = \sum_i (1 - ERA) \times (P - IL) \times A_i \]  
(A.2)
IRUN = \sum_i ERA \times (P - IL) \times A_i \tag{A.3}

where i represents each of the paved areas of a typical household like road, roof, etc. ERA represents the effective road areas proportion. P is the rainfall depth falling on the household (m), IL is the interception and evaporation loss (m) evaluated as shown in equation A.4. A_i is the proportionate area of a roof, a road, or paved sections of a household cluster (m^2).

\[ IL = \max(0, P - \text{IntLoss} - \text{EvapLoss}) \tag{A.4} \]

where P represents the rainfall depth (m), IntLoss is the interception loss (m), and EvapLoss is the evaporation loss (m) off the impervious surface. The Evaporation loss was taken as the maximum evaporation rate that the surface can face (potential evaporation).

Appendix A.3. Pervious Stormwater Hydrology

Figure A.6 provides an alternative view of how stormwater hydrology is modelled across an urban water system in the modelling system. The required spatial discretisation of this city was represented through an innovative hierarchy of schematisation shown in figure 2. The urban water catchment was split into a series of subcatchments, then within every subcatchment the resident households were represented as clusters of household groups (in figure 2b) including the public open spaces.

Within a cluster of households, the urban water system was schematised as shown in figure 2c. Every household or group of households was modelled to receive input from the rainfall and mains water (water used), which together pass through the system, to output as evaporation, stormwater runoff, and as sewer wastewater. Each household space (and hence cluster of households) was divided into four surfaces that can generate runoff, that is, roof, pavement, open space, and road. In addition, at the cluster scale, it assumed that the cluster contains a larger public open space. In figure 2, these surfaces are grouped as either impervious (road, roof, pavement) or pervious (household open space, and public open space). The runoff off the impervious surfaces drains either to the pervious surfaces or to the stormwater drain (the river system), subdividing the surface according to a site specific space dividing parameter, as applied in Mitchell and Diaper (2005). The approach thus divides a catchment into areas that produce runoff (contributing areas) and those that do not during a rainfall-runoff event, hence allowing for the spatial variability of surface storage in a catchment to be modelled (Mitchell et al. (2001); Mitchell (2005)).
The runoff (and rainwater) falling on the pervious surfaces is modelled to follow physical process of water flow through subsurface soil mass. The pervious hydrology is modelled in the same way as represented in (Mitchell et al., 2001) and in Last (2010), which utilises a soil-moisture accounting algorithm known as the Australian Water Balance Model (AWBM). It splits the pervious area into two stores, with different storage depths and different areas. Input to the pervious stores is split between the two stores proportional to their relative surface area. There are no flows between the stores. The only outflow from the stores is evaporation until the capacity of either store is exceeded. The excess water above the capacity is divided between groundwater recharge and overland flow (pervious surface runoff). These divisions are dependent upon the user-defined proportions for each cluster. The overland flow from pervious stores is directed to the stormwater drainage system (the river in this case). The computation of water flow through pervious surfaces was based on the Partial Area model was chosen for this study because it is well suited for areas with high levels of evapotranspiration and intense rains (Last, 2010), just like the study area which is located in tropical conditions.

The partial area model is based on the Australian Water Balance Model (AWBM) involves splitting the pervious area into stores: pervious store 1 (PS1) and pervious store 2 (PS2). PS1 and PS2 can have different storage depths and different areas. The two pervious stores receive water (input) from precipitation, wastewater and surface runoff from impervious areas, as shown in figure A.6. This input to the pervious area is split between the two stores proportional to their relative surface area. There are no flows between the stores. The amount of excess water (overflow) from these stores is calculated separately, then combined according to their respective proportional areas of the catchment. The only outflow from the stores is evaporation until the capacity of the store is exceeded, as shown in equation A.5 and in figure A.7.

The approach used to calculate actual evapotranspiration in the study, is based on work in Aquycle, the approach assumes that the supply of water to a plot is a linear function of available water in the root zone. The maximum amount of evapotranspiration that can occur in a given day is termed $E_p$, the potential evapotranspiration rate. Actual evapotranspiration is the amount which did actually evapotranspire in that day, given the potential rate, the soil moisture content in the pervious stores (pervious store level) and the capacity of the vegetative cover to transpire ($E_{pc}$).

Evaporation from the pervious store is computed as:

$$E = \min(E_p, (A1 \times PS_{1cap} / PS_{1cap} + (1 - A1) \times PS_{2cap} / PS_{2cap}) \times E_{pc})$$

where $E_p$ is the daily potential evaporation rate (m), $E_{pc}$ is the capacity of vegetative cover to transpire (m), $PS_{cap}$ pervious store current level (m), $PS_{cap}$ pervious store capacity level (m), $A1$ is the proportion of the total household area overlain by PS1.

The maximum evapotranspiration rate has a fixed value and is used as a second control on evaporation from pervious areas. It is to be calibrated, however when it is set too high it represents evapotranspiration from denser vegetation.

Excess water above the capacity is divided between groundwater recharge (GWR) and overland flow (PRUN) as shown in figure A.6. The division is dependent on the user defined proportions for each cluster. It is assumed that overflow from the pervious stores is directed to the storm water system.

The capillary drawdown is modelled using equation A.6. When the groundwater is deeper than a specified depth there is no capillary draw up (see figure A.7). If it rises above this level, then draw up occurs up to a maximum daily potential evaporation. If the ground water level rises above the base of the soil, then it is assumed that the whole soil profile becomes saturated. If the groundwater level rises above then it contributes to stormwater system.

$$C_d = E_p \times (SDSD / SDSD_{max}) \times (GWL - D_t) / (S_{base} - D_t)$$

where $SDSD$ is the soil moisture deficit that is $PS_{cap} - PS_{cap}(m)$, $GWL$ is the ground water level above datum (m), $S_{base}$ is the soil column thickness (m), $D_t$ is the maximum capillary action depth (m).

The amount of excess soil moisture as illustrated in figure A.7b is calculated for the two pervious stores and combined according to the proportional area of each store, according to the following equation:

$$EXC = \max(PS1 - PS1, 0) + \max(PS2 - PS2, 0) \times (100 - A1)$$

where $PS1$, $PS2$ are the field capacity levels of either partial stores, and $PS1$, $PS2$ are the current soil moisture levels. $A1$ is the percentage of pervious model PS1 across the whole catchment.
The excess proportion of the excess soil moisture recharges the ground water store. The ground water store is drained according to a recession function, creating baseflow.

\[ GWR = BI \times EXC \]  \hspace{1cm} (A.8)

\[ BF = BRC \times GWS \]  \hspace{1cm} (A.9)

The amount of pervious surface runoff contributing to the total stormwater flow (SRUN) is equal to the excess soil moisture less the infiltration and the ground water recharge (in equation A.10).

\[ SRUN = EXC - RIS - GWR \]  \hspace{1cm} (A.10)

In this study, as much as the impact of groundwater recharge on runoff is recognised, the ground water store was not modelled. Hence, the impact of baseflow on the stormwater runoff was not represented. This was due to the unavailability of ground water flow data. However, further details of the impervious storage, pervious storage, and ground water storage are found in Mitchell (2005).

