Ripley Valley – an Application of GIS Based Runoff Modelling to Strategic Stormwater Harvesting Assessment

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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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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.

C. Davis

Chris Davis
Chair, Urban Water Security Research Alliance

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EXECUTIVE SUMMARY

Stormwater management broadly has been well accepted as necessary for both flood avoidance and importantly also the prevention of aquatic ecosystem degradation within and around cities. Harvesting stormwater to provide diversification of water supplies offers a way of avoiding flooding and ecosystem degradation as well as acting to improve the climate resilience of cities. With Australia's population overwhelmingly urban in character, and the climate well known to oscillate between droughts and flooding rains, the opportunities represented by stormwater harvesting are significant, for both greenfield and brownfield developments.

A key question associated with implementing stormwater harvesting is how to decide where to site stormwater schemes in urban developments. This question can be broken down into a set of specific questions covering harvestable volume potential, harvesting location and collection strategy:

1. Which sites offer the highest harvestable volume potential and the closest proximity to sub-potable demands?
2. Should stormwater be harvested in a decentralised manner, with urban runoff collected close to where it arises, or more centrally downstream?
3. How sensitive to rainfall variation are different harvesting site locations and centralisation / decentralisation strategies for collection?

The work reported here provides answers to these questions in the context of a strategic stormwater harvesting assessment for the Ripley Valley development, a major 120,000 population development currently being planned to be built 5km south west of Ipswich City in South East Queensland (SEQ). Current work and approaches to assessing stormwater harvesting options have employed planned street and development layouts to assess yield, reliability and cost rather than starting from the clean slate of a greenfield development at full catchment (river basin) scale. Situating assessment for stormwater harvesting options at full catchment scale enables a broader range of siting options for the collection point locations to be considered in relation to planned development patterns and densities, and in relation to potential rainfall variability. Assessment at this scale also enables the relative merits of harvesting in many smaller sub-catchments versus harvesting in one single downstream sub-catchment from harvestable volume, supply ratio or proximity to demand perspectives.

To undertake the assessment of locations within the Ripley Valley, a GIS-based runoff modelling approach was developed and applied. The land cover and runoff coefficients of the Ripley Valley currently and under the proposed development plan were characterised using GIS. ArcHydro was used to characterise the sub-catchment hydrology of the river basin within which the Ripley development lies, based on topographical information. A stochastic rainfall time series generator was used to generate a dry 30-year time series of rainfall, a median 30-year time series of rainfall and a wet 30-year time series of rainfall for the development based on measured 30-year rainfall data. The three rainfall scenarios were then applied to determine the volume of runoff at each sub-catchment pour point (drainage outlet) using a simple land cover runoff modelling approach. Harvestable runoff was determined by subtracting the existing (undeveloped) land cover runoff from the calculated runoff under urban development. Two urban development scenarios were modelled – a current planned density scenario and an increased density scenario. Both used the same spatial distribution of development land covers taken from the Master Plan map.

Differences in annual average harvestable volume (in ML) and in supply ratio (the ratio of annual average harvestable volume) were used to compare two harvesting scenarios – the first being harvest at the pour point of every sub-catchment occupied by and upstream of the development, and the second being to only harvest at the most downstream sub-catchment pour point. In addition, the maximum distance to urban area within each sub-catchment was used as a way of approximating relative cost of supply – the logic being that sub-catchments where the harvesting location (the pour point) is far away from where the sub-potable demand is will have a higher distribution infrastructure cost and therefore potentially be less attractive. Household sub-potable demand was calculated for each sub-catchment and used as the basis for calculating supply ratios for each rainfall, development and harvesting location (many smaller or single larger) scenario combinations. Public space irrigation was not explored as a sub-potable water use.

Average annual harvestable stormwater volumes ranged from 1,181 ML/yr for the planned density dry rainfall scenario over the whole development to 1,338 ML/yr under the wet rainfall scenario. At the planned density, the total (domestic) sub-potable demand was calculated as being 1,968 ML/yr, yielding an overall supply ratio of between 0.60 (dry rainfall scenario) and 0.68 (wet rainfall scenario). For the increased density development scenario average annual harvestable stormwater volumes ranged from 2,764 ML/yr (dry rainfall scenario) to 3,130 ML/yr (wet rainfall scenario). Against a total (domestic) sub-potable demand of 4,745 ML/yr, the overall supply ratio varied between 0.58 (dry rainfall) and 0.66 (wet rainfall), marginally poorer than for the planned density development supply scenario, due to a proportionally higher increase in domestic sub-potable demand with the increase in housing density than the increase in harvestable runoff from increased imperviousness.

At sub-catchment scale, there was variability in the supply ratio at both planned and increased density developments, with the increased density development sub-catchment supply ratios largely tending to be poorer (0.59 – 0.67 range dominating). However, this was not universally the case, indicating sub-catchment specific outcomes as a consequence of the local balance between imperviousness, housing density and sub-potable demand.

Incorporating a distance to supply, or infrastructure cost, perspective to supply ratios, the best (highest supply ratio first then least distance to supply next) sub-catchments are 77, 70, 80, 83, 86, 76, 69 and 88 (all supply a ratio of 0.74) under the planned development density, and 67 and 61 (both supply a ratio of 0.72) under the increased density development. This suggests that if only some sub-catchments are to be selected for harvesting then the sub-catchments which are best will vary depending on rainfall, density and area of development along with the nature and size of the sub-potable demand.

In conclusion, rainfall variation was observed to have around a 13-14% impact on both total harvestable volumes and supply ratio at sub-catchment and whole of development scales. Harvestable volumes were larger under increased density development and of course, wetter rainfall. Supply ratios were poorer under increased density of development, and higher under wetter rainfall. There was an overall decrease in supply ratios as the development densified due to the proportionally higher increase in domestic sub-potable water demand than additional runoff. If the sub-potable water demand had been public space irrigation, a different pattern would have been observed – that of increasing supply ratio with increasing urban development density. As a consequence, the results suggest that there is a balance to be struck with regards to urban development density - harvestable volume increases with density, but domestic sub-potable demand also increases with density, and depending on the density, the sub-potable demand increase may outstrip the harvestable volume increase.

There was no clear argument from a harvestable volume, supply ratio or distance to supply perspective to preference a single, larger or centralised harvesting strategy over a decentralised strategy, with harvesting situated at the sub-catchment scale. The additional benefit of sub-catchment scale harvesting is that the potentially ecological degrading impacts of stormwater flows into creeks can be managed, unlike harvesting centrally.

With regards to the approach used, GIS analysis for sub-catchment hydrological and land cover characterisation proved easy to use and sufficiently reliable. Validation against the nearest stream gauge showed the predicted runoff to be within 10% of flows – close enough, given that the rainfall series used was statistically generated from actual rainfall data rather than being a single historical time series. There are a number of aspects of the approach which could be improved, including the way in which environmental flow requirements are calculated, and the way in which land cover runoff coefficients are characterised and then represented.

1. INTRODUCTION

Together with population growth, increasing urbanisation forms one of the most significant forces of 21st century; significantly shaping the land, water and ecological processes of almost every country in the world. In Australia, almost 16 million people, around two thirds of the total population, are already resident in major cities, and almost 80% of population growth nationally occurs within those cities (ABS 2013). In Queensland, approximately 66% of the total population growth occurs in major cities, with almost all of the remaining 34% occurring in other urban areas (ABS 2013). Very few people in Australia live in rural or remote settings.

The need to manage the hydrological impacts of urbanisation is clear – a complex set of degrading symptoms known as the ‘urban stream syndrome’ has been observed to be characteristic of urban streams world-wide (Walsh *et al.* 2005). These occur as a consequence of changes to hydrology arising from the increased imperviousness of typical urban surfaces, and consequent changes to water quality, ecology and stream morphology. In Queensland, the nature of the changes to urban streams have recently been confirmed by UWSRA funded work (McIntosh *et al.* 2013) – there are significant departures from reference (or undisturbed) stream hydrology although the nature of the changes depends on the catchment and the pattern of urbanisation. There are also significant differences in the composition of urban stream ecological assemblages with fewer sensitive taxa. In short there is a clear need to act to protect the function of aquatic ecosystems and the services they provide from the various degrading impacts of urbanisation.

Beyond the need to act to manage the hydrological, water quality and ecological impacts of urbanisation, there is a need to act to secure the water supplies for urban areas in Australia. There is a recognised need that, in the medium term, the challenge is to ensure that Australian cities have resilient water supplies, with improved capacity to cope with climatic uncertainty, and less reliance on surface water sources (PMSEIC 2007). Diversification of supply sources is required strategically, and important within the portfolio of options is stormwater harvesting. “Often more water falls on a city than is consumed by it” (PMSEIC 2007), a statement demonstrated to be the case for Australian capital cities, where rainfall over urban areas could, if fully captured, easily replace total centralised water use (Kenway *et al.* 2011).

Harvesting stormwater could in principle provide a significant component of supply diversification and climate resilience to Australian water supply systems. Harvesting stormwater could also act to control the ecologically damaging flows and water quality issues which occur as a result of increased urbanisation, and as a consequence, provide a means of generating two sets of benefits for a single investment.

Within Queensland, stormwater harvesting and reuse have already been identified as a potential alternative for potable water demand reduction (DIP 2008). Stormwater harvesting and reuse schemes require infrastructure for capture, storage, treatment, maintenance and supply to end users in cost effective ways. Stormwater capture, storage and treatment infrastructure in particular requires space which may preclude uses for other purposes, and may increase the overall costs of any greenfield development, where less space for housing usually equates to lower profit margins for the developer. With 35 identified greenfield development areas in South East Queensland (SEQ) which will add an additional 754,000 new dwellings by 2031 (SEQ Regional Plan 2009), a key implementation question is how to decide where to site stormwater schemes. This question can be broken down into a set of specific questions covering harvestable volume potential, proximity to demand, harvesting location and strategy for collection:

1. Which sites offer the highest harvestable volume potential and the closest proximity to sub-potable demand?
2. Should stormwater be harvested in a decentralised manner, with urban runoff collected close to where it arises, or more centrally downstream?

3. What are the differences in harvestable volume and in the extent to which demand can be satisfied across different harvesting site locations and centralisation / decentralisation strategies for collection?
4. How sensitive to rainfall variation are different harvesting site locations and centralisation / decentralisation strategies for collection?

Comparative analysis of stormwater harvesting options across a range of housing densities in SEQ urban developments (Bligh Tanner and Design Flow 2009) has concluded that medium density (40 dwellings per ha) developments of at least 20ha, (and ideally 100ha or more), are preferable from a cost perspective, and that harvesting, storage, treatment and reuse by large, external (off-site) non-potable users maximises yields and reduces costs more effectively than reuse for irrigation at allotment or sub-catchment scales. The extent to which stormwater yields and supply volumes are sensitive to watershed topographic, land cover, precipitation and hydrologic characteristics remains unclear however.

Current work has employed planned street and development layouts to assess yield, reliability and cost rather than starting from the clean slate of a greenfield development at full catchment (river basin) scale. Situating assessment for stormwater harvesting options at full catchment scale enables a broader range of siting options for the collection point locations to be considered in relation to planned development patterns and densities, and in relation to potential rainfall variability. Being able to compare different locations across a catchment, and different strategies for collection (many, decentralised points to fewer, centralised points) on the basis of their harvesting potential as determined by topography, land cover and rainfall via a rapid, relatively low cost could offer benefits to the practice of strategic stormwater harvesting assessment.

