COSTING OF WATER CYCLE INFRASTRUCTURE SAVINGS ARISING FROM WATER SENSITIVE URBAN DESIGN SOURCE CONTROL MEASURES.

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Abstract

Water Sensitive Urban Design (WSUD) source control measures include rainwater tanks, infiltration trenches, detention basins and constructed wetlands used in housing allotments and subdivisions. A case study based on the Lower Hunter region in Australia is used to compare the provision of traditional water supply and WSUD infrastructure. The Lower Hunter has a population of 455,000 people with a growth rate of 0.9%. Average rainfall varies from 800 mm to 1500 mm per year in the region.

Use of rainwater tanks to supplement the water supply network delayed the construction of new water supply headworks infrastructure by up to 34 years. Peak demands on water supply trunk systems were reduced by up to 5%, stormwater discharges from roofs by up to 56% and household mains water demand by up to 55%. The scenario that required all new housing developments to use WSUD source controls including rainwater tanks provided the greatest benefit to the community.

Keywords: rainwater tanks, source control, economics, urban development, water supply

1. Introduction

Urban development and its constructed hydraulic systems cause profound changes to the natural water cycle. The area of impervious surfaces is increased whilst natural watercourses are replaced with hydraulically efficient pipes and channels.

Water demand resulting from urban development is met by importing large volumes of treated water, across large distances and at considerable cost, from neighboring catchments. At the same time similar volumes of stormwater from roofs are discharged unused from urban developments via expensive stormwater systems.

Water Sensitive Urban Development (WSUD) source controls include reuse of rainwater, stormwater and wastewater. Research into WSUD from the urban water cycle management (Andoh and Declerck,1999 and M^c Alister, 1998) perspective shows that significant economic, social and environmental benefits to the community may be derived from more efficient use of water resources and infrastructure . However, a major impediment to the use of the WSUD approach is a perception that it is expensive to implement and it has limited economic benefits.

This study considers the benefits of the use of rainwater stored in tanks to supplement domestic indoor and outdoor water use in the Lower Hunter region, New South Wales, Australia. It describes the development of a simulation of household water demand partly satisfied from rainfall and then shows how this model is included in the simulation of the drought security of the water supply headworks system. The impact on delaying augmentation of the headworks system is examined. A comparative economic analysis is also presented.

2. Demographic Data

The Lower Hunter region has a population of 455,000 people with an overall growth rate of 0.9%. Domestic water demand accounts for approximately 43% of total water use.

The Lower Hunter region spans five local government areas, namely Newcastle, Lake Macquarie, Maitland, Cessnock and Port Stephens. The region has been divided into nine zones to facilitate water supply modeling. The Australian Bureau of Statistics (1996) provides annual population growth and annual dwelling growth for these zones.

The dwellings in the five local government areas were categorised as either a detached house or a housing unit (Table 1). The housing unit category includes flats and apartments. All dwellings in the five areas were also categorised by number of occupants (Table 1). This enabled water use modeling for different numbers of occupants and different dwelling types.

3.0 Simulation of Household Water Use

The mains water demand of a dwelling that also uses water from rainwater tanks will depend on local climatic conditions, water use patterns, dwelling size and the number of occupants. Five housing (H1-H5) and two unit cluster scenarios (C1 and C2) (Table 2) were considered for each zone. Roof areas were assumed to increase with the number of occupants and tank sizes were estimated as a function of available land area in typical housing allotments.

Table 1. Dwelling categories

Area	Houses (%)	Units (%)	Occupants per dwelling by area population (%)				
			1	2	3	4	5+
Newcastle	91.5	8.5	20	33.8	16.9	18.1	11.1
Cessnock	95.6	4.4	21.8	31.6	17	17.5	12.1
Port Stephens	95.6	4.4	19.9	35.9	15.6	17.1	11.5
Maitland	95.6	4.4	19.9	30.2	17.9	19.5	12.6
Lake Macquarie	91.5	8.5	20	33.8	16.9	18.1	11.1

Table 2. Housing scenarios with roof areas

Item	Occupants	Dwellings	Roof area (m^2)	Tank size (kL)
H1	1	1	100	10
H2	2	1	135	10
H3	3	1	175	10
H4	4	1	215	10
H5	5+	1	250	10
C1	11	4	415	20
C2	24	9	600	30

Two water use options were evaluated for each dwelling. The first option used mains water supply. The second option that was motivated by the favourable water quality results at the Figtree Place project (Coombes, Kuczera and al., 2000), used rainwater collected from roofs and stored in tanks for outdoor, hot water and toilet flushing uses. Mains water supply is used to supplement the rainwater supply and for other in-house uses.