The flow to groundwater is further split into either infiltration or ground water recharge. The capacity of the infiltration flow depends on the pervious surface soil moisture, which is equivalent to the field capacity. The groundwater store is assumed to be unconfined, and is expected to contribute base flow to the river. However in this study, ground water flow was not considered and thus not pursued any further in the model.

Appendix A.4. Stormwater Infiltration

Stormwater infiltration into the wastewater sewerage system occurs during periods of excess soil moisture storage. The infiltrated water (RIS) from the soil moisture enters into a temporary infiltration storage, then dains into the wastewater sewerage system (INF).

\[ RIS = II \times EXC \]  \hspace{1cm} (A.11)

\[ INF = IRC \times \sqrt{INFS} \]  \hspace{1cm} (A.12)

The inflow of stormwater into the wastewater system is represented as a proportion of the total surface runoff generated:

\[ ISI = IFRate \times (SRUN + IRUN) \]  \hspace{1cm} (A.13)
Appendix A.5. Summary - Stormwater Flow Hydrology

Stormwater runoff is usually separated into two components for modelling purposes, these being surface runoff and base flow. Surface runoff from urban areas is further separated into components sources from pervious and impervious surfaces due to the differing hydrological response of these surface types. Impervious surfaces can be further divided up into roofs, roads, and paved areas. Pervious surfaces include grassed areas such as lawns and parks as well as garden beds and bare soil. Therefore, four surface types are used in the model; i) pervious areas, ii) roofs, iii) paved areas, and iv) roads, with each surface generating runoff.

The total amount of water discharged as stormwater runoff, \( R_s \), is given by the following equation:

\[ R_s = IRUN + SRUN + BF - ISI \]  \hspace{1cm} (A.14)

where

\( IRUN \) represents contribution from the impervious surface runoff,
\( SRUN \) the pervious surface runoff,
\( BF \) the baseflow, and
\( ISI \) the infiltration to the wastewater sewerage system.

Appendix A.6. Modelling Subcatchment to Subcatchment flow

The flow of stormwater downstream a channel is represented accurately in three-dimensions through the Navier-Stokes systems of equations, which are then simplified to the St. Venant equations (Achleitner, 2006) based on the assumption that the flow is one-dimensional, the pressure distribution is hydrostatic, the length of the channel is much greater than its flow depth, and that the water density is constant (Walski et al., 2007). The St. Venant equations are based on the assumption that the average velocity in a cross-section is adequate to describe the flow and water surface only slopes in the direction of the flow. However, due to the complexity involved in fully solving numerically the Navier-Stokes or the St. Venant equations, a variety of hydrological rainfall-routing conceptual models have been introduced and applied to describe the flow of stormwater downstream a channel. All these methods in principle provide a simplified representation of the St. Venant equations under certain assumptions Walski et al. (2007). The Modified Muskingum routing method is one of those methods, and was utilised in this study.

Hydrologic routing methods, such as the Muskingum routing approach, track the flow and momentum effects of the stormwater flow downstream, through an approximation of the temporary storage across each channel reach, using simplified storage equations. The approach is based on equation (which is an expression of mass balance):

\[ I - O = \frac{dS}{dt} \]  \hspace{1cm} (A.15)

where
\( I \) is the inflow rate
\( O \) is the outflow rate,
\( S \) is the storage, and
\( t \) is the time.

Then, the expression for storage in a channel reach used in the Muskingum approach is:

\[ S = K[XI + (1 - X)O] \]  \hspace{1cm} (A.16)

where \( K \) and \( X \) represent storage parameters.

For most streams, \( X \) is approximated as 0.2, while \( K \) is an approximation to the travel time of the reach. There are numerous formulae in literature to estimate the travel time of a reach that depend on its topographical parameters.

The discharge from a reach is then given by:

\[ Q_i = c_{i-1}I_{i+1} + c_iI_i + c_{i+1}O_i \]  \hspace{1cm} (A.17)

where \( i \) represents a given time step. The coefficients are given by (where \( t \) is the time step duration):

\[ c_{i+1} = \frac{0.5t - XX}{K - XX + 0.5t} \]  \hspace{1cm} (A.18)
\[ c_i = \frac{KX + 0.5t}{K - XX + 0.5t} \]  
(A.19)

\[ c_{i+1} = \frac{K - XX - 0.5t}{K - XX + 0.5t} \]  
(A.20)

Achleitner et al. (2007) encapsulated this algorithm, into an open-source modelling system, denoted as CITY DRAIN (also developed within the Matlab/Simulink environment). This platform was employed in this study to represent the flow of stormwater downstream from subcatchment to subcatchment.

Using the physical characteristics of each subcatchment (as represented by its topography), the travel time of each subcatchment was computed. This computation was used to represent the K constant in the Muskingum approach of the modelling system, so that the geographical representation (and consequently gravity) of each subcatchment dominates the stormwater flow downstream. In this way, a more realistic contribution of each catchment can be represented in the overall urban water modelling system. The dimensionless X constant was taken as 0.25.

Appendix A.7. Software Platform

The development environment selected for the integrated urban water modelling model is Simulink, which forms part of the MATLAB suite of tools developed by Mathworks. Simulink enables the modelling, simulation, and analysis of dynamic systems, whose outputs change over time. Simulink was chosen as it facilitates the representation of processes and flows in a in a block-wise modelling manner. This modularised or block-oriented approach is convenient for the creation of coupled models. Blocks are connected to each other providing information flow between each other. Then also, the detailed computational algorithms of a given block are created with aid of pre-existing blocks provided by Simulink and or the creation of own blocks that can contain user created routines created through by coding in either m-functions, s-function or Cpp languages. This approach was employed for the development of the modelling system.

To build this system, the platform in Matlab/Simulink provided by City Drain was used as the building block(s). City Drain was designed to simulate the flow of storm water flow in urban centres following the different spatial units (sub-catchments). Though, from an integrated urban system perspective, City Drain was designed to model and represent downstream portions of an urban water system, it does not describe any urban water upstream systems for example the water supply system. The system in its form has found applications in the Rauch et al. (2002); Achleitner and Rauch (2007); Freni et al. (2008); Achleitner et al. (2008); Rodríguez et al. (2009); Rodríguez and Díaz-Granados (2011); Rodríguez et al. (2013) but only for the downstream urban water systems. Therefore, in this modelling system, utilising the City Drain platform was utilised as the baseline platform to encapsulate the subcatchment to subcatchment flows. Then within each subcatchment blocks upstream modules of mains water usage, wastewater generation, impervious/pervious hydrology were added to it to complete an integrated urban water modelling.