The aim of this report is to document the application of a GIS based runoff modelling approach to providing this kind of method. More specifically the report aims to:

(1) Provide a whole-of catchment assessment of the stormwater harvesting potential of the Ripley Valley development under different harvesting location, centralisation / decentralisation strategies, rainfall and urban development density scenarios; and to

(2) Provide a critical assessment of the strengths and weaknesses of GIS based runoff modelling for the strategic assessment of stormwater harvesting options by means of a case study, the development of the Ripley Valley in SEQ.

The report follows a traditional scientific format. The methods employed are first described, then the results presented before a critical discussion is presented.

As a consequence of the work presented here, the authors hope to both have contributed to improving the way in which stormwater harvesting is assessed as a supply option, and to have provided some insight into the potential represented by the Ripley Valley, as an example of a significant urban development in SEQ which has the opportunity to embed stormwater harvesting at its core.

2. METHOD

A Geographical Information System (GIS) approach using Spatial Analysis was developed and used to model catchment scale hydrology and stormwater runoff based on knowledge of topography, land cover (current and planned under urban development) and rainfall. ArcHydro (part of the ArcGIS suite) was used to charactertise the sub-catchments across the full extent of the Ripley Valley based on topographic information and the way in which they are connected through hydrological flow.

Average annual harvestable volumes of stormwater were calculated based on the average of annual rainfall values over a thirty-year period combined with knowledge of the typical imperviousness of different kinds of land cover from roads and vegetated areas through to varying forms and densities of urban development. A range of rainfall values were used to assess the sensitivity of the calculated harvestable volumes based on stochastic modelling of potential thirty-year rainfall patterns for the case study area, Ripley Valley, near Ipswich in SEQ.

The Ripley Valley Structure Plan (Ipswich City Council 2006) was used to identify the spatial distribution and nature (cover and density) of planned urban development. Stormwater runoff was then simulated based on the imperviousness of planned land cover and housing density. Two different harvesting strategies were modelled – collection at the drainage outlet (or pour point) of every sub-catchment within the planned development area, and collection only at the final (i.e. furthest downstream) sub-catchment pour point of all the upstream sub-catchment runoff flows. Harvestable volumes were calculated as the difference between the runoff from existing land cover and runoff under urban development land cover. In doing so, the runoff from existing land cover was used as a base-line and rough calculation of flows to be maintained within the Ripley Valley for environmental purposes.

Two different urban development scenarios were modelled to test the extent to which harvestable volumes would vary in total volume and as a ratio of stormwater runoff to sub-potable water demand. The first urban development scenario modelled was the current planned development of the Ripley Valley in terms of density. The second was a deliberately extreme scenario of building to the highest density, 55 dwellings per hectare (dw/ha), across the planned area of development for the Ripley Valley. This was done to assess what would happen to harvestable volumes at maximum land cover imperviousness and consequently runoff proportion and volume. That 55 dw/ha is a realistic development scenario is not proposed here – the scenario was assessed purely to understand the stormwater harvesting consequences of high imperviousness and high runoff conditions.

The extent to which annual stormwater harvestable volumes could satisfy sub-potable water demand annually was assessed using a simple ratio of harvested stormwater to sub-potable demand. Sub-potable demands examined were purely household – toilet, laundry and garden irrigation – and data for these taken from UWSRA research into SEQ household water demand locally in Ipswich (Beal *et al.* 2010).

The following sub-sections provide more detail on each of the main elements of the method employed:

- Ripley Valley urban development description;
- Characterising the hydrology of the Ripley Valley;
- Rainfall data generation;
- Stormwater runoff and harvesting modelling:
    - Imperviousness characterisation.
    - Harvesting locations and strategies.
    - Development scenarios.
    - Comparing harvesting options.

2.1. Ripley Valley Urban Development Description

The Ripley Valley forms one of the key urban growth areas identified in the SEQ Regional Plan (DIP 2009) (Figure 1).

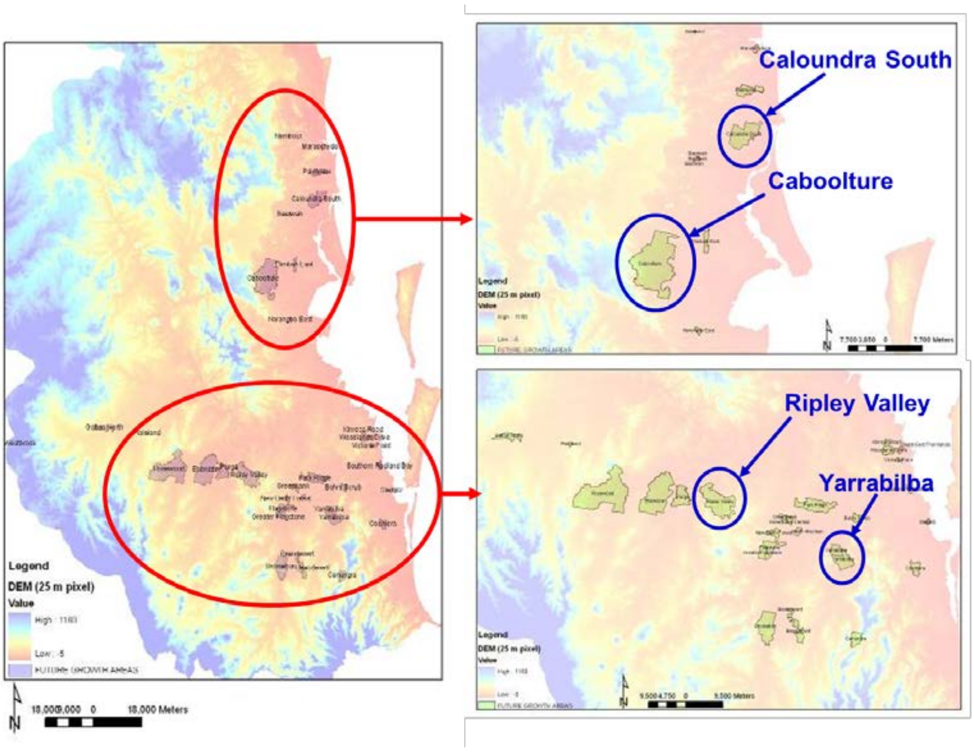

Figure 1. Strategic urban growth areas in SEQ and the location of the Ripley Valley development (adapted from DIP 2009).

The Ripley Valley development area covers approximately 4,680 ha of land about 5km to the south west of Ipswich City CBD. It has been master planned to grow to an eventual population of 120,000 people with around 60,000 people requiring employment.

Ipswich City Council provide detailed Master planning documents (Ipswich City Council 2006) as do the QLD Urban Land Development Authority (ULDA), who have developed and published the Ripley Valley Urban Development Area Development Scheme (ULDA 2011). The current land use of the Ripley Valley is shown below in Figure 2 and then the planned land cover for the area under the development plans in Figure 3.

There are four main types of residential land cover distinguished in the Ripley Valley Master plan:

- Urban core – the most dense mixed use including residential (55 dw/ha).
- Secondary urban centres – the next most dense mixed use including residential (35 dw/ha).
- Neighbourhoods - less dense residential (15 dw/ha).
- Villages - the least dense residential (8 dw/ha).

These land covers are presented in Figure 3, with the planned development area shown in the context of the whole hydrological catchment. In official development documents, the development area is typically only shown as a part of the catchment – the upstream component to the south is not usually shown, but is important for determining runoff volumes, hence its inclusion here. In addition to the residential land covers, Figure 3 shows the other types of land cover used to characterise the Ripley Valley for runoff modelling purposes – forest or shrub; grass; reservoir; rural residential; existing urban; and road.

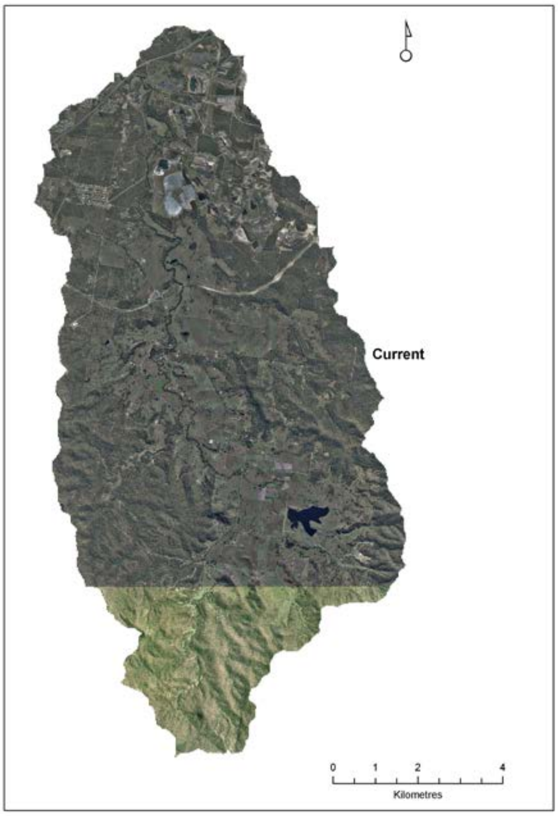

Figure 2. **Current land cover of the Ripley Valley (from aerial photography).**

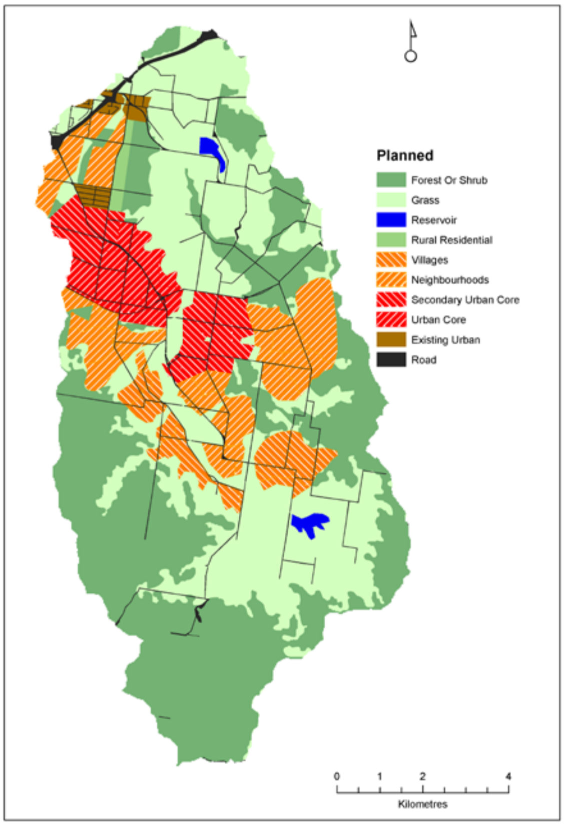

Figure 3. **Ripley Valley Master Planned land cover set in the context of the whole catchment.**

2.2. Characterising the Hydrology of the Ripley Valley

Catchment characterisation was undertaken using the ArcHydro model (ESRI) based on topographic information for the catchment containing the Ripley Valley development area. The full suite of requisite input feature classes was generated - slope, flow direction, flow accumulation, sub-catchments, pour points (drainage points or outlets), drainage lines and adjoint catchments. This identifed some 65 sub-catchments within the Ripley development and containing catchment. Figure 4 shows the set of sub-catchments identified.

