STORMWATER HARVESTING TO MEET FLOW MANAGEMENT OBJECTIVES

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Abstract

There is increasing focus on rainwater and stormwater harvesting in Australian cities. Rainwater and stormwater harvesting has the potential to reduce demand on mains water supplies; however there is also significant potential for rainwater and stormwater harvesting to contribute to other sustainability objectives, including reducing stormwater pollutant loads, reducing erosion and maintaining natural flow regimes in urban streams. This paper focuses on the latter two objectives.

It is well established that urbanisation creates profound changes to the hydrological cycle. Increased connectivity between impervious areas and streams increases flow rates and volumes and dramatically alters wetting and drying cycles. These changes accelerate erosion in waterways and reduce the diversity of aquatic habitat. Emerging flow management objectives seek to address these issues, typically by preserving the natural or pre-development frequency of flow events in waterways and minimising the erosive potential of these events.

Flow management objectives with a focus on stream health can be difficult to meet, as they require stormwater managers to address the frequency, magnitude and duration of flows. Neither stormwater detention nor stormwater quality treatment devices provide a complete solution. A carefully designed stormwater harvesting scheme theoretically has the potential to fill this gap. In this paper, we look at two case studies from Victoria and NSW, which have investigated a range of typical rainwater and stormwater harvesting scenarios, including domestic rainwater tanks, irrigation schemes and regional stormwater reuse systems. These studies investigate how these schemes contribute to meeting flow management objectives.

1 Urbanisation, hydrology and stream health

Urbanisation has profound impacts on hydrology, particularly in small, ephemeral streams. Walsh et al (2004) summarise the key impacts of urbanisation on catchment hydrology as follows:

- In perennial streams, baseflow is usually decreased
- Rainfall response is more rapid, with rainfall events more likely to lead to runoff in streams; therefore runoff is both more frequent and volumes are greater
- Peak flows are increased

These changes in hydrology can lead to significant and intractable problems in urban streams, including increased stream erosion, leading to loss of habitat and loss of biodiversity. Direct impacts can include increased scour of algal assemblages, rapid export of nutrients and organic matter, and direct physical washout of fauna (Wenger et al 2009). Konrad and Booth (2005, p.160) found that “many ecological investigations have documented how the rate, timing, and sources of streamflow affect the structure, composition, and productivity of lotic assemblages by regulating habitat conditions, availability of food sources, or natural disturbance regimes”.

Changes to hydrology and stream health are linked in complex ways, so it is difficult to address stream health issues by focusing on a single aspect of urban hydrology. For example, methods that focus on reducing peak flows (such as stormwater detention) cannot replicate pre-development flow patterns in streams (Konrad and Booth 2005). Increased flow durations (as in those released from detention basins) may have a significant impact on downstream ecosystems, for example McRae (1997) found that detention basins designed for the 2 year ARI peak flow increased the duration of erosive flows, and Maxted and Shaver (1999) found significant impacts on aquatic ecosystems downstream of detention basins. They suggested that in order to protect aquatic ecosystems, further efforts may be required to restore pre-development hydrology.

Konrad and Booth (2005, p.174) state that "Three types of hydrologic changes of ecological significance are likely to result from urban development: increased frequency of high flows; redistribution of water from periods of base flow to periods of storm flow, and increased daily variation in streamflow". This is supported by Walsh et al (2004), who found that the full range of flow conditions is important in the ecology of urban streams:

- Small storm events are thought to be the most important. In undeveloped catchments, these frequent events lead to little runoff, while in developed catchments, they lead to a fast, peaky response. These events cause erosion and sedimentation and over time, lead to substantial modification in stream form.
- Large storm events produce more severe disturbances than in streams of natural catchments, because they bring larger inputs of contaminants and there are few refugia for animals within the degraded stream.
- In dry weather, the stream bears the channel degradation from previous storm events, including erosion and sedimentation and loss of riparian vegetation. Baseflows also contribute to poor water quality, algae growth and loss of biodiversity.

Konrad and Booth (2005, p.173) suggest "hydrologic rehabilitation" as one of several actions required to restore urban streams. They emphasise the importance of this action as a fundamental requirement for stream restoration: "Streamflow is a key habitat-forming process, and failure to reestablish streamflow patterns almost certainly precludes full restoration of the ecosystem." In the context of preserving the health of existing streams during new development, Walsh et al (2004, p.33) state that "stormwater drainage in all developments in the catchment must retain water for infiltration, evapotranspiration or re-use from all rain events up to the size of event that would have produced overland flow from the development in its pre-urban state." This suggests a clear role for stormwater harvesting. Key questions are how to design an effective stormwater harvesting strategy, and how to measure its effectiveness to provide confidence in its results.

