Is stormwater harvesting beneficial to urban waterway environmental flows?


*Institute for Sustainable Water Resources, Building 60, Department of Civil Engineering, Monash University, VIC 3800, Australia
**École des Ingénieurs de la Ville de Paris, 15, rue Fénelon, 75010 Paris, France

Abstract Urbanization degrades the hydrology and water quality of waterways. Changes to flow regimes include increased frequency of surface runoff, increased peak flows and an increase in total runoff. At the same time, water use in many cities is approaching, and in some cases exceeding, sustainable limits. Stormwater harvesting has the potential to mitigate a number of these detrimental impacts. However, excessive harvesting of stormwater could also be detrimental to stream health. Therefore, a study was undertaken to test whether typical stormwater harvesting scenarios could meet the dual objectives of (i) supplying urban water requirements, and (ii) restoring the flow regime as close as possible to ‘natural’ (pre-developed). Melbourne and Brisbane, which have different climates, were used along with three land use scenarios (low, medium and high density). Modelling was undertaken for a range of flow and water quality indicators. The results show that using these typical harvesting scenarios helped to bring flow and water quality back towards their pre-developed levels. In some cases, however, harvesting resulted in an over-extraction of flow, demonstrating the need for optimizing the harvesting strategy to meet both supply and environmental flow objectives. The results show that urban stormwater harvesting is a potential strategy for achieving both water conservation and environmental flows.

Keywords Environmental flows; stormwater harvesting; stormwater reuse

Introduction

Urbanization degrades natural waterways through changes to flow patterns, water quality, loss of riparian vegetation, and in many situations, replacement of the natural channel with either underground pipes or lined constructed channels (e.g. Booth and Jackson, 1997; Hatt et al., 2004; Walsh et al., 2005a, b). At the same time, water use in many cities throughout the world is rapidly approaching sustainable limits (Mitchell et al., 2004). For this reason, alternative water supplies are being considered, including the harvesting of urban stormwater (Hatt et al., in press). Despite common concerns about storage requirements, stormwater harvesting has been shown by Mitchell et al. (2005) to be a viable alternative.

In the rural context, much attention has been paid, in recent times, to the concept of ‘environmental flows’, which, at its broadest level, refers to the requirements of organisms and ecosystems for an amount and variability of flow within a channel (Poff and Allan, 1995). Defining exactly what is the flow regime necessary to sustain a particular organism or community is difficult, but recent gains have been made in defining key indicators, or ‘flow events’, and their required frequency or duration (Stewardson and Gippel, 2003). In the rural context, the principal focus is on restoring flows which have been depleted by high levels of extraction and storage (Close, 1990).

In the urban context, the problem is different, with flows increased due to increased imperviousness, and drainage connection within the catchment (Walsh et al., 2005b). Resulting changes to flow regimes in the urban context include: increased frequency of...
stormwater flow events (thus reduced ‘inter-event period’) (Ladson et al., 2005; Walsh et al., 2005b), increased peak flows across a wide range of Average Recurrence Intervals (ARIs) (Leopold, 1968), alterations to base flow pattern (usually reduced, but sometimes increased, particularly where anthropogenic sources are introduced) (Rose and Peters, 2001), increased total runoff volume, and increased variability in flow rate (Konrad et al., 2005). Increased pollutant loads are also expected (Hatt et al., 2004; Soranno et al., 1996) with urbanization. The consequence of changes to these indicators is degradation in the structure, composition and function of aquatic ecosystems (Booth and Reinelt, 1994; Roy et al., 2003; Walsh et al., 2005b; Walsh et al., 2000).

Stormwater managers are thus searching for techniques to reduce these indicators back to their pre-development. Stormwater harvesting has the potential to serve this role, in addition to its benefits in providing an alternate water supply. However, it is also acknowledged that harvesting excessive amounts of urban stormwater runoff could be detrimental to stream health if critical aspects of the flow regime were changed away from, rather than toward, their pre-urban condition.

Given this background, the aims of this study were to examine the impacts of stormwater harvesting, for a range of typical land uses and water demand types, on a suite of hydrologic and water quality indicators which have been shown to be important predictors of aquatic ecosystem health. This work was undertaken as part of a much broader study on the application of integrated stormwater treatment and reuse (Mitchell et al., 2007).

