Impact of Spatial Lumping on Modelling of Stormwater Harvesting Systems: Scoping Study

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February 2013

Urban Water Security Research Alliance
Technical Report No. 107

Queensland Government
National Research FLAGSHIPS Water for a Healthy Country
CSIRO
Griffith UNIVERSITY
THE UNIVERSITY OF QUEENSLAND AUSTRALIA

Urban Water Security Research Alliance Technical Report ISSN 1836-5566 (Online)
Urban Water Security Research Alliance Technical Report ISSN 1836-5558 (Print)

The Urban Water Security Research Alliance (UWSRA) is a $50 million partnership over five years between the Queensland Government, CSIRO's Water for a Healthy Country Flagship, Griffith University and The University of Queensland. The Alliance has been formed to address South East Queensland's emerging urban water issues with a focus on water security and recycling. The program will bring new research capacity to South East Queensland tailored to tackling existing and anticipated future issues to inform the implementation of the Water Strategy.

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Neumann, L. and Maheepala, S. (2013). *Impact of Spatial Lumping on Modelling of Stormwater Harvesting Systems: Scoping Study*. Urban Water Security Research Alliance Technical Report No. 107.

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ACKNOWLEDGEMENTS

This research was undertaken as part of the South East Queensland Urban Water Security Research Alliance, a scientific collaboration between the Queensland Government, CSIRO, The University of Queensland and Griffith University.

Our thanks go to reviewers of the report, in particular to Don Begbie, Director of the Urban Water Security Research Alliance, for his valuable advice.

FOREWORD

Water is fundamental to our quality of life, to economic growth and to the environment. With its booming economy and growing population, Australia's South East Queensland (SEQ) region faces increasing pressure on its water resources. These pressures are compounded by the impact of climate variability and accelerating climate change.

The Urban Water Security Research Alliance, through targeted, multidisciplinary research initiatives, has been formed to address the region's emerging urban water issues.

As the largest regionally focused urban water research program in Australia, the Alliance is focused on water security and recycling, but will align research where appropriate with other water research programs such as those of other SEQ water agencies, CSIRO's Water for a Healthy Country National Research Flagship, Water Quality Research Australia, eWater CRC and the Water Services Association of Australia (WSAA).

The Alliance is a partnership between the Queensland Government, CSIRO's Water for a Healthy Country National Research Flagship, The University of Queensland and Griffith University. It brings new research capacity to SEQ, tailored to tackling existing and anticipated future risks, assumptions and uncertainties facing water supply strategy. It is a $50 million partnership over five years.

Alliance research is examining fundamental issues necessary to deliver the region's water needs, including:

- ensuring the reliability and safety of recycled water systems.
- advising on infrastructure and technology for the recycling of wastewater and stormwater.
- building scientific knowledge into the management of health and safety risks in the water supply system.
- increasing community confidence in the future of water supply.

This report is part of a series summarising the output from the Urban Water Security Research Alliance. All reports and additional information about the Alliance can be found at http://www.urbanwateralliance.org.au/about.html.

(USWRA Executive to insert digital signature when approved for release)

Chris Davis
Chair, Urban Water Security Research Alliance

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EXECUTIVE SUMMARY

As part of the strategy to improve reliability of water supply, all building development applications lodged since January 2007 for the construction of new homes in South East Queensland (SEQ) must meet a mandatory water savings target of 70 kL per year for detached dwellings and 42 kL per year for townhouses (Queensland Water Commission, 2010)[1]. To achieve the water savings target, the suggested solutions were: rainwater tanks, decentralised stormwater harvesting and decentralised wastewater recycling.

This report focuses on decentralised stormwater harvesting, to estimate the potential amount of stormwater that could be harvested for urban use at a regional scale. The objectives of the study were to:

- Examine whether individual stormwater harvesting schemes (or systems) can be linearly combined to estimate the yield and runoff at a catchment scale; and
- Examine the effect of development density, demand variability, indoor/outdoor use and catchment size on both individual and linearly combined stormwater harvesting schemes.

The study was undertaken as a scoping exercise. The methodology involved examining the sensitivity of the modelled overflow and demand met (i.e. yield) of a range of stormwater harvesting systems for hypothetical developments, when the systems were modelled as individual harvesting systems or as an up-scaled version combining the catchment areas, demands and storages. The modelling was undertaken using the MUSIC (version 5) model (CRC-CH, 2005).

The hypothetical developments and the stormwater harvesting schemes were based on the individual systems described in the report 'Stormwater Infrastructure Options to Achieve Multiple Water Cycle Outcomes' (Bligh Tanner and DesignFlow, 2009), which considered a range of harvesting schemes for different development densities in two separate sites, North Lakes and Sippy Downs.

North Lakes was a residential greenfield development covering an area of 465 ha, with residential areas around two creek corridors. It was a low density residential area with approximately 11-12 dwellings per ha (gross). The dwellings were considered to be detached houses with a lot size of between 400 and 700 m^2. The development in North Lakes considered three options: a harvesting scheme at a small scale of 20 ha; a medium option at 100 ha; and a large scale option at 465 ha. For the purpose of this study, we considered these developments to be independent catchments, to allow comparison of aggregating different spatial scales. The stormwater harvesting scenario considered supplied treated stormwater to households (for indoor and outdoor use) and public open space irrigation via dual reticulation.

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[1] Buildings in Qld no longer have to meet compulsory water savings targets following the repeal of laws mandating the installation of water supply systems on 1 February 2013. Previously, all new homes and commercial and industrial buildings in Queensland were required to install rainwater tanks or other water supply systems such as grey water treatment plants.

Provisions have been made for local governments to opt-in to water savings requirements in recognition of Queensland's varying climatic conditions and regional circumstances. Builders in these local government areas will still need to comply with water savings requirements.

Water supply systems such as rainwater tanks and grey water treatment plants can still be installed voluntarily by homeowners and builders in all areas of the state. Builders who install a water saving system (either voluntarily or to meet local government requirements) must comply with the health and safety standards set out in the Queensland Development Code Part 4.2 – Rainwater tanks and other supplementary water supply systems (for residential – class 1, 2 and 10 - buildings) and Part 4.3 – Supplementary water sources – commercial buildings (for commercial and industrial - class 3-9 - buildings) (Source: Department of Housing and Public Works, 2013).

Supplementary water sources – commercial buildings (for commercial and industrial - class 3-9 - buildings) (Source: Department of Housing and Public Works, 2013).

Sippy Downs consisted of a 40 ha mixed commercial and medium density residential development, with 40 dwellings per hectare. Five different stormwater harvesting schemes were considered. For the purpose of this study, we considered these developments to be five independent catchments to allow comparison of aggregating at different spatial scales and densities. Similar to North Lakes, treated stormwater was supplied to households (for indoor and outdoor use) and public open space irrigation via dual reticulation.

Eight scenarios were considered to examine the impact of linearly aggregating individual harvesting systems into a single system, on the aggregated (or total) yield and overflow from the system as a whole. Scenario A modelled three catchments in North Lakes individually, and then the result of the sum was compared to an up-scaled system where the catchment areas, demands and storages were a sum of the individual values for each catchment. Scenario B modelled five catchments in Sippy Downs individually, and then the result of the sum was compared to an up-scaled system where the catchment areas, demands and storages were a sum of the individual values for each catchment.

Scenarios C and D examined the impact of mixed development densities on the yield and overflow of individual and up-scaled systems. Scenario C consisted of five catchments with medium residential density and five catchments with high residential density (100 dwellings per hectare). Scenario D consisted of three low density, one medium density and one high density development.

