Comparison of storage requirements for two different stormwater harvesting strategies.

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ABSTRACT
As stormwater flows are intermittent, the requirement to store urban runoff is important to the design of a stormwater re-use scheme. In many urban areas, the space available to provide storage is limited and thus the need to optimise the storage volume becomes critical. This paper will discuss the advantages and disadvantages of two different approaches of providing storage: 1) a single storage in which stormwater capture and a balanced release for supply use is provided by the one unit and 2) a dual storage in which the roles of stormwater capture and supply release is provided by two separate storage units. The comparison between the two strategies is supported by predictive modelling assessing the supply reliability and storage volume requirements for both options. The results of the comparison provide guidance to the design of more efficient storages associated with stormwater harvesting systems.

Introduction
The harvesting of stormwater for re-use is becoming recognised as a viable component of sustainable urban water management. The capture, storage, treatment and subsequent use of urban runoff can meet a range of water conservation, water quality and streamflow objectives. Due to these multiple benefits, the widespread drought conditions in recent years and the effectiveness of impervious urban surfaces (roofs, roads and other paved areas) to generate runoff, stormwater re-use systems have been rapidly introduced into Australia.

Despite the growing number of re-use schemes, the technology of urban stormwater harvesting can be considered as emerging, compared to alternatives such as seawater desalination and water recycling. More research on developing compact, efficient and reliable stormwater harvesting systems is required to deliver the substantial water resource opportunities of urban runoff. This paper considers ways to improve the efficiency of storing stormwater which is an integral part of any re-use system.

Single and Dual Storage Systems
The features of stormwater harvesting vary considerably between projects, but a review of existing schemes (DEC NSW, 2006) indicate some common elements including 1) capture - collection or diversion of stormwater from the urban drainage system; 2) storage - temporary detention of stormwater in tanks or ponds to balance supply and demand; 3) treatment - to meet the quality requirements of the use of treated water; and 4) distribution -

conveyance of treated water to the location of use. In practice, each of the four common elements may require some form of storage.

This paper considers the storage components associated with the first two functional elements, referred to as Capture Storage and Balancing Storage. As shown schematically in **Figure 1**, these storage components may be able to be combined together (as a Single Storage) or separated (as Dual Storages).

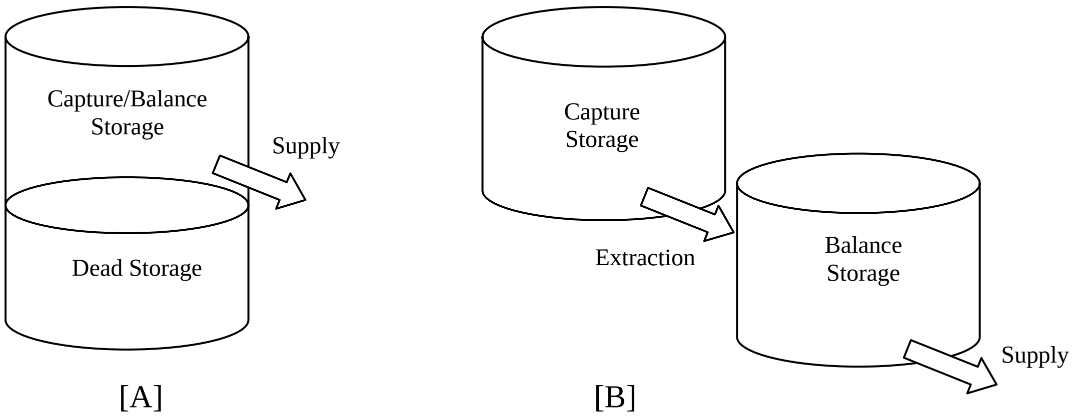

Figure 1: Concept layout of [A] Single Storage and [B] Dual Storage systems

An example of a single storage system is the direct extraction of water from an urban pond or constructed wetland for further treatment and distribution. If sited within public open space, extraction typically occurs only above a minimum water level. In this situation, the supply of water is regulated within an 'active' storage zone that is above a lower 'dead' storage. Water is retained in the dead storage in dry periods to maintain the aquatic habitat and/or aesthetic values of the pond. This (opportunistic) approach to stormwater harvesting is often used in the irrigation of golf courses and parkland, particularly if it can be retrofitted into an existing waterbody without compromising other functions such as visual amenity, stormwater pollution control or flood mitigation.