2 Stream health indicators and objectives

In the stormwater management sector new management objectives are being developed that include flow management targets focused on stream health. These emerging flow management targets mostly focus on two key aspects of stream health:

- Channel form
- Low flow regime

Targets that focus on channel form seek to minimise erosion in urban streams, by preserving the sediment transport capacity at pre-development levels. Sediment transport is a complex process, but it is possible to quantify the sediment transport capacity of a stream by analysing shear stresses in the stream. A general procedure is as follows:

1. The 'critical shear stress" is estimated for the stream. This is an estimate of the shear stress (force per unit area) that is required to mobilise the sediment particles that make up the stream bed and banks. The critical shear stress depends on the specific soil conditions within the stream;
2. A hydrologic (rainfall-runoff) model is developed for the catchment, and used to produce a flow time series for the stream. Several different versions of the catchment model may be developed, for example to represent pre- and post-development scenarios;
3. A hydraulic model is developed for the stream and used to convert the flow time series to a time series of shear stress throughout the modelled reach. The relationship between flow and shear stress in a channel depends on the channel slope, cross-section geometry and hydraulic roughness;
4. Estimated shear stresses are compared to the critical shear stress estimated for the bed and bank sediments. The excess shear stress (i.e. the magnitude of shear stress above the critical shear stress) is calculated for each time step in the time series then summed over time. This result, which represents the total effective work done in the stream over the time period of analysis, is termed the "erosion potential" for the scenario in question; and
5. An "erosion potential index" (EPI) can be calculated, which compares the erosion potential against a baseline scenario (e.g. post-development is compared to pre-development).

As this process is time consuming and dependent on significant data to set up the hydrologic and hydraulic models, sediment transport capacity is sometimes quantified using simpler surrogate measures. An approach suggested for Sydney's Growth Centres (DEC 2006) is to use flow as a surrogate. Instead of a critical shear stress, a critical flow threshold is estimated for the stream. Instead of summing excess shear stress over time, excess flow is summed over time to produce a measure of the erosion potential in the stream. Again, results can be compared to a baseline (e.g. pre-development) scenario. In NSW, this metric (based on flow) has generally been called a "stream erosion index" (SEI) (DEC 2006). Note that the SEI published in the NSW Growth Centres objectives (DEC 2006) and the modified SEI published in the WSUD DCP Guide (SMCMA 2009) are based only on the *duration* of flows above a critical threshold, however in this study we followed Brookes and Wong's (2009) methodology, where the SEI is based on both the *duration and magnitude* of flows above the critical threshold.

The SEI approach relies on an estimate of the critical flow threshold. This parameter does not have as strong a theoretical basis as the critical shear stress (which can be estimated using Shields' entrainment function or other empirical relationships). Earth Tech (2005) recommended a critical flow threshold for NSW urban streams in stiff clays as 50% of the 2-year ARI flow. This threshold has been adopted in our study.[1]

Stormwater targets that focus on the low flow regime seek to minimise changes to wetting and drying cycles. Wetting and drying cycles are often represented using low flow duration, high flow duration and spells frequency curves, which can be used to interpret flooding and drying hydrology. They summarise the frequency of particular flow conditions, e.g. spells of low or high flows. They have been used in HCCREMS (2007) to define the hydrologic conditions important to sensitive wetlands in NSW, and can also be applied to streams.

Simpler metrics may also be used to describe key aspects of the flow regime, for example Konrad and Booth (2005) used parameters including the following:

- Frequency of daily flows that exceeded three times median flow

[1] There is good reason to suggest that in the soil landscapes of Western Sydney, where salinity and sodicity are widespread, and associated with dispersive soils, a lower erosion threshold may be relevant. However 50% of the 2 year ARI flow has been set as an objective in the South Western Growth Centre of Sydney (DEC 2006) and therefore is used here to maintain a consistent approach, comparable with other studies.

- Frequency of events greater than 10th percentile flow
- Frequency of daily flow corresponding to annual peak flow with 1.67 return interval
- 90th percentile flow
- 90th percentile flow/median daily flow

In Victoria a frequent flow objective based on the average annual number of surface runoff days, is currently being investigated and is discussed further below. Table 1 summarises the stream health indicators used in this paper. Note that stream health is also influenced by a range of other factors, including water quality, riparian vegetation condition, existing stream form, barriers to fish passage etc, which are not directly related to stream flows and not included in Table 1.

Table 1: Summary of stream health indicators

Focus	Stream characteristics	Quantification methods	Indicators
Channel form	Sediment transport capacity	Analysis of shear stress time series	EPI (Erosion Potential Index)
		Analysis of flow time series	SEI (Stream Erosion Index)
Low flow regime	Wetting and drying hydrology	Flow duration and spells analysis	Metrics such as the average annual number of surface runoff days

3 Role of stormwater harvesting in flow management

Previous studies have investigated several options for meeting different types of flow management objectives. For example, Gillam (2008) investigated three different stormwater management strategies, assessing them for their effectiveness in meeting stream flow objectives including a low flow duration frequency curve and a 30-day dry flow spells frequency curve. Gillam found that:

- A typical stormwater management scheme for new residential development, including lot-scale rainwater harvesting and bioretention systems designed to meet best practice water quality objectives, would do little to meet the stream flow objectives
- A stormwater management scheme involving extensive infiltration could hypothetically meet the stream flow objectives, but the scale of infiltration required was rarely likely to prove feasible.
- A scheme utilising diversion pipes to remove excess flows from the catchment would also hypothetically meet the stream flow objectives, however this would involve significant cost, and it may not always be possible to find a suitable discharge location downstream of sensitive environments.