Scenarios E and F examined the impact of reduced runoff on the yield and overflow, while Scenarios H and I examined the impact of altered demand on the yield and overflow of individual and up-scaled systems.

For scenarios A, B, C and D, comparisons between the sum of results from individual catchments and the up-scaled system showed an overestimation of the yield and an underestimation of the overflow for all scenarios. The amount of overestimation of the yield of up-scaled case was less than 5% of the aggregated yield of individual catchments. The amount underestimation of the overflow of up-scaled case was less than 2% of the aggregated yield of individual catchments.

For scenarios E and F, a reduction of inflow up to 50% introduces very little differences between modelling the developments and harvesting systems as individual systems and modelling them as a scaled-up, large development with a single harvesting system. When the three separate systems in scenario E or F were modelled as one development with combined storages, the inflow from the two developments without inflow runoff reduction compensated for the reduction in the other development. If the systems were modelled separately, lower yields were expected as the storage in the development with reduced runoff inflow had no access to the inflow from the other two developments, as would occur if the systems were independent catchments and not hydrologically connected.

For the last two scenarios investigated, i.e. scenarios H and I, changes in demand for one of the individual developments were shown to be more influential if the system was modelled as a combined system. As the demand was increased, the harvesting schemes became supply-limited systems, and the two developments which had excess supply compensated for the one that had an increased demand when the systems were modelled as one.

In all scenarios considered, the use of an up-scaled system resulted in only a small error in the prediction of the yield and overflow, within 2% underestimation and 5% overestimation compared to the sum of overflow and yield, respectively, of individual harvesting schemes. For scenarios E, F, H and I, large errors occurred only when large changes in inflow runoff or requested demand were considered, usually representing unrealistic cases.

The overall conclusion of the study is that, if the individual stormwater systems are well designed and show a reasonable performance in terms of the yield, the error introduced by linearly combining the individual stormwater harvesting systems (i.e. sum of storages, catchments and demands of the individual stormwater systems) for the combined system is likely to be small, i.e. within 5% of the sum of the yield of individual stormwater harvesting systems.

An alternative approach to the up-scaling method examined in this report is the use of average values for the input variables to represent the combined system. This study has not examined the implication of this alternative up-scaling approach. Based on the studies of rainwater tanks reported in the literature, it can be expected that the use of average values of input variables to represent the combined system could also introduce errors. Hence, further work is recommended to understand the magnitude of errors, with the aim of recommending a method to up-scale yield and overflow (as well as water quality) impacts of decentralised stormwater harvesting systems at a city/regional scale.

1. INTRODUCTION

1.1. The Need

As part of strategy to improve reliability of water supply, all building development applications lodged since January 2007 for the construction of new homes in South East Queensland (SEQ) must meet a mandatory water savings target of 70 kL per year for detached dwellings and 42 kL per year for townhouses (Queensland Water Commission, 2010)[2]. To achieve the water savings target, one possible solution is to install a rainwater tank which must be internally plumbed to provide water for, at a minimum, toilet flushing and washing machine cold water taps, as well as outdoor use (Queensland Development Code, 2008). Another possible solution for compliance is the adoption of a stormwater harvesting scheme with or without rainwater tanks in dwellings (Queensland Water Commission, 2010). Consequently, understanding the potential contribution of stormwater harvesting schemes to securing the supply at the SEQ regional scale became an essential need in SEQ.

A study was initiated in 2009 by the Queensland Water Commission (QWC) to examine the ability of decentralised stormwater harvesting schemes to meet the water savings target. The study was conducted by Bligh Tanner and DesignFlow (2009), which investigated the adoption of stormwater harvesting systems across a range of scales from 20 to 500 ha, in low, medium and high density developments. The study considered two different sites: North Lakes, a low density greenfield site located in Brisbane's north, and Sippy Downs, a medium density development located in the Sunshine Coast. The selection of sites provided a mix of land use and stormwater infrastructure. It was considered that North Lakes and Sippy Downs could provide a good representation of the future development in SEQ. The results indicated that there was a significant spread in terms of yield and cost for different stormwater harvesting systems, depending on the demand placed on the harvested stormwater and the cost of infrastructure needed to store, treat and distribute stormwater as an alternative supply to the potential users. Further, the study showed that higher yields could be obtained for larger demands as storages would be drawn down quicker, which allowed capturing more of the next rainfall event. The conclusion of the study was that stormwater harvesting could deliver water supply to meet and sometimes exceed the water savings target at a comparable cost to (or cheaper then) rainwater tanks.

The study of Bligh Tanner and DesignFlow (2009) did not address the amount of stormwater that could be harvested across the SEQ region, but it provided a valuable assessment on the ability of typical decentralised stormwater harvesting schemes to meet the water savings target. Understanding the potential amount of stormwater that could be harvested across the SEQ region was an essential need for water supply planning in the SEQ. A commonly asked question was how to up-scale the findings of the Bligh Tanner and DesignFlow (2009) study to provide a robust estimate for the potential amount of stormwater that could be harvested across the SEQ region. Given the variation in yield found for the harvesting schemes considered by Bligh Tanner and DesignFlow (2009), and the yield (as well as overflow) was generally a function of inflow, demand and storage, it was not clear if the yield of individual harvesting schemes could be linearly up-scaled to estimate the potential yield at the SEQ regional scale.

In addition, studies conducted in relation to rainwater tanks have shown that linear up-scaling of the yield of individual rainwater tanks to estimate the yield of tanks spread across a large area could introduce errors, which were in the order of 14% for Melbourne-based data (Mitchell *et al.,* 2008; Xu *et al.,* 2010; Maheepala *et al.,* 2011), 18% for Canberra-based data (Maheepala *et al.,* 2011) and 15% for Brisbane-based data (Maheepala *et al.*, 2013 and Coultas *et al.,* 2011). An over estimation of tank supply led to an under estimation of overflow from the tank. Neumann *et al.* (2011) showed that the amount of overflow can be underestimated by as much as 30% due to the non-linearity in rainwater tank behaviour due to variation in roof area, demand and tank volume. All these studies which examined up-scaling of the yield and overflow aspects of rainwater tanks recommended the use of

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[2] See footnote 1.

stochastic simulation for a large number of tanks to better estimate the yield and overflow from a large group of rainwater tanks.

Given the over estimation related to up scaling of rainwater tank yields, and the variation exhibited in the yields of stormwater harvesting schemes examined in the Bligh Tanner and DesignFlow (2009) study, this study was designed as a scoping exercise to address the appropriateness of linear up-scaling in relation to yield and overflow of decentralised stormwater harvesting schemes.

1.2. Research Objectives

The objective of this scoping study is to:

- Examine if individual stormwater harvesting schemes can be linearly combined to estimate the yield and runoff at a catchment scale; and
- Examine the effect of development density, demand variability, indoor/outdoor use and catchment size on both individual and linearly combined stormwater harvesting schemes.

1.3. Report Structure

Chapter 1 describes the need and the research objectives of the study.

Chapter 2 describes the methodology.

Chapter 3 describes results and a discussion on results.

Chapter 4 describes the conclusions of the study.