In the dual storage system, stormwater is captured or diverted into an online or offline storage. This harvested water is then extracted, usually treated and then detained in a separate balancing storage prior to distribution and use. The dual storage approach is consistent with the conventional design of urban potable water systems. Several stormwater re-use schemes have used this approach, especially for projects that have the sole purpose of water supply. Examples include re-use schemes for golf course irrigation at Five Dock and Bexley in Sydney (described in DEC NSW, 2006).

Storage System Analysis
A comparative analysis of the Single and Dual Storage systems was performed to identify the advantages and disadvantages of the two general

approaches. The analysis used a simple water balance spreadsheet to predict the storage behaviour and supply reliability of a hypothetical stormwater re-use system that has the following basic features:

1) Captures stormwater runoff from a 10ha low-density residential located in Toowoomba, Queensland
2) Storages have a simple geometry with a constant surface area. The active storage depth of the single storage configuration is restricted to 0.5m (as assumed retrofitted into an existing waterbody with associated limitations to available depth). In the case of the dual storages, the active storage depth was set at 2m.
3) Extraction of water from the storages is assumed constant. Supply of water from the single storage system ceased if the water level was below the Minimum Supply Level (MSL corresponding to the top level of the dead storage) and recommenced when the water level exceeded MSL. Water supply from the dual storage system ceased when the Balance Storage is empty.
4) Storage capacities were sized to yield an 80% supply reliability, defined as the proportion of time that the system is able to fully provide the assumed rate of supply.

The storage analysis was based on a seven-year historical sequence (2000 to 2006) of hourly rainfall data obtained from the Bureau of Meteorology Toowoomba raingauge. The MUSIC model (Wong et al., 2002) was applied to estimate stormwater runoff volumes generated from the adopted residential catchment. An EXCEL spreadsheet was developed to calculate storage behaviour in response to the predicted stormwater volumes. **Equation 1** was applied in the spreadsheet analysis to model water balance:

$SV_t = SV_{t-1} + I_t + P_t - E_t - S_t - O_t$ **Equation (1)**

where SV_t is the volume in storage at end of the current timestep, SV_{t-1} is the volume in storage at the end of the previous time step, I_t is the stormwater inflow volume, P_t is direct rainfall on storage surface (assumed to be open), E_t is the evaporation from the storage surface, S_t is the spill volume due to overflow in excess of storage capacity and O_t is the stormwater outflow volume.

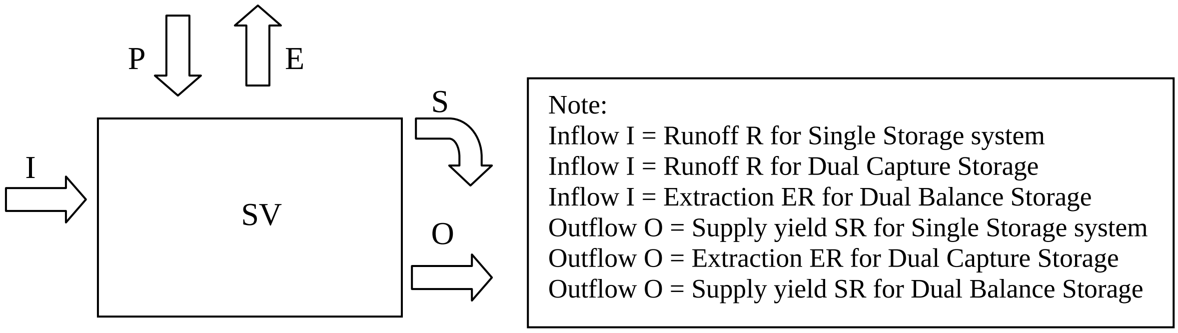

Figure 2: Key water balance components used in storage system analysis

The water balance components that influence storage behaviour are shown schematically as **Figure 2**. It was assumed that there was no seepage from the water storages.

