Stormwater Harvesting and Water Sensitive Urban Design Detention: A Compatibility Analysis

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ABSTRACT

Harvesting stormwater from urban catchments provides a supplementary water resource and, due to the physical abstraction of polluted water, also leads to environmental benefits. These benefits include the reduction of frequent ecosystem disturbance during small storms and less waterway erosion; hydrological impacts which are currently addressed by WSUD guidelines for stormwater detention. Although WSUD detention and stormwater harvesting share the same store-release behaviour, they have a very different underlying basis to their design and operation. This paper explores the level of compatibility between these two systems and hence the potential for their integration. It was found by water balance analysis that the harvesting storage required to maximise most yields are similar to the recommended storage volume for detention. This analysis was performed for a temperate-climate location in South East Queensland under historically low rainfalls. Environmental benefits associated with runoff quantity and pollutant load reductions are highest when the capture storage is rapidly emptied after storms.

KEYWORDS

Water Sensitive Urban Design (WSUD); stormwater detention; stormwater harvesting; water yield

INTRODUCTION

The hydrological effects of urbanisation are well known and include increased frequency and magnitude of runoff and diffuse-source pollution generated during storms. These effects lead to waterway degradation by erosion and deteriorating water quality. Water Sensitive Urban Design aims to mitigate these impacts and a range of WSUD measures (including grass swales, bioretention devices and constructed wetlands) are available to address both runoff quantity and quality issues. A WSUD approach aims to reduce stormwater flows and remove pollutants prior to discharge to the environment.

Stormwater harvesting for reuse is rapidly emerging as a means of supplementing urban water supplies. The capture or diversion, storage and treatment of stormwater offer the potential to utilise an environmentally damaging discharge. Treated stormwater is currently used for mainly non-potable demands such as open space irrigation and toilet flushing (Hatt et al., 2006). As both flow reduction (due to the physical extraction of stormwater from the urban area) and pollutant removal (to achieve end-use water quality standards) are involved, stormwater harvesting has outcomes that share the aims of WSUD. Previous studies have recognised this overlap and have quantified the potential WSUD benefits of various stormwater harvesting scenarios (Mitchell, et al 2007; Fletcher, et al 2007).

In addition to overlapping objectives, stormwater harvesting also has a similar functionality to some WSUD measures. Stormwater harvesting requires the controlled release of water from storage, as is the case for WSUD stormwater detention installed to attenuate peak stormwater flows. Although both are reliant on a store-release strategy, the design basis for stormwater harvesting differs to that for WSUD detention.

Stormwater is an intermittent resource governed by rainfall, thus comparatively large storages are needed to consistently yield a supply at a high reliability (Apostolidis and Hutton, 2006). The impracticality of providing stormwater storage facilities within urban areas having limited available space is often given as a reason for not utilising stormwater. WSUD detention also requires water stores that are needed to be housed within the catchment and consequently share the same space constraint as stormwater harvesting. Given this constraint, stormwater detention and harvesting should be planned in an integrated way so overall landtake for storage purposes can be optimised.

The objective of this paper is to assess the compatibility of stormwater harvesting with WSUD detention. Two factors will be considered in detail: the size of the water store needed to harvest stormwater and the rate of extraction from storage. The sizing and operation of stormwater harvesting storage to achieve both water supply and environmental outcomes are investigated. The paper has the following structure to document the outcomes of the compatibility assessment: 1) a basic stormwater harvesting scheme and associated yield and environmental performance indicators are described, 2) a water balance and pollutant load analysis was conducted for a hypothetical stormwater harvesting scheme servicing a 50ha residential catchment located in Toowoomba, Queensland, 3) the results of the predictive analyses are discussed, and 4) conclusions drawn.

BASIC STORMWATER HARVESTING SCHEME AND PERFORMANCE INDICATORS

Description of SHS under analysis

Figure 1 shows a schematic of the simplified type of stormwater harvesting scheme (SHS) under analysis. As described in Brodie (2008), the storage of stormwater in a SHS can be conceptualised as having the prime functions of initial capture or harvesting of stormwater (Capture Store) and flow balancing to meet the demands of the urban end use (Balance Store). In this paper, these two stores are separated and are referred to as a Dual Storage system. Dual Storage SHS are recognisable in stormwater harvesting in scenarios involving the diversion of raw stormwater into a dedicated pond or tank; this harvested water is then extracted, treated and then detained in a ‘clean water’ balancing storage prior to distribution to the end user. Aquifer storage and recovery is a large-scale example of a Dual Storage SHS.