In-house and outdoor water use for each of the zones has been based on data monitored by Hunter Water Corporation (HWC) (Berghout, personal communication, 1999). The data consist of in-house and outdoor water use monitored in over 130 houses located in the 5 zones of Table 1 during the period 1986 to 1998.

3.1 Outdoor water demand simulation

Outdoor water demand is a large and highly variable portion of total household demand in the region (8.3% - 53.4% of total water use). Traditional models (for example Dandy, 1986; Kuczera and Ng, 1992), that depend on variables such as soil moisture store, number of occupants, garden area, rainfall and evaporation, are poor predictors of outdoor water use with R^2 values ranging from 0.3 to 0.4. A more reliable simulation of outdoor demand was required.

Examination of HWC data revealed that outdoor demand could be best simulated using a behavioural probabilistic model that accounted for daily rainfall, days without rainfall, daily maximum temperature, daily average rainfall and monthly average daily demand. A new outdoor demand model was created (Coombes, Kuczera and al, 2000b) that produced improved predictions with R^2 varying from 0.51 to 0.68 for the different zones.

The model was calibrated to HWC outdoor data from each of the 5 zones in Table 1 to using SCE-UA global optimisation methods (Duan, Sorooshian and al, 1994). An example of calibration to outdoor demand data for the Mayfield area of the Newcastle zone is shown in Figure 1. The outdoor demand model was able to reliably simulate the strong seasonal demand trends experienced in the

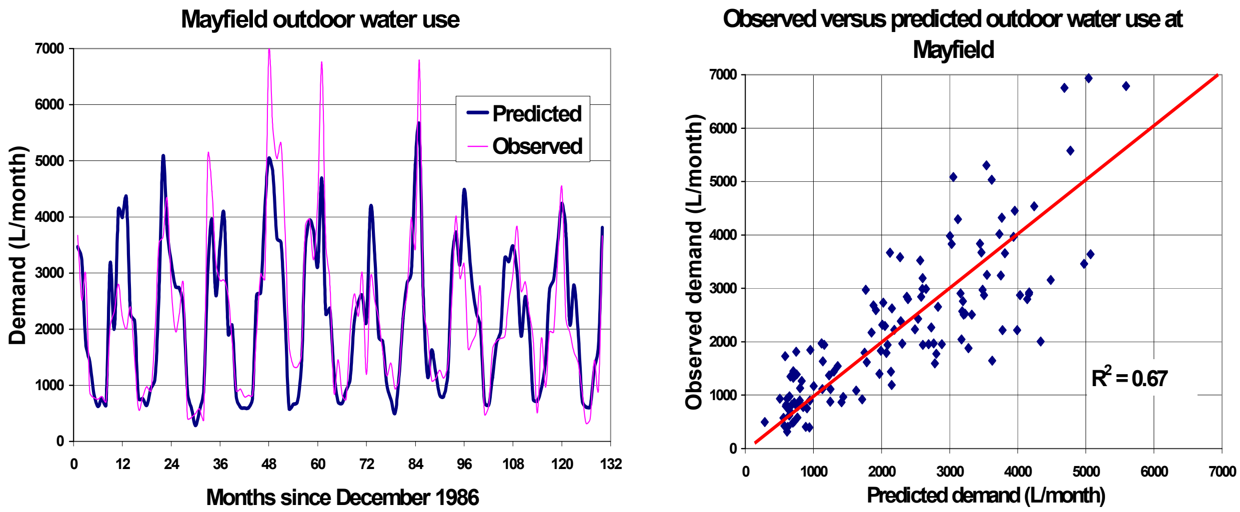

Figure 1. Observed and predicted outdoor water use at Mayfield

Mayfield area. Strong seasonal outdoor demand trends are typical for all the zones in the Lower Hunter region.