Appendix A.8. Data Employed

Appendix A.8.1. Catchment Characteristics

From the topographical characteristics of the subcatchments as shown in table A.3, the time of concentration of each catchment (reflected in form of the number of sub-reaches in table A.3) was computed. This computation was used to represent the K constant in the rainfall-routing algorithm of the modelling system, so that the geographical representation (and consequently gravity) of the sub-catchment dominates the stormwater flow downstream. In this way, a more realistic contribution of each catchment can be represented in the overall urban water modelling system. The dimensionless X constant in the Muskingham rainfall routing model was taken as 0.25.

Appendix A.8.2. Household physical characteristics

For each subcatchment, an average household area was defined, sourced from the image data of the area. However for the paved, road, pervious, and roof area of the households, due to the unavailability of their data, they were estimated as 10%, 5%, 25% and 60% respectively. For the low-income communities, the household areas and roof areas were correspondingly reduced to 10%, 1.5%, 65.5%, and 30% of the household area respectively.

Appendix A.8.3. Soil moisture accounting characteristics

In addition soil moisture accounting model parameters were defined for each subcatchment. These parameters are usually estimated from detailed catchment soil data survey, and or calibrated with aid of the catchment flow monitoring records. However, due to the absence of these data(s) of this catchment in this study, these parameters were borrowed from studies carried out in other regions of the country. These parameters are shown in table A.4.

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Table A.3: Gravity flow hydraulics parameters across the sub-catchments

<table>
<thead>
<tr>
<th>ID**</th>
<th>Area [ha]</th>
<th>Length [m]</th>
<th>Slope, So</th>
<th>Time [s]</th>
<th>Sub Reaches [No.]</th>
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<tr>
<td>9</td>
<td>236.0</td>
<td>5570.3</td>
<td>0.006</td>
<td>3261.8</td>
<td>36.2</td>
</tr>
<tr>
<td>10</td>
<td>43.9</td>
<td>3224.9</td>
<td>0.010</td>
<td>1526.7</td>
<td>17.0</td>
</tr>
<tr>
<td>11</td>
<td>193.7</td>
<td>3224.9</td>
<td>0.011</td>
<td>1602.3</td>
<td>17.8</td>
</tr>
<tr>
<td>12</td>
<td>301.1</td>
<td>5640.6</td>
<td>0.013</td>
<td>2255.6</td>
<td>25.1</td>
</tr>
<tr>
<td>13</td>
<td>376.2</td>
<td>8697.7</td>
<td>0.013</td>
<td>3606.3</td>
<td>40.1</td>
</tr>
<tr>
<td>14</td>
<td>216.1</td>
<td>5898.0</td>
<td>0.007</td>
<td>3283.5</td>
<td>36.5</td>
</tr>
<tr>
<td>15</td>
<td>181.8</td>
<td>4051.5</td>
<td>0.009</td>
<td>1995.0</td>
<td>22.2</td>
</tr>
<tr>
<td>16a,b,c*</td>
<td>327.2</td>
<td>2785.9</td>
<td>0.003</td>
<td>555.8</td>
<td>6.2</td>
</tr>
</tbody>
</table>

*Includes decentralised, centralised, and low-income sub-units  
**Sub-catchment ID as shown in figure 2

Appendix A.8.4. Contaminant Loading characteristics

Finally, to account for the ingress of contaminants in the urban water system, another set of parameters was defined that represents the amount of contaminant (total nitrogen in this case) for each stream of water in the urban water system. These parameters are shown in table A.5.
### Table A.4: Soil moisture accounting model parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potential Evaporation [mm]</td>
<td>1.5</td>
</tr>
<tr>
<td>Maximum Evapotranspiration [mm]</td>
<td>0.5</td>
</tr>
<tr>
<td>Field Capacity [mm]</td>
<td>2.0</td>
</tr>
<tr>
<td>Infiltration Rate [-]</td>
<td>0.095</td>
</tr>
<tr>
<td>Effective Runoff Rate [-]</td>
<td>0.6</td>
</tr>
<tr>
<td>Percolation Rate [-]</td>
<td>0.55</td>
</tr>
<tr>
<td>Initial Loss [mm]</td>
<td>2.0</td>
</tr>
<tr>
<td>Soil Column [mm]</td>
<td>20</td>
</tr>
</tbody>
</table>

### Table A.5: Contaminant Parameters employed in the model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Quantity [g/m3 person]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urine</td>
<td>10.4</td>
</tr>
<tr>
<td>Feces</td>
<td>1.5</td>
</tr>
<tr>
<td>showering water</td>
<td>1.0</td>
</tr>
<tr>
<td>washing Dishes water</td>
<td>1.0</td>
</tr>
<tr>
<td>Laundry water</td>
<td>1.0</td>
</tr>
<tr>
<td>General Cleaning water</td>
<td>1.5</td>
</tr>
<tr>
<td>Rainfall water</td>
<td>0.01</td>
</tr>
</tbody>
</table>
Appendix D

Paper IV

This section of the thesis displays the contents of the journal paper (denoted as Paper 4) that has been recently submitted to a peer-reviewed international journal - Water Science and Technology.

D.1 The paper as submitted to IWA’s Water Science and Technology
An integrated assessment methodology for the sustainable performance of an urban water system of the developing world

Kenneth Muniina, Cedro Maksimovic, Nigel Graham
Imperial College London
muniinakenneth@yahoo.co.uk

Abstract

This study proposes a novel methodology for assessing the sustainability performance of an urban water system in the developing world. It utilises an integrated urban water modelling system to assess the sustainable performance of numerous urban water interventions (both conventional and unconventional) across the three principal urban water subsystems, that is, the water supply subsystem, the stormwater subsystem, and the sanitation subsystem. The methodology has revealed valuable insights of relevance to both conventional and unconventional urban water systems, insights which are usually ignored in their design and assessment. For example, the study revealed that none of the 28 tested interventions provided significant positive a sustainable performance across all the three subsystems, indicating that no single urban water system intervention is able to provide the required sustainable performance.

1. Introduction

In conventional urban water systems, the constituent urban water subsystems are managed, analysed, and assessed in isolation from one another (Cook et al., 2013) which makes them vulnerable to any external pressures (Loftus, 2011). This weakness has led to the conclusion that conventional urban water systems across both the developing and developed world are unable to sustain the provision of appropriate water services to their users or to sustain the avoidance of environmental degradation. The unsustainable behaviour of these systems is related to their inherent weaknesses that are centred on the lack of integration of the urban water subsystems.

This vulnerability of the conventional urban water management model has led many authors such as Memon et al. (2005), Porto et al. (2007), Zhang et al. (2007), Blackmore and Plant (2008), Bjour et al. (2009), Fidar et al. (2010), Sharma et al. (2010), Loftus (2011) and Clossas et al., 2012), to advocate for the alternative urban water management model as a viable option to introduce sustainability within existing urban water systems. The alternative urban water management model is centred on the application of alternative urban water technologies (strategies and interventions) across the boundaries of the individual urban water subsystems, to generate a total urban water solution that is sustainable holistically across the whole system and across each of the individual subsystems (Clossas et al., 2012, Sharma et al., 2008, Loftus, 2011). This integration within the alternative urban water management systems leads an integrated management of the urban water system.