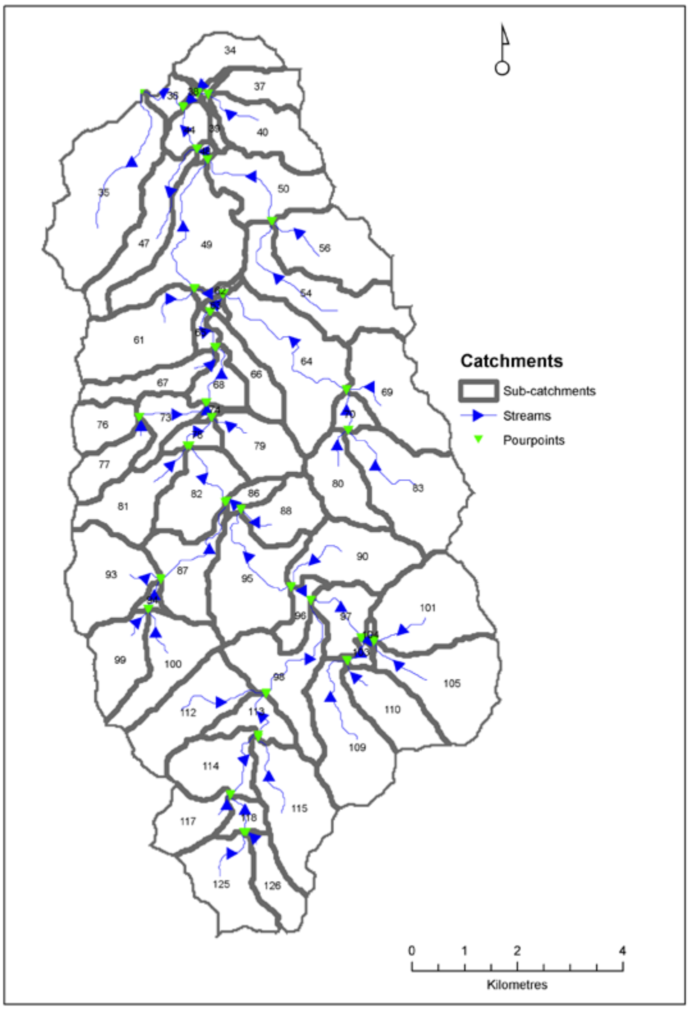

Figure 4. **Ripley Valley hydrological sub-catchments (overall flow from south to north).**

The decision was taken to focus only on modelling the runoff as far down the Ripley Valley catchment as the planned development area reached, but based upon modelling the runoff from the whole of the upstream catchment. Figure 5 shows the cropped set of sub-catchments used to model the hydrology and runoff. Figure 6 shows the same cropped set of sub-catchments overlain on top of the existing land cover aerial photographic data for reference.

A landuse spatial layer was created attributing polygons for each existing feature entity (urban, roads, forest, grassland, reservoirs) within each sub-catchment (ArcGIS geo-processing; spatial merge from sourced vector, development, digital cadastral database (DCDB) and vegetation layers). Figure 3 shows the whole spatial layer illustrating the planned development area. Figure 7 shows the spatial layer cropped to focus only on the sub-catchments of relevance within and upstream of the planned development area. This layer was used to characterise the area of land under different land covers, and to then, based on area and the imperviousness of each land cover, to calculate the runoff under different rainfall scenarios.

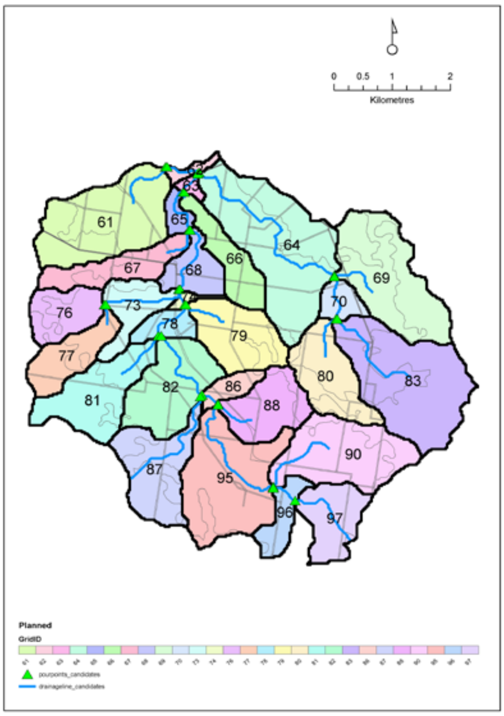

Figure 5. **Cropped set of sub-catchments used for runoff modelling of the Ripley Valley (numbers are for sub-catchment ID, green triangles indicate sub-catchment pour points).**

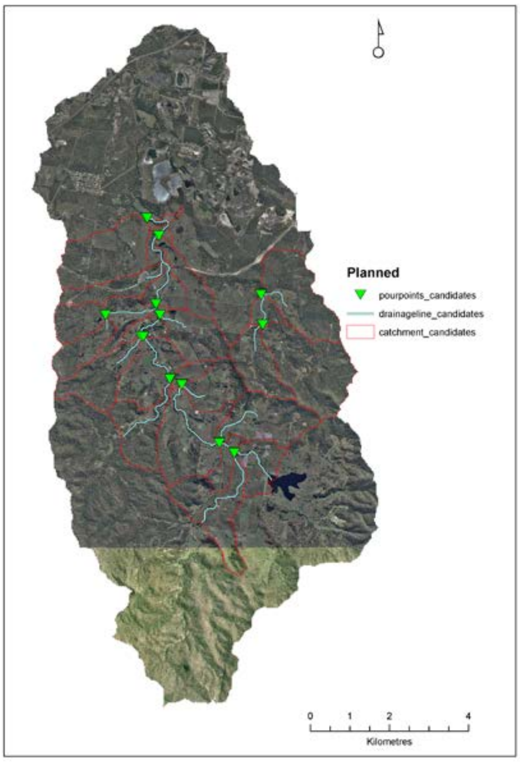

Figure 6. **Ripley Valley cropped set of sub-catchments overlain on current land cover aerial photography data.**

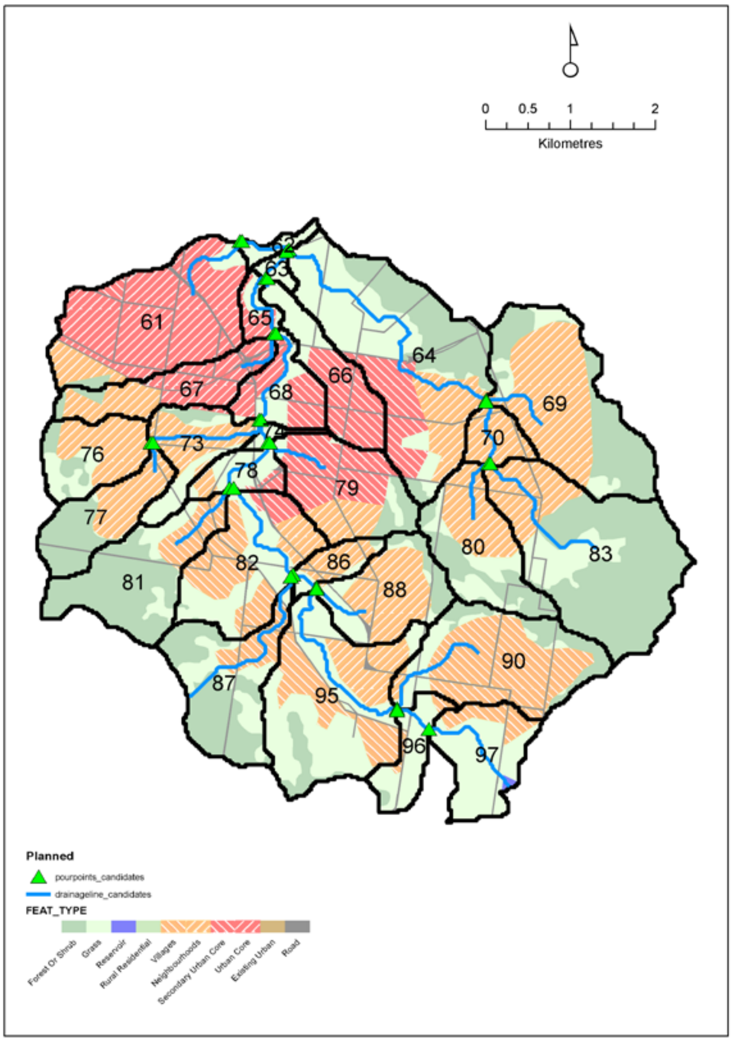

Figure 7. Ripley Valley spatial layer used for runoff modelling showing land cover and sub-catchment hydrology (sub-catchment ID numbers and pour points).

2.3. Rainfall Data Generation

Stormwater harvesting, as a supply option, is clearly prone to climatic variation. Existing work to assess the harvestable volumes and yield of different harvesting options in SEQ have not typically incorporated an assessment of the impact of rainfall variability. We did so here by way of taking the real rainfall data over the 30 years from 1980 until 2010 and stochastically generating a larger set of 30-year rainfall time series. From the many 30-year time series data sets generated we selected the driest overall (i.e. overall average annual rainfall and overall total rainfall), the wettest overall and the median.

The daily stochastic rainfall data were generated using the eWater CRC’s Stochastic Climate Library (http://www.toolkit.net.au/Tools/SCL). Thirty years of daily rainfall data from 1980 for the Ripley Valley Urban Development Area obtained from the Queensland Government’s SILO data was used (http://www.longpaddock.qld.gov.au/silo; Jeffrey *et al.* 2001). One hundred stochastic replicates each of 30 years length was generated. These replicates were then used to determine the dry, median and wet rainfall scenario given by bottom 10 percentile, median and top 90 percentile total annual rainfall series.

The Stochastic Climate Library tool uses a transition probability matrix method as described in (Srikanthan *et al.* 2006). In the Transition Probability Matrix model, the seasonality and magnitude of daily rainfall are taken into account by considering each month separately. The daily rainfalls are divided into a number of states (1 to 7). State 1 is dry and the other states are wet. The recommended number of states for each month is determined for a specific location and is given in Srikanthan and McMahon (1985). The transition probabilities are estimated from the historical frequency of transition from one state to the other within a month using a uniformly distributed random number from 0 to 1. The generated daily rainfall is adjusted so that the model reproduced the mean and standard deviation of the historical annual rainfall data (see Srikanthan *et al.* 2006 for further details).

The resulting dry, median and wet rainfall time series were used to drive the runoff modelling and to enable assessment of the extent to which harvestable runoff volume would vary depending on rainfall variation. Table 1 shows the rainfall data series used.

Table 1. Rainfall data time series used.

Year	Rain Scenario	Rain (mm/yr)	Rain Scenario	Rain (mm/yr)	Rain Scenario	Rain (mm/yr)
1980	dry	1,472	median	753	wet	961
1981	dry	563	median	1,220	wet	507
1982	dry	456	median	751	wet	892
1983	dry	619	median	502	wet	587
1984	dry	579	median	715	wet	910
1985	dry	1,117	median	627	wet	924
1986	dry	619	median	1,185	wet	704
1987	dry	746	median	839	wet	944
1988	dry	924	median	825	wet	964
1989	dry	930	median	898	wet	1,207
1990	dry	547	median	968	wet	828
1991	dry	757	median	906	wet	1,186
1992	dry	692	median	1,162	wet	1,055
1993	dry	967	median	737	wet	1,249
1994	dry	1,055	median	710	wet	572
1995	dry	975	median	631	wet	1,498
1996	dry	1,168	median	802	wet	1,412
1997	dry	675	median	851	wet	651
1998	dry	771	median	1,505	wet	984
1999	dry	1,658	median	1,295	wet	876
2000	dry	637	median	963	wet	877
2001	dry	1,105	median	708	wet	919
2002	dry	803	median	676	wet	709
2003	dry	1,082	median	971	wet	1,000
2004	dry	549	median	1,092	wet	864
2005	dry	554	median	815	wet	1,000
2006	dry	926	median	1,125	wet	1,122
2007	dry	790	median	788	wet	1,218
2008	dry	779	median	1,117	wet	1,083
2009	dry	846	median	892	wet	846
2010	dry	668	median	906	wet	924
Total Rain (mm)		26,026		27,937		29,475
Average Rain (mm/yr)		840		901		951

2.4. Stormwater Runoff and Harvesting Modelling

2.4.1. Imperviousness and Runoff Coefficient Characterisation

A range of different values exists for the imperviousness of urban land cover types such as housing and roads. Table 2 below shows a range of impervious area values for different densities of housed urban area. There are other higher values reported in some places such as in the Queensland Urban Drainage manual where, as reported in Water by Design (2009), high density residential is between 70% and 90% impervious. Rather than using the higher values, the approach to assessing stormwater harvesting volumes taken was conservative, assuming lower values rather than higher values, so as to avoid over-estimation.