Rainfall, Evaporation and Runoff Estimation

Based on **Equation 1**, the key hydrological inputs to the storage analysis are rainfall, evaporation and runoff. Measured rainfalls and predicted estimates of stormwater runoff and evaporation were used in the analysis.

As indicated in **Figure 3**, the selected rainfall sequence from 2000 to 2006 is the driest seven-year period on record for Toowoomba. The shortfall in rainfall over the period is equivalent to two years of average rainfall. Rainfall event statistics based on measured daily rainfall data for 2000 to 2006 is provided in **Table 1**.

Table 1: Rainfall event statistics for period 2000-2006 at Toowoomba

Statistic	Average	Minimum	Maximum
Annual Rainfall (mm)	636[1]	531	782
Number of events/year[2]	56	46	64
Event rainfall (mm)	18.3	1.2	221.2
Event duration (days)	1.7	1	8
Antecedent dry period (days)	9.1	1	62

1. Long-term average annual rainfall = 939mm. 2. Rainfall event corresponds to days of consecutive rainfall >1mm/day

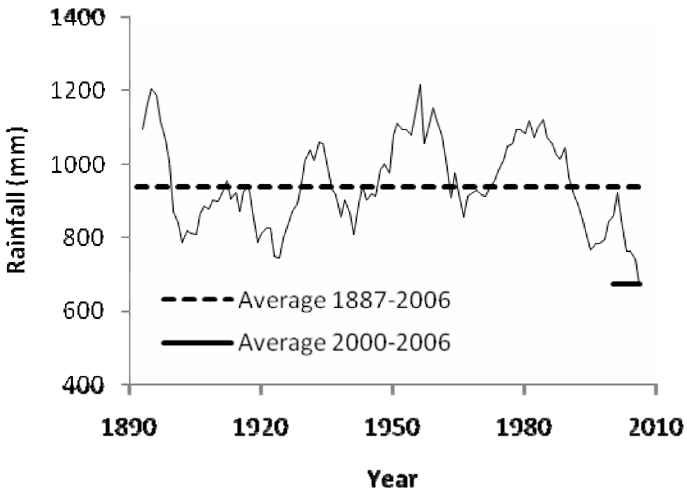

Figure 3: Seven-year moving average annual rainfall (mm) for Toowoomba

Estimates of daily evaporation for Toowoomba were provided by the Queensland DNRW SILO Data Drill data service. These estimates were derived from meteorological data by use of the Morton method to estimate evaporation from shallow lakes (Morton, 1983). Average annual lake evaporation for the 2000 to 2006 period was estimated to be 1500 mm/yr.

Stormwater runoff estimates were predicted using MUSIC. The hypothetical urban residential catchment was assumed to be 42% impervious. Runoff from the pervious part of the catchment were calibrated against data collected by Brodie and Porter (2006) that showed that an initial loss of 20mm is required prior to runoff initiation.

Water Balance Analysis for Single Storage System
Water balance estimates (using **Equation 1**) were made of a Single Storage system on an hourly timestep for the 2000-2006 simulation period. Supply yields corresponding to 80% reliability for a range of storage capacities were determined by iteration. The 'base scenario' that was evaluated assumed that 1) the maximum 'active' storage depth was 0.5m, 2) storage surface was open to full evaporation loss and direct rainfall, and 3) there was no topping up by an external water supply to maintain a constant water level once the stored water level drops below MSL. The last assumption is referred to as 'unregulated MSL' in this analysis.