Alternatively, Single Storage SHSs are designed to have flow capture and balancing integrated within the one store. A rainwater tank which collects roof water and is directly plumbed for household use is an example. Previous research has focused on the multiple benefits of Single Storage SHSs that have a storage release fixed by a water demand pattern (e.g. Mitchell et al, 2007).

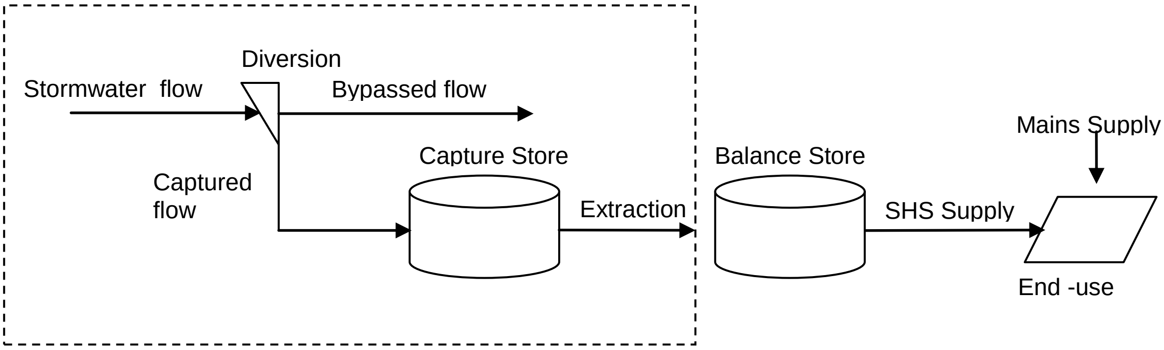


Figure 1. Layout of Dual Storage SHS. Treatment elements are not shown for clarity.

As flow balancing storage is engineered in most urban water supply systems, this paper will investigate the water supply and environmental benefits of a Dual Storage SHS. The stormwater capture and associated extraction from storage (as indicated by the dashed box in Figure 1) has a marked similarity to recommended WSUD practices to detain and release runoff from urban development. For example, WSUD guidelines for South East Queensland (OUM, 2008) suggest that, depending on development density, the first 10 to 15 mm of impervious surface runoff should be detained in storage. Emptying of the storage is required within 24 hours to ensure full capture of the design runoff volume in subsequent storms.

SHS yield and storage performance indicators

The performance of the basic SHS was assessed against indicators of the water volume able to be extracted from the Capture Store and hence the 'yield' available for urban supply purposes. A range of performance measures associated with water supply storages are compiled in Table 1. The time-based and volume-based indicators exist in the literature in various forms (e.g. McMahon et al, 2006) and have been drawn from Storage-Reliability-Yield (SRY) analysis where reservoirs are assumed to be directly connected to the end-use demand and act as a Single Storage system. As the hydrological behaviour of the Capture Store is not directly connected to the end use demand, it was found that modified indicators of water yield are needed (Brodie, 2010); these are the frequency-based indicators shown in Table 1 and described in more detail later in this paper. Indicators to quantify the hydrological behaviour of the Capture Store itself are also defined (P_0 and SET).

Table 1 Yield and storage performance indicators used in SHS assessment

Type	Indicators	Units	Description
Time-based	Target Yield Y_T Time-based Reliability R_T	kL/yr %	Y_T can be supplied by the storage outflow for R_T % of time
Volume-based	Expected Yield Y_E	kL/yr	Y_E is the storage outflow volume averaged over a specified time period[1]
Frequency-based	Frequency-based Yield Y_F Frequency-based Reliability R_F	kL/hr→kL/yr %	R_F is the frequency of occurrence when the storage outflow equals or exceeds Y_F[2]
Storage behaviour	Storage emptying time SET	days	Elapsed time to empty storage from full capacity
	Probability of empty storage P_0	%	% of time that the storage is empty

1. Typically, an annual average is used (time period = yearly)
2. Yield volume is aggregated over various time periods from hourly to yearly, as required

SHS environmental performance indicators

The performance of the simplified SHS under various operational scenarios was also assessed against selected environmental indicators. The indicators are given in Table 2 and the first two are compatible with South East Queensland WSUD objectives (OUM, 2008). The peak flow indicator Q1 is intended to represent the potential geomorphic impact of urban flows in worsening the channel bed and bank erosion of downstream waterways. Average Annual TSS load is selected as an indicator of stormwater-related pollution. For South East Queensland, the minimum target for a developed urban area is at least an 80% reduction of the TSS load (QDERM, 2009). A third indicator, Average Annual Runoff, was added to provide a broad indication of the expected runoff reduction associated with stormwater harvesting. AAR was included in Fletcher et al (2007) in their investigation of the environmental effects of stormwater harvesting in Melbourne and Brisbane. Zero baseflow conditions were assumed in the analysis.