Table 2. Impervious area estimations for urban areas with different housing densities.

Housing Density	Reference	Pervious Area	Impervious Area (paved only, assuming roof area will be rainwater connected)
11 dw/ha	Bligh Tanner & Design Flow 2009	50%	10%
40 dw/ha	Bligh Tanner & Design Flow 2009	33%	32%
100 dw/ha	Bligh Tanner & Design Flow 2009	25%	35%
Traditional, not specified further	Fletcher *et al.* 2007	Unspecified	42%
Typical single house, no stormwater	Walsh *et al.* 2004	50%	15.5%

Major open space in Australia has a runoff coefficient of 0.2 (Melbourne Water 2011) and should be represented separately from houses. Roads have a different imperviousness again and are detailed next.

Walsh *et al.* (2004) provide detailed calculations of the impervious and pervious areas for typical houses in the Dandenong area near Melbourne. They calculate that for an 18 house development occupying 12,800m^2 (1.28 ha), 1,600m^2 or 12.5% will be occupied by public road. This equates to 88.9m^2 of public road attributable to each dwelling, a total of 30.8% imperviousness per household.

Bligh Tanner and Design Flow (2009) estimate the Brisbane locality Sippy Downs as having 22.2% or 60,000m^2 of total development area (270,000m^2) in the form of public roads regardless of housing density (40 dw/ha or 100 dw/ha). This equates to an additional 55m^2, giving a total of 135m^2 impervious area or 44.2% of 305m^2 (250m^2 block size + 55m^2 public road) for each house at 40 dw/ha density. At 110 dw/ha density this equates to an additional 22.2m^2, to give a total of 57.2m^2 impervious area or 46.8% of 122.2m^2 (100m^2 block size + 22.2m^2 public road) per house.

The same authors estimate the Brisbane locality North Lakes, with 11 dw/ha, as having 34.2% or 77,000m^2 of total development area (225,000m^2) in the form of public roads. This equates to an additional 311m^2 impervious area, giving a total of 401.9m^2 or 32.9% of 1220m^2 (909m^2 block size + 311m^2 public road) per house.

For the purposes of this project we will select the Bligh Tanner figures as they are more likely to be representative of Brisbane locality and current housing development patterns.

Combining both housing and road values of urban residential areas to give total imperviousness / runoff we get the values shown in Table 3.

Table 3. Total imperviousness (runoff coefficient) of residential areas (housing and roads).

Housing Density	Reference	Housing Impervious Area (paved only)	Public Road Impervious Area (allocated per house)	Total Imperviousness / Runoff Coefficient (rounded)
11 dw/ha (909m^2 block size)	Bligh Tanner & Design Flow 2009	90.9m^2	311m^2	33% / 0.33
40 dw/ha (250m^2 block size)	Bligh Tanner & Design Flow 2009	80m^2	55m^2	44% / 0.44
100 dw/ha (100m^2 block size)	Bligh Tanner & Design Flow 2009	35m^2	22.2m^2	47% / 0.47

The best fit curve (R^2 = 0.952) through the points relating housing density (dw/ha) to total imperviousness as given in Table 3 provides a relationship with R^2 (Relationship 1):

$$\text{Total imperviousness} = 0.0649\ln(\text{housing density}) + 0.1822 \qquad (1)$$

Relationship 1 was therefore used to calculate the total imperviousness of residential areas in the Ripley Valley for runoff modelling. Four types of residential area are distinguished (see Section 2.1) – urban core, secondary urban centre, neighbourhoods and villages - each with different densities and consequently total imperviousness values.

Total imperviousness values were then modified to provide residential area runoff coefficients for the purposes of the work according to the average rainfall for Ripley Valley based on the work of Fletcher *et al.* (2004) (also documented in WBD 2009 - Figure 4-2 on page 37) who show how the relationship between percentage imperviousness and runoff coefficient varies according to average annual rainfall in an area. The runoff coefficient is normally higher than the imperviousness of a surface, and this is the case for the range of annual rainfall values for Ripley Valley used in this study (804 mm/yr – 951 mm/yr), although the difference between runoff and imperviousness is not great at these rainfall values.

The remaining land cover types in the Ripley Valley (see Figure 3) were modelled using runoff coefficients as shown in Table 4. Note that the roads land cover type represents roads outside of the area occupied by one of the residential land cover types.

Table 4. Runoff coefficients used (see Figure 3 for distribution of land cover types).

Land Cover	Runoff Coefficient Used	
	Planned Density Scenario	Increased Density Scenario
Forest or shrub	0.3	0.3
Grass	0.3	0.3
Rural residential	Not in development area	Not in development area
Urban core	0.44	0.48
Secondary urban centre	0.41	0.48
Neighbourhoods	0.36	0.48
Villages	0.33	0.48
Existing urban	Not in development area	Not in development area
Roads	0.9	0.9
Reservoirs	0	0

2.4.2. Harvesting Locations and Strategies

Figure 7 shows the map of the planned Ripley development area, with hydrological sub-catchments and pour points super-imposed. Two harvesting strategies were employed:

- Decentralised – stormwater harvesting locations set at all of the sub-catchment pour points (or drainage outlets), the locations where runoff will naturally drain towards. This scenario involves harvesting at each of 27 separate sub-catchments – 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 73, 74, 76, 77, 78, 79, 80, 81, 82, 83, 86, 87, 88, 90, 95, 96, 97.
- Centralised – stormwater harvesting only located at the pour point of the most downstream sub-catchment represented, the confluence of the drainage points for sub-catchments 61, and 62, into which all the other sub-catchments drain.

Of course, realising the runoff flows as harvested stormwater will require drainage infrastructure as part of the residential development. The operation of the infrastructure hydraulically was not represented in the runoff modelling.

2.4.3. Development Scenarios

The development area, as described by Ipswich City Council (2006) and the ULDA (2011) (see Figure 3), was maintained spatially for each land use category across the two development scenarios assessed. Instead, the density of housing across the four types of residential area planned for Ripley Valley was varied by increasing the density of development to 55 dw/ha (see Table 5 for the details).

Table 5. Development scenario housing densities.

Residential Land Use	Planned Density Development (dw/ha)	Increased Density Development (dw/ha)
Urban core	50	55
Secondary urban centres	35	55
Neighbourhoods	15	55
Villages	8	55

The increased density development scenario is not intended to be taken literally – it is clearly absurd in the sense that it represents covering the all residential areas in Ripley Valley with 55 dw/ha housing density. This would not be a sensible or attractive option to implement from many perspectives. The rationale, as explained towards the start of Section 2, was to maximise the impervious area and consequently to also maximise the potential harvestable volume of stormwater. Increasing housing density also has the effect of increasing water demand, so although the total harvestable volume is likely to be higher under increased density housing, the ratio of stormwater harvested to sub-potable water demand may be lower.

2.4.4. Sub-Potable Water Demand

A simple multiplicative approach was used to determine sub-potable water demand, using average demand figures taken from the work of Beal *et al.* (2010) locally in Ipswich. Three sub-potable uses were identified with the demand figures per person and per household shown in Table 6. Based on Beal *et al.* (2010), 2.7 people were taken as the average household occupancy rate.

Table 6. Ripley Valley household sub-potable water demand figures.

Water Use	Demand (l/pp/d)	Demand (l/hh/d)
Laundry	24.5	66.6
Toilet	21.4	57.8
Gardening	1.7	4.6
Total	**47.6**	**128.6**

Knowing the area in each sub-catchment planned to be under each of the four residential land covers, the total planned number of houses for each sub-catchment was determined by multiplying area by housing density (either planned or increased density as shown in Table 5). The annual sub-potable water demand for each sub-catchment was then calculated by multiplying the total number of houses by the daily demand figure from Table 6 (128.6 l/hh/d) and then by the number of days in a year (365). The results in litres were then converted to ML, the choice of standard unit for harvestable volume and water demand calculation.

2.4.5. Comparing Harvesting Options

We compared harvesting options (locations) in terms of three simple criteria:

- The ratio of annual harvested stormwater volume to sub-potable water demand (the supply ratio) – ratios of <1 representing less than 100% of sub-potable demand can be supplied annually by stormwater harvesting. The rationale is that higher ratio values represent harvesting locations which are more reliably able to supply the nearby sub-potable demand. Ratios of ≥ 1 represent complete and even excess supply.
- The maximum distance of the urban area away from the sub-catchment pour point. The rationale here is that longer maximum distances away from the pour point mean that the CAPEX and OPEX for supplying the stormwater to dwellings in the sub-catchment will cost more.
- The average annual harvestable stormwater volume. The rationale here is that simply knowing the harvestable volume enables calculations to be undertaken to understand the storage volume required if the harvesting was to be realised.

2.4.6. A Note on Validation

The runoff modelling approach undertaken was deliberately coarse – the intention being to use GIS and a simple calculation process rather than detailed hydrological modelling so that the method may be used more easily for practical application to strategic stormwater harvesting assessment. GIS and spreadsheet modelling capacities are widespread across local governments and consulting firms and so these tools were utilised as the basis for the method. Having said that, checking that the approach was producing sensible results compared to what is known about the hydrology of the catchment being modelled is essential to have confidence in the absolute aspects of the assessment – the extent to which modelled harvestable stormwater volumes can supply likely sub-potable water demands. Consequently a quick form of validation was employed.

As the Ripley Valley development region lies in an ungauged catchment, validation was undertaken by comparing the modelled runoff values with the closest stream gauge in the wider region. This compared the rainfall runoff volume between modelled hydrology and runoff data and historical river gauge data (Gauge #143114A 1972-1983 ref stream gauge station index). The comparison indicated that the the modelled data was within 10% of the actual, which given the potential error introduced by means of the basis of runoff modelling – the estimated runoff coefficients for different land covers – was deemed a satisfactor fit.

3. RESULTS

Harvestable annual volumes of stormwater were determined for both the planned and increased density scenarios, under dry, median and wet 30-year rainfall time series for all the pour points concerned. This section will present the results as follows:

- Characterising sub-catchment area and land cover – providing the total ha for each area, and the breakdown of ha per residential land cover in each.
- Characterising sub-catchment sub-potable water demands under planned and increase density urban development scenarios.
- Characterising average annual harvestable stormwater volume at each pour point under each rainfall scenario.
- Comparing the total sub-potable water demand of each sub-catchment with the average annual harvestable stormwater volume at each pour point under each climate and development scenario.
- Identifying the best locations in terms of distance for stormwater harvesting.

The results will be presented in sub-sections following the order of these points.

3.1. Sub-Catchment Area and Land Cover

Figure 8 shows the total land area of each sub-catchment. A range of spatial data sources were utilised to provide an analysis of the area occupied by the land cover of each residential land cover type in each sub-catchment – shown in Figure 9.