Methods
The Model for Urban Stormwater Improvement Conceptualisation (MUSIC) (Cooperative Research Centre for Catchment Hydrology, 2005) was used (Figure 1) to investigate the impact of a range of stormwater harvesting scenarios on flow and water quality.

Analysis was undertaken for two cities, with distinctly different climates: Brisbane (sub-tropical, 1,772 mm mean annual rainfall) and Melbourne (temperate, 653 mm mean annual rainfall). Long-term historical climate data (1950–1999) were used for the assessment. Two different catchment types were examined: those with no baseflow (i.e. small upland catchments, with ‘deep seepage’ to groundwater, whose only discharge to streams is through pervious- or impervious-area runoff) and those with permanent baseflow (i.e. large lowland catchments, where flow to streams comes from either or both of runoff, and baseflow contribution from groundwater).

The stormwater harvesting scenarios were based on three representative development patterns of Australian cities, for peri-urban, traditional suburban and inner high density areas (14, 42 and 70% imperviousness respectively). Harvesting demand was matched to...
the development patterns, based on typical demand scenarios for these cities (Table 1) (Mitchell et al., 2005). Comparisons were made by modelling three scenarios: (a) ‘natural’ or pre-developed, (b) developed (according to the development scenarios in Table 1) and (c) developed with stormwater harvesting applied (according to the development and water demand scenarios in Table 1).

Stormwater harvesting was provided by a stormwater pond with a surface area of 1% of the catchment area (a unit-approach was taken, and thus the modelled catchment was 1 ha), a permanent pool depth of 1 m and an extended detention depth of 1 m (assuming vertical sides). The pond was modelled with an infiltration loss of 0.18 mm/hour (typical of the heavy clay that will line many stormwater ponds), and an evaporative loss set to equal potential evapotranspiration. The stormwater pond was designed to have a detention time (of the extended detention volume) of 70.5 hours, typical of Australian design guidelines for stormwater management (Wong, 2003).

The performance of each scenario was assessed against a range of environmental flow and water quality indicators. The indicators are explained in Table 2, and allow different aspects of the flow regimes to be considered. For example, use of the peak flow indicators has been commonly considered over the last decade or so, as a good indicator of geomorphic and/or ecological disturbance (Wong et al., 2000), whilst more recent research has demonstrated, based on empirical evidence, that the frequency of surface runoff to streams may be a better predictor of ecological condition (Walsh et al., 2005b). Other indicators tested identify changes to the total volume of flow or total mass of pollutants, and the frequency and duration of specific flow conditions. The results are presented as the ratio of the post:pre-development value. For example, if the pre-development (i.e. natural) annual runoff volume is 10 ML/yr, and the post-developed is 20 ML/yr before application of stormwater reuse, and 15 ML/yr with reuse, the ratios would be 2.0 and 1.5, respectively.

Results
As expected, urbanization results in major alterations to both the flow and water quality regime of the catchment. For example, even low density (14% impervious) development (Figure 2) leads to runoff frequency increasing by 10 fold in Melbourne, and 18 fold in Brisbane, whilst runoff volume nearly doubles in both cities. Consequently, the length of low-flow periods is much shorter. Pollutant loads are also greatly increased, particularly for TN and TP. In the dense urban context (72% impervious, Figure 3) flow and water quality indicators show even greater deviation from the pre-developed case.

Application of the stormwater harvesting scenarios as described in Methods results, in most cases, in substantial restoration towards the pre-developed flow and water quality. For example, runoff frequency in Melbourne (which has a relatively uniform rainfall distribution throughout the year) is restored to less than twice the natural frequency in the case of Melbourne low-density development, and is restored almost exactly to the natural

<table>
<thead>
<tr>
<th>Location</th>
<th>Demand pattern</th>
<th>% Imperviousness</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Peri-urban: 14%</td>
</tr>
<tr>
<td>Melbourne</td>
<td>Constant</td>
<td>237</td>
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<tr>
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<td>2,093</td>
</tr>
<tr>
<td>Brisbane</td>
<td>Constant</td>
<td>628</td>
</tr>
<tr>
<td></td>
<td>Seasonal</td>
<td>3,139</td>
</tr>
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</table>

Table 1 Representative catchment impervious and stormwater harvesting patterns for Melbourne and Brisbane
frequency in the dense urban development scenario. The difference is explained by the
greater water demand in the high-density case (resulting in greater frequency of available
freeboard in the storage pond, thus being able to detain runoff more often). Similarly,
pollutant loads are substantially reduced. This removal occurs through two mechanisms;
through the treatment inherent in stormwater ponds (Wong, 2003) and through the har-
vesting of stormwater, leading to the removal of both stormwater volume and its
contaminants.