Integrated management of urban water systems, in this case, implies the exploitation of the interactions (that is, the integration) between the different urban water subsystems to generate a sustainable performance of the urban water (Makropoulos et al., 2008). The integration between different subsystems can either contribute to the successful behaviour of the urban water system (if the system comprises of the appropriate urban water subsystem forms) or amplify its poor performance (if the urban water system comprises of inappropriate urban water subsystem forms).
1.1. Strategies for improving the performance of urban water systems

In urban water practice, the procedures that are followed to enhance the sustainable performance of an urban water system involves the application of an appropriate urban water intervention to the system. The intervention(s) chosen for a given urban water system is (are) usually driven and dominated by its water service model, that is whether it is a conventional system or an alternative system. In conventional systems, due to the approach of considering each subsystem in isolation, urban water supply subsystems are prescribed an increased mains-water supply (Sharma et al., 2010), urban stormwater systems are prescribed an increased stormwater conveyance (Butler and Davies, 2011, Schreier, 2014), and urban sanitation subsystems are prescribed an increased wastewater conveyance with treatment (Butler and Davies, 2011). Thus, conventional urban water management provides only three possible urban water options for intervening in an urban water system to boost its sustainable performance.

Alternative urban water management system approaches on the other hand, also follow the same strategy as the conventional systems, that is they also prescribe an intervention for an urban water system according to the subsystem being targeted. Their major difference from conventional systems, is that they provide more interventions options than conventional systems. Guideline texts such as Melbourne and Water (2006), Department of Environment Conservation NSW (2006), Turner et al. (2008), Philip (2011a), Philip (2011b), Philip (2011c), Kayaga and Smout (2011), Graham et al. (2012), Poleto and Tassi (2012), Bahri (2012) (including reference texts Luthi et al. (2011), Porto et al. (2009), Katukiza et al. (2012) and (Closas et al., 2012), prescribe numerous interventions as alternatives to the conventional systems interventions.

Both categories of interventions are summarised in table 1, showing the specific urban water subsystem they are designed to target for performance improvement. If all these interventions are combined into an urban water interventions sample space, they total up to 28 possible interventions. Of these, 32% are applied to target an improvement of the water supply subsystem (here denoted as Water Supply Interventions), 39% to target the stormwater subsystem (here denoted as Stormwater Interventions), and 28% the sanitation system (here denoted as Sanitation Interventions). In addition, of these interventions, 53% are applied at centralised scales, while 47% at decentralised scales.

Despite the existence of a relatively large number of performance improvement options for urban water systems, the most appropriate intervention to achieve a sustainable performance of a given urban water system is still largely unknown. Although modern urban water management calls for the integrated assessment of urban water systems in consideration of all the possible interventions options, the studies by Dixon et al. (1999), Butler (2007), Hunt et al. (2006), Burns et al. (2012) and (Fewkes and Wam, 2000), reveals that water supply interventions are evaluated solely for water supply subsystem performance, and not for the stormwater system performance, nor for the sanitation subsystem performance. In other words, the impact of the interventions on the other subsystems has been ignored in the assessment.

Therefore, the lack of adequate integrated assessments of urban water interventions limits the development of total systems solutions for urban water systems ((Mitchell, 2006); (Sitzenfrei and Rauch, 2014)). Not only is information required for the performance of every possible intervention across every subsystem required for a complete integrated assessment, but also information on the comparative performance of one intervention against another. This paper, therefore, presents an approach to generate this novel integrated assessment of an urban water system, to illustrate its value in the sustainable
development of urban water systems.

2. Methods

For an integrated assessment of an urban water system, an integrated modelling system is required. In this study, the novel integrated modelling system, WaterCycle, developed by Muniina et al. (2017), was employed. WaterCycle employs a novel methodology for the integrated modelling of urban water use, urban stormwater flow, and urban sanitation dynamics in a developing country town. It models the town from the household scale to the whole city. The mains water use (and consequently waste water generation) is represented through a stochastic variation of the water end-uses. The stormwater, human waste water, and contaminant flow are cascaded from a household scale (specifically defined specifically for this kind of city) through an advanced rainfall-runoff algorithm. WaterCycle was designed to allow the disintegration of water into various water end-uses (specific to a developing country), to provide a way of allowing for recycling and reuse of various waste streams, and also to allow for the application of various interventions (both centralised and local, or both conventional and unconventional). Further details of this modelling system are presented in Muniina et al. (2017).

To assess the integrated performance of numerous interventions across an urban city, it was necessary to find a way to model and simulate the multitude of urban water interventions in a single integrated urban water modelling system. Therefore, in this study, urban water interventions were modelled and added to WaterCycle. The interventions studied included a spectrum of conventional, alternative, water-supply-related, stormwater-related, and sanitation-related interventions. The details of how each of the urban water interventions was represented within WaterCycle are illustrated in table 1, and the details of how these interventions were modelled in WaterCycle are appended as supplementary material.

The second addition of this study to WaterCycle was the performance measurement regime of an urban water intervention. The performance assessment of an intervention was designed to relate to the main objective of an urban water system is to boost its sustainable performance. Although the precise definition of Sustainable Development (SD) is debatable (Ashley et al., 2005), this study adopted the description of a sustainable urban water system by Lundin (2003) that prescribes an urban water system as one that provides its water services to its users including preventing environmental degradation over a long term.

It was presumed in this study that the objective was to ensure the successful provision of services across each urban water subsystem, and therefore the measurement of urban water system performance measurement was by the development of performance indicators for each urban water subsystem. In the urban water supply subsystem, the mains water savings indicator was employed (in similar ways to studies by Fewkes and Wan (2000); Chatfield and Coombes (2007); Rooijen (2010); Schuetze and Santiago-Fandino (2013)). Mains water savings were defined to reflect the level of mains water use that has been conserved within the new system (with the intervention) relative to the original (baseline) system. It was presumed that an increase of mains water use would reflect a less sustainable urban water supply subsystem, since an increased mains water use is attributed to increased environmental degradation.

For the urban stormwater subsystem, a sustainable performance was reflected through the total volume of stormwater runoff discharged, (in similar ways to studies by Chatfield and Coombes (2007); Burns et al. (2012); Li and Babcock Jr (2013); Huang et al. (2014), Fagan et al. (2010), Rodriguez (2012)). For the urban sanitation subsystem, this was assessed through the total mass of contaminant (total nitrogen in this case) discharged from the urban water system. In each case, the performance indicators
Table 1: Modelling of urban water interventions