3.2 In-house water demand simulation

Data from HWC and from the Figtree Place development (Coombes, Kuczera and al., 2000b) was used to develop in-house water use profiles for the different zones of Table 1. The HWC data was used to define monthly average daily in-house demand for households with 1, 2, 3, 4 and 5+ residents. The in-house demand data varied from month to month. The Figtree Place data was used to define the portion of the monthly average daily in-house demand related to hot water and toilet use.

3.3 Household water use model

A household water use model (Figure 2) was developed to enable comparison between households that use mains water and those that supplement mains water supply with rainwater stored in tanks. Rainfall captured on roofs is directed via a first flush separation device to a rainwater tank that supplies hot water, toilet flushing and outdoor water use. The rainwater tank overflows to the street drainage system. Mains water supplies all other in-house water uses and supplements the rainwater supply when water levels are low in the tank.

The model was used to continuously simulate main water demand using pluviograph and temperature data over the 62-year period, 1932 to 1994, which coincides with the period for which streamflow and rainfall data were available from HWC's headworks system. The model provided household water use data that can be compiled to create mains water demand scenarios for the housing and cluster scenarios in the 5 zones of Table 1.

Table 3 summarises the impact of rainwater tanks. Very significant reductions in mains water use and stormwater discharge volumes are noted. However, reductions in peak mains water use are minimal, primarily because peaks mains water use occurs during hot, dry spells when irrigation use is high and rainwater tanks have been depleted.

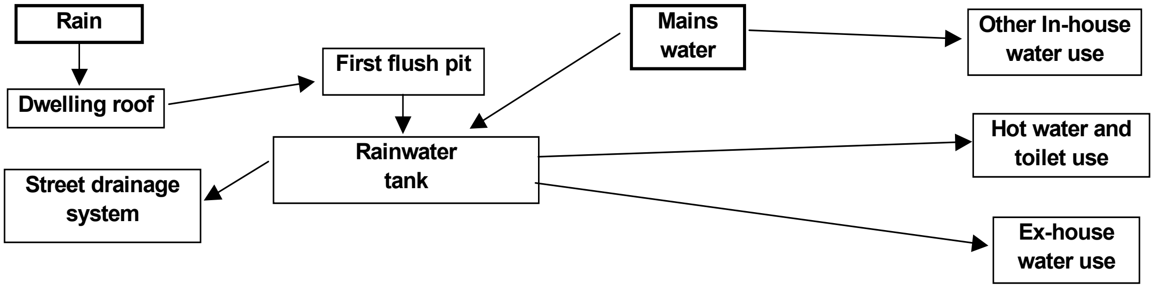

Figure 2. Household water demand model

Table 3. Impact of rainwater use on household water demand and stormwater discharge

Zone	Reduction (%)			Ave. rainfall (mm/yr)	Temperature	
	Mains water use	Stormwater discharge	Peak mains water use		Min.	Max
Inner SE Newcastle	50.3	52.1	1.69	932	9	42
Hamilton Mayfield	54.3	43.1	4.61	932	9	42
Lambton Jesmond	54.6	38.6	4.29	932	9	42
NW Wallsend	44.7	55.4	2.83	932	9	42
Lake Macquarie East	50.4	50.8	4.13	1013	9	42
Lake Macquarie West	50.0	46.6	1.41	1182	9	42
Maitland	40.9	52.9	0.14	901	9	48
Cessnock	40.3	59.0	0.04	754	9	48
Port Stephens	49.1	45.1	0.35	1257	9	45

3.4 Compiling regional demand

The household water use model provided 62 years of daily demand data for the dwelling scenarios of Table 2 in each of the zones in Table 1. Domestic demand for each zone was compiled by multiplying predicted dwelling demand by population data and dwelling mix (Table 2). One thousand replicates of monthly water use for each dwelling scenario were generated for the years 2000 to 2099 to be used with synthetically generated monthly streamflow and rainfall in the headworks system.