Table 2. Environmental indicators used in SHS assessment

Category	Indicator	Unit
Peak flow	Peak 1-year average recurrence interval discharge (Q1)	m^3/s
Pollutant load	Average Annual Total Suspended Solids Load (TSS)	kg/ha/yr
Runoff volume	Average annual runoff (AAR)	ML/yr

ANALYSIS OF A SUBDIVISION-SCALE STORMWATER HARVESTING SCENARIO

Description of SHS scenario

A water balance analysis was performed for a hypothetical 50ha urban residential catchment located in Toowoomba. The simulation period covered a historical rainfall period from 2000 to 2006. This rainfall sequence is the driest seven-year period within the Toowoomba record dating from 1887. Annual rainfalls ranged from 531 to 782mm (mean 636mm) with dry periods up to 62 days. Further statistics of the selected rainfall sequence is provided by Brodie (2010).

The suburban residential catchment was assumed to consist of 70% allotments (density 12 lots/ha), 20% road corridor and 10% public open space. Fraction impervious is 0.56, within the expected range of 0.45 to 0.85 for low-density detached housing subdivisions in Queensland (QNRW, 2007). It is assumed that there are no WSUD measures including rainwater tanks within the catchment that potentially reduce stormwater volumes.

Stormwater harvesting was assumed to occur at the catchment outlet, facilitated by an offstream open Capture Storage consistent with Figure 1. The storage capacity used in the analysis ranged from 1400 to 5600 kL, corresponding to 5 to 20mm of impervious surface runoff from the residential catchment. Evaporation loss from storage was based on daily data provided by the SILO Data Drill service (QNRW, 2009). Shallow lake evaporation estimates are based on Morton (1983). Average annual evaporation for Toowoomba for the 2000 to 2006 period is 1500mm/yr.

Water balance and pollutant load model

An EXCEL spreadsheet was used to estimate the water flows associated with various stormwater harvesting scenarios. The behaviour of the Capture Store was modelled at an hourly timestep using historical rainfalls over a sequence of several years. The following water balance relationship was used in the computations:

$$SV_t = SV_{t-1} + I_t - E_t - B_t - O_t \qquad (1)$$

where SV_t is the volume in storage (kL) at the end of the current timestep, SV_{t-1} is the volume in storage (kL) at the end of the previous timestep, I_t is the stormwater inflow volume (kL), B_t is the stormwater volume in excess of storage capacity that bypasses and is not captured by the SHS, E_t is the loss due to evaporation (kL) and O_t is the storage outflow (kL) equivalent to the extraction rate ER when water is available in storage. O_t is zero when storage is empty. The 'yield after spill' approach (Jenkins et al, 1978) is used in the water balance analysis. At each timestep, any runoff volume in excess of storage capacity (C, kL) is assigned as bypass, followed by an extraction of stored volume corresponding to the nominated ER.

The TSS loads generated from the urban area draining to the SHS and the amounts of TSS removed with harvested stormwater were taken into account. TSS loads were derived from event mean concentrations (EMCs) estimated using the Rainfall Depth Adjusted EMC (or RDAE) method proposed by Brodie and Porter (2007). The RDAE method allows for the generally observed trend of decreasing EMC with increasing rainfall depth and provides better TSS estimates than adopting a constant EMC across all storms.

Frequency-based yields and selection of an appropriate storage capacity

Frequency-based yields used to evaluate Dual Storage SHSs are described by Brodie (2010). These have been adapted from the more conventional SRY metrics to fully evaluate Capture Storage operation. It may be appropriate to maximise harvesting efficiency by quickly draining the Capture Store after a storm in readiness for the onset of the next event. This means the store is often empty (high P_0) and hence the time-based reliability R_T is low. However, this strategy can harvest significant volumes of stormwater when aggregated over a sufficiently long time period (e.g a year). Providing adequate Balance Storage is available, this strategy may be a viable option. Time-based yield analysis is unable to provide the level of operational information needed to assess this type of option.