Predicted supply yields plotted against storage capacity for the base scenario exhibits a characteristic curve as presented in **Figure 4**. The supply yield increases in response to storage capacity, but plateaus at approximately 2000 kL storage. As more storage capacity is provided, the supply yield slightly decreases. This is because, as the maximum storage depth is fixed, the requirement for increased storage volume translates to a larger storage surface area which leads to more evaporation loss.

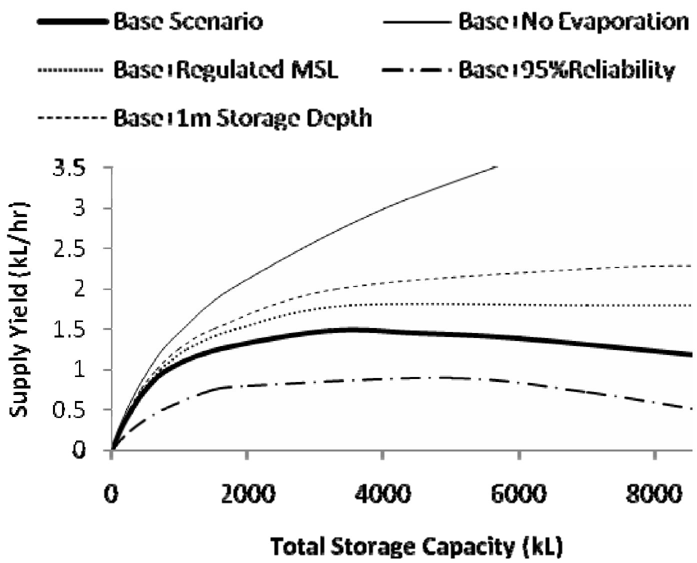

Figure 4: Storage capacity-supply yield curves for Single Storage system

The water balance analysis was repeated to check the sensitivity of supply yield to the assumptions made in the base scenario. The resulting curves are also presented on **Figure 4** and correspond to the base scenario adjusted to represent the following conditions: 1) no loss due to evaporation, representing a closed storage; 2) the storage water level is maintained constant at MSL during dry periods ('regulated MSL'); 3) an increase in maximum active storage depth from 0.5m to 1m; and 4) an increase in supply reliability from 80% to 95%.

Evaporation has a significant effect on supply yield obtained from the Single Storage system, particularly as storage increases in volume and hence surface area. For example, full control of evaporation loss increases the supply yield for a 2000 kL storage from 1.3 kL/hr to 2.1 kL/hr (a 62% increase). To a lesser extent, increasing the active storage depth also increases supply yield and this effect is also caused by evaporation. A storage with a deeper maximum depth has a smaller surface area for a given volume capacity and this leads to less evaporation loss.

Regulating the storage water level at MSL during dry periods also increases supply yield, however the effect is minor compared to evaporation. As extraction of water from storage occurs at water levels above MSL, the effect of a 'regulated MSL' is to increase the time period that supply can be provided. A regulated MSL may be needed for ponds that have high aesthetic or aquatic habitat values. This benefit is offset by the requirement to provide water to maintain a constant MSL during dry periods.

Supply yield is significantly influenced by the target reliability. The supply yield of a 2000 kL storage at 80% reliability decreases from 1.3 kL/hr to 0.79 kL/hr (a 39% decrease) if a 95% reliability is required. This sensitivity of supply yield to reliability is a function of the intermittent flow characteristics of urban stormwater.

Water Balance Analysis for Dual Storage System
The water balance of the Dual Storage system was simulated under the same hydrological inputs as used in the Single Storage analysis. The 'base scenario' that was tested assumed that 1) the maximum 'active' storage depth in both the Capture Storage and Balance Storage was 2m; 2) storage surfaces were open to full evaporation loss and direct rainfall; and 3) both storages are able to be emptied completely and have no dead storage or the need to regulate MSL.