<table>
<thead>
<tr>
<th>Intervention</th>
<th>Modelling Concept</th>
<th>Scope</th>
<th>Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Water Supply Interventions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Conventional</td>
<td>Increase the mains water use by a factor (2016) for showering, dishwashing, laundry, and general cleaning water use</td>
<td>All HHs</td>
<td>Local</td>
</tr>
<tr>
<td>2. DM Toilets</td>
<td>Reduce the toilet water use by a reduction factor. Factor sourced from Makropoulos et al. (2008)</td>
<td>HC HHs</td>
<td>Local</td>
</tr>
<tr>
<td>3. DM Showers</td>
<td>Reduce the shower or bathing water use by a reduction factor. Factor sourced from Makropoulos et al. (2008)</td>
<td>HC HHs</td>
<td>Local</td>
</tr>
<tr>
<td>4. DM Taps</td>
<td>Reduce the handwashing water use by a reduction factor. Factor sourced from Makropoulos et al. (2008)</td>
<td>All HHs</td>
<td>Local</td>
</tr>
<tr>
<td>5. Rainwater Harvesting</td>
<td>Roof rain water collected, stored and employed for all water uses. Excess to drainage</td>
<td>All HHs</td>
<td>Local</td>
</tr>
<tr>
<td>6. Stormwater Harvesting</td>
<td>Stormwater collected, stored and employed for only potable water uses. Excess to drainage</td>
<td>All HHs</td>
<td>Local</td>
</tr>
<tr>
<td>7. Greywater Harvesting</td>
<td>Greywater collected, stored and employed for non-potable water uses. Excess to drainage</td>
<td>HC HHs</td>
<td>Local</td>
</tr>
<tr>
<td>B. Storm water Interventions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Infiltration Basins</td>
<td>Stormwater collected, stored and infiltrated to soil moisture module. Excess to drainage</td>
<td>All HHs</td>
<td>Centralised</td>
</tr>
<tr>
<td>2. Infiltration Drains</td>
<td>Increase HH previous proportion, increase infiltration rate, Increase precipitation rate, by a factor</td>
<td>All HHs</td>
<td>Local, Centralised</td>
</tr>
<tr>
<td>3. Infiltration Stips</td>
<td>Stormwater directed to the large open spaces of the catchment</td>
<td>NA</td>
<td>Centralised</td>
</tr>
<tr>
<td>4. Precipitation Pavements</td>
<td>Stormwater directed to the large open spaces of the catchment</td>
<td>NA</td>
<td>Centralised</td>
</tr>
<tr>
<td>5. Conventional</td>
<td>Effective Runoff proportion reduced, Infiltration rate reduced</td>
<td>NA</td>
<td>All HHs</td>
</tr>
<tr>
<td>6. Storage Ponds</td>
<td>Stormwater directed to the large centralised storage. Excess to drainage</td>
<td>NA</td>
<td>Centralised</td>
</tr>
<tr>
<td>C. Sanitation Interventions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Urine Diversion</td>
<td>Total Nitrogen (of Urine) Concentration reduced significantly.</td>
<td>All HHs</td>
<td>Local</td>
</tr>
<tr>
<td>2. Solids Reuse</td>
<td>Total Nitrogen (of Excreta) Concentration and toilet water use (for HC HHs) reduced significantly</td>
<td>All HHs</td>
<td>Local</td>
</tr>
<tr>
<td>3. Solids &amp; Liquids Reuse</td>
<td>Total Nitrogen (of Excreta and Urine) Concentration and toilet water use (for HC HHs) reduced significantly</td>
<td>All HHs</td>
<td>Local</td>
</tr>
<tr>
<td>4. Greywater Harvesting</td>
<td>All greywater produced, directed and stored, then employed for toilet and general cleaning use</td>
<td>All HHs</td>
<td>Centralised</td>
</tr>
<tr>
<td>5. Conventional (No-Shama)</td>
<td>All human wastewater directed to sewer, but not for low-income settlements</td>
<td>All HHs</td>
<td>Centralised</td>
</tr>
<tr>
<td>6. Conventional (All HHs)</td>
<td>All human wastewater directed to sewer</td>
<td>All HHs</td>
<td>Centralised</td>
</tr>
</tbody>
</table>

DM: Demand Management, Conventional water supply, mains water supply, Conventional storm water, open storm water storage, Conventional Sanitation, separate sanitary sewage
were computed as the relative change between the new urban water system (with the intervention) and the original (baseline) urban water system.

Thus, in this study, despite the employment of indicators usually employed in other urban water studies, the novelty of the approach is the application of all three indicators to assess an urban water system.

3. Results

3.1. Introduction

As WaterCycle is a stochastic model, it can generate numerous outputs (simulated 1000 times) of the total mains water use hydrograph, the hydrograph of the final stormwater flow effluent from the urban water system, and the total nitrogen pollutograph of the stormwater flow effluent from the urban water system. Then from the simulated hydrographs, a median hydrograph of each case was computed from which the performance indicators were generated: these being the mains water saving indicator (as the representative measure of the urban water supply subsystem performance), the reduction in stormwater flow effluent (as a representative measure of the urban stormwater subsystem performance), and the reduction in contaminant effluent (as the representative measure of the urban sanitation subsystem performance). In addition, the attributes of each intervention were considered, such as (1) the intervention type (either a water supply intervention, a stormwater intervention, or a sanitation intervention), (2) its scale of application (either local or centralised), and finally (3) whether the intervention involves recycling, reuse or none of them.

Populating the performances and the attributes of the interventions generated a rare dataset of the urban water systems that were then statistically analysed to generate information about the sustainability performance of the urban water system. The major aspects of this dataset are summarised in figures 1 and 2.

3.2. Performance of Water Supply Interventions

Figure 1 displays the performance of the water supply subsystems, stormwater subsystems, and sanitation subsystems of each of the water supply interventions (interventions that target the urban water supply subsystem). This study revealed that among the water supply interventions, only the conventional water supply intervention led to a poor water supply subsystem performance (a median of $-0.14$). The roof rainwater harvesting (RWH) system, the stormwater harvesting (SWH) system, and the localised greywater harvesting (GrWH) system provided a moderate urban water subsystem performance (of $+0.37$, $+0.36$, $+0.24$ respectively), and the demand management systems provided a varied performance (of $+0.2$ for Toilets, of $+0.05$ for Showers, and of $+0.24$ for Taps).

The urban stormwater subsystem performance arising from water supply interventions provided a generally similar trend to that of the water supply subsystem performance. All the water supply interventions provided a positive performance except the conventional water supply. The recycling-dependent interventions of RWH, SWH, and GrWH led to a reduction in downstream storm water flow of $+0.17$ for RWH, $+0.19$ for SWH, and $+0.17$ for GrWH. The demand management interventions, however, led to marginal stormwater subsystem performance of $+0.033$ for toilets, $+0.05$ for showers, and $+0.02$ for taps.

The urban sanitation subsystem performance arising from water supply interventions follows a relatively opposite trend to that of the water supply subsystem or stormwater subsystem performances. The recycling-dependent interventions of RWH, SWH, and GrWH, in general, led to negative sanitation subsystem performances of $-0.12$ for RWH, $-0.25$ for SWH, and $-0.20$ for GrWH. The demand management and the conventional water supply interventions led to a marginal impact on the sanitation
Figure 1: The performance of the various urban water subsystems across all the interventions

The integrated performance of water supply interventions in a city of the developing world illustrates the importance of in-house appliance use on the performance of these interventions, as compared to their performance in the developed world (in Plan. 2012). The demand management interventions (as well as greywater recycling intervention) are provided moderate urban water subsystem performances due to the low-penetration rate of in-house water use appliances across the study area. The demand management (taps) intervention provided a greater performance because of the greater availability of taps than showers or flushing toilets. In addition, this study also demonstrated an observation Erni et al. (2010) made of the integrated performance of interventions - that interventions which led to a positive stormwater performance generally also lead to a negative sanitation subsystem performance.