Yield and reliability are considered to be interdependent variables, such that for a given frequency-based yield Y_F, the corresponding reliability R_F can be calculated from Equation 2:

$$R_F(Y_F) = \frac{N_{\geq Y_F}}{N_{TP}} \times 100 \qquad (2)$$

where Y_F = frequency-based yield (kL/period) depending on time period TP=hour, day, week, month or year. $R_F(Y_F)$ = reliability (%) for a given yield Y_F. $N_{\geq YF}$ = number of time periods in the simulation with O_{TP} values greater than or equal to yield Y_F, where O_{TP} are the aggregated outflows corresponding to time period TP. N_{TP} = total number of time periods in the simulation.

Frequency-based yields were determined on a daily, monthly and yearly basis (i.e. Daily Y_F, Monthly Y_F and Yearly Y_F estimates were made). A daily outflow volume timeseries from the Capture Store was computed based on adding the predicted hourly flows for each day. Timeseries of monthly and yearly outflow volumes were derived in the same way. The yield for each time period was iteratively determined; a trial value of yield volume was assumed, the number of occasions when this volume was equalled or exceeded was counted ($N_{\geq Y_F}$) and if the calculated reliability from Equation 2 was different to the adopted R_F (in this case, 80%), then an adjusted yield was re-trialled until a match was achieved.

Frequency-based yields were estimated for various extraction rates for each of the Capture Store capacity values within the adopted range. This produced a set of yield curves for each nominated capacity and an example for a 4200kL capacity is provided as Figure 2. Yields reach a peak for daily and monthly time periods and then reduce as ER increases. Maximum yield conditions were selected based on the plotted data maxima and are given in Table 3. In the case of the yearly yield, the yield increases asymptotically with ER. To account for marginal increase in yield (i.e. a diminishing return) with higher ER, an extraction rate corresponding to 80% of the asymptotic yield was selected (marked as ◊, Figure 2).

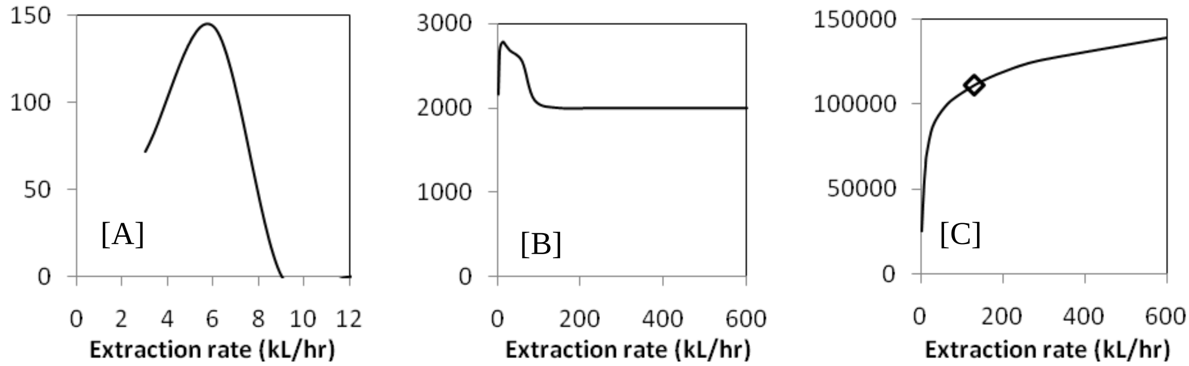
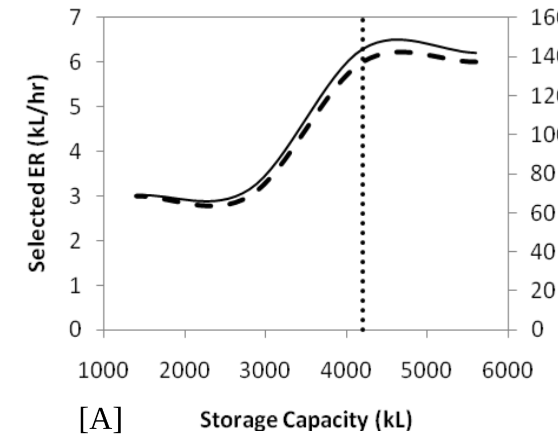