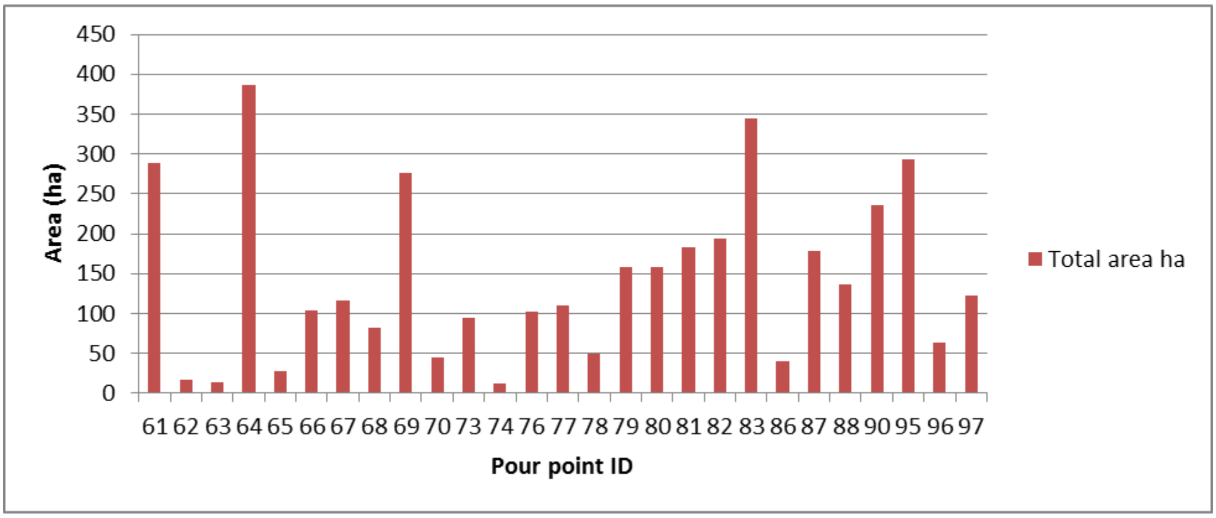

Figure 8. Total land area of each sub-catchment.

As can be seen from Figure 9, planned urban core land cover is primarily concentrated in sub-catchment 61, at the most downstream point in the catchment, with sub-catchments 67 and 68 also containing a significant area of urban core. Secondary urban centres are located primarily in sub-catchments 64, 66 and 79; neighbourhoods are more evenly spread across the sub-catchments from around the middle of the overall catchment towards upstream (a southerly direction), whilst; villages are concentrated towards the upper sub-catchments, particularly 81 and 90.

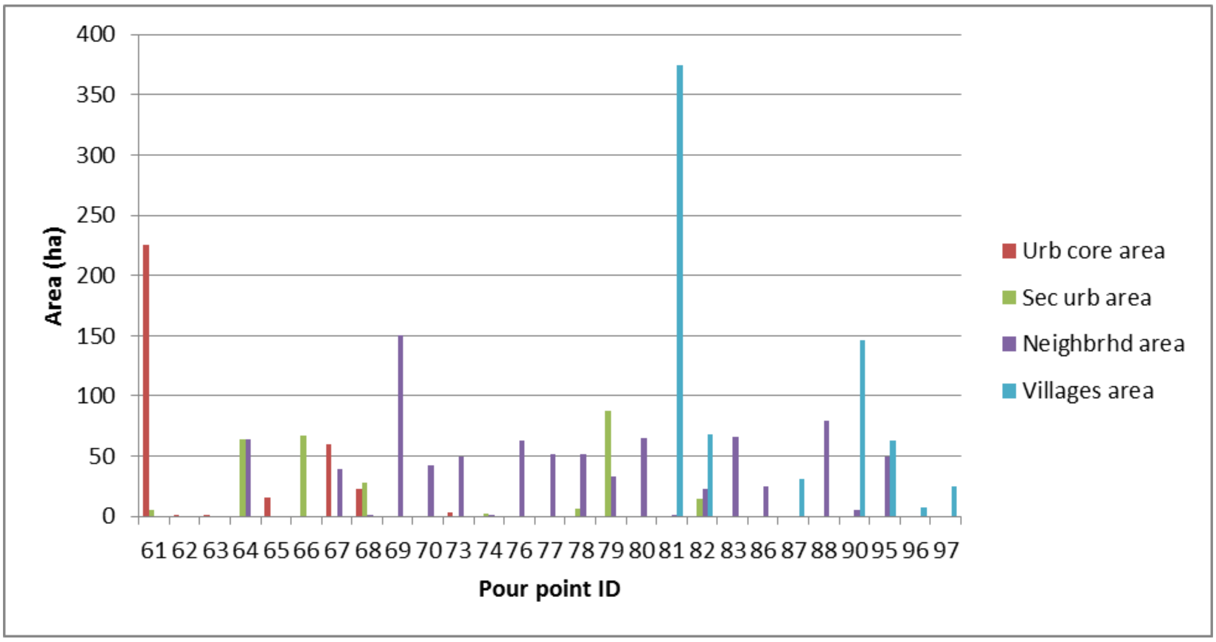

Figure 9. **Total land area under each residential land cover area in each sub-catchment.**

3.2. Sub-Potable Water Demand

Figure 10 shows the sub-potable water demands calculated for the planned and increased density development scenarios.

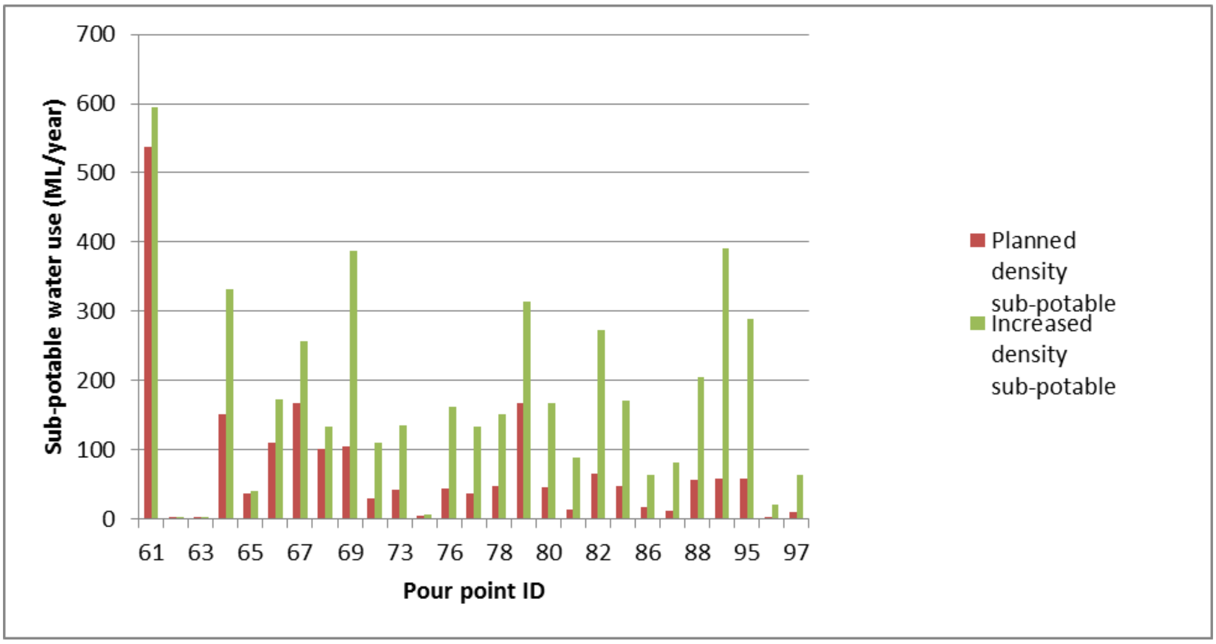

Figure 10. **Sub-potable water use for each sub-catchment under each development scenario.**

Under the planned development scenario, the greatest sub-potable water demand is in sub-catchment 61, where the urban core land cover is primarily located. This changes under the increased density scenario where the currently planned areas for lower density residential (neighbourhoods and villages) are densified to 55 dw/ha. As a consequence the sub-potable water demand for these sub-catchments increases significantly e.g. sub-catchments 79, 81, 90 and 95.

3.3. Average Annual Harvestable Stormwater Volumes

The average annual harvestable stormwater volume for each sub-catchment (the decentralised harvesting strategy) was calculated as the difference between the runoff under the existing land cover and the increased runoff occurring under the planned or increased density development. Total harvestable stormwater volume was calculated in this way for each of the three rainfall scenarios.

Figure 11 shows the average annual harvestable stormwater for each sub-catchment under the dry rainfall scenario, Figure 12 under the median rainfall scenario and Figure 13 under the wet rainfall scenario.

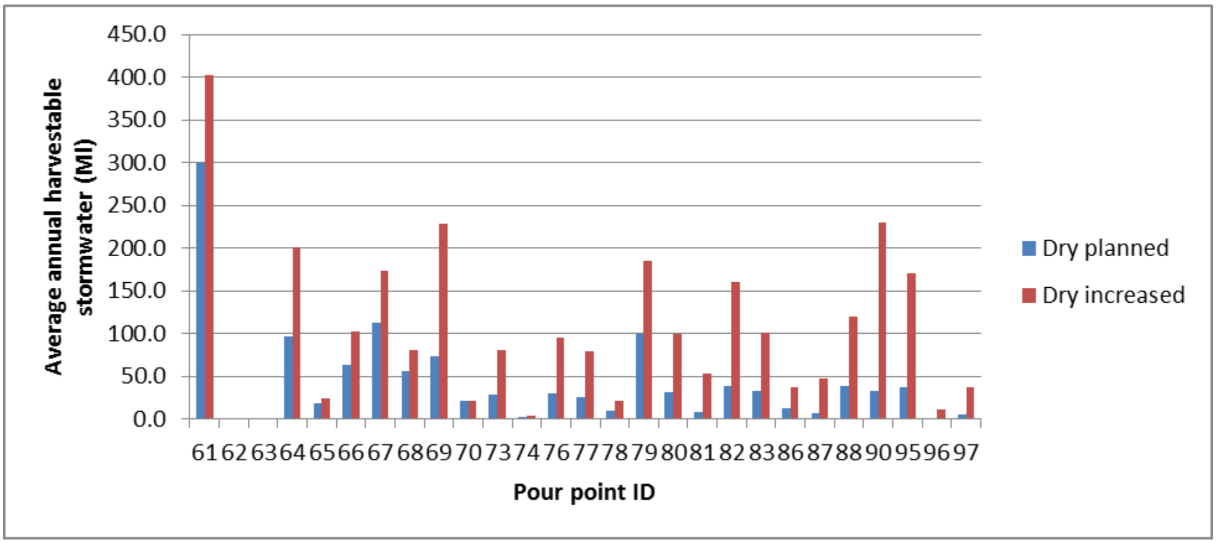

Figure 11. Average annual harvestable stormwater volume under dry rainfall for each sub-catchment.