2. MODELLING METHODOLOGY

Yield and overflow of individual harvesting systems can be linearly up-scaled using two approaches: (1) combine the input variables of individual systems to represent the combined system; and (2) use the average of input variables to represent the combined system. This scoping study examines approach #1. That is, to evaluate the over or under estimation of the stormwater harvesting schemes when using linear up-scaling, results from individual and "averaged" systems are compared to provide an estimate of the errors introduced by the aggregation. The individual systems are based on the systems described in the report "Stormwater Infrastructure Options to Achieve Multiple Water Cycle Outcomes" (Bligh Tanner and DesignFlow, 2009), which considered a range of harvesting scheme sizes for different development densities in two separate sites, North Lakes and Sippy Downs. A brief description of the scenarios adopted in this study is given below, including any assumptions that differ from the Blight Tanner and DesignFlow (2009) study.

2.1. Development Sites

The two development sites considered in Bligh Tanner and DesignFlow (2009) are: North Lakes, a 500 ha, low density development in the Moreton Bay Regional Council area to the north of Brisbane; and Sippy Downs, a 40 ha development in the Sunshine Coast which was considered to be either medium or high density.

2.1.1. North Lakes

North Lakes is a residential greenfield development covering an area of an area of 465 ha, with residential areas around two creek corridors. The area consists of rolling hills of moderate slopes of around 5-10%. The development is a low density residential area with approximately 11-12 dwellings per ha (gross). The dwellings are considered to be detached houses with a lot size of between 400–700 m^2 (Bligh Tanner and DesignFlow, 2009).

The development in North Lakes considered three options, a harvesting scheme at a small scale of 20 ha, a medium option at 100 ha and a large option at 465 ha. For the purpose of this study, we considered these developments to be three *independent* catchments, to allow comparison of aggregating different spatial scales.

The stormwater scenario modelled here considers stormwater harvesting at a catchment scale, with dual reticulation providing treated stormwater to households (for indoor and outdoor use) and public open space irrigation (Scenario 5b, Bligh Tanner and DesignFlow, 2009). Households were considered to not have rainwater tanks installed. The characteristics of each development are shown in Table 1.

Table 1. North Lakes development characteristics (derived from Bligh Tanner and DesignFlow, 2009).

Development	**20 ha**	**100 ha**	**500 ha**
Area (ha)	22.5	88	465
Land Use	Residential	Residential	Residential/Commercial Centre
Roads (ha)	7.7	21.5	100
Parks and Open Space (ha)	2.2	17.3	108
Pervious area (ha, total)	6.3	24.45	128.5
Paved area (ha, total)	1.26	4.89	25.7
Roof area (ha, total)	5.04	19.56	102.8
Indoor Demands (kL/d)	69.78	27.29	1442.3
Outdoor Demands (kL/yr)	4840	38060	237600
Storage size (kL)	1500	8500	37500
Bioretention filter area (m^2)	2000	6500	38000

2.1.2. Sippy Downs

The proposed Sippy Downs development is located in the Sunshine Coast and consists of 40 ha of mixed commercial and medium density residential with 40 dwellings per hectare. A high density option of 100 dwelling per hectare is also considered. The site layout results in three separate hydrological catchments, which are further divided into commercial and residential areas, resulting in five separate areas. Once more, for the purpose of this study, we considered these developments to be five *independent* catchments, to allow comparison of aggregating at different spatial scales and densities.

The stormwater scenario modelled here considers stormwater harvesting at a catchment scale, with treated stormwater reticulated to households only for outdoor use and public open space irrigation (Scenario 5, Bligh Tanner and DesignFlow, 2009). Households were considered to have a rainwater tank installed which was used for indoor demand. In this scenario, the demands and volumes of individual household tanks are aggregated despite the fact that this approach leads to an over estimation of yield and an under estimation of runoff (Mitchell *et al.*, 2008, Neumann *et al.*, 2011). This under estimation of runoff is not considered for consistency with Bligh Tanner and DesignFlow (2009). Also, this study is focused on the impacts of aggregating a large number of individual harvesting schemes and the impact of aggregating those systems. Thus, in the context of this study, aggregation of dwellings' indoor demands, roof areas and tank sizes is considered to be a separate harvesting scheme providing water for indoor demands, with the Sippy Downs developments considered to have two harvesting schemes.

The characteristics of each development are shown in Table 2 and Table 3.

Table 2. Sippy Downs medium density development characteristics (derived from Bligh Tanner and DesignFlow, 2009).

Development	1 West	2 West	Town Centre 2	Town Centre 3	3 East
Area (ha)	7.07	11.74	7.74	6.03	8.03
Land Use	Residential	Residential	Commercial	Commercial	Residential
Roads (ha)	1.58	2.63	2.24	1.75	1.79
Parks and Open Space (ha)	0.95	1.57	0.67	0.52	1.08
Pervious area (ha, total)	1.5	2.49	0.72	0.56	1.7
Paved area (ha, total)	1.45	2.41	2.41	1.87	1.65
Roof area (ha, total)	1.58	2.64	1.68	1.31	1.8
Indoor Demands (kL/d)	16	24	18	18	17
Outdoor Demands (kL/yr)	10220	21535	6205	5110	9855
Roofwater storage size (kL)	171	254	210	206	199
Harvesting storage size (kL)	235	800	67	67	140
Bioretention filter area (m^2)	413	560	757	512	540

Table 3. Sippy Downs high density development characteristics (derived from Bligh Tanner and DesignFlow, 2009).

Development	**1 West**	**2 West**	**Town Centre 2**	**Town Centre 3**	**3 East**
Area (ha)	7.07	11.74	7.74	6.03	8.03
Land Use	Residential	Residential	Residential / Commercial	Residential / Commercial	Residential
Roads (ha)	1.58	2.63	2.24	1.75	1.79
Parks and Open Space (ha)	0.95	1.57	0.67	0.52	1.08
Pervious area (ha, total)	1.13	1.88	0.48	0.37	1.29
Paved area (ha, total)	1.59	2.64	2.41	1.8	1.65
Roof area (ha, total)	1.82	3.01	1.92	1.5	2.06
Indoor Demands (kL/d)	35	51	40	39	36
Outdoor Demands (kL/yr)	8760	20075	4380	3650	6935
Roofwater storage size (kL)	641	950	791	771	749
Harvesting storage size (kL)	275	800	100	100	250
Bioretention filter area (m^2)	668	952	1081	812	776

2.2. Water Balance

Yield and runoff from the stormwater harvesting systems were simulated using the MUSIC version 5 model using the catchment schematics described in Table 1, Table 2 and Table 3.

The assumptions in terms of rainfall data, time-step, water losses and rainfall-runoff parameters follow the assumptions in Bligh Tanner and DesignFlow (2009):

- The simulation was run for 50 years using Brisbane Airport rainfall data and monthly areal PET (potential evapotranspiration);
- The time-step was 1 hour to minimise the effect of time-step on the water balance and improve accuracy;
- Water balance assessments used 50 years of rainfall data (1950 to 2000);
- The rainfall runoff parameters are the default parameters from MUSIC version 5, with the exception of the initial storage which was set at 30%, the daily baseflow rate set at 0% and the deep seepage set at 5%; and
- The water losses in the bioretention basins and stormwater ponds are negligible compared to the overall runoff volume and do not influence the choices of stormwater size or the yield.

It is also important to note that all storage sizes used in the Bligh Tanner and DesignFlow (2009) study are optimised using yield versus storage curves, as shown in Figure 1. The choice of storage is based on the fact that after a certain storage size, an increase in storage volume and hence cost leads to minimal increases in yield.