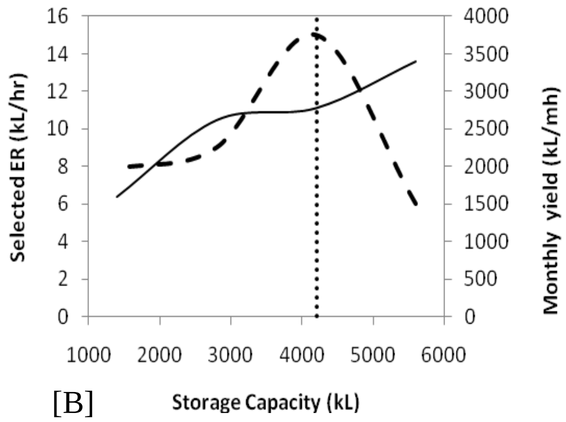
Figure 2. Plots of frequency-based yields Y_F at R_F=80% reliability against ER (kL/hr) for SHS with 4200kL capacity: [A] Daily Y_F (kL/d), [B] Monthly Y_F (kL/mth) and [C] Yearly Y_F (kL/yr).

Table 3. Results of frequency-based yield analysis at R_F=80% of SHS with 4200 kL Capture Store capacity.

Time period	ER (kL/hr)	Frequency-based yield Y_F (kL/period)	SET (days)	P_0 (%)
Daily	6	142 kL/dy	29.2	15
Monthly	15	2800 kL/mth	11.7	45
Yearly	131	111 000 kL/yr	1.3	90

The process of selecting appropriate extraction rates based on the frequency-based yields was repeated for the full range of storage capacities, leading to the series of curves shown in Figure 3. Yield increases as capacity becomes larger in volume, increasing the ability to capture stormwater. For daily and yearly yields, a plateau is reached and increases in yield are minimal for Capture Store capacity in excess of 4200kL. For yearly yields, water volumes of similar magnitude are achieved by operating a larger capacity store at a lower ER. However, a capacity larger than 4200kL with a reduced ER leads to an increased monthly yield.





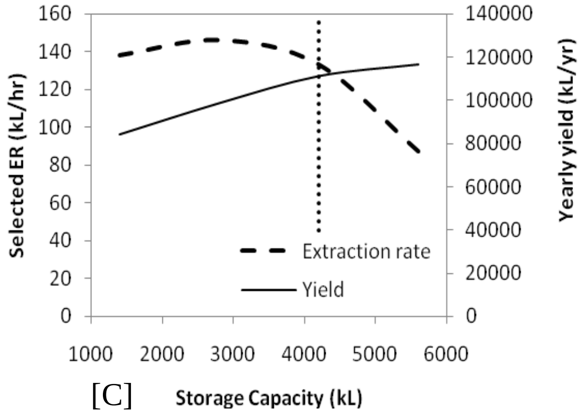


Figure 3. Plots of selected ER (kL/hr) and frequency-based yields Y_F at R_F=80% reliability against Capture Store capacity (kL) for hypothetical SHS. [A] Daily Y_F (kL/d), [B] Monthly Y_F (kL/mth) and [C] Yearly Y_F (kL/yr). Capacity of 4200 kL shown as vertical dotted line.

Based on these results, a 4200kL storage capacity (shown as vertical dotted line, Figure 3) produces daily and yearly yields that are at, or close to, the maximum yields associated with the hypothetical SHS. Monthly yields can be further enhanced by incorporating a Capture Store larger than 4200kL.

Performance indicators for selected Capture Store capacity

Environmental performance indicators for the 4200kL storage operating at the different ERs to maximise the various frequency-based yields (in Table 3) are provided in Table 4.

Table 4: Environmental indicators for hypothetical SHS with 4200kL open storage operating at various selected ERs. No SHS scenario included for comparison. Percentage reductions are shown in brackets.