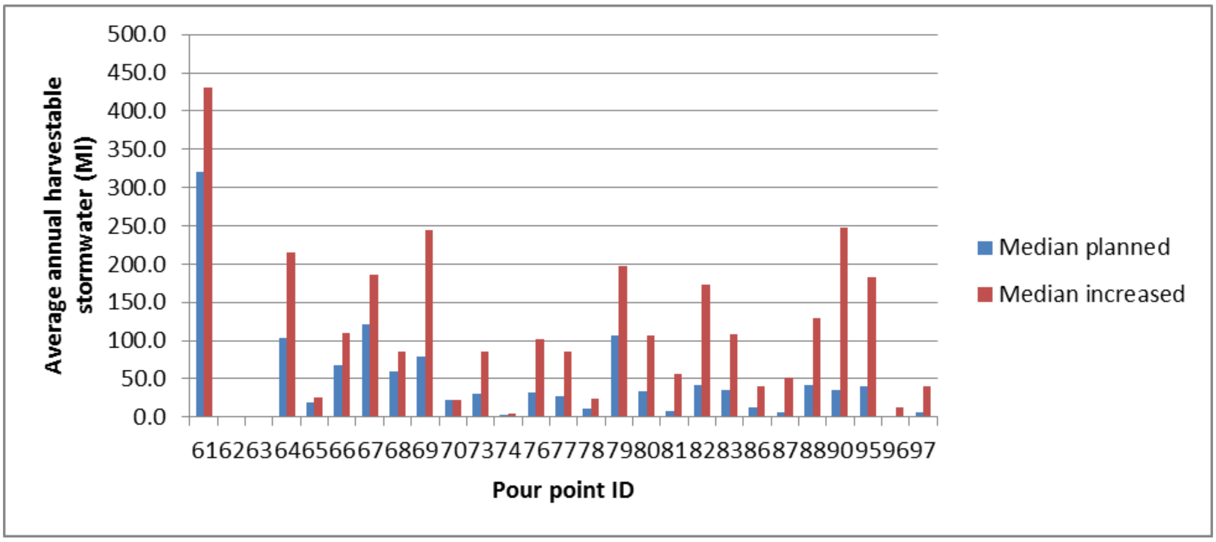

Figure 12. Average annual harvestable stormwater volume under median rainfall for each sub-catchment.

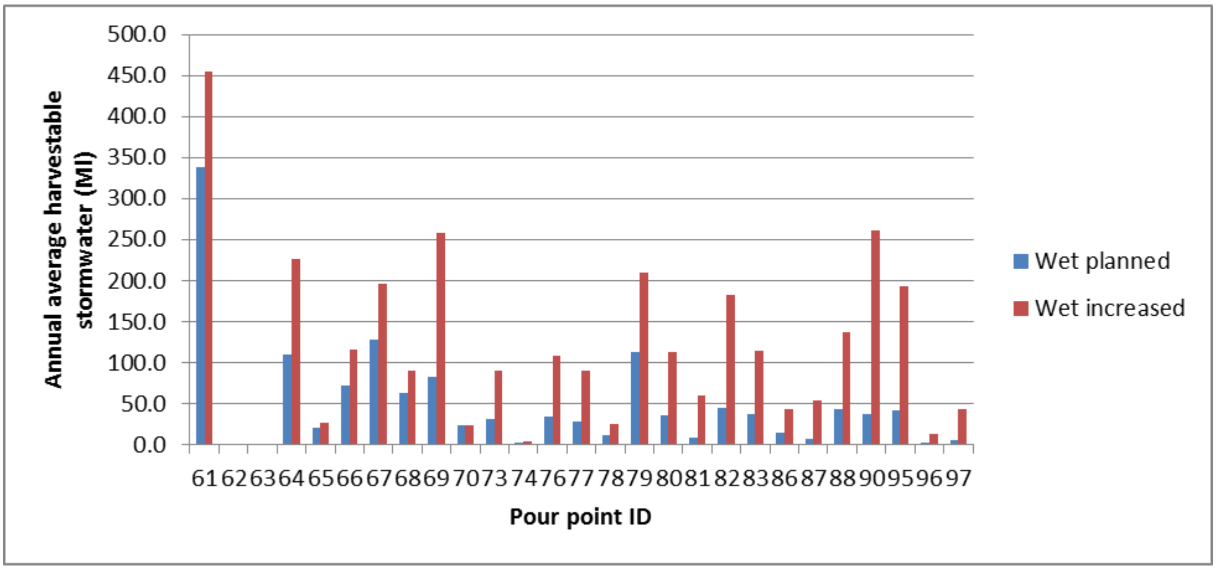

Figure 13. Average annual harvestable stormwater volume under wet rainfall for each sub-catchment.

The harvestable volumes ranges from a few ML/year in sub-catchments to be developed less through to over 450 ML/year in sub-catchment 61, which is to be urbanised more.

To provide an easier means of comparing the difference in harvestable volume within each sub-catchment depending on development and rainfall scenario, Figure 14 presents all the harvestable volume results. Tables 7 and 8 in Section 3.4 will present the harvestable volume result figures in comparison to the sub-potable water demand and ratio of harvestable volume to sub-potable demand.

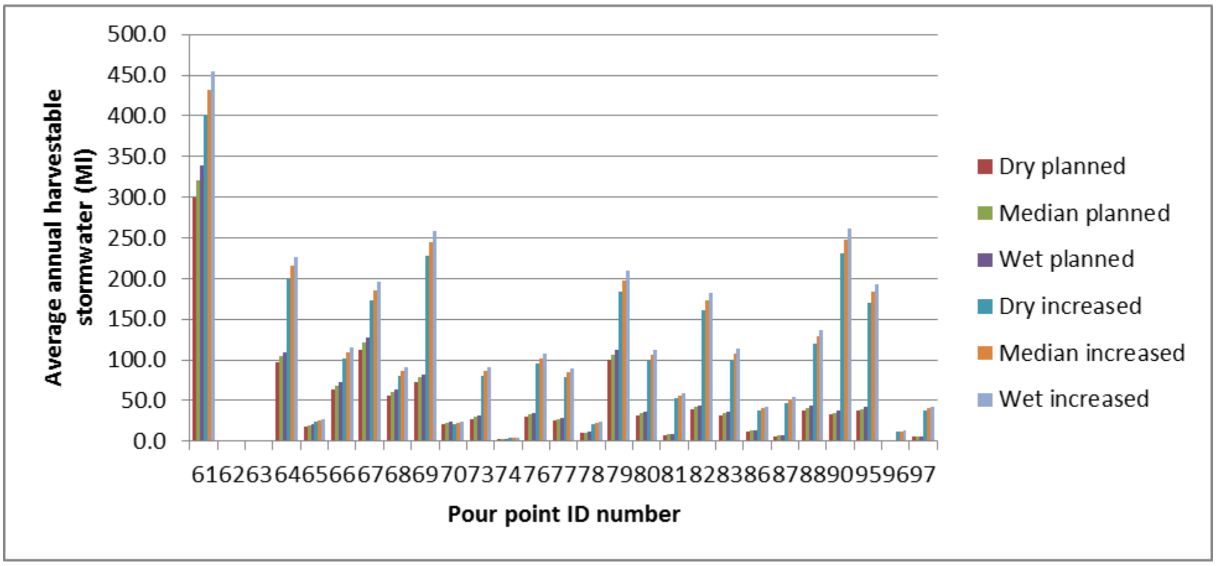

Figure 14. Comparison of differences in average annual harvestable stormwater volume across development and rainfall scenarios for each sub-catchment.

As shown in Figure 14, there is an increase in harvestable volumes across all sub-catchments as rainfall increases and as development density is increased. The differences across the rainfall scenarios are most pronounced in absolute terms for sub-catchment 61 for both planned and increased densities due to that sub-catchment having the greatest area of urban core land cover.

Showing the harvestable volumes by sub-catchment provides an assessment of the decentralised strategy for harvesting locations. The centralised strategy involves harvesting the additional stormwater runoff from development of the Ripley Valley at the most downstream sub-catchment outlet – the pour point at the confluence of sub-catchments 61 and 62. Figure 15 shows the range of harvestable stormwater volumes collected by this strategy depending on rainfall and development density – essentially the sum of the harvestable stormwater volumes from all the other sub-catchments.

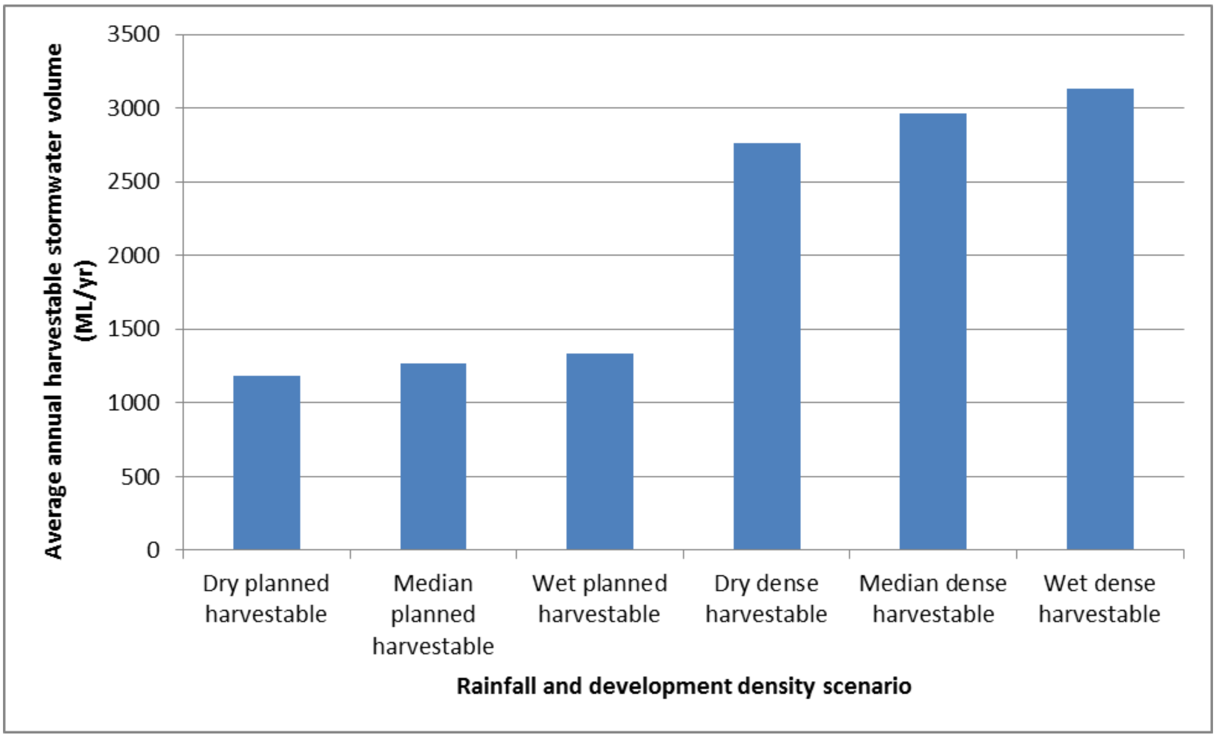

Figure 15. Centralised strategy average annual harvestable stormwater volume.

The average annual harvestable stormwater volume totals under current planned development density range from around 1,100 ML/yr to 1,300 ML/yr, and under increased density from around 2,700 ML/yr to 3,100 ML/yr, more than double the planned density volumes.

3.4. Comparing Harvestable Volumes to Sub-Potable Water Demands

Table 7 compares the annual average harvestable volume of stormwater for each of the three climate scenarios under the current planned density development to the sub-potable water demands, and shows the ratio of harvestable stormwater volume to sub-potable demand. This is done for each sub-catchment (the decentralised strategy) and as a total (the centralised strategy).

The centralised strategy yields a supply ratio of between 0.60 (dry rainfall scenario) and 0.68 (wet rainfall scenario), which is lower than the supply ratios for some of the sub-catchments, notably 69, 70, 76, 77, 80, 83, 86 and 88. The centralised supply ratio is also lower than the average across all sub-catchments (0.58 – 0.68). Sub-catchments 69, 70, 76, 77, 80, 83, 86 and 88 all have supply ratios ranging from 0.69 to 0.78. None of these sub-catchments have significant areas of dense urban area under the planned development scenario (see Figure 9). Where there is significant dense urban area (urban core) under the planned development scenario (sub-catchments 61 and 67) the supply ratios are lower. Sub-catchment 61, the most densely urbanised, itself ranges in supply ratio from 0.56 to 0.63, lower than the centralised strategy, whilst sub-catchment 67 ranges from 0.67 to 0.76 in supply ratio, better than the centralised strategy. Sub-catchment 67 is smaller and less urbanised than 61.