Brookes and Wong (2009) found that a wetland designed to meet stormwater quality management objectives could also achieve an SEI of 1 (i.e. equivalent to pre-development conditions), however wetland outflows are strongly influenced by the hydraulic design of the wetland, including the high flow bypass, extended detention and overflow arrangement, and not every wetland would produce this result.

In recent years, long-term drought, water supply shortages and restrictions on urban water consumption have encouraged a focus on stormwater and rainwater harvesting in Australian cities. The most common forms of rainwater and stormwater harvesting are domestic rainwater tanks and local government stormwater harvesting schemes for open space irrigation. The availability of government grants has encouraged a proliferation of these projects.

Rainwater and stormwater harvesting has the potential to reduce demand on mains water supplies; however there are more efficient ways to achieve this objective. Knights and McAuley (2009) found that typical stormwater harvesting schemes are less than ideal as a water conservation measure; however there is potential for rainwater and stormwater harvesting to contribute to other sustainability objectives, including reducing stormwater pollutant loads and maintaining natural flow regimes in urban streams. Stormwater harvesting in an urban catchment can theoretically be designed to mimic the interception and loss of rainfall within a natural catchment. Excess runoff generated from impervious surfaces can be retained, stored and prevented from reaching urban streams.

4 Stormwater strategies to meet flow management objectives

The following sections summarise two case studies, which have investigated the potential for stormwater harvesting to meet flow management objectives in case study catchments at Shepherd Creek (Victoria) and Oran Park (NSW). The case studies were structured to reflect realistic development scenarios. At Shepherd Creek, calibrated hydrology and hydraulic models were available, which allowed an assessment of the EPI for this catchment. At Oran Park, assessment of the EPI was not possible, however SEI was analysed instead. In both case studies, an assessment was also made of the number of surface runoff days associated with each stormwater management scenario. These results are easier to compare, however they are dependent on local rainfall. Results have therefore only been compared on a broad scale.

Shepherd Creek

Recent research undertaken by the authors in conjunction with Melbourne Water has investigated stormwater management scenarios designed to meet two types of objectives:

- An EPI of one (i.e. erosion potential equivalent to pre-development conditions, based on shear stress analysis)
- A frequent flow objective (FFO) based on the number of surface runoff days. The objective was tested to maintain the number of surface runoff days either:
  - At the same number as in the pre-development scenario; or
  - At no more than 10-30 additional days compared to pre-development.

Shepherd Creek is located north-east of Melbourne in the Yarra River catchment. The catchment area is 7,110 hectares, which is currently a mixture of forest and rural land use. Shepherd Creek has uncohesive bed and bank sediment composition, (primarily sand, fine gravel and some silt/clay) and a relatively high entrenchment ratio (defined as the channel width at two times the bankfull depth divided by the channel width at bankfull) and therefore was identified as being particularly sensitive to erosion as a result of changes in hydrology.

A hypothetical urban development scenario was considered for the Shepherd Creek catchment, whereby:

- All the identified creeklines would have a 20 m buffer from the centreline.
- Other areas would be developed in a similar manner to Caroline Springs, a new suburb on the north-west fringe of Melbourne. The estimated land use breakdown and impervious areas at Caroline Springs are shown in Table 2.

Table 2: Land use and impervious areas for Caroline Springs, as used for hypothetical development scenario in the Shepherd Creek catchment

	Actual area (m^2)	Overall %	Roads (inc. carparks)	Roofs %	Other impervious %	Pervious %	Total Impervious %
Land Use							
Open space	588,291	13.3%	0%	2%	10%	88%	12%
Commercial	46,908	1.1%	10%	80%	5%	5%	95%
Community facilities	61,101	1.4%	30%	40%	10%	20%	80%
Attached dwellings	101,578	2.3%	0%	60%	25%	15%	85%
Detached dwellings	3,495,886	78.7%	9%	42%	20%	29%	71%
Major roads	146,162	3.3%	60%	0%	0%	40%	60%
Total	4,439,925						64%

A range of water management scenarios were tested for the Shepherd Creek catchment. These are summarised in Table 3. Key assumptions in these scenarios were:

- All stormwater quality treatment systems were sized to meet current best practice targets (45% of total nitrogen loads).
- In the scenarios with unlined bioretention systems, the infiltration rate was assumed to be 4 mm/hour (representative of medium clay soils).
- In Scenarios 3, 4 and 7, rainwater tanks were sized at 3.5 kL per detached dwelling and 0.75 kL per attached dwelling. In Scenario 8, these were increased to 5 kL and 1.25 kL respectively.
- The stormwater storage tanks were sized for each scenario to meet a high proportion of demands, without being oversized. In Scenarios 5 and 6, the storage was 150 ML, in Scenario 7 it was 200 ML and in Scenario 8 it was 500 ML. This is equivalent to a maximum of 4.6 kL per dwelling.
- The public open space area (irrigated with stormwater in Scenarios 5-8) was estimated at 13% of the development.