Scenario	Selected ER (kL/hr)	AAR (ML/yr)	Q1 (m^3/s)	TSS (kg/ha/yr)
No harvesting	-	198	2.92	188
Max. Daily Y_F	6	153 (-23%)	2.50 (-14%)	129 (-31%)
Max. Monthly Y_F	15	124 (-37%)	2.45 (-16%)	98 (-48%)
Max, Yearly Y_F	131	80 (-60%)	2.20 (-25%)	56 (-70%)

DISCUSSION OF RESULTS

Compatibility with WSUD detention

The results of the water balance analysis indicate that stormwater harvesting is highly compatible with WSUD detention. The Capture Store capacity which produces the highest (or close to highest) yields over daily and yearly periods is equivalent to the capture of 15 mm impervious surface runoff. This capacity is consistent with the recommended South East Queensland WSUD detention volume for >40% impervious urban areas (OUM, 2008). The hypothetical catchment falls into this imperviousness category. This outcome raises the prospect of directly integrating stormwater harvesting with WSUD detention or vice versa. An exception is monthly yield; Capture Store in excess of 15mm runoff capture is required if maximising this frequency yield is a priority.

Frequency-based yields and stormwater harvesting potential

The extraction rate of stored water is a key operating factor having a significant effect on stormwater harvesting. Current WSUD detention guidelines recommend a rapid SET of 1 day, which means that storage is very quickly reset to empty in readiness for subsequent runoff events. Operation of the Capture Store to maximise the yearly yield has a slightly slower SET of 1.3 days. These conditions lead to the greatest volumetric capture of stormwater over the course of a year period (Table 3, Yearly Y_F). Under this operating scenario, the Capture Store is empty for 90% of time.

Operation of a SHS at a rapid ER means that a form of water 'banking' such as aquifer storage and recovery would be needed to balance the intermittent extraction of large stormwater volumes. In the absence of water banking (the provision of a large Balance Store), greater reliance would be placed on the Capture Store itself to provide flow balancing to the end water user. To maximise the daily yield, a low ER is needed so water is held in storage longer to provide a supply over most (80%) days. In other words, water is released slowly to provide a more continuous water delivery to the user. Based on the estimated SET (Table 3, Daily Y_F), water is held in storage for up to approx. one month.

Environmental outcomes of stormwater harvesting

Operation of the Capture Store to maximise the yearly yield also provides the best environmental outcomes (Table 4). Reductions in TSS load and runoff (both annual volume and, to a lesser extent, peak Q1 discharge) are substantial. The predicted 70% TSS load reduction represents a significant contribution to the recommended 80% target reduction for WSUD stormwater pollution control.

Operation of a SHS at a slow ER to maximise the daily yield at the nominated 80% frequency-based reliability means that the storage is frequently partly full when runoff occurs. This reduces runoff capture and hence the environmental outcomes of reduced runoff and TSS load are less than would be the case if the SHS is operated with a rapid ER (Table 4).

CONCLUSIONS

Water balance analysis of a hypothetical Toowoomba residential catchment under historically low rainfalls strongly indicates that, although the design basis are different, the storage volume required for stormwater harvesting is consistent with the recommended storage for WSUD detention. Current WSUD guidelines (OUM, 2008) recommend a detention storage equivalent to the capture of 15mm of impervious surface runoff from catchments that are >40% impervious. This same storage was also effective in optimising daily and yearly yields, but for monthly yields it was found that these yields could be further enhanced by providing a larger storage (and reducing the extraction rate).

In addition to storage volume, the extraction rate (ER) from storage and hence the storage emptying time (SET) are key factors. Current guidelines recommend WSUD detention storage should be operated at a rapid ER so it can be emptied within 1 day. For the range of scenarios analysed based on 15mm impervious runoff capture, a harvesting storage operated under a slightly slower ER yielded the greatest volume of stormwater over a year period and the best environmental outcomes in terms of annual runoff reduction (by 60%), peak Q1 discharge reduction (by 25%) and annual TSS load reduction (by 70%). These reductions are significant and demonstrate the potential of stormwater harvesting in delivering WSUD environmental objectives, as well as substantial quantities of useable water. The environmental benefits are reduced if the harvesting storage is operated at a slower ER, as would be the case if maximising daily or monthly frequency-based yields is a water supply priority. These outcomes are based on an 80% frequency-based reliability.

The analysis indicates that stormwater storages for WSUD detention and harvesting are highly compatible. This raises the potential for stormwater harvesting to be directly integrated or retrofitted into WSUD detention strategies, and vice versa. Although the study has focussed on a South East Queensland temperate-climate location, the methods used in this paper are considered to be easily transferable to similar investigations in other Australian climatic zones. Further research is recommended including the effect of different reliabilities, land use composition/density and the length of simulation period used in the water balance analysis on the predicted outcomes.

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