3.3. Performance of Stormwater Interventions

Figure 1, also, displays the urban water systems’ performances of the storm water interventions. Stormwater systems, in general, provided marginal or almost non-existent impact on the urban water supply subsystem performance, except for those interventions that employ recycling (that is regional storm water harvesting (+0.18) and infiltration boxes with recycling (+0.05)). However, across the stormwater subsystem, stormwater interventions lead to a significant reduction in the volume of stormwater exiting the urban water system thereby leading to a significantly high stormwater performance (all > +0.5) except for conventional stormwater drainage (of −0.68). In the sanitation subsystem performance, the stormwater
interventions generally provide marginal sanitation subsystem performance.

The stormwater interventions (except for conventional stormwater systems) in general divert more stormwater to the pervious system of the urban water system, hence reducing the surface stormwater flow effluent and in turn, reducing the contaminant concentration exiting the urban water system. This explains the significant stormwater subsystem performance and the non-negative sanitation subsystem performance. However, the lack of significant sanitation system improvement could be attributed to the high level of pervious flow within urban water systems of the developing world.

3.4. Performance of Sanitation Interventions

Figure 1 again, displays the urban water subsystems' performance arising from sanitation interventions. Their water supply subsystem performance shows (1) the greywater recycling interventions generate significant performance (of +0.8 for regional GrWH, and of +0.24 for local GrWH respectively), (2) the reuse interventions lead to marginal water supply subsystem performance (of +0.05 for Urine reuse, of +0.1 for the reuse of both Urine and Faeces reuse, of +0.1 for Faeces only reuse), and (3) the conventional sanitation systems have marginal water supply subsystem performance.

Across the sanitation subsystem performance, the all-households conventional sanitation intervention system led to a poor performance (of −0.1), which was worse compared to a conventional system designed without the slums (which is a marginal positive +0.01 performance). However, it should be noted that the sanitation performance is measured against the contaminant flow within the surface water runoff. The conventional system without slums implies that more of the contaminants are diverted to the pervious system. The grey water interventions lead to varied sanitation subsystem performance. Regional greywater recycling leads to a marginal positive performance (of +0.05) while local greywater recycling leads to a poor sanitation subsystem performance (of −0.2). The reuse interventions of urine reuse, solids reuse, or solids and liquids reuse however lead to a positive impact on the sanitation subsystem performance, of +0.05, −0.1, and +0.1 respectively.

3.5. Cross-sectional Performance Interventions

As mentioned earlier, urban water systems can be further characterised according to: (1) their initially intended target subsystem (as such characterised as either Water Supply, Stormwater, or Sanitation Interventions), (2) their scale of application (that is either Local or Centralised), and (3) their employment of recycling, or reuse of waste streams, or none of them. The performance of the urban water interventions was therefore explored according to this characterisation to generate further cross-sectional information about the performance of urban water interventions. The summary of this performance is shown in figure 2.

On the water supply subsystem scale, it is the water supply interventions and recycling-based interventions that generate the most optimal (> +0.2) positive performance. All the other interventions provide a marginal positive performance. While on the stormwater subsystem performance scale, the exceptionally high positive performance of stormwater interventions dominates the performance of all the other categories. Also, it should be noted, that a more positive stormwater subsystem performance was generated with a centralised scale rather than a local scale.

On the sanitation subsystem performance scale, all the interventions provide poor to marginal subsystem performance. Even the sanitation interventions provided a marginal poor performance (> −0.1). In
addition, the sanitation subsystem performance is not sensitive to the scale of application. It is, however, sensitive to recycling or reuse of urban water streams. Recycling systems generate significant negative sanitation subsystem performance (−0.3) while the waste reuse systems generated a positive performance (+0.2). The interventions that utilised neither recycling nor reuse had a marginal sanitation subsystem performance.

In summary, it should be observed that only the waste reuse urban water interventions (as well as interventions applied at local scale) provided an all-positive subsystem performance across all three urban water subsystems including across the sanitation subsystems.

3.6. Relationship between the Subsystems

Figure 3 shows a novel relationship between the performances of the urban water subsystems for all the interventions. The figure shows that there is a moderate negative relationship between the urban water supply subsystem performance and the urban sanitation subsystem performance. This, in essence, implies that interventions that generally lead to a positive water supply subsystem performance, in turn, tend to lead to a negative sanitation subsystem performance and vice versa.

The relationship between the water supply subsystem performance and the stormwater subsystem performance showed a weak positive relationship in a similar way as the relationship between the stormwater subsystem performance and the sanitation subsystem performance. This relationship implies that the interventions that lead to positive water supply subsystem performance (or positive sanitation subsystem performance) have no performance relationship with those that lead to positive stormwater subsystem performance. In other words, the interventions that lead to positive stormwater subsystem performance appear unrelated or independent from all the other interventions.
4. Discussion

4.1. Introduction

This paper presents an integrated and holistic performance assessment of an urban water system (of a low-income country) to demonstrate its relevance to the improvement of its sustainable performance. The study has demonstrated that an integrated assessment of urban water systems reveals a huge amount of information about the performance of interventions that has implications on the choice of intervention required for a given urban water system.

4.2. Validation of the performance of urban water interventions

In the scientific literature, there is a general absence of studies that place emphasis on the integrated performance of urban water interventions across all three urban water subsystems. This absence makes it difficult to validate the results generated in this study. Therefore, to validate the results generated from this study, similar studies that were not necessary integrated assessment studies, but urban water performance studies (even if they concentrated on only one subsystem) were sourced to validate comparative performance results generated in this study.

Rainwater harvesting systems have been widely studied in the literature for their urban water supply subsystem and stormwater subsystem performance, such as those by Dixon et al. (1999), Butler (2007), Hunt et al. (2006), Burkhard et al. (2000), Fewkes and Wam (2000), Sharma et al. (2008). In these studies, rainwater harvesting systems were assessed and found to generate urban water supply subsystem performances in the range of $0.3 - 0.6$, with a stormwater subsystem performance of $+0.2 - 0.3$ in Sharma et al. (2008). This was comparable to the rainwater harvesting systems results generated in this study of urban water supply subsystem performance of $+0.24 - 0.44$. The similarity in urban
water supply subsystem performance appears to imply that performance of rainwater harvesting systems across different cities is insensitive to rainfall fluctuations across the climatic landscape of both areas.