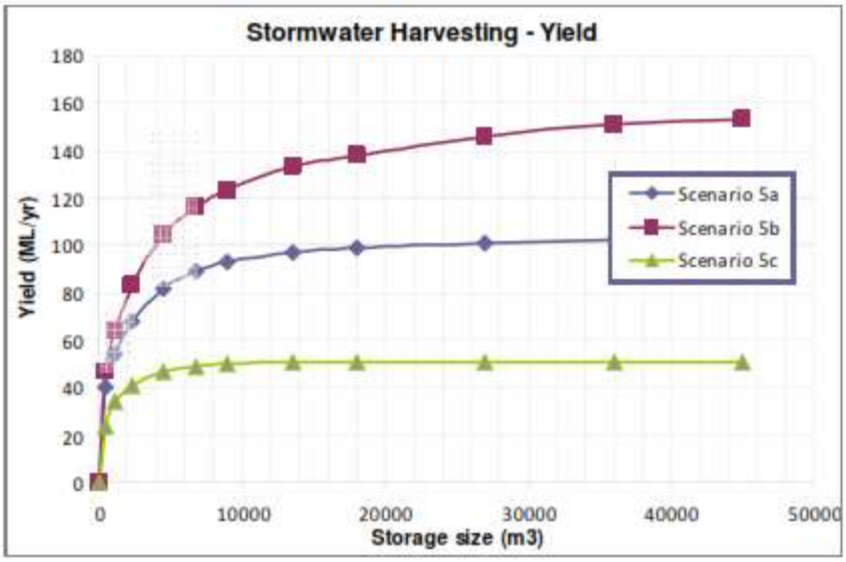

Figure 1. Stormwater Storage Yield Curve and Economic Limit of performance (Bligh Tanner and DesignFlow, 2009).

2.3. Model Scenarios

The different modelled scenarios described below considered the effect of three different variables in the yield and overflow of stormwater harvesting systems, namely catchment area (and land use), storage size and demand. The variation in catchment area indirectly considers the impact of land use in the amount of runoff generated, as a highly impervious catchment will generate more runoff than a catchment with low imperviousness and identical size.

The behaviour of stormwater harvesting systems in terms of yield is described by Bligh Tanner and DesignFlow (2009), and the behaviour of systems as demand, catchment area and storage size changes is identical to rainwater tank systems as described elsewhere (Mitchell *et al.*, 2008, Neumann *et al.*, 2011). As such, this study does not include a sensitivity analysis for variations in yield or overflow (such as increase in yield versus storage as shown in Figure 1).

2.3.1. Catchment Area and Development Density

The scenarios in this section evaluate the effect of simulating the developments of North Lakes and Sippy Down as one development with a single stormwater harvesting system. Four scenarios are considered:

- Scenario A: The three North Lakes catchments - 20 ha, 100 ha and 500 ha - are modelled individually (as in this study they are considered as three *independent* developments), and then the result of the sum is compared to an up-scaled model where the catchment areas, demands and storages are a sum of the individual values for each catchment.
- Scenario B: Similarly to the North Lakes scenario A, all five medium density sub developments in Sippy Downs are modelled as five *independent* developments and then compared to the sum of demands, catchment areas and storages.
- Scenario C, Mixed Density: In this scenario, the performance of systems with different development densities is simulated by comparing the performance of the 10 individual sub catchments in the Sippy Downs medium (five sub-developments) and high density (five sub-developments) to a system which is a sum of the demands, catchment areas and storages of the 10 sub-developments.

- Scenario D, Mixed density and scales: the final scenario compares the results of North Lakes individual developments (20 ha, 100 ha and 500 ha) and the two Sippy Down cases (medium and high density) to the performance of a system using the sum of sum of demands, catchment areas and storages. The harvesting system does not include the rainwater tanks from Sippy Downs.

2.3.2. Runoff

Factors such as slope, land use, and imperviousness may affect the amount of runoff generated by a catchment. As noted in Bligh Tanner and DesignFlow (2009), none of the stormwater harvesting systems investigated were runoff limited, with most of the runoff not being captured in all of the systems analysed, thus leaving the catchment. However, if the runoff in a system is reduced due to diversions, other runoff capture, etc, the yield may be significantly reduced due to the reduction in inflow to the stormwater harvesting system. The potential errors due to reductions in runoff are investigated using two scenarios, one using the medium scale development at North Lakes, and one including the large scale development:

- Scenario E: The three North Lakes catchments - 20 ha, 100 ha and 500 ha - are modelled individually as the result of the sum as per Scenario A, however the runoff from the 100 ha catchment is reduced by a factor of 0.75, 0.5, 0.25 and 0.1.
- Scenario F: The three North Lakes catchments - 20 ha, 100 ha and 500 ha - are modelled individually as the result of the sum as per Scenario A, however the runoff from the 500 ha catchment is reduced by 0.75, 0.5, 0.25 and 0.1.

2.3.3. Storage Representation

For the Sippy Downs development scenarios (scenarios B and C), the proposed development uses rainwater tanks at an allotment scale with a stormwater harvesting system at a catchment scale to supply irrigation demands. In scenarios B and C, the two systems are modelled separately, with the rainwater tanks storage and the stormwater harvesting system in series, as the overflow from the rainwater tanks is directed to the stormwater harvesting system. The impact of modelling both systems as one storage instead of in series is investigated in scenario G, which follows scenario B but using a single storage equivalent to the sum of the rainwater tanks and stormwater harvesting storages.

2.3.4. Demand Variability

The last two scenarios investigated here consider variation in demand across different developments. In systems that are not runoff limited, increases in demand usually lead to an increase in yield and a reduction in overflow (until the system becomes supply limited). Inversely, a reduction in demand leads to a reduction in yield and an increase in overflow. The last two scenarios analyse changes in runoff using two different scales in North Lakes:

- Scenario H: The three North Lakes catchments - 20 ha, 100 ha and 500 ha - are modelled individually as the result of the sum as per Scenario A, however the demand from the 100 ha catchment is modified by a factor of 0.25, 0.5, 0.75, 0.875, 1.125, 1.5, 1.75, 1.75, 2, 3 and 5.
- Scenario I: The three North Lakes catchments - 20 ha, 100 ha and 500 ha - are modelled individually as the result of the sum as per Scenario A, however the demand from the 500 ha catchment is modified by a factor of 0.25, 0.5, 0.75, 0.875, 1.125, 1.5, 1.75, 1.75, 2, 3 and 5.

3. RESULTS AND DISCUSSION

In general, the results of the simulations for all the scenarios described in the previous section suggest that the errors associated with linearly up-scaling the behaviour of stormwater harvesting systems by using the sum of demands, catchment areas and storages are not significant under most of the scenarios. The errors increased for the scenarios where either runoff or demand where significantly different from the "design values", as discussed below, or if the presence of storages in series is misrepresented by lumping the storages.

3.1.1. Catchment Area and Development Density

The results for the scenarios looking at different densities and catchments areas are shown in Table 4, Table 5, Table 6, Table7 and Table 8. The scenarios in which the North Lake developments are present, A and D, show a small difference in the estimations of overflow and reuse supplied (yield) (Table 4). The results also show minor difference in the reuse requested even though the input values (a parameter value) for the demand requested in the scaled-up scenario is a summation of the requested demand for the other three scenarios. This is likely to be a rounding error in the MUSIC model but, as will be shown below in the demand analysis, the minor difference in requested demand will not significantly influence the results.

Table 4. Inflow, overflow and demand results for individual and scaled-up developments in Scenario A (North Lakes).