Table 7. Harvestable stormwater volumes, sub-potable water demands and supply ratios for each sub-catchment, averaged over all sub-catchments and overall (centralised collection) under planned development density and each rainfall scenario.

Pour Point ID	Dry Harvestable Volume (ML/yr)	Median Harvestable Volume (ML/yr)	Wet Harvestable Volume (ML/yr)	Sub-Potable Water Demand (ML/yr)	Supply Ratio Dry	Supply Ratio Median	Supply Ratio Wet
61	299	321	339	537	0.56	0.60	0.63
62	0	0	0	0	0.51	0.55	0.58
63	0	0	0	0	0.51	0.54	0.57
64	97	104	110	151	0.64	0.69	0.73
65	18	20	21	36	0.51	0.55	0.58
66	64	68	72	110	0.58	0.62	0.65
67	113	121	127	168	0.67	0.72	0.76
68	56	60	63	101	0.56	0.60	0.63
69	73	78	83	105	0.69	0.74	0.78
70	21	22	23	30	0.69	0.74	0.78
73	28	30	32	42	0.66	0.71	0.75
74	2	3	3	4	0.58	0.63	0.66
76	30	33	34	44	0.69	0.74	0.78
77	25	27	29	37	0.69	0.74	0.78
78	10	11	12	48	0.21	0.23	0.24
79	100	107	113	168	0.59	0.64	0.67
80	32	34	36	46	0.69	0.74	0.78
81	8	8	9	13	0.57	0.61	0.64
82	39	42	44	66	0.60	0.64	0.68
83	32	35	37	47	0.69	0.74	0.78
86	12	13	14	18	0.69	0.74	0.78
87	7	7	7	12	0.55	0.60	0.63
88	39	41	44	56	0.69	0.74	0.78
90	33	35	37	59	0.56	0.61	0.64
95	37	40	42	58	0.64	0.68	0.72
96	2	2	2	3	0.55	0.60	0.63
97	5	6	6	9	0.55	0.60	0.63
Avg.	44	47	50	73	0.60	0.64	0.68
Centrl	1,181	1,268	1,338	1,968	0.60	0.64	0.68

Table 8 details the same information for the increased development density scenario. Here, the centralised strategy supply ratios range from 0.58 to 0.66, a little poorer than under the planned development density scenario, but a little better than average supply ratio for all sub-catchments (ranges from 0.57 – 0.64). Overall, for the decentralised strategy where collection occurs at sub-catchment pour points, the supply ratios have deteriorated compared to the planned density scenario (averages have decreased from 0.60 – 0.68 to 0.55 – 0.62). This is not universally true though and in some sub-catchments, notably the most densely urbanised in the planned development scenario, 61, which increased in density by 5 dw/ha (from 50 to 55 dw/ha) and has seen an increase in supply ratio from 0.56 – 0.63 to 0.68 - 0.76 (sub-catchment 61). The other originally most densely urbanised sub-catchment was 67, which has the same supply ratio between planned and increased density development scenarios.

Table 8. Harvestable stormwater volumes, sub-potable water demands and supply ratios for each sub-catchment, averaged over all sub-catchments and overall (centralised collection) under increased development density and each rainfall scenario.

Pour Point ID	Dry Harvestable Volume (ML/yr)	Median Harvestable Volume (ML/yr)	Wet Harvestable Volume (ML/yr)	Sub-Potable Water Demand (ML/yr)	Supply Ratio Dry	Supply Ratio Median	Supply Ratio Wet
61	402	431	455	595	0.68	0.72	0.76
62	0	0	0	0	0.59	0.63	0.67
63	0	0	0	0	0.59	0.63	0.67
64	200	215	227	332	0.60	0.65	0.68
65	24	25	27	40	0.59	0.63	0.67
66	102	110	116	173	0.59	0.63	0.67
67	173	186	196	256	0.67	0.72	0.76
68	80	86	91	134	0.60	0.64	0.68
69	228	245	258	387	0.59	0.63	0.67
70	21	22	23	110	0.19	0.20	0.21
73	80	86	91	136	0.59	0.63	0.67
74	4	4	5	7	0.59	0.63	0.67
76	95	102	108	161	0.59	0.63	0.67
77	79	85	89	134	0.59	0.63	0.67
78	22	23	25	152	0.14	0.15	0.16
79	185	198	209	313	0.59	0.63	0.67
80	99	106	112	168	0.59	0.63	0.67
81	52	56	59	89	0.59	0.63	0.67
82	161	173	182	273	0.59	0.63	0.67
83	101	108	114	171	0.59	0.63	0.67
86	38	41	43	64	0.59	0.63	0.67
87	48	51	54	81	0.59	0.63	0.67
88	120	129	136	204	0.59	0.63	0.67
90	230	247	261	391	0.59	0.63	0.67
95	171	183	193	290	0.59	0.63	0.67
96	12	13	13	20	0.59	0.63	0.67
97	38	40	42	64	0.59	0.63	0.67
Avg.	102	110	116	176	0.57	0.61	0.64
Central	2,764	2,966	3,130	4,745	0.58	0.63	0.66

Figure 16 provides a graphical comparison, sub-catchment by sub-catchment of the differences between average annual harvestable stormwater and total sub-potable water use under the three rainfall scenarios for planned development density. Figure 17 shows the same information for the increased development density.

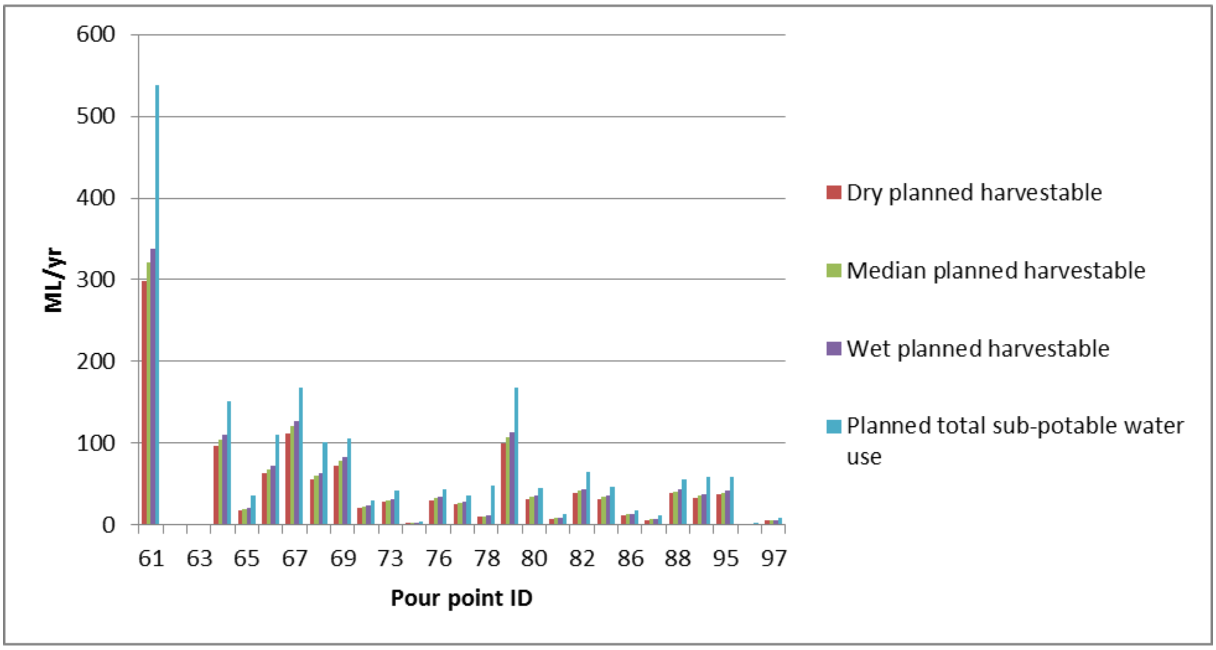

Figure 16. **Comparison of average annual harvestable stormwater under each rainfall scenario with total non-potable water use for each sub-catchment at planned development density.**

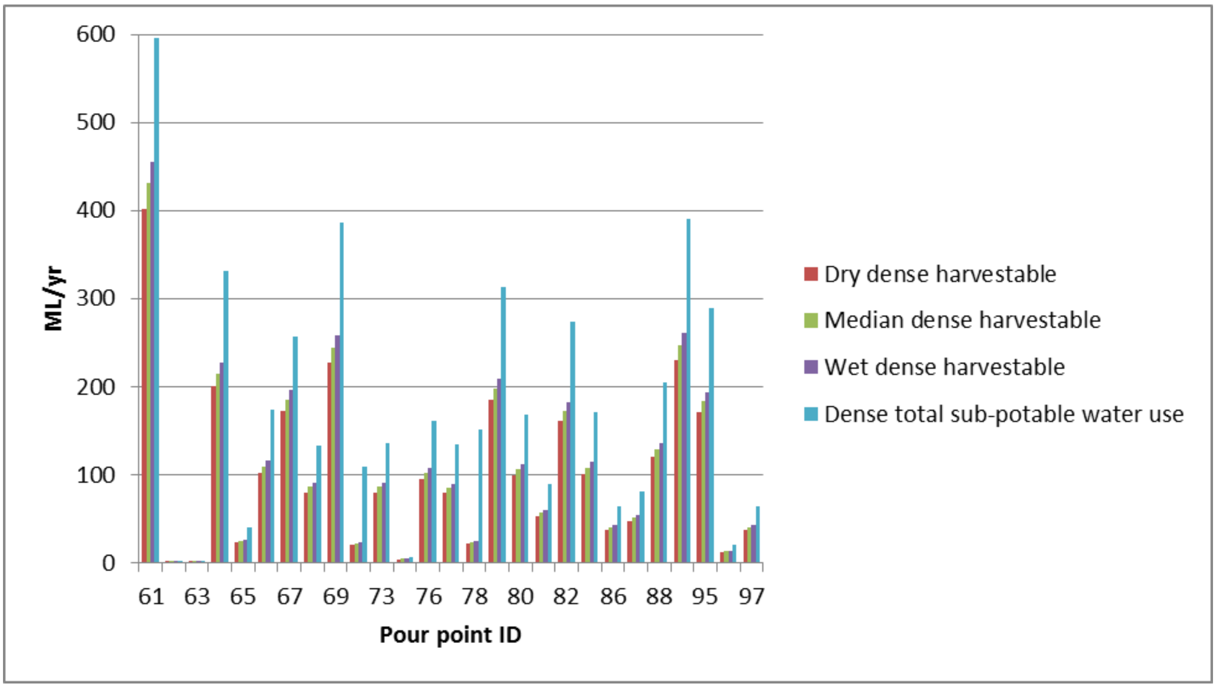

Figure 17. **Comparison of average annual harvestable stormwater under each rainfall scenario with total non-potable water use for each sub-catchment at increased development density.**

Comparing Figures 16 and 17 provides a way of understanding the changes in supply ratio shown in Tables 7 and 8 as a consequence of increasing the development density. It can be seen that the total sub-potable water use increases dramatically across the sub-catchments in absolute terms as density increases but not necessarily in relative terms for each sub-catchment. For example, in sub-catchment 61 the total harvestable volume has increased proportionally more than the increase in sub-potable water use, so the supply ratio has improved. Conversely, in sub-catchment 69, there has been a smaller increase in harvestable volume and a relatively larger increase in sub-potable water demand, so the supply ratio has deteriorated. Sub-catchment 61 is 289 ha in area, with 225 ha of urban core, 5 ha of secondary urban centre and almost 9ha of road. Sub-catchment 69 is 276 ha in area, with 150 ha of neighbourhood area, a lower density of planned residential land cover types, and about 1.4 ha of road.