Table 3: Water management scenarios tested for Shepherd Creek

No	Description	Stormwater quality treatment systems	Rainwater tanks	Stormwater harvesting
0	Post-development	None	None	None
1	Stormwater quality	Bioretention systems; lined to exclude infiltration	None	None
2	Stormwater quality + infiltration	Bioretention systems; unlined to allow infiltration	None	None
3	Stormwater quality + rainwater tanks	Bioretention systems; lined	Rainwater tanks for all non potable demands	None
4	Stormwater quality, rainwater tanks + infiltration	Bioretention systems; unlined	Rainwater tanks for all non potable demands	None
5	**1** + stormwater harvesting	Bioretention systems; lined	None	Stormwater harvesting for public open space
6	**2** + stormwater harvesting	Bioretention systems; unlined	None	Stormwater harvesting for public open space
7	**4** + stormwater harvesting	Bioretention systems; unlined	Rainwater tanks for all non potable demands	Stormwater harvesting for public open space

No	Description	Stormwater quality treatment systems	Rainwater tanks	Stormwater harvesting
8	Large-scale stormwater harvesting	Bioretention systems; unlined	Rainwater tanks for hot water + laundry demands	Stormwater harvesting for public and private open space + toilet flushing

Each of these scenarios was modelled in MUSIC to produce a flow time series at a 6 minute time step. The flow time series was analysed to calculate the EPI and the FFO.

The EPI was estimated using a hydraulic model of Shepherd Creek. Hydraulic conditions in the study reach were simulated for 147 different flow rates ranging from 0.001 m^3/s to 50 m^3/s, which encompasses the full range of flows in the simulated flow record. The reach average shear stress was estimated for each of the 147 flows to develop a relationship between flow rate and shear stress. The critical shear stress was estimated for Shepherd Creek at 2.70 N/m^2, however a range of shear stress thresholds were considered, ranging from 1-16 N/m^2.

A summary of the EPI results is shown in Figure 1. This shows that most of the scenarios tested (Scenarios 1-6) did not meet an EPI of one. However the EPI improved with the addition of infiltration, rainwater tanks and stormwater harvesting. The addition of stormwater harvesting for public open space had some benefit; while the large-scale stormwater harvesting scenario (Scenario 8) produced the best results. For this scenario, the EPI was less than one for a critical shear stress up to approx. 7 N/m^2. Scenario 7 (including unlined bioretention systems, rainwater tanks for all non-potable demands and stormwater harvesting for public open space) also resulted in an EPI less than one for a critical shear stress up to approx. 4 N/m^2.

The FFO required an estimate of the number of surface runoff days for the pre-development scenario. For this study, stream gauging data was available for the existing (undeveloped) catchment, and therefore the pre-development MUSIC model was calibrated to the gauge data. The number of days of surface runoff was estimated at 9 to 10 days for the pre-development scenario.