The introduction of highly impervious surfaces, such as roads and roofs causes a dramatic shift in the frequency of runoff for 'small-to-moderate' rainfalls of the order of 10 to 15mm. This often leads to increased channel erosion, poor water quality, lack of aquatic habitat and limited species diversity in downstream creeks, even in partly urbanised areas with less than 10% development (Walsh et al, 2005). In response, the Capture Storage capacity was sized on the basis of capturing runoff predominately from impervious surfaces. As noted previously, pervious surface runoff for the hypothetical catchment typically requires rainfall in excess of 20mm. Thus, the volume capacity of the Capture Storage was set at 840 kL, equivalent to 20mm runoff from the impervious surfaces that occupy 42% of the 10ha urban catchment. The volume of the Balance Storage was a variable in the water balance analysis and was adjusted with the supply rate to achieve the target 80% reliability.

The extraction rate (ER) from the Capture Storage to the Balance Storage was fixed at a constant discharge of 17.5 kL/hr, corresponding to a 2-day time period to empty the storage (if starting full). This means that the Capture Storage can be emptied relatively quickly so a full capacity to store water is made available in advance of the next storm event.

Predicted supply yields for a range of total storage capacities (Capture Storage plus Balance Storage) for the base scenario is shown in **Figure 5**. As was the case for the Single Storage scenario, the supply yield increases asymptotically in response to storage capacity, but the yield from the Dual Storage system plateaus at approximately 4000 kL storage.

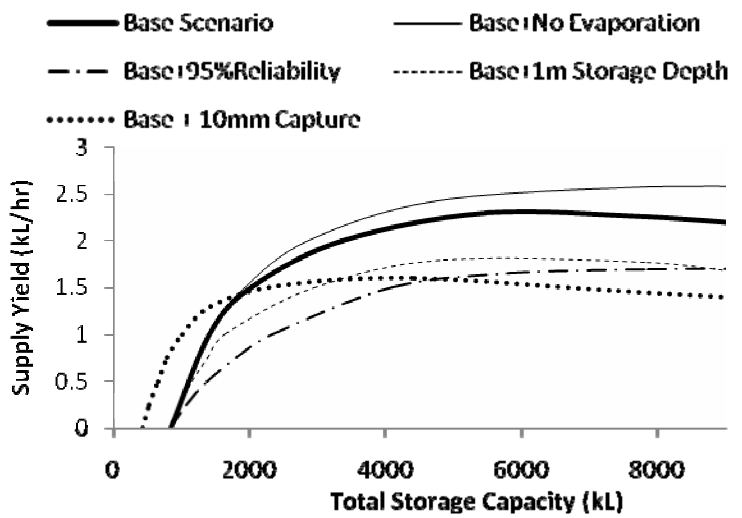

Figure 5: Storage capacity-supply yield curves for Dual Storage system

The sensitivity of supply yield to underlying assumptions in the baseline scenario was also checked. The resulting curves are also presented on **Figure 5** and correspond to the base scenario with the following adjustments: 1) no loss due to evaporation; 2) a decrease in maximum active storage depth from 2m to 1m; 3) an increase in supply reliability from 80% to 95%; and 4) a decrease in the Capture Storage volume from 20mm runoff capture to 10mm.

Relative to the Single Storage system, the Dual Storage system is less sensitive to the effects of evaporation. This is expected to be partly due to the rapid emptying of the Capture Storage which effectively minimises the opportunity to lose water by evaporation. The deeper maximum storage depth of 2m gives a reduced overall surface area that also reduces evaporation loss. Restricting the storage depths to 1m, however, doubles the total storage surface area relative to the baseline scenario which introduces a higher evaporation loss and reduces supply yield (**Figure 5**).