To be consistent with the synthetically generated headworks data, it was important to preserve the spatial correlation between rainfall in the catchments and in the demand zones. Also it was important to preserve the negative correlation between monthly rainfall and monthly domestic demand. This was achieved by correlating monthly mains water use totals against zonal monthly rainfall totals. These correlations were typically weak for each zone, ranging from -0.2 to -0.3. Figure 3 presents a time series plot of monthly household demand residuals for the Mayfield area with rainwater tanks installed. The Figure demonstrates that the use of a correlation between monthly mains water demand and monthly zonal rainfall does not produce any significant systematic under or over-estimation of actual demand.

The simple model of commercial and industrial water use developed by Kuczera and Ng (1992) was modified for this study to preserve the ratio between domestic and total water use for the Lower Hunter region. This model accounts for about 57% of total main water use including unaccounted-for consumption and losses. It is used identically in all the demand scenarios reported below.

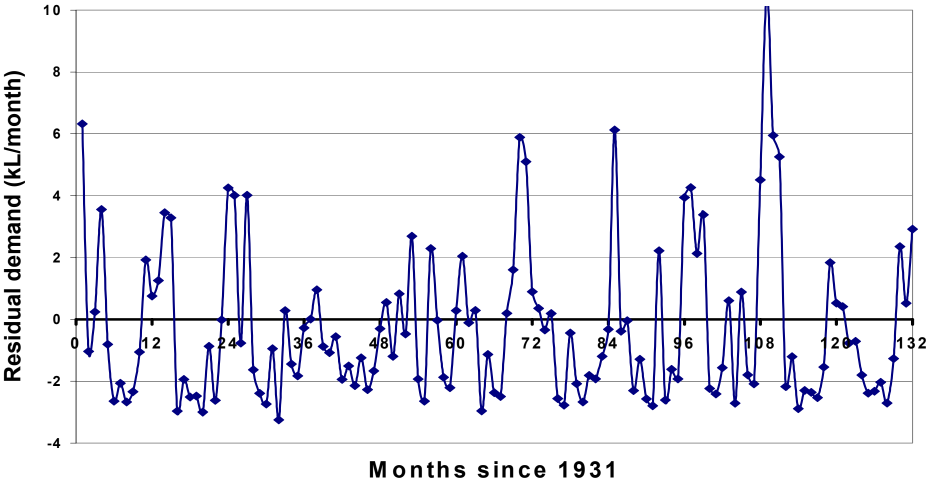

Figure 3. Time series of residual household mains water demand for a house with a rainwater tank

4. Water Supply Headworks Modeling

The drought security of the Lower Hunter water supply headworks system was assessed using WATHNET (Kuczera, 1992) for different household demand scenarios. WATHNET is a suite of programs for generalised water supply headworks simulation using network linear programming.

4.1 Description of headworks system

A schematic of the Lower Hunter region water supply headworks system is presented in Figure 4. The system presently consists of two major surface reservoirs that harvest water from the Williams River catchment and a sub-surface reservoir, the Tomago Sand Beds unconfined aquifer.

Chichester reservoir has a capacity of 21500 megalitres (ML). Current environmental flow constraints for the Chichester River require all flows below 14 ML/day to be released from the reservoir. A gravity pipeline delivers up to 95 ML/day to the region via the Dungog treatment plant.

Seaham diversion weir is used to divert water from the Williams River into Grahamstown reservoir via Ballickera pumping station and canal. The pumping station has a maximum capacity of 1330 ML/day. At low river flows water quality and environmental constraints limit pumping from Seaham weir. The peaky nature of high flows in the Williams River also limits the volume of water that can be pumped from Seaham weir.

The final stage of Grahamstown reservoir with a capacity of 198200 ML has been used in the study. It is supplied with water via diversions from Seaham weir and local runoff from a 99 km^2 catchment. Water from the reservoir is distributed to the region via the Tomago treatment plant.

Tomago Sand Beds is an extensive unconfined aquifer with a storage capacity of approximately 232800 ML. Water from the Sand Beds is used to supplement water from the Williams River system. When the combined capacity of Chichester and Grahamstown reservoirs falls below 80% up to 100 ML per day is drawn from the Tomago Sand Beds.