Development	20	100	500	Sum of Individual Developments	Scaled Up	Difference (%)
Inflow (ML/yr)	158.7	545.32	2747.41	3451.43	3451.22	0.01%
Total Overflow (ML/yr)	133.44	427.49	2135.17	2696.1	2694.4	0.06%
Reuse Supplied (ML/yr)	25.37	118.18	613.49	757.04	759.16	-0.28%
Reuse Requested (ML/yr)	30.38	137.4	764.1	931.88	930.76	0.12%
% Reuse Demand Satisfied	83.51	86.01	80.29	81.24	81.56	-

For scenario B, the comparison between the sum of results from individual catchments and the scaled-up version shows a small difference for the rainwater tanks total storage (reuse supplied, or yield), but the error for the stormwater harvesting yield is almost 5% (Table 5). In this instance, the difference between the errors in the rainwater tank scale-up and the stormwater harvesting scale-up is explained by the performance of individual systems. In the case of the rainwater tanks, all tanks perform at a similar level of requested demand met, between 67.4 and 72.5%. On the other hand, the difference in performance for the stormwater harvesting systems is much larger, between 55.5 and 73.9%. The harvesting system in the East 3 development supplies only 55.5% of its requested demand of 9.86 ML/yr, and as the inflow is 54.15ML/yr and the overflow is 48.71 ML/yr, the storage size is the limiting factor to meet the demand. In the scaled-up case, more of the demand is met as now the tank is modelled as a larger storage, even though physically the harvesting stores are separate and can only meet a demand in the development they are located. The increase in yield due to increases in storage is also illustrated in Figure 1.

The aggregation of the tanks introduces a perceived increase in available storage, but this is an artefact which is equivalent to allowing part of the storages in the other parts of the development to store water to meet the East 3 demand. A similar pattern can be seen in Table 6~~Table 6~~ although the error in the stormwater harvesting yield estimation is smaller.

Table 5. Inflow, overflow and demand results for individual and scaled-up developments in Scenario B (Sippy Downs medium density).

Rainwater Tanks	1 West	2 West	3 East	Town centre 2	Town centre 3	Sum of Individual Developments	Scaled Up	Difference (%)
Inflow (ML/yr)	16.85	28.16	19.2	17.92	13.97	96.1	96.09	0.01%
Total Overflow (ML/yr)	12.79	21.98	14.7	13.25	9.53	72.25	72.17	0.11%
Reuse Supplied (ML/yr)	4.08	6.2	4.48	4.66	4.44	23.86	23.88	-0.08%
Reuse Requested (ML/yr)	5.86	8.81	6.18	6.59	6.59	34.03	34	0.09%
% Reuse Demand Met	69.51	70.4	72.51	70.72	67.38	70.11	70.24	-
Harvesting Storage								
Inflow (ML/yr)	47.58	80.24	54.15	62.33	47.81	292.11	292.04	0.02%
Total Overflow (ML/yr)	41.01	64.36	48.71	58.85	44.77	257.7	255.99	0.66%
Reuse Supplied (ML/yr)	6.6	15.91	5.47	3.52	3.06	34.56	36.27	-4.95%
Reuse Requested (ML/yr)	10.22	21.54	9.86	6.21	5.11	52.94	53.03	-0.17%
% Reuse Demand Met	64.57	73.88	55.52	56.6	59.89	65.28	68.40	-

Table 6. Inflow, overflow and demand results for individual and scaled-up developments in Scenario B (Sippy Downs high density).

Rainwater Tanks	1 West	2 West	3 East	Town Centre 2	Town Centre 3	Sum of Individual Developments	Scaled Up	Difference (%)
Inflow (ML/yr)	19.41	32.1	21.97	20.48	16	109.96	109.95	0.01%
Total Overflow (ML/yr)	10.4	18.45	12.18	10.25	6.75	58.03	57.75	0.48%
Reuse Supplied (ML/yr)	9.05	13.7	9.78	10.27	9.23	52.03	52.25	-0.42%
Reuse Requested (ML/yr)	12.83	18.7	13.18	14.59	14.27	73.57	73.22	0.48%
% Reuse Demand Met	70.52	73.3	74.24	70.37	64.71	70.72	71.36	-
Harvesting Storage								
Inflow (ML/yr)	46.7	79.13	51.52	59.77	44.75	281.87	281.5	0.13%
Total Overflow (ML/yr)	40.17	63.62	46.01	56.55	41.93	248.28	247.09	0.48%
Reuse Supplied (ML/yr)	6.57	15.55	5.55	3.26	2.85	33.78	34.59	-2.40%
Reuse Requested (ML/yr)	8.78	20.07	6.95	4.39	3.65	43.84	43.84	0.00%
% Reuse Demand Met	74.79	77.49	79.91	74.32	77.95	77.05	78.90	-

Table 7 shows the results for Scenario C, where the two options for Sippy Downs, medium and high density, are considered and compared to a scaled-up version including both density options. In this scenario, the increase in perceived storage discussed above occurs for both the rainwater tanks and the stormwater harvesting combined storages.

Table 7. Inflow, overflow and demand results for medium and high density individual developments in Sippy Downs and the scaled-up case, Scenario C.

	Rainwater Tanks			Stormwater Harvesting		
	Sum of Individual Developments	**Scaled Up**	**Difference (%)**	**Sum of Individual Developments**	**Scaled Up**	**Difference (%)**
Inflow (ML/yr)	206.06	206.06	0.00%	573.98	570.77	0.56%
Total Overflow (ML/yr)	130.28	127.16	2.39%	505.98	499.85	1.21%
Reuse Supplied (ML/yr)	75.89	78.75	-3.77%	68.34	71.19	-4.17%
Reuse Requested (ML/yr)	107.6	107.09	0.47%	96.78	96.76	0.02%
% Reuse Demand Met	70.53	73.54	-	70.61	73.57	-

For the scenario D, the results in Table 8~~Table 8~~ also show minor differences between the reuse supplied and overflow values when the developments are model separately or as one development. In this particular case, it is important to note that the demand requested in the North Lake developments (931.88 ML/yr, as shown in Table 4~~Table 4~~) is significantly higher than the demand 204.36 ML/yr (i.e. sum of 107.6 ML/yr and 98.78 ML/yr shown in Table 7~~Table 7~~) requested from the developments in Sippy Downs. The total storage in North Lakes (47500 kL, as shown in Table 1~~Table 1~~) is also much larger than the total harvesting storage for Sippy Downs (2834 kL, as shown in Table 2~~Table 2~~). Hence, the results are dominated by the dynamics of the North Lake developments resulting in a much smaller error in overflow or reuse supplied.

Table 8. Inflow, overflow and demand results for individual developments in Sippy Downs and North Lakes and the scaled-up case, Scenario D.

Development	Sum of Individual Developments	Scaled Up	Difference (%)
Inflow (ML/yr)	4025.41	4022.05	0.08%
Total Overflow (ML/yr)	3202.08	3187.17	0.47%
Reuse Supplied (ML/yr)	825.38	835.99	-1.29%
Reuse Requested (ML/yr)	1028.66	1029.1	-0.04%
% Reuse Demand Satisfied	80.24	81.24	-

In all scenarios considered, the use of an up-scaled representation of the catchment by summation of areas and storages resulted in an error in the prediction of requested demand met and total overflow. However, in scenarios A and D, the error for the requested demand was small, in the order of 0.5 and 1.3% respectively, while for scenarios B and C the errors were larger, varying between 2.4 and 5%. In volumetric terms, the largest errors are found in Scenario D, where the supplied demand is overestimated by 10.6 ML/yr for a requested demand in the order of 1000 ML/yr. In either case, the errors are well within uncertainties associated with rainfall runoff and demand modelling.