Demand Management interventions reported by Sharma et al. (2008) displayed an urban water supply system performance of 0.11 – 0.24 and a stormwater subsystem performance of 0.01. In our analysis, demand management interventions generated an urban water subsystem performance of 0.02 – 0.2 with a stormwater system performance of 0.02 – 0.03. The slightly lower performance compared to Sharma et al. (2008) could be attributed to the lower penetration rate of demand management interventions in the developing world (in our analysis) compared to the developed world (in Sharma et al. (2008)). Localised greywater recycling considered in the studies of Dixon et al. (1999), Burkhand et al. (2000), Sharma et al. (2008) generated an urban water systems performance of 0.12 – 0.3 which is very similar to the performance generated in our analysis of 0.13 – 0.33. The stormwater system performance also led to relatively similar results with a performance of 0.14 – 0.20 in the literature, compared to 0.15 – 0.17 in this paper.

In summary, it can be concluded that the performance of most urban water supply interventions, across the urban water supply and stormwater subsystems, generated in this study are comparable to those in other studies. However, the sanitation subsystem was not compared owing to the lack of similar data in the literature. Therefore, it would not be prudent to conclude that the performance of urban water interventions is generally comparable, for both urban water systems, those represented in this paper (developing world) and those represented in other studies (the developed world).

Despite the popularity of stormwater interventions, among the alternative urban water interventions, they are the least studied or recorded studies in the literature (from an integrated urban water management perspective). In the literature, only green roofs in Li and Babcock (2014), urban wetlands in Wong et al. (2002), and stormwater harvesting in Hunt et al. (2006) were found, and they were all assessed across the stormwater subsystem only. Green roofs generated a stormwater performance of 0.64 – 0.66, urban wetlands 0.08, and stormwater harvesting 0.3 – 0.6. In our study, green roofs generated a performance of 0.48, ponds (as a proxy for wetlands) a performance of 0.72, and stormwater harvesting 0.68. The variation in performances across both developing and developed worlds demonstrates the impact of the different urban landscape on the performance of stormwater systems.

In the literature, in terms of the performance of sanitation interventions, urine separation or reuse was mentioned in Achleitner et al. (2007), Friedrich (2006), and solids reuse in Burkhand et al. (2000). Urine separation or reuse was found to generate a sanitation subsystem performance of 0.1 – 0.25. The performance of solids reuse was not quantified per se, was the intervention was described as one that leads to a positive sanitation performance. In this study, urine reuse generated a sanitation system performance of 0.04 – 0.13, while solids reuse a performance of 0.07 – 0.14. These performances demonstrate a similarity in the general performance despite the significantly different urban landscapes.

4.3. Urban Water Management

In urban water management practice, the process of improving the sustainable performance of an urban water system requires the selection of an intervention to generate the required performance. The selection of the urban water intervention required is usually limited to: (1) the urban water paradigm employed, and (2) the urban water subsystem whose performance is targeted for improvement. Most studies (such as those by Dixon et al. (1999), Butler (2007), Hunt et al. (2006), Burns et al. (2012), Fewkes and Wam (2000) etc) assess urban water
systems across a single subsystem of interest, ignoring the impact the interventions have on the other subsystems. The studies however that provide an integrated assessment similar to the one in this paper, such as Sharma et al. (2008), Mitchell (2006), Erni et al. (2010), Mah et al. (2009), Wong et al. (2002), Achleitner et al. (2007) and Friedrich (2006) were carried out on a limited number of interventions (and also did not assess the interventions across all three subsystems).

This paper has therefore attempted to fill this gap by providing a novel approach to assessing various urban water interventions across all three urban water subsystems. The approach was tested on 28 possible urban water interventions to illustrate the relevance of this kind of assessment to modern urban water management. The approach revealed that none of the 28 interventions provided a significant positive urban water subsystem performance across all the three urban water subsystems. This implies that to achieve sustainable urban water management, the usual approach of considering a single urban water intervention as the most appropriate intervention to boost sustainability in that system flawed and misleading.

In addition, this paper has also revealed that the popular conventional interventions (of water supply, of stormwater, or sanitation) actually provide negative subsystem performances across all subsystems, including the subsystem they are designed for. In other words, this study provides an argument contrary to that expected when intervening with conventional systems. Although conventional systems generate acceptable urban water services for their human water users, they cause considerable negative environmental systems impacts in terms of the performance of stormwater or sanitation subsystems. This is consistent with the sentiments of numerous authors that conventional urban water systems are failing to achieve sustainable performance.

The performance of all the alternative urban water interventions showed considerable variation. The study has revealed that these interventions are still designed to target a single urban water subsystem and as such, no single intervention provided an all-round positive performance across all the three urban water subsystems. It has further revealed that interventions that lead to positive water supply subsystem performance in turn generally lead to significant negative sanitation subsystem performance. The interventions that lead to positive stormwater subsystem performance though are generally independent of all the other interventions (except for recycling-based interventions).

In summary, this study has revealed that to achieve an all-round sustainable performance of an urban water system, that is sustainable across the whole urban water system and across each of the individual subsystems, as advocated by Closas et al. (2012), Sharma et al. (2008), Loftus (2011). The process of choosing the most appropriate ‘intervention’ should allow for the consideration of a mix of interventions, instead of the usual procedure of considering only a single intervention.

5. CONCLUSION

This paper has presented a novel methodology for the assessment of an urban water systems that has provided useful insights into the integrated performance of urban water interventions. This integrated assessment approach illustrates that the current practice of urban water assessments, that considers each intervention according to the urban water subsystem it targets, is misleading in terms of the sustainable performance of these interventions. The integrated assessment of interventions is novel because it summarises the performance of numerous interventions (both conventional and alternative) across all the urban water subsystems. No previous studies have reported a similar methodology of form of assessment.

The paper proposes that this assessment is of rele-
vance to modern urban water management in that it reveals information about the system that cannot be generated by current isolated urban water assessment methods. The study has shown that of all the 28 urban water interventions studied, none of them provided a significant positive performance across all the three urban water subsystems. It showed that most interventions provide a performance that is strong in one or two of the subsystems but poor or negative in the third subsystem. This implies then that for an optimal and sustainable performance of an urban water system, it is inevitable that two or three interventions will have to be combined in a single urban water system.

Hence, as an overall conclusion, this paper reveals that it is not prudent to assume or presume that one kind of urban water intervention will generate all the required subsystem performances required of a sustainable urban water system. This study, therefore, recommends that the urban water procedure for selecting the most optimal intervention(s) for a given urban water system should consider an optimisation procedure that tests the urban water subsystem performance(s) of each of the interventions.

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A. SUPPLEMENTARY MATERIAL

A.1. The Integrated Urban Water Modelling System

For an integrated assessment of an urban water system, an integrated modelling system is required. In this study, the novel integrated modelling system, WaterCycle, developed by Muniina et al. (2017), was employed. The integrated modelling system was developed based on a developing world medium-sized city, Mbarara town, located in south-west Uganda.

WaterCycle is a novel methodology for the integrated modelling of urban water use, urban stormwater flow, and urban sanitation dynamics in a developing country town. It models the town from the household scale to the whole city. The mains water use (and consequently waste water generation) was developed through a stochastic variation of the water end-uses. The stormwater, human waste water, and contaminant flow were cascaded from a household scale (specifically defined for this city) through a more advanced rainfall-runoff algorithm. WaterCycle was designed to allow the disintegration of water into various water end-uses (specific to a developing country), to allow for recycling and reuse of various waste streams, and also to allow for the application of various interventions (both centralised and local, or both conventional and unconventional). Further details of this modelling system are presented in Muniina et al. (2017).