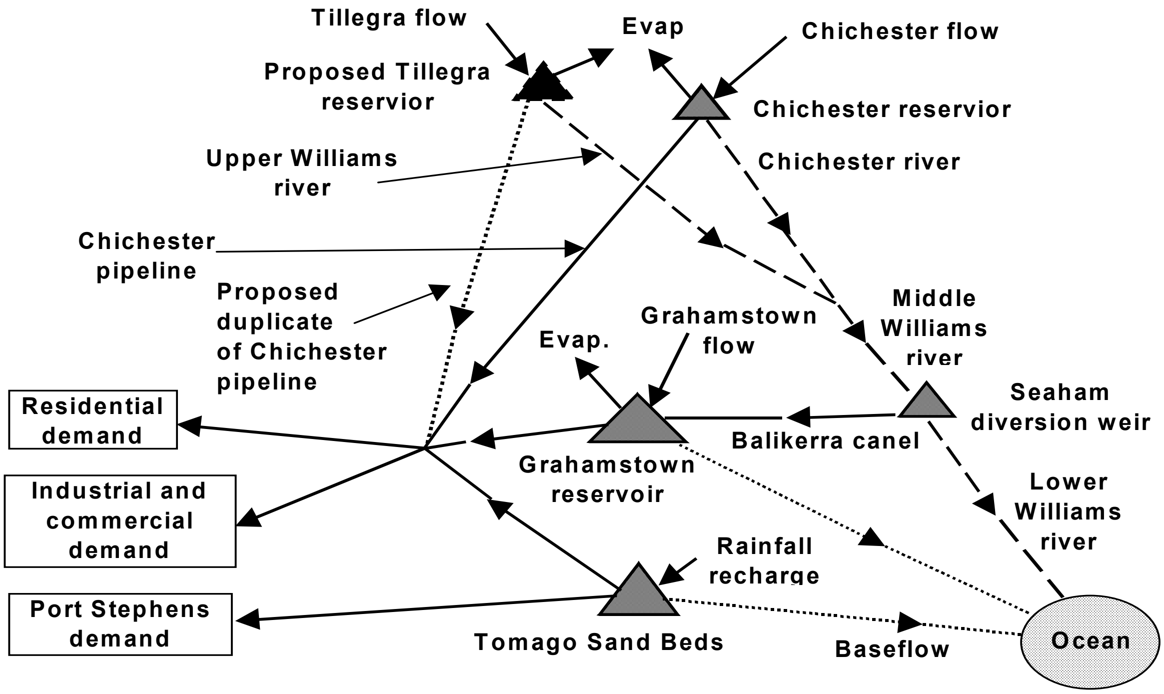

Figure 4. Schematic of Lower Hunter water supply headworks system

4.2 Restriction policy and augmentation strategy

In this study, reliability is defined as the probability that water restrictions will not be imposed in a particular year. Restrictions on demand are triggered when the combined storage of Chichester and Grahamstown reservoirs falls below 60%. The water restriction policy is summarised in Table 4.

Table 4. HWC water restriction policy

Storage (%)	Demand reduction (%)
60	5
50	10
40	15
30	25

When the reliability of the system falls below 90% current policy requires that the system be augmented. In this study following the recommendation of Hunter District Water Board (1982), augmentation consists of construction of a reservoir on the Williams River at Tillegra. The Tillegra reservoir (Figure 4) is to be constructed in two stages..The augmentation strategy is:

1/. Stage 1 of Tillegra reservoir with a capacity of 240000 ML combined with installation of pumps to increase the hydraulic capacity of Chichester Pipeline at a cost of $103.7M.

2/. Construction of a water supply pipeline parallel to the Chichester pipeline at a cost of $101.7M

5. Results

A number of demand scenarios were simulated using 1000 100-year replicates of future rainfall and streamflow. The base scenario considers the status quo, namely:

- Provision of traditional stormwater systems to areas undergoing urbanisation; and
- Provision of additional mains water supply by further regulation of river systems.

Alternative scenarios consider several WSUD approaches that include the use of rainwater tanks. Seven alternative scenarios are considered: In the growth scenario (denoted as G), WSUD source controls (including rainwater tanks, infiltration and detention strategies) are installed for all new housing. In the other six scenarios (denoted as G +0.25% to G +3%), source controls are installed for all new housing and existing housing is retrofitted with water tanks at rates varying from 0.25% to 3% per year until 90% of dwellings have a water tank.