Reducing the volume of the Capture Storage equivalent to 10 mm runoff significantly reduced the yield for total storage capacities in excess of 2000 kL. However, the 10mm capture volume was more effective than the baseline scenario in delivering yields less than 1.5 kL/hr.

As was the case for the Single Storage system, supply yield of the Dual Storage system is significantly influenced by the reliability that is required. The supply yield of a total 2000 kL storage capacity at 80% reliability decreases from 1.5 kL/hr to 0.85 kL/hr (a 43% decrease) if a 95% reliability is required.

A further sensitivity analysis was performed on the effect of the extraction rate (ER) from the Capture Storage to the Balance Storage. The baseline Dual Storage scenario was rerun with extraction rates of 7, 35 and 70 kL/hr (corresponding to emptying times of 5 days, 1 day and 0.5 day). The resulting supply yield curves are presented on **Figure 6** and show minor changes in the supply yield for total storage volumes in excess of 4000 kL.

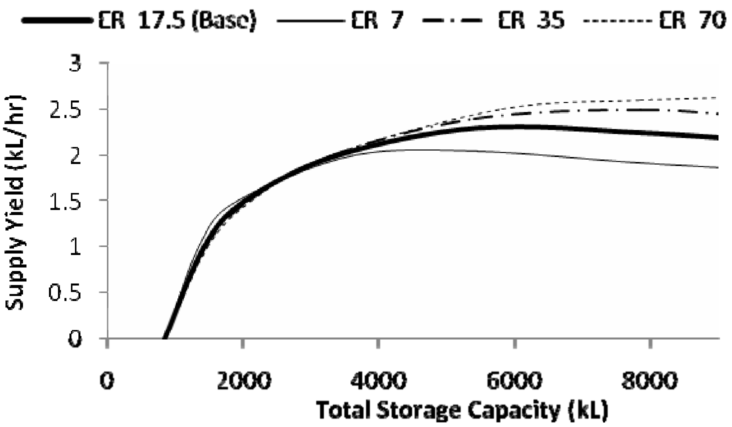

Figure 6: Storage capacity-supply yield curves for Dual Storage system for various emptying rates (ER).

The emptying times are all less than 5 days which is substantially less than the average dry period between rainfall events (9 days as given in **Table 2**), so the probability of the Capture Storage being empty at the start of an event remains high. The effect of varying the extraction rate is thus mainly associated with the performance of the Balance Storage.

Performance Comparison of Baseline Single and Dual Storage Systems
The supply yield curves for the baseline scenarios of the Single and Dual Storage systems are reproduced in **Figure 7** for direct comparison. Both curves are asymptotic, and the upper supply limit that is achieved by the

Dual Storage system (2.3 kL/hr) exceeds that produced by the baseline Single Storage (1.5 kL/hr). The Dual Storage curve is offset from the origin, corresponding to the capacity of the Capture Storage (840 kL). For total storage capacities less than 1600 kL, the supply yield achieved by the Single Storage system exceeds that of the Dual Storage system.

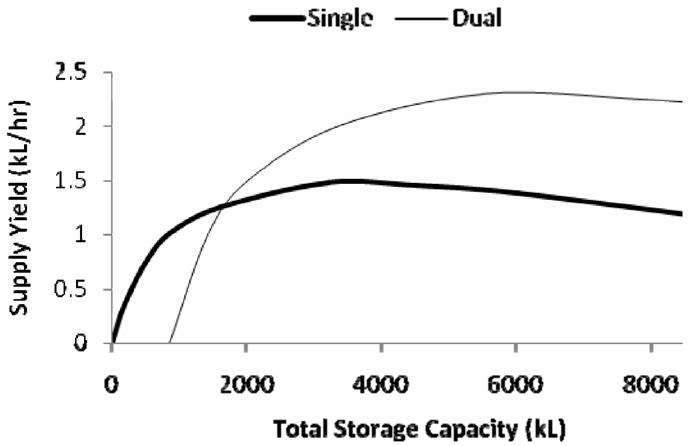

Figure 7: Base scenario storage capacity-supply yield curves for Single Storage and Dual Storage systems

To provide a more detailed comparison between the two approaches, results of the water balance analysis were extracted for the 'crossover' point of 1600 kL storage capacity giving a yield of 1.2 kL/hr at 80% reliability. Features of both storage systems are summarised in **Table 2** and annual averages of key water balance components are given in **Table 3**.