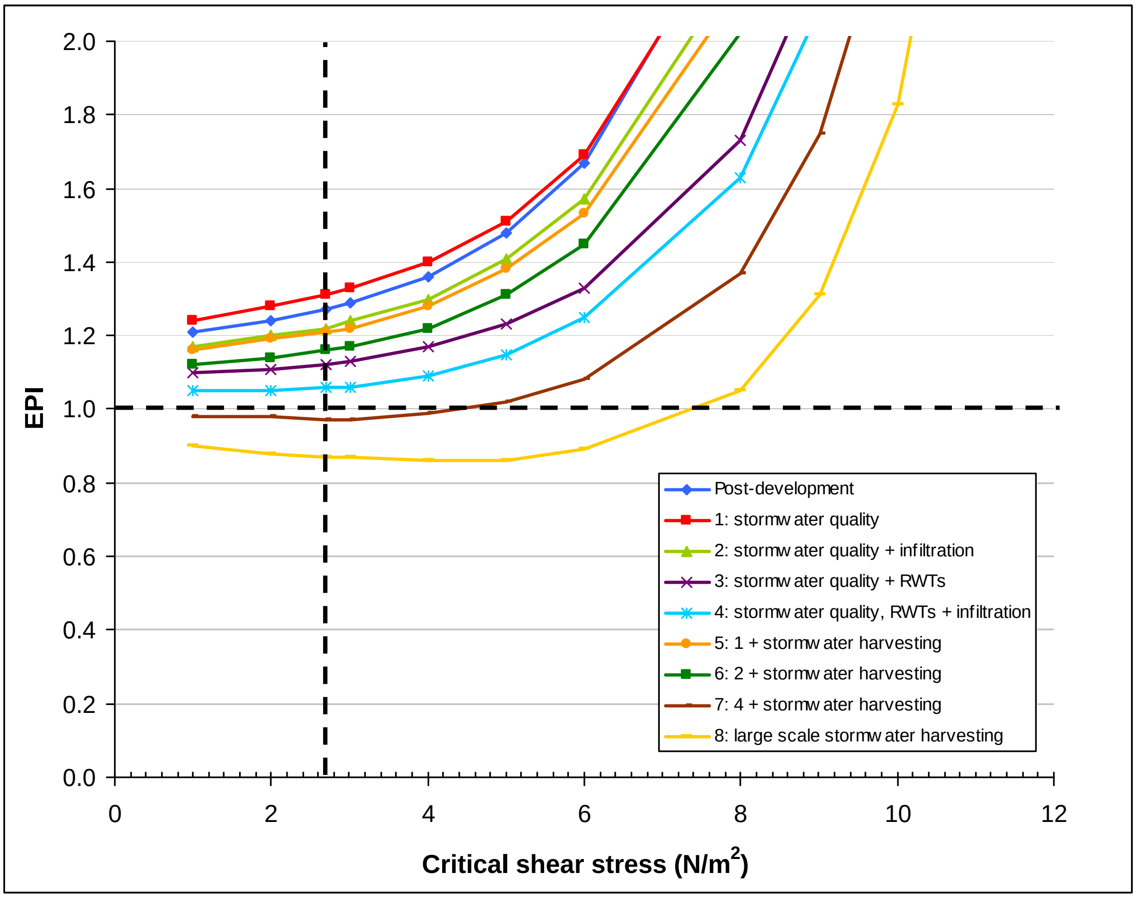

Figure 1: EPI results for Shepherd Creek catchment

Results for the post-development scenarios are summarised in Table 4. These show that the mean annual number of surface runoff days was very high for scenarios with no infiltration (Scenarios 1, 3 and 5). This is due to gradual outflows from bioretention systems and attenuation of flashy storm flows from impervious areas; however these flows, which have been treated in the bioretention system, are unlikely to have a negative impact on stream health. The mean annual number of surface runoff days was reduced substantially with the addition of infiltration, and reduced further with rainwater and stormwater harvesting. Results for the mean annual runoff volume and volume of rainwater/stormwater harvested are also included for comparison, and these show that the most effective scenarios (7 and 8) were those which harvested the most water. None of the scenarios tested could reduce the number of surface runoff days to pre-development levels.

Table 4: Frequent flow results for Shepherd Creek catchment

No	Description	Mean annual number of surface runoff days	Mean annual runoff volume (ML/year)	Mean annual harvested volume (ML/year)
1	Stormwater quality	318	37,900	0
2	Stormwater quality + infiltration	134	34,900	0
3	Stormwater quality + rainwater tanks	314	24,250	13,650

No	Description	Mean annual number of surface runoff days	Mean annual runoff volume (ML/year)	Mean annual harvested volume (ML/year)
4	Stormwater quality, rainwater tanks + infiltration	120	22,990	11,910
5	**1** + stormwater harvesting	130	33,950	3,950
6	**2** + stormwater harvesting	103	31,840	3,060
7	**4** + stormwater harvesting	86	19,870	18,030
8	Large-scale stormwater harvesting	50	15,980	22,720

Oran Park

Key elements of the research described above have been extended to Western Sydney, to investigate similar scenarios in the Sydney context. A study catchment was selected in the South-West Growth Centre, at Oran Park. This catchment drains to a small ephemeral tributary of South Creek, in the upper reaches of the South Creek catchment. The catchment area is 543 ha and the existing land use is rural. The proposed development includes a mixture of residential, commercial, employment lands and public facilities. Information on the proposed land use breakdown and estimated impervious areas is shown in Table 5. This land use plan was derived from indicative layout plans for Oran Park and projected population and employment rates published by the Growth Centres Commission (2007).

Table 5: Land use and impervious areas for the Oran Park study catchment

Land use	Area (ha)	% Imperv.	Imperv.area (ha)	Pervious Area (ha)	Roofs (ha)	Paved & Road (ha)	Land-scaped (ha)
Riparian (approx)	37.4	0%	0.0	37.4	0.0	0.0	37.4
Parklands (includes SWQ infra)	45.6	0%	0.0	45.6	2.3	6.8	36.5
High Density	10.9	90%	9.8	1.1	8.2	1.6	1.1
Med Density	101.6	83%	84.4	17.3	50.8	33.5	17.3
Typical Density	250.5	73%	182.8	67.6	100.2	82.7	67.6
Bulky goods commercial	5.3	86%	4.6	0.7	2.4	2.2	0.7
Major retail commercial	17.4	86%	15.0	2.4	7.8	7.1	2.4
Community buildings	12.2	86%	10.5	1.7	5.5	5.0	1.7
Mixed development commercial	19.1	86%	16.4	2.7	8.6	7.8	2.7
Employment	18.4	86%	15.8	2.6	8.3	7.6	2.6
Schools	15.0	65%	9.8	5.3	4.5	5.3	5.3
Mixed Use	10.0	68%	6.8	3.2	3.5	3.3	3.2
TOTAL	**543.4**	**62%**	**355.8**	**187.6**	**202.0**	**162.9**	**178.5**

Table 6 summarises the scenarios which were considered for this catchment at Oran Park. In these scenarios, the following key assumptions were made:

- In the pre-development scenario, soil parameters were those given in the draft NSW MUSIC Modelling Guidelines (BMT WBM 2008) for non-urban conditions with mean annual rainfall less than 1000 mm/year.
- The rainwater tanks in Scenario 3 (to meet BASIX) were an average size of 3.3 kL per dwelling.
- In Scenarios 3-9, bioretention systems were sized to remove 45% of total nitrogen loads.

- In Scenario 4, the surrounding soil was assumed to have a hydraulic conductivity of 0.36 mm/hr (consistent with stiff clays).[2]
- The rainwater tanks in Scenarios 5 and 7 (for all non-potable demands) were an average size of 10 kL per dwelling. In these scenarios, rainwater tanks were also included on commercial roofs for hot water, toilet flushing and cooling tower demands.
- The rainwater tanks in Scenario 8 (for laundry and hot water) were also an average size of 10 kL per dwelling.
- The stormwater storage tanks were sized for each scenario to meet a high proportion of demands, without being oversized. The largest storage was 64 ML in Scenario 9, which is equivalent to 12.5 kL per dwelling.
- Irrigation demands for public open space (POS) were estimated to be 5,000 kL/ha/year, seasonally distributed.