5.1 Impact on mains demand and augmentation timing

Table 5 summarises the timing of the water supply augmentation required to maintain reliability at or above 90% for each of the demand scenarios. Figure 5 displays the growth in annual mains water demand for selected demand scenarios. The symbol NR indicates augmentation was not required.

Table 5. Years in which augmentation of water supply is required

Augment stage	Augmentation required for scenario (year)							
	Base	Growth	G+0.25%	G+0.5%	G+0.75%	G+0.9%	G+2%	G+3%
1	2041	2049	2050	2055	2064	2067	2075	2075
2	NR	NR	NR	NR	NR	NR	NR	NR

The results demonstrate the very significant reduction in mains water demand that can be achieved by use of rainwater tanks to supplement mains water supply for outdoor, toilet flushing and hot water use in the Lower Hunter region. By the year 2032 the G+3% scenario has reduced annual mains consumption from 95,800 ML to 77,700 ML, a 19% reduction in demand on the headworks system. It needs to be stressed that domestic water demand is only about 43% of total water demand for the region. In urban areas with a similar climate but higher domestic demand component, larger savings in mains water demand would be expected.

The introduction of rainwater tanks delays augmentation from 8 to 34 years depending on the rate of rainwater tank adoption. For scenarios G+0.75% to G+3% reliability of the water supply headworks system remains at 99% after augmentation stage 1. Population growth is expected to decline due to depletion of land available for development during that period. Therefore the need for further augmentation of the system in the twenty-second century is eliminated.

5.2 Economic comparison of WSUD and traditional approaches

The WSUD approach to new urban development is commonly believed to be more expensive than traditional approaches. Although costs of the two approaches have not been compared, this "common-sense" belief is an impediment to implementation of WSUD. Accordingly, this study compares the economic efficiency of the WSUD and traditional base scenarios using the methods of annual and present equivalence (Smith, 1979). All costs or benefits considered are in year 2000 dollars.

Although little information is available about the cost of WSUD, this study has used information from demonstration projects (Figtree Place and Maryville developments), published studies and desktop analysis to estimate costs. These sources of information are briefly discussed:

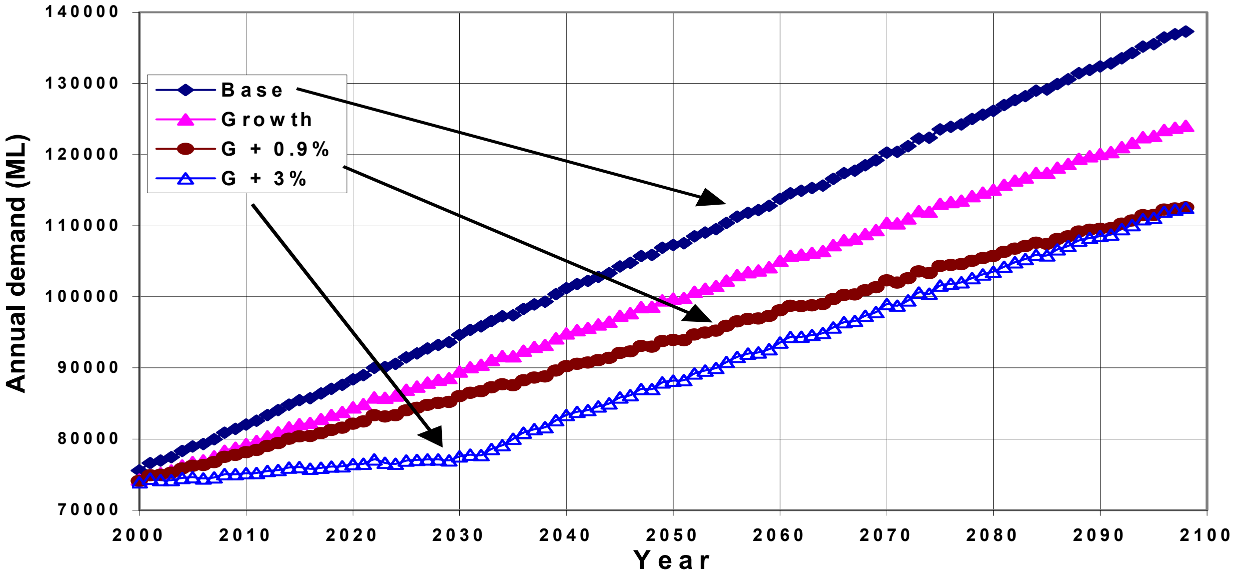

Figure 5. Mains water demand with different levels of rainwater tank use

1) **Figtree Place:** Figtree Place is a water sensitive urban redevelopment consisting of 27 residential) units located in Hamilton, an inner suburb of Newcastle, NSW, Australia. The site uses rainwater tanks, infiltration trenches and a central basin where cleansed stormwater enters an unconfined aquifer for water retention and retrieval. The WSUD elements of Figtree Place resulted in a saving of $25,900 or 1% of construction cost(Coombes, Kuczera and al, 2000a). This equates to a saving of $959 per dwelling in construction costs.

2) **Greenfield subdivisions:** A comparison between traditional and WSUD approaches for large allotment subdivision (Coombes and Kuczera, 2000) in Newcastle, Australia has revealed that the WSUD approach resulted in a 53% ($23,300 per dwelling) saving in construction costs and is expected to considerably reduce environmental impacts. The WSUD approach included rainwater tanks, contour banks, retention trenches and vegetated filter strips. This result is consistent with the cost savings (25% to 80%) from use of source controls reported by Andoh and Declerck (1999). However M^{c}Alister (1998) found that the development costs of WSUD and traditional approaches to an urban development in Brisbane, Australia were similar, although the WSUD approach yielded significantly improved environmental impacts that result from reduced stormwater discharges and water conservation.

3) **Maryville retrofit development:** An existing house in Maryville, Australia with a roof area of 125 m^2 and allotment area of 265 m^2 was fitted with a rainwater tank and a retention trench. Rainwater from the house roof is collected in the tank and used to supply outdoor, toilet and hot water uses via a small pump. If the water level in the rainwater tank is low (see Figure 2) it is filled to minimum level from the mains water supply to ensure continuity of supply. Overflow from the rainwater tank is directed to the retention trench that allows infiltration into the soil and overflows to the street drainage system. The rainwater tank, pump and retention trench system cost $1,500 to install.

5.3 Comparative results

In the annual equivalence analysis each scenario starts in year 2000 with $17M. Each year expenses are deducted, income is added and interest is earned on the balance. The following assumptions are used:

- Real interest rate = Commonwealth bonds interest – consumer price index = 4.78%;
- Maintenance/replacement of the rainwater tank and retention system costs $73.30 per year;
- WSUD in new development areas results in a saving, conservatively set at $959 per dwelling;
- Cost to install a rainwater tank and retention system is $1500 per house; and
- A kilolitre of mains water costs $0.92.

The analysis considers comparative costs and benefits using the base scenario as the reference. For the base scenario, the net benefit in year t is

$$NB_t = i\,(Bal_{t-1} - augCost_t) \qquad (1)$$

where i is the real interest rate, Bal_{t-1} is the balance of the initial $17M investment at the end of year t-1, $augCost_t$ is the augmentation cost (if any) in year t. For the other scenarios, the net benefit in year t is

$$NB_t = i\,(Bal_{t-1} - augCost_t - conCost_t - mainCost_t + waterSav_t + savDev_t) \qquad (2)$$

where for year t $conCost_t$ and $mainCost_t$ are the construction and maintenance costs for the rainwater tank and retention system, $waterSav_t$ is the savings in foregone mains water consumption, and $savDev_t$ is the saving in new stormwater infrastructure from using WSUD.

Figure 6 presents a time series of Bal_t for the different scenarios. Table 6 presents the results of the present equivalence analysis. The present equivalent is the capital investment required in year 2000 to finance the scenario over the next 100 years. The present equivalence analysis (Table 6) reveals that for the base, G+2% and G+3% scenarios capital investment is required to ensure viability of the strategy. However for the scenarios growth to G+0.9% capital investment is not required and additional funds are generated.