3.1.2. Runoff

The influence of inflow runoff variations was simulated using the three North Lakes developments considered in Scenario A. Using the same storage size and demands, Scenario E considered a reduction of runoff in the medium development (100 ha), whilst in Scenario F, the reduction was considered to occur in the largest development (500 ha). For both cases, the runoff was reduced by a factor of 0.75, 0.5, 0.25 and 0.1, and the results for the modelling as individual developments or as a scaled-up development are shown in Figure 2 and Figure 3.

In both scenarios, a reduction of inflow runoff of up 50% introduces very little differences between modelling the developments and harvesting systems as individual systems and modelling them as a scaled-up, large development with a single harvesting system. As noted previously, the supplied demand in the systems considered for North Lakes are demand limited with most inflow runoff from developments leaving the sites as stormwater (overflow).

However, as inflow runoff is reduced, the systems are not demand limited but become supplied limited, as shown in Table 9 for Scenario F. For a reduction of runoff in the order of 90%, only approximately 20% of the requested demand is met. If the three separate systems in scenario F are modelled as one development with combined storages, the inflow from the 20 ha and 100 ha developments compensates for the reduction in the 500 ha development. This results in an over prediction of the yield and an under prediction of overflow when the reduction in runoff for the 500 ha development is large, as shown in Figure 3. If the systems are modelled separately, there is less yield as the storage in the 500 ha development has no access to the inflow from the 20 and 100 ha developments. In the same manner, the overflow is now large as any water overflow from the 20 and 100 ha overflow cannot be utilised by the 500 ha development.

Table 9. **Runoff reduction factor and requested demand met for the individual 500 ha development in Scenario F.**

Runoff Reduction Factor	Requested Demand Met (%)
1	80.29
0.75	75.58
0.5	66.54
0.25	46.25
0.1	20.02

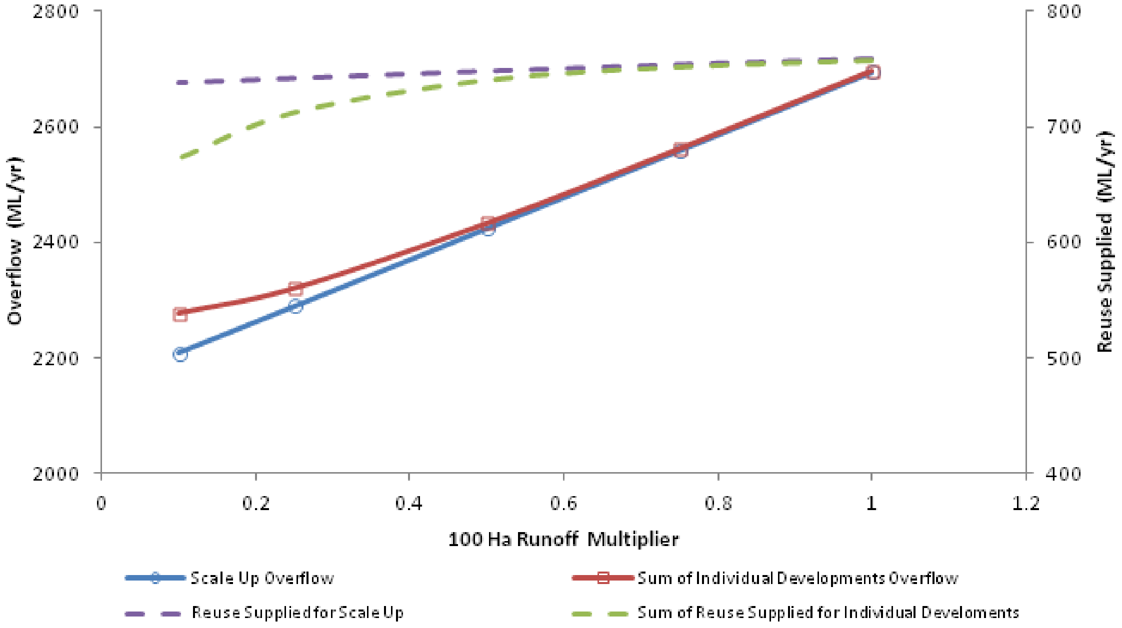

Figure 2. **Reuse supplied and overflow as a function of 100 ha inflow runoff reduction for Scenario E.**

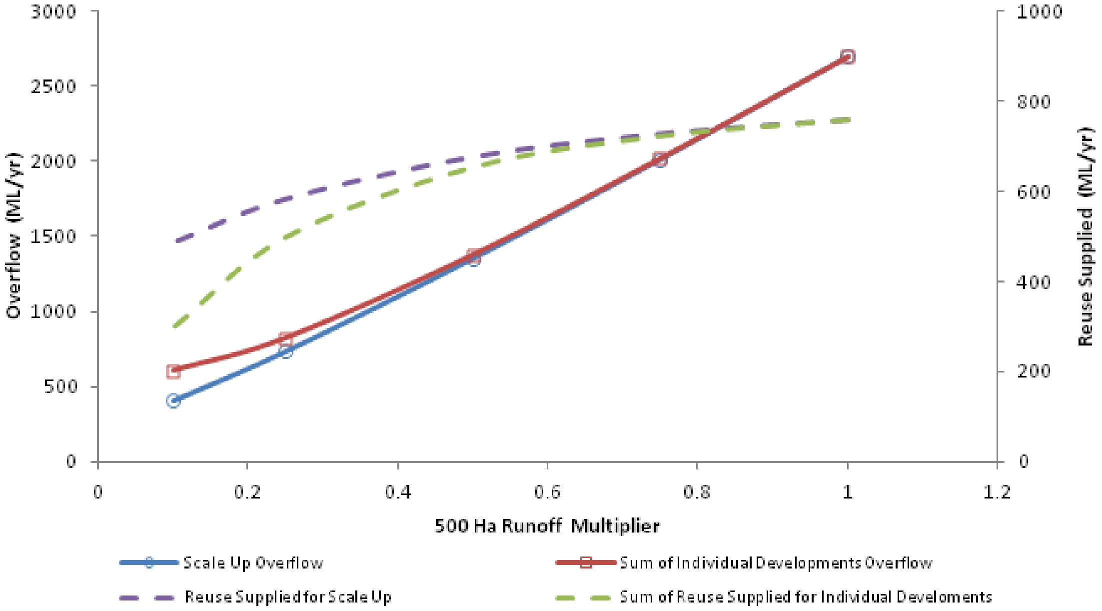

Figure 3. **Reuse supplied and overflow as a function of 500 ha inflow runoff reduction for Scenario F.**

For scenarios E and F, the magnitude of the errors can be much larger than for the Scenarios A-D discussed above. In volumetric terms, the difference is up to 66.3 ML/yr and 190 Ml/yr for scenarios D and E respectively. For both scenarios, the largest error is for a reduction of runoff in the order of 90%. However, for more realistic runoff reduction in the order of 25-50%, the errors are much smaller (i.e. about 75-10 ML/yr, as seen from the difference between curves corresponding to ‘up-scaled’ case and ‘sum of individual’ cases in Figure 2 and Figure 3). In practical terms, if the stormwater systems are well designed and show a reasonable performance in terms of demand requested met, the combined error using a sum of storages, catchments and demands is likely to be small.

3.1.3. Storage Representation

In scenario B, the Sippy Downs medium development was modelled using two separate types of storages, rainwater tanks and stormwater harvesting, supplying the indoor and outdoor demands respectively. Only roof runoff drained into the rainwater tanks, and any overflow was directed to the drainage system and then the stormwater harvesting system. In scenario G, we considered the possibility of representing both storages as a single storage, supplying both demands, and the results are shown in Table 10. The inflow into the storages in Scenario B was the roof runoff for the rainwater tanks, and the subsequent overflow plus runoff from the remainder of the catchment was the inflow to the stormwater harvesting system.