Each of these scenarios was modelled in MUSIC at a 6 minute timestep. Rainfall data was from Richmond for 1954-1994. Results are summarised in Table 6.

In order to calculate the SEI, an estimate was made of the 2 year ARI flow from the pre-development catchment. The Probabilistic Rational Method (AR&R Volume 1, Institution of Engineers) for rural catchments was used and the peak 2 year ARI flow was calculated as 16.6 m^3/s. This was verified against an annual flood series analysis performed on a continuous predevelopment hydrograph simulated using 40 years of rainfall in MUSIC. The annual flood series yielded a 2 year ARI flow of 16 m^3/s.

These results show that basic water cycle management measures will *increase* the number of surface runoff days downstream of urban development. As per Shepherd Creek, this is due to gradual outflows from bioretention systems and attenuation of flashy storm flows from impervious areas. If the bioretention outflows are disconnected from creeks and allowed to infiltrate, the results improve. Surface runoff days were further reduced by increased rainwater and stormwater harvesting; however as per Shepherd Creek, none of the scenarios could reduce surface runoff days to pre-development conditions.

SEI results show that none of the scenarios tested could achieve an SEI of one (equivalent to pre-development conditions). The SEI improved with increasing rainwater and stormwater harvesting, however reached a minimum value of 3.7 in Scenario 7. The maximum value was 5.5 in Scenario 2 (with no water cycle management measures).

[2] The feasibility of infiltration systems would need to be tested in the context of the local soil conditions. Infiltration is not generally recommended in western Sydney, where saline and sodic soils are common.

Table 6: Scenarios considered at Oran Park

No.	Description	Development conditions	Rainwater harvesting	Stormwater treatment	Stormwater harvesting and reuse	Volume of rainwater/ stormwater harvested (ML/ yr)	Percentage of demands met by rainwater/ stormwater (%)	Residual average runoff Volume (ML/ yr)	Stream Erosion Index	Mean annual surface runoff events (days)
1	Pre-development	Forested	N/A	N/A	N/A	0	N/A	1050	N/A	1.5
2	Developed with no WCM measures	Urban, as per Table 5	None	None	None	0	0	3250	5.5	98
3	Developed with basic water cycle management	Urban, as per Table 5	Rainwater tanks to meet BASIX	Bioretention systems, lined to exclude infiltration	None	419	70%	2830	4.8	148
4	**3** + limited infiltration	Urban, as per Table 5	Rainwater tanks to meet BASIX	Bioretention systems, unlined	None	419	70%	2800	4.8	118
5	Developed with stretch WCM measures	Urban, as per Table 5	Rainwater tanks for all non-potable demands	Bioretention systems, unlined	None	932	66%	2300	3.8	99
6	**4** + basic stormwater harvesting	Urban, as per Table 5	Rainwater tanks to meet BASIX	Bioretention systems, unlined	Stormwater harvesting for POS	619	73%	2620	4.7	98
7	**5** + basic stormwater harvesting	Urban, as per Table 5	Rainwater tanks for all non-potable demands	Bioretention systems, unlined	Stormwater harvesting for POS	1103	67%	2120	3.7	82

No.	Description	Development conditions	Rainwater harvesting	Stormwater treatment	Stormwater harvesting and reuse	Volume of rainwater/ stormwater harvested (ML/ yr)	Percentage of demands met by rainwater/ stormwater (%)	Residual average runoff Volume (ML/ yr)	Stream Erosion Index	Mean annual surface runoff events (days)
8	Large-scale stormwater harvesting	Urban, as per Table 5	Rainwater tanks for laundry, hot water	Bioretention systems, unlined	Stormwater harvesting for POS + reticulated for toilets and outdoor	1204	73%	2090	3.9	41
9	Large-scale stormwater harvesting and no rainwater tanks	Urban, as per Table 5	None	Bioretention systems, unlined	Stormwater harvesting for POS + reticulated for all non-potable uses	1200	72%	2030	4.1	46

Results for Scenarios 5 and 9 allow a comparison between the effectiveness of rainwater tanks and large-scale stormwater harvesting. Scenario 5 includes rainwater tanks to meet all non-potable demands, while Scenario 9 excludes rainwater tanks but includes stormwater harvesting for all non-potable demands. These scenarios resulted in similar SEI values, but Scenario 9 resulted in only 36 days of surface runoff, while Scenario 5 resulted in 99. This difference is due to the fact that stormwater harvesting will reduce runoff from all impervious surfaces, while rainwater tanks only reduce flows from roof areas. Also, a large tank with large demands is a better buffer than several smaller tanks with smaller demands which are more prone to overflows.