In increasing the density of development without changing the area designated to residential land cover development, the increase in sub-potable demand in sub-catchment 69 has simply outpaced the increase in harvestable volume arising from the increase in imperviousness and consequently runoff.

3.5. Integrating Cost and Supply Ratio to Assess Harvesting Locations

The supply ratio is one way of assessing the extent to which a stormwater harvesting location is able to satisfy demand, and consequently to select the best harvesting locations. In addition there is a need to also assess for storage location potential (how much space is available and required, and how much the storage will cost) and for supply infrastructure cost. There was not the possibility to undertake detailed storage sizing and space availability assessment as part of this work, nor was there the opportunity to undertake detailed costing work on how stormwater might be distributed from the harvesting and storage location to where it is needed. However, it was possible to measure using simple GIS tools, the maximum distance upstream in a straight line from a sub-catchment pour point (representing the harvesting and storage location) to the edge of the urban (residential) land cover within that sub-catchment. This measurement was taken as an approximation of how far and consequently how much it would cost to distribute harvested stormwater to where it is demanded.

Table 9 shows an ordering of the best sub-catchments in terms of: (i) their supply ratio (taken as the most important criteria); and then (ii) the lowest maximum distance from pour point to the edge of urban residential land cover as a proxy for cost of supply. Median rainfall performance was used.

Table 9. Ordered set of sub-catchments in terms of their suitability for stormwater harvesting under median rainfall (sub-catchments 62 and 63 are excluded as they only contain grass).

Planned Density Development			Increased Density Development		
Pour Point ID	**Supply Ratio Median Rain**	**Max. Dist. to Urban Edge**	**Pour Point ID**	**Supply Ratio Median Rain**	**Max. Dist. to Urban Edge**
77	0.74	680	67	0.72	2,619
70	0.74	776	61	0.72	2,735
80	0.74	842	64	0.65	1,725
83	0.74	894	68	0.64	1,258
86	0.74	1,036	65	0.63	292
76	0.74	1,039	77	0.63	680
69	0.74	1,238	96	0.63	707
88	0.74	1,359	80	0.63	842
67	0.72	2,619	83	0.63	894
73	0.71	1,305	86	0.63	1,036
64	0.69	1,725	76	0.63	1,039
95	0.68	2,271	81	0.63	1,101
79	0.64	1,630	74	0.63	1,166
82	0.64	1,794	87	0.63	1,175
74	0.63	1,166	69	0.63	1,238
66	0.62	1,537	73	0.63	1,305
81	0.61	1,101	97	0.63	1,315
90	0.61	1,510	88	0.63	1,359
96	0.60	707	90	0.63	1,510
87	0.60	1,175	66	0.63	1,537
68	0.60	1,258	79	0.63	1,630
97	0.60	1,315	82	0.63	1,794
61	0.60	2,735	95	0.63	2,271
65	0.55	292	62	0.63	grass only
62	0.55	grass only	63	0.63	grass only

4. DISCUSSION

In the Introduction, four key questions were posed, both for Ripley Valley and more generally for how stormwater harvesting is planned for greenfield urban development areas. These questions will be used to structure the discussion and remainder of the report along with a critical reflection on the use of GIS based runoff modelling for strategic stormwater harvesting assessment.

Which sites offer the highest harvestable volume potential and the closest proximity to sub-potable demand?

To answer this question first one must ask the question whether maximising harvestable volume or maximising supply ratio is the objective. If total volume is the objective, perhaps because the sub-potable demand is non-domestic (e.g. open space irrigation), then the pour points of large sub-catchments which contain high degrees of impervious area and consequently generate both absolutely and proportionally higher runoff will be the best sites for harvesting. Such sub-catchments will either have high density residential or mixed use, or large areas under road or industrial development. Larger sub-catchments with greater degrees of imperviousness will generate more stormwater runoff. Non-domestic demand will likely not be higher in such sub-catchments as the demand is potentially either in another sub-catchment (e.g. open space irrigation downstream) or will be lower as imperviousness increases (e.g. open space water demand will decrease as imperviousness increases within a sub-catchment).

If, however, the sub-potable demand to be satisfied is domestic (laundry, toilet, garden), then in more densely urbanised sub-catchments the demand for stormwater will be higher – more houses, more people, higher demand for water. The higher demand may: either outstrip the increase in stormwater runoff as a consequence of higher imperviousness, as with sub-catchment 69, and deteriorate the supply ratio (see below); or, as with sub-catchment 61, higher stormwater runoff from higher imperviousness might be greater than the higher levels of domestic sub-potable demand. Answering the question about which site is best from a stormwater volumetric perspective therefore requires a knowledge of total urbanised area, the imperviousness of that area and the nature and location of sub-potable demand, which itself may require a knowledge of housing density.

Instead, if maximising the supply ratio is the objective, then harvesting locations are not necessarily large, and indeed may be relatively small catchments. For example, the second highest supply ratio sub-catchment in Ripley Valley under the planned density of development is number 70, a 45 ha sub-catchment, one of the smallest in the development area. Maximising supply ratio will come about not as a consequence of sheer sub-catchment size and harvested volumes, but from achieving a balance between demand and imperviousness (proportion of area urbanised within the sub-catchment). From the Ripley Valley, this can be achieved at either planned or increased development density for individual sub-catchments, but on average over all of the sub-catchments, the supply ratio decreased at the increased development densities. This indicates that the ideal density of development, which drives demand in the case of sub-potable domestic water use and also drives increases in harvestable runoff volume, and sub-potable water demand is lower than 55 dw/ha. Indeed, there were significantly fewer sub-catchments with a supply ratio >0.7 in the increased density urban development scenario. Most had a supply ratio of 0.63.

Further complicating matters is the fact that the sites with the highest supply ratio or the highest harvestable volumes may not be the sites with the lowest distance to supply stormwater from where it is harvested to where it is needed. Looking at the Ripley Valley under the planned development density, four of the highest supply ratio sub-catchments all had their urban land cover less than 1km from the pour point (harvesting location), and were from a range of areas and consequently total harvestable volumes (small – 70 at 45 ha, medium - 77 at 110 ha, 80 at 158 ha, large – 83 at 345 ha). Conversely, in the increased density development scenario, the top two supply ratio sub-catchments had urban areas extending to beyond 2.6 km from the pour point location – sub-catchments 61 (large at 289 ha) and 67 (medium at 116 ha). This indicates that the highest volume sub-catchments may have the highest cost for supply of harvested stormwater to where it is needed.

Should stormwater be harvested in a decentralised manner, with urban runoff collected close to where it arises, or more centrally downstream?

From the Ripley Valley results, there seems to be little compelling evidence to preference a centralised strategy for harvesting over a decentralised strategy. The centralised strategy had essentially the same range of supply ratio values as the decentralised strategy and could come with the additional cost of ecological degradation if additional urban runoff is allowed to pulse into streams following rain events. The decentralised strategy, whilst on average providing essentially the same supply ratio as the centralised strategy, offered significantly better supply ratios for some sub-catchments, depending on the balance between imperviousness, size and sub-potable demand.

What are the differences in harvestable volume and in the extent to which demand can be satisfied across different harvesting site locations and centralisation / decentralisation strategies for collection?

There are significant differences in harvestable volume ranging from just 2 ML/yr (dry rainfall, sub-catchment 96, with an area of 63 ha) to 339 ML/yr (wet rainfall, sub-catchment 61 with an area of 289 ha), and also significant differences in supply ratio from 0.78 (several sub-catchments under wet rain, planned density) to 0.14 (wet rain, sub-catchment 78, area of 49 ha under increased density development). Centralisation as a strategy essentially harvested the sum of all the individual sub-catchments, so there was no overall volumetric difference between the strategies and little supply ratio difference. The centralised strategy had a very slight edge in terms of supply ratio (see Tables 7 and 8).

What does this mean for stormwater harvesting? In practical terms it means that there is ample scope to achieve both high harvested volume and high supply ratios. The extent to which increased housing density is needed to achieve both is not clear as already discussed, and higher levels of housing density (55dw/ha) may actually be counterproductive to securing high supply ratios.

How sensitive to rainfall variation are different harvesting site locations and centralisation / decentralisation strategies for collection?

Three rainfall scenarios were used to model the stormwater runoff for Ripley Valley ranging in annual average rainfall from 840 mm/yr to 951 mm/yr. These values indicate that whilst the Ripley Valley is not arid, it is not abundant in rainfall, and has relatively consistent levels of rain. Volumetrically, under the planned density of development the average annual total of harvested stormwater across all of Ripley Valley varied by just over 13% from the dry rainfall scenario to the wet rainfall. At the increased density of development, the same increase in harvested rainfall was observed across the whole of the Ripley Valley between the dry rainfall and the wet rainfall scenarios. Supply ratios changed by a similar amount - on average over all the sub-catchments they changed by 13.3% from dry to wet rainfall under planned development density, and by 13.8% from dry to wet rainfall under increased development density. As a consequence, it may be necessary to factor in a margin of around 15% to any stormwater harvesting system implemented in the region e.g. design for a yield 15% higher than needed.

Using GIS based runoff modelling for strategic stormwater harvesting assessment

The approach to assessing the harvestable volumes and supply ratios for different harvesting locations employed a mixture of GIS analysis, some stochastic modelling for rainfall generation and spreadsheet-based modelling for runoff. The stochastic modelling is probably conceptually the most challenging element of the method, requiring an understanding of statistical modelling and computation, but the tools are well documented. GIS and spreadsheet skills are widespread across government and consulting firms, making the overall approach, at least in principle, feasible for use without significant investment in training or software.

The nature of the modelling approach was deliberately coarse, to suit initial strategic assessment and screening of options for stormwater harvesting in terms of harvesting location and how location should be decided upon in conjunction with decisions about the nature and density of urban land cover to be developed. Inamdar *et al.* (2013) developed independently a similar method for use in screening potential locations for harvesting stormwater in existing urban areas for use in open space and parkland irrigation. The method they report uses a different way of characterising distance from harvesting location and therefore cost of supply of stormwater, but in principle both approaches use distance as the way of proxying cost. The approach reported here extends the method documented by Inamdar *et al.* (2013) by including rainfall sensitivity testing, and by incorporating development density scenarios. Both approaches could be improved by attending to the following issues:

- Imperviousness and runoff coefficient estimation – understanding how substantial an error is introduced into the results by assuming all areas under the same land-cover have the same runoff behaviour would help determine if improvements are required. Also there is a need to develop standard regionally (climatically and in town planning terms) specific runoff values related to imperviousness.
- Environmental flows – both Inamdar *et al.* (2013) and this report assumed that environmental flows could be determined by means of taking away existing land cover runoff from increased runoff under urbanisation. Investigation to understand whether this is reasonable and the conditions under which more sophisticated methods might be need would help improve runoff calculation.
- Storage, yield and reliability – the method described in this report and by Inamdar *et al.* (2013) use coarse time grained simulation to model runoff. There is a need to go one step further once suitable sites for harvesting are identified based on supply ratio and total volumetric supply, to identify how the harvested water might be stored, and in what size of storage relative to inflows and demand in order to maximise yield and reliability. These calculations might change the set of overall strategically preferred harvesting site locations, so being able to combine both the overall GIS and runoff modelling based prioritisation of potential sites with some simple engineering on storage, yield and reliability might provide a more complete approach to identifying where and how to harvest stormwater.

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