The amalgamation of the two storages as single storage to supply the same demand resulted in a further over estimation of the yield and an under estimation of the total overflow due to the increased in available storage.

Table 10. Inflow, overflow and demand results for individual developments and the two scaled-up cases, Scenario B (Sippy Downs medium density).

Rainwater Tanks	Sum of Individual Developments	RWT and SWH Storages Separated (Scenario B)	Difference (%)	RWT and SWH Storages Combined	Difference (%)
Inflow (ML/yr)	315.96*	315.96*	0.00%	315.87	0.03%
Total Overflow (ML/yr)	257.7	255.99	0.66%	255.44	0.88%
Reuse Supplied (ML/yr)	58.42	60.15	-2.96%	60.66	-3.83%
Reuse Requested (ML/yr)	87.03	87.03	0.00%	87	0.03%
% Reuse Demand Met	67.13	69.11	-	69.72	-

*Total development runoff. In Scenario B, harvesting storage overflow was runoff from development (excluding roof) plus rainwater tank overflow.

Similarly to cases A-D, the use of a scaled-up representation of the catchment by summation of areas and storages resulted in an error in the prediction of requested demand met and total overflow. However, the magnitude of the errors in percent or volumetric terms is small and the errors are well within uncertainties associated with rainfall runoff and demand modelling.

3.1.4. Demand Variability

The last two scenarios investigated here consider variation in demand across different developments, based on a variation of Scenario A. Using the same storage size and runoff, Scenario H considered a change in demand for the medium development (100 ha), whilst in Scenario I the change was considered to occur in the largest development (500 ha). In both scenarios, the requested demand was modified by a factor of 0.25, 0.5, 0.75, 0.875, 1.125, 1.5, 1.75, 1.75, 2, 3 and 5. The results for the modelling as individual developments or as a scaled-up development are shown in Figure 4 and Figure 5.

In both scenarios, a change in demand in the order of 0.75 – 1.5 times the original demand introduces very little differences between modelling the developments and harvesting systems as individual systems and modelling them as a scaled-up, large development with a single harvesting system. Once more, this occurs as the supplied demand in the systems considered for North Lakes are demand limited with most runoff from developments leaving the sites as stormwater (overflow). As demand increases, the systems are not demand limited but become supplied limited, and the two developments which have excess supply compensate for the one that has an increased demand when the systems are modelled as one. On the other end of the spectrum, if the demand is drastically reduced in one development, the other two developments benefit as they have more flow available in the case where they are modelled as a single storage.

Once more, the magnitude of the errors can be much larger than for the Scenarios A-D discussed above, particularly for large increases in demand. However, unless the changes in demand are reasonably large (i.e. the demand multiplier is in the order of greater than 2.5) the combined error using a sum of storages, catchments and demands is likely to be small and within other associated uncertainties in rainfall runoff and demand modelling.

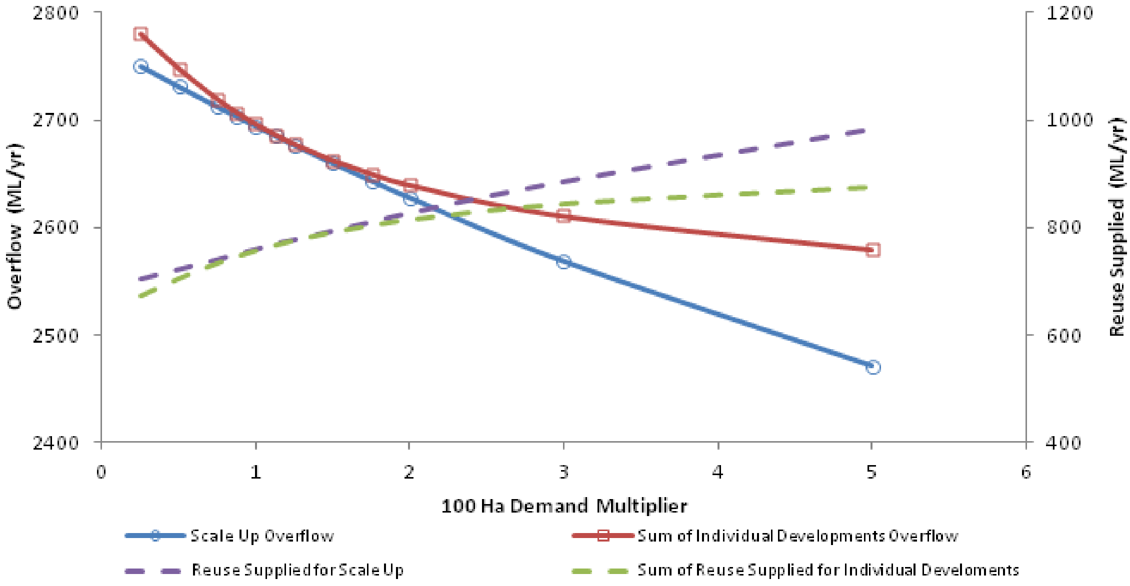

Figure 4. Reuse supplied and overflow as a function of demand for Scenario H.

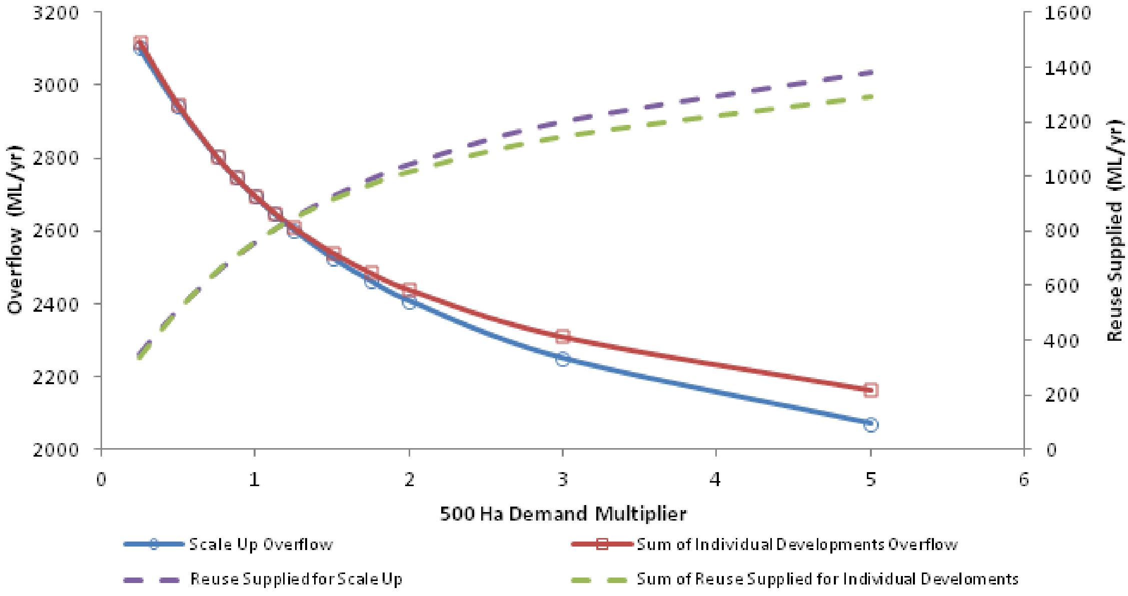

Figure 5. Reuse supplied and overflow as a function of demand for Scenario I.