The results for the pre-development scenario showed an average of 1.5 days of surface runoff for the 40 year simulation period. This appears to be a very low frequency of surface runoff, and so some effort was made to sanity check this result. A model was set up which included an initial loss, and no other losses. The initial loss was varied between 5 and 55 mm, the model was run over the 40 year simulation period and the resulting mean annual surface runoff days were calculated. Results are shown in Figure 2. This shows that to replicate the result of 1.5 days/year, initial losses need to be approximately 55 mm. Initial losses are expected to be in the range 15-35 mm/rain event (as per the Rational Method for flood estimation), which would suggest that 5-15 surface runoff days/year may be a more reasonable estimate for the pre-development scenario. This needs further investigation to establish a reasonable estimate of surface flow events for pre-development conditions, acknowledging that neither the Probabilistic Rational Method nor the MUSIC rainfall-runoff model is ideally suited to this type of analysis.

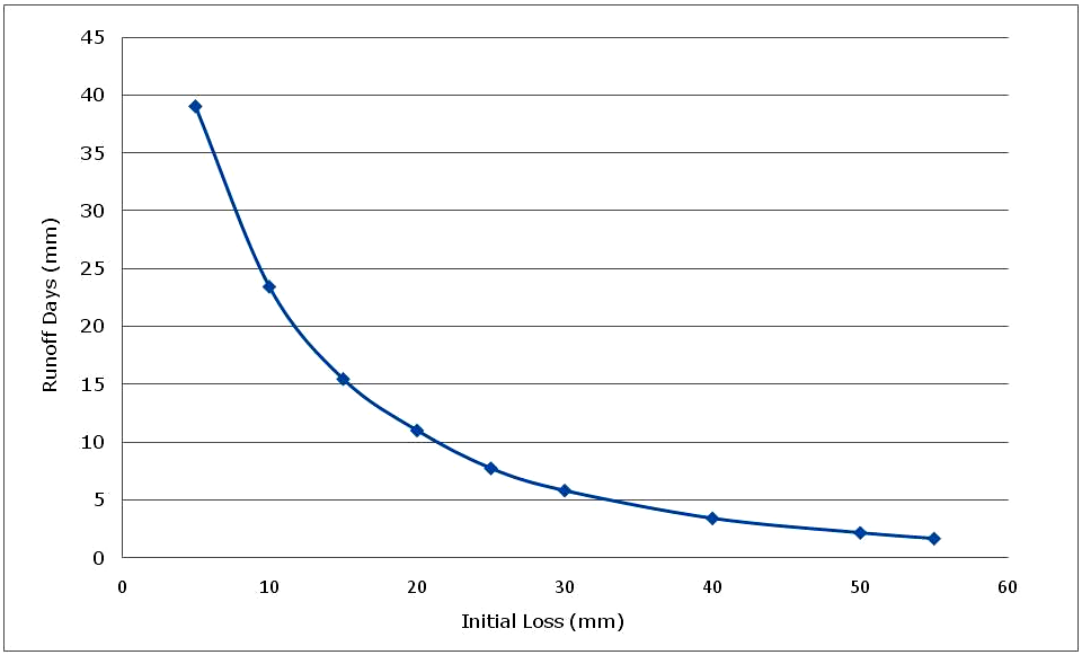

Figure 2: Relationship between mean annual surface runoff days and equivalent initial losses

5 Key attributes of a stormwater harvesting scheme to meet flow management objectives

The case studies in Victoria and NSW have supported the findings of previous studies, confirming that existing best practice water cycle management measures (small scale rainwater harvesting and stormwater quality management measures) alone are not sufficient to meet new flow management objectives for either erosion or flow regime management. However the two case studies presented show that there is potential for rainwater and stormwater harvesting to contribute substantially to meeting these objectives, particularly with respect to erosion.

The Shepherd Creek case study showed that it is possible to meet an EPI of one using a large-scale stormwater and rainwater harvesting scheme, which indicates significant erosion is unlikely to occur in the receiving waterway. The harvesting scheme needs to be designed to meet all non-potable demands, including laundry, hot water, toilet flushing and outdoor demands. There is some flexibility as to whether rainwater or stormwater is supplied to each end use, but the best result is achieved when stormwater is used within the private domain as well as the public domain. This is because stormwater harvesting captures runoff from a larger portion of the catchment (including roads and other impervious areas), meets a higher proportion of demands and prevents more water from running off.

The Oran Park case study showed that it would not be possible to meet an SEI of one with any of the rainwater or stormwater harvesting scenarios tested. It would also not be possible to reduce the number of surface runoff events to pre-development levels. However as in the Shepherd Creek study, the best results were achieved when there was maximum use of rainwater or stormwater.

The relationship between the harvesting volume and each of the stream health objectives was analysed by comparing the volume of rainwater/stormwater harvested with the EPI, SEI and average annual surface runoff days. These results are summarised in Figure 3 for Shepherd Creek and Figure 4 for Oran Park. Figure 3 shows that at Shepherd Creek there was a strong relationship between the harvested volume and the EPI. A relationship with surface runoff days is not immediately apparent, however if Scenarios 1, 3 and 5 are removed from the analysis, and the results are compared only for Scenarios 2, 4, 6, 7 and 8 (which all include identical unlined bioretention systems) then the R^2 value improves to 0.72. Similarly, Figure 4 shows that at Oran Park there was a strong relationship between the harvested volume and the SEI. The relationship with the surface runoff days is also less clear, however if Scenarios 2 and 3 are removed from the analysis, and the results are compared only for Scenarios 4-9 (which all include identical unlined bioretention systems) then the R^2 value improves to 0.77.