Table 6. Present equivalence results for the water supply scenarios

Scenario	Investment ($M)
Base	17
Growth	-50
G+ 0.25%	-33
G + 0.5%	-23
G + 0.75%	-13
G + 0.9%	-6
G + 2%	62
G + 3%	102

The results show that scenarios using installation rates of greater than 0.9% per year of rainwater tanks to existing dwellings and to all new dwellings were not financially viable when compared to the base scenario. However, scenarios using installation rates of up to 0.9% per year provide greater benefits to the community than the traditional water supply option.

Another perspective on the results can be obtained by considering the G+0.9% scenario. The G+0.9% scenario enables a delay of up to 26 years in the construction of new headworks infrastructure and eliminates the need for a second augmentation of the system by reducing regional annual mains water demand by up to 24700 ML. The benefit of this reprieve to the environment has not been quantified but arguably would be very significant.

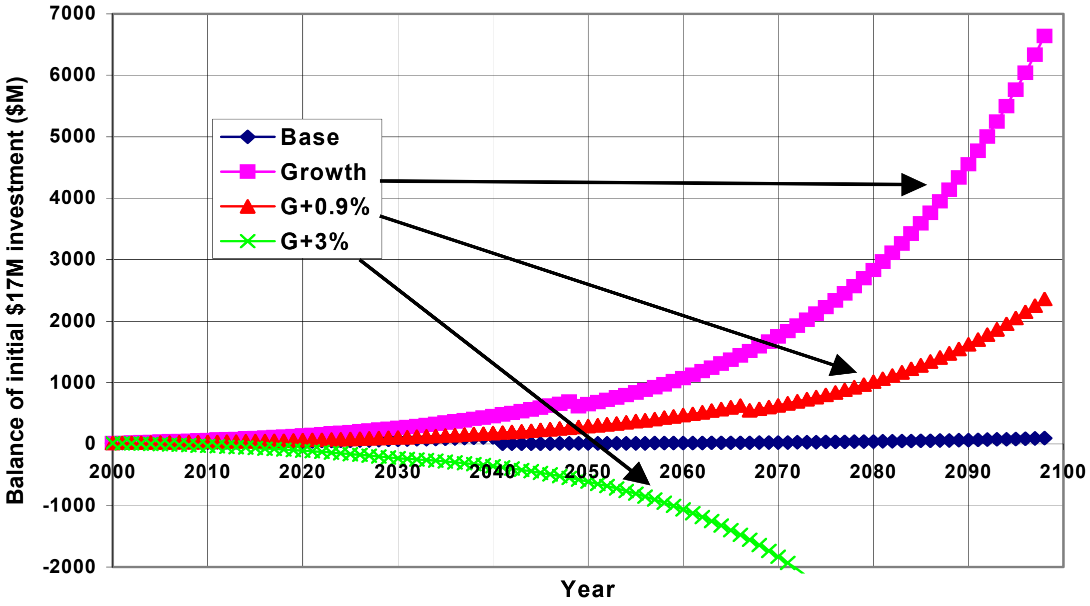

Figure 6. Annual equivalence for the different demand scenarios

6. Conclusions

The benefits of WSUD source control approaches arise from reduced mains water use, reduced stormwater infrastructure and improved environmental performance. A case study for the Lower Hunter region demonstrates that the use of rainwater tanks used to supply outdoor, hot water and toilet flushing demand can delay construction of new water supply headworks infrastructure by up to 34 years and reduce annual regional water demand by up to 24,700 ML.

In addition, the case study demonstrates that use of WSUD source controls including rainwater tanks in new urban developments offers the economically most efficient infrastructure solution. The use of WSUD source controls for new developments and the installation of rainwater tanks to existing housing at rates up to 0.9% per annum is economically more efficient than the provision of traditional water supply infrastructure.

The use of WSUD source controls for new developments and the installation of rainwater tanks to existing housing at rates of 0.75% and 0.9% per annum will also eliminate the need for provision of additional water supply headworks infrastructure after construction of Tillegra reservoir.

However, these conclusions need to be tempered by the limitations of the study. This study has not valued the environmental benefit associated with delaying the construction of dams to augment water supply. Moreover, the construction and lifecycle costs of WSUD approaches have only been assessed approximately, albeit conservatively. Therefore, the benefits of WSUD source control approaches have most likely been understated. Current work is directed at addressing these limitations.

7. Acknowledgment

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