4. CONCLUSIONS

This report investigates the sensitivity of the modelled overflow and demand met of a range of combinations of stormwater harvesting systems for hypothetical developments, when the systems are modelled as individual developments or as a scaled-up version combining the development areas, demands and storages.

In general, comparisons between the sum of results from individual catchments and the up-scaled system shows that the up-scaled system overestimates the demand met (yield) and underestimates the overflow for all scenarios. This difference in estimates is because the combined systems provide either a perceived increase or a perceived decrease in available storage, inflow and demand, which is not realistic. These perceived changes, however, are artefacts due to the assumption that the *independent* individual systems can be represented by a *single* system composed of the sum of demands, areas and storages.

For example, in scenario B, the harvesting system in the East 3 development supplies only 55.5% of its requested demand of 9.86 ML/yr. In this scenario, the storage size is the limiting factor to meet the demand. In the scaled-up case, more of the demand for this development is met as now the storage is modelled as a larger storage as it incorporates the storages from the other developments. However, physically, the harvesting stores are separate and can only meet a demand in the development in which they are located. Thus the aggregation of the storages introduces a perceived increased in available storage yield that is not realistic.

For scenarios E and F, when the three separate systems are modelled as one development with combined storages, the inflow from the two developments without inflow runoff reduction compensates for the reduction in the other development. If the systems are modelled separately, there is lower yield as the storage in the development with reduced runoff inflow has no access to the inflow from the other two developments, as would occur if the systems were independent catchments and not hydrologically connected.

In the last two scenarios investigated, scenarios H and I, changes in demand for one of the individual developments were shown to be more influential if the system was modelled as a combined system. As demand increases the systems are not demand-limited but become supply-limited, and the two developments which have excess supply compensate for the one that has an increased demand when the systems are modelled as one.

In all scenarios considered, the use of an up-scaled representation of the catchment by summation of areas and storages resulted in an error in the prediction of requested demand met and total overflow. However, in most cases in volumetric terms, the errors are well within uncertainties associated with rainfall runoff and demand modelling.

For scenarios E, F, H and I, the magnitude of the errors can be much larger than uncertainties in rainfall runoff or demand estimation. However, large errors only occurred when large changes in inflow or requested demand were considered, usually representing unrealistic cases. In practical terms, if the stormwater systems are well designed and show a reasonable performance in terms of meeting the demand requested, the combined error using a sum of storages, catchments and demands is likely to be small.

This study has examined up-scaling of yield overflow of individual systems by combining the input variables of individual systems to represent the combined system. The overall conclusion of the study is that the input variables of a number of stormwater harvesting systems spread across a catchment can be linearly combined (or summed) into a single system without introducing significant errors provided that the individual harvesting systems are well designed (i.e. storage volume just adequate to acquire the required yield).

An alternative approach would be the use of average values for the input variables to represent the combined system. Even though both approaches can be classified as linear up-scaling of input variables, this study has not examined the implication of this alternative up-scaling approach. Based on the studies of rainwater tanks reported in the literature, it can be expected that the use of average values of input variables to represent the combined system could also introduce errors. Hence, further work is recommended to understand the magnitude of errors, with the aim of recommending a method to up-scale yield and overflow (as well as water quality) impacts of decentralised stormwater harvesting systems at a city/regional scale.

REFERENCES

Bligh Tanner and DesignFlow 2009. Stormwater Infrastructure Options to Achieve Multiple Water Cycle Outcomes Report prepared for Queensland Water Commission by Bligh Tanner and DesignFlow.

Clark, R., Pezzaniti, D. and Cresswell, D. Year. WaterCress-Community Resource Evaluation and Simulation System-A tool for innovative urban water systems planning and design. *In:* Hydrology and Water Resources Symposium, 2002 20-23 May, Melbourne.

Coombes, P. J. 2006. Integrated water cycle modelling using PURRS (probabilistic urban rainwater and wastewater reuse simulator). Version 7.2.: Carrington, New South Wales, Australia, Urban Water Cycle Solutions.

Coultas, E.H., Maheepala, S. and Mirza, F. (2011). Towards the quantification of water quantity and quality impacts of rainwater tanks in South East Queensland, Paper submitted to MODSIM 2011, International Congress on Modelling and Simulation, 12-16 December, Perth Australia.

CRC-CH 2005. Model for Urban Stormwater Improvement Conceptualisation (MUSIC) (Version 3). Melbourne, Australia: Cooperative Research Centre for Catchment Hydrology.

Department of Housing and Public Works (2013). Web site accessed 15 February 2013. http://www.hpw.qld.gov.au/construction/BuildingPlumbing/Building/WaterSupplySystems/Pages/default.aspx

Khastagir, A. and Jayasuriya, L. 2010. Impacts of using rainwater tanks on stormwater harvesting and runoff quality. *Water science and technology,* 62**,** 324-9.

Lucas, S.A., Coombes, P.J., Hardy, M.J. and Geary, P.M. Year. A comparative study of common uses of selected modelling tools for evaluating rainwater harvesting strategies. *In:* The 7th International Conference on Urban Drainage Modelling and the 4th International Conference on Water Sensitive Urban Design, 2006 2006 Melbourne, Australia. ICMS, 327-334.

Maheepala, S., Loonat, N., Mirza, F. and Coultas, E. (2011). Quantifying potable water savings of rainwater tanks at a city scale by considering the effect of spatial lumping, OzWater 2011 conference, May 9-11, 2011, Adelaide, Australia, Published by Water Services Association of Australia.

Mashford, J., Maheepala, S. Neumann, L. and Coultas, E. (2011). Computation of the expected value and variance of the average annual yield for a stochastic simulation of rainwater tank clusters, Proc. of the 2011 International Conference on Modeling, Simulation and Visualization Methods, 2011, pp. 303-309.

Mitchell, V., Siriwardene, N., Duncan, H. and Rahilly, M. 2008. Investigating the Impact of Temporal and Spatial Lumping on Rainwater Tank System Modelling. *International Conference on Water Resources and Environment Research.* Modbury, SA: Engineers Australia ; Causal Productions.

Mitchell, V. G. 2007. How important is the selection of computational analysis method to the accuracy of rainwater tank behaviour modelling? *Hydrological processes,* 21**,** 2850-2861.

Neumann, L., Coultas, E., Moglia, M. and Mashford, J. 2011. Errors in yield and overflow estimation in rainwater tank cluster modeling. *12th International Conference on Urban Drainage, Porto Alegre/Brazil, 11-16 September 2011.*

Queensland Development Code (2008). MP4.2 Water Savings Target, Publication Date: 22 October 2008, Queensland Government, Australia, http://www.dlgp.qld.gov.au/resources/laws/queensland-development-code/current-parts/mp-4-2-water-savings-targets.pdf.

Queensland Water Commission 2010. South East Queensland Water Strategy. The State of Queensland (Queensland Water Commission).

Siriwardene, N.R., Mitchell, V.G., Duncan, H. and Rahilly, M. 2008. The impact of spatial averaging on rainwater tank performance modelling. *11th International Confernece on Urban Drainage.* Edinburgh, Scotland, UK.

Vieritz, A., Baisden, J. and Gardner, T. 2005. Rainwater TANK Manual. Natural Resource Sciences, Department of Natural Resources and Mines. March 2005.

Xu, H., Rahilly, M. and Maheepala, S. (2010). Assessing the impact of spatial lumping on rainwater tank performance using daily modelling", Proceedings of the 9th International Conference on Hydro-informatics, September 7-11, 2010, Chinese Academy of Sciences, China.

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