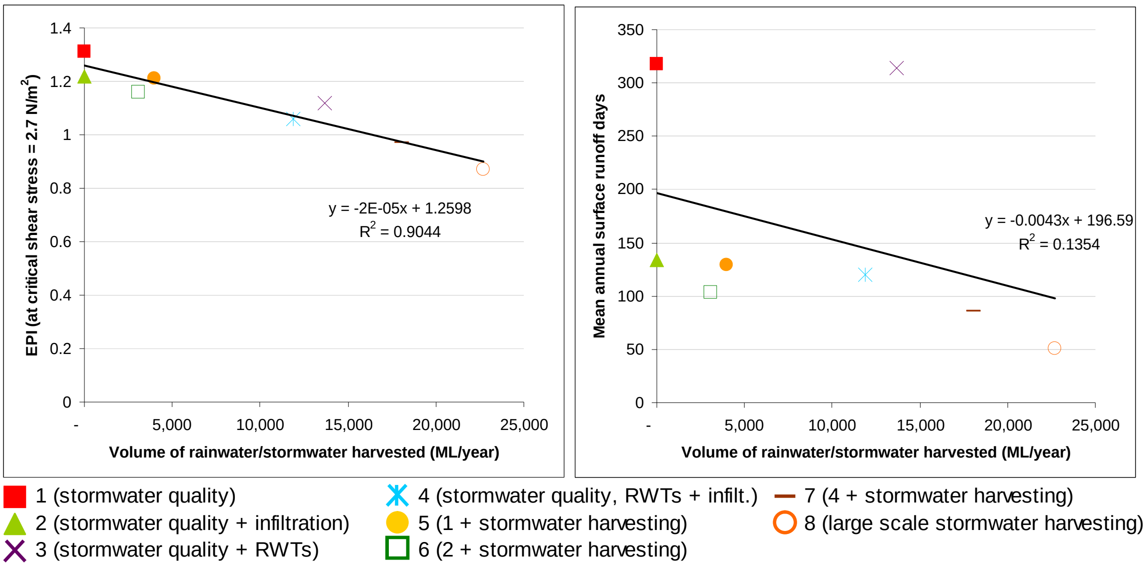

Figure 3: Relationship between harvesting volume and EPI/mean annual surface runoff days for Shepherd Creek

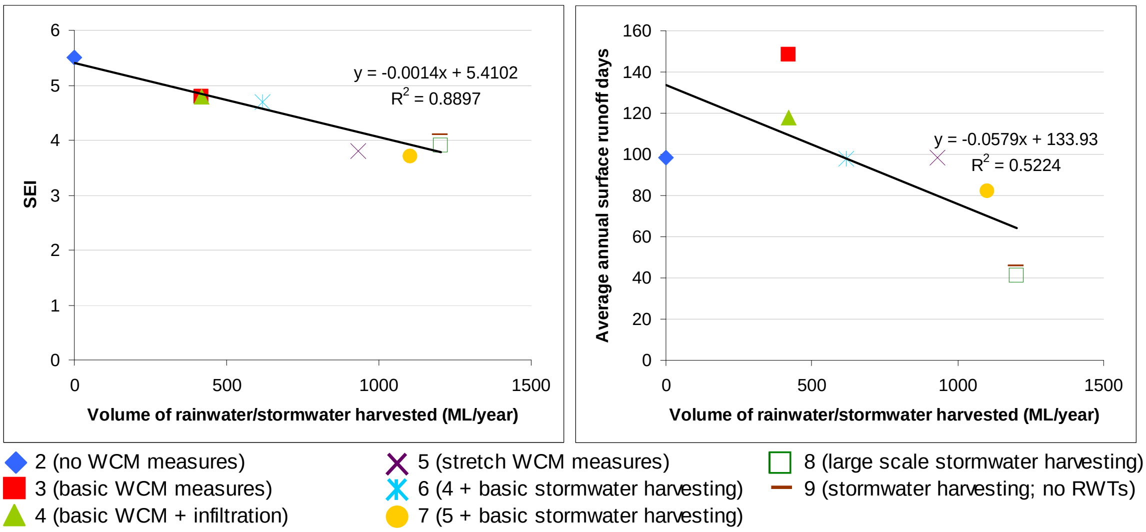

Figure 4: Relationship between harvesting volume and SEI/mean annual surface runoff days for Oran Park

Both case studies showed that while stormwater harvesting can reduce the number of surface runoff days significantly, it would not be possible to reach pre-development levels. Even though at Oran Park there was some uncertainty over the estimation of pre-development surface runoff events using the rainfall runoff models selected, the results for all of the post-development scenarios were well above the range expected for the pre-development scenario. This suggests that in order to meet objectives relating to the flow regime, stormwater harvesting will need to be coupled with other measures, including infiltration. While previous studies have found that it would be difficult to meet flow regime objectives using infiltration alone, a large-scale stormwater harvesting scheme could reduce the required size of infiltration systems and make it more feasible to meet these objectives.

6 Acknowledgements

The authors wish to thank Matt Potter from Melbourne Water and Tim Fletcher from Monash University, who contributed to the Shepherd Creek project.

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