Table 2: Features of Single and Dual Storage systems with total storage = 1600 kL, supply yield=1.2 kL/hr.

Feature	Single	Dual	
	Capture/Balance	Capture	Balance
Max. storage depth (mm)	500	2000	2000
Storage area (m^2)	3200	420	380
Storage capacity (kL)	1600	840	760
Harvesting capacity (mm)[1]	38	20	-
Storage ER or SR (kL/hr)[2]	1.2	17.5	1.2
Nominal residence time (days)	56	2	26

1. As equivalent impervious area runoff, 2. ER= extraction rate, SR = supply rate

Table 3: Comparison of average annual water balances (kL/year) for Single and Dual Storage systems with total storage = 1600 kL, supply yield=1.2 kL/hr. Values in (brackets) are outflows from storage.

Water component	Single Storage	Dual Storage	% Difference
Runoff	32440	32440	0
Direct rainfall	2040	510	-75
Evaporation	(4820)	(800)	-83
Spill	(20870)	(23690)	+14
Supply	(8580)	(8360)	+3

The surface of the Single Storage is significantly larger in area than the combined surfaces of the Dual Storages, resulting in greater volumes of direct rainfall gain and evaporation loss. The Dual Storage system thus hydrologically performs at a better efficiency. The spill from the Dual Storage system exceeds that from the Single Storage as it utilises a separate and relatively small Capture Storage, equivalent to 20mm of impervious area runoff. By comparison, the harvesting capacity of the Single Storage is much greater at 38mm impervious area runoff. This means that the Single Storage system needs to capture runoff from larger and less frequent storms to have the same performance as the Dual Storage system.

The nominal residence times for the storages are also given in **Table 2**. These times are indicative and were calculated simply as the time taken to empty the storage from full capacity for the given outflow (equivalent to extraction rate or supply rate depending on the storage). The residence time of the Single Storage is long (56 days) and is a factor that may lead to algal bloom conditions within the stored water. Risk of algal blooms are expected to be very high at residence times longer than 20 days when summer water temperatures exceed 25 °C, or 50 days at 15 °C (EA, 2006), leading to poor water quality and increased treatment requirements.

Due to the adopted approach to quickly drain the Capture Storage of the Dual Storage system, its residence time is short (2 days). The residence time of the Balance Storage is 26 days, indicating a moderate to high risk of algal blooms. This risk can be reduced if the water extracted from the Capture Storage is treated before released into the Balance Storage, as is usually the case in practice.

Conclusions

Several findings can be noted from the comparative analysis of the Single Storage and Dual Storage approaches to stormwater harvesting:

1) Above a critical storage capacity, the Dual Storage system is expected to provide a greater supply yield compared to a Single Storage system of similar volume.

2) Due to the adopted constraints to the active storage depth, the Single Storage is more prone to evaporation loss which reduces the yield able to be supplied for larger systems. The Single Storage system is also more susceptible to algae blooms due to relatively long water residence times.
3) The Dual Storage system is less sensitive to evaporation loss due to the rapid emptying of the Capture Storage and the overall smaller surface footprint of this system.
4) The Capture Storage of the Dual Storage system can be specifically sized to harvest runoff for storms up to a pre-set magnitude (in this case 20mm). Above a critical storage capacity, the Single Storage system needs to capture runoff from larger, more infrequent events (in this case up to 38mm) to achieve the same performance as the Dual Storage system.
5) For both systems, the supply yield that is produced is significantly influenced by the required reliability of supply.

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