A.2. Modelling the Urban Water Interventions

In this study, it was necessary to find a way to model and simulate the multitude of urban water interventions in a single integrated urban water modelling system. This was undertaken by first modularising the fundamental unit processes that cascade together to generate particular urban water interventions. The interventions can include some or all of the following processes: storage, infiltration, water flow reduction, and (contaminants reduction) process, these unit processes are illustrated in figure 4. An intervention was then represented as a combination of the various component unit processes. The details of how each of the urban water interventions was represented within WaterCycle are illustrated in table 1.

A.2.1 The Storage Unit Process

As shown in figure 4, a number of the urban water interventions (e.g. rainwater harvesting, greywater harvesting, ponds, wetlands, infiltration boxes) employ storage as one of their unit fundamental processes. In WaterCycle, storage was modelled by extending the algorithm described in Dixon et al. (1999); Fewkes and Wam (2000), Ward et al. (2008). It involves the representation of a single storage entity that collects source water (which could be rain water or greywater depending on the intervention being designed) as an input and water exits the storage system either as overflow, or to meet the demand, or as a controlled exit (for storm water options). The input to the storage is either rainwater (for rainwater harvesting), stormwater (for stormwater reuse), or wastewater (for wastewater reuse), depending on the interventions employing the storage. If the storage is exceeded, the excess water (overflow) passes directly to the pervious system to join the overland flow (or to the sewer for households employing centralised sanitation). The yield from the storage system represents the controlled or required output, which could be directed to satisfy the required component demand or the controlled exit directed to the overland flow. If the yield is to meet the required demand, it is added to the mains water supply. The outflow from the storage, for a controlled exit, was
modelled to follow uniform steady flow (with a normal depth), in a similar manner to that described by Mackay and Last (2010) and Last (2010).

### A.2.2 The Infiltration Unit Process

The infiltration process involved the diversion of storm water from the overland flow path to the ground water flow path. Within WaterCycle, the infiltration process for a given intervention was introduced through an increased infiltration rate. The interventions of Infiltration Drains, Pervious Gardens and Pervious Pavements all employed infiltration to improve their urban water performance. Bioswales and Infiltration Boxes, however, employ a combination of infiltration and storage or reduction of contaminants (or treatment) respectively.

### A.2.3 The Treatment Unit Process

The contaminant treatment process was represented here as the percentage 'reduction' of the concentration of contaminants, across any water or wastewater stream (as per the intervention) within the integrated model. The percentage reduction is a representation of the treatment efficiency of the intervention. Wetlands, green roofs, urine diversion, solids diversion, and low-cost sewerage all employed wastewater treatment as part of their processes.

### A.2.4 Low-cost sewerage

In addition to the treatment process, in WaterCycle, low-cost sewerage sanitation systems were added by introducing a specific pathway for the waste streams, from their source (households) to their disposal and
then to the receiving water. If the households were originally employing on-site sanitation, their wastewater was not diverted to a sewer but to a septic tank or a pit latrine. For the households employing centralised sanitation, sewers were employed to direct the wastewater flow to the centralised treatment system.

A.2.5 The capacity reduction process

The demand management interventions (that is the use of low flushing capacity toilets, the use of low capacity showers, and or the use of low capacity taps) were modelled through an introduction of a percentage reduction its corresponding water end-use. For low capacity showers, a reduction in showering end-use was applied, for flushing toilets on the flushing water end-use, and for tap or cistern water use on the tap water end-use. This kind of demand management representation is also employed in Makropoulos et al. (2008) and in Rooijen (2010).

A.3. Measuring the Performance of the Urban Water System

The main objective of intervening in an urban water system is to boost its sustainable performance. Although the precise definition of Sustainable Development (SD) is debatable (Ashley et al., 2005), this study adopted the description of a sustainable urban water system by Lundin (2003) that prescribes an urban water system as one that provides its water services to its users including preventing environmental degradation over a long term. It was presumed in this study that the objective was to ensure the successful provision of services across each urban water subsystem, and therefore the measurement of urban water system performance measurement was by the development of performance indicators for each urban water subsystem. In the urban water supply subsystem, the mains water savings indicator was employed (in similar ways to studies by Fewkes and Wam (2000); Chatfield and Coombes (2007); Rooijen (2010); Schuetze and Santiago-Fandino (2013)). Mains water savings were defined to reflect the level of mains water use that has been conserved within the new system (with the intervention) relative to the original (baseline) system. It was presumed that an increase of mains water use would reflect a less sustainable urban water supply subsystem, since an increased mains water use is attributed to increased environmental degradation.

For the urban stormwater subsystem, a sustainable performance was reflected through the total volume of stormwater runoff discharged, (in similar ways to studies by Chatfield and Coombes (2007); Burns et al. (2012); Li and Babcock Jr (2013); Huang et al. (2014); Fagan et al. (2010), Rodriguez (2012)). For the urban sanitation subsystem, this was assessed through the total mass of contaminant (total nitrogen in this case) discharged from the urban water system. In each case, the performance indicators were computed as the relative change between the new urban water system (with the intervention) and the original (baseline) urban water system.

Thus, in this study, despite the employment of indicators usually employed in other urban water studies, the novelty of the approach is the application of all three indicators to assess an urban water system.
D.2 Hydraulic Performance of interventions
D.2 Hydraulic Performance of interventions

(a) Simulated mains water demand hydrograph (median)

(b) Simulated stormwater flow hydrograph (median)

(c) Simulated effluent stormwater pollutograph

Fig. D.1 Detailed hydraulic and relative performance of water supply interventions

RWH - Rainwater Harvesting, SWH - Stormwater Harvesting, GrWH - Greywater Handling, DM1 - Demand management with toilets, DM2 - Demand management with showers, DM3 - Demand management with taps, Conv - Conventional water supply
Figure D.2 Detailed hydraulic performance of stormwater interventions

GrfS - Green Roofs, Ponds - Stormwater storage ponds, rgSWH - regional Stormwater Harvesting, Dms - Infiltration Drains, Pvmts - Infiltration Pavements, Strps - Infiltration Strips,
iBox1 - Infiltration Boxes, iBox2 - Infiltration Boxes with recycling
D.2 Hydraulic Performance of interventions

(a) Simulated mains water demand hydrograph (median)

(b) Simulated stormwater flow hydrograph (median)

(c) Simulated effluent stormwater pollutograph

Fig. D.3 Detailed hydraulic performance of sanitation interventions

ConvAll - Conventional Sanitation for All households, ConvNoSlums - Conventional Sanitation without Slums, rgGrWH - regional Greywater Harvesting, LcGrWH - local Greywater Harvesting, Urine - Liquids only reuse, S & L - Solids and Liquids (Urine) reuse, Solids - Solids only reuse
Appendix E

Paper II