In Brisbane, however, the challenge of restoring flow and water quality to pre-devel-
opment levels is more difficult, due to the greater rainfall intensities associated with this
sub-tropical climate. For example, whilst total runoff volume increases can be redressed

<table>
<thead>
<tr>
<th>Category</th>
<th>Indicator (and abbreviated name)</th>
<th>Analysis timestep</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Runoff</td>
<td>Total runoff</td>
<td>daily</td>
<td>ML/yr</td>
</tr>
<tr>
<td></td>
<td>Frequency of surface runoff</td>
<td>daily</td>
<td>times/yr</td>
</tr>
<tr>
<td>Flow spells</td>
<td>Duration (total time of low flows)</td>
<td>daily</td>
<td>days/yr</td>
</tr>
<tr>
<td></td>
<td>Average length of low-flow spells</td>
<td>daily</td>
<td>days in a row (average/yr)</td>
</tr>
<tr>
<td></td>
<td>Number of low-flow events</td>
<td>daily</td>
<td>events/yr</td>
</tr>
<tr>
<td></td>
<td>Duration (total time of high flows)</td>
<td>daily</td>
<td>days/yr</td>
</tr>
<tr>
<td></td>
<td>Average length of high-flow spells</td>
<td>daily</td>
<td>days in a row (average/yr)</td>
</tr>
<tr>
<td></td>
<td>Number of high-flow events</td>
<td>daily</td>
<td>events/yr</td>
</tr>
<tr>
<td>Peak flow</td>
<td>Q1 month</td>
<td>hourly</td>
<td>m³/sec</td>
</tr>
<tr>
<td></td>
<td>Q3 month</td>
<td>hourly</td>
<td>m³/sec</td>
</tr>
<tr>
<td></td>
<td>Q1 year</td>
<td>hourly</td>
<td>m³/sec</td>
</tr>
<tr>
<td></td>
<td>Q1.5year</td>
<td>hourly</td>
<td>m³/sec</td>
</tr>
<tr>
<td></td>
<td>Q5year</td>
<td>hourly</td>
<td>m³/sec</td>
</tr>
<tr>
<td>Flow duration curve</td>
<td>Integral of the flow duration curve</td>
<td>hourly</td>
<td>Integral of curve</td>
</tr>
<tr>
<td>Pollutant loads</td>
<td>Total Suspended Solids (TSS) load</td>
<td>daily</td>
<td>kg/ha/yr</td>
</tr>
<tr>
<td></td>
<td>Total Nitrogen (TN) load</td>
<td>daily</td>
<td>kg/ha/yr</td>
</tr>
<tr>
<td></td>
<td>Total Phosphorus (TP) load</td>
<td>daily</td>
<td>kg/ha/yr</td>
</tr>
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</table>

Figure 2 Relative changes to flow and water quality indicators from natural conditions for a catchment with
no permanent baseflow (i.e. typical small upland catchment). The post-development ratio of the pre-
developed level (which is denoted by the dotted line) is shown for (a) urban development at 14%
imperviousness, and (b) after application of stormwater harvesting. The peak flow indicators for 1 and
3 month ARI have not been calculated, because at an hourly timestep for a catchment with no baseflow,
they are zero for the pre-development case.
in the low-density development (Figure 2), it remains relatively high (3.5 times natural) in the dense urban case. The differences between urban development densities are even more apparent, and the application of stormwater harvesting actually increases the frequency of runoff in the 70% impervious case. This occurs because the highly impervious catchment, combined with the intense rainfall pattern in Brisbane, results in the stormwater pond spilling frequently. When the pond spills, it is likely to discharge “runoff” to the stream over several days (a function of the flow attenuation inherent in the storage), meaning that runoff occurs over more days than if the water had been allowed to flow un-attenuated to receiving waters. However, the attenuation does reduce peak flows.

The stormwater harvesting regime modelled for the dense urban catchment in Melbourne (with high levels of daily demand: Table 2) can result in over-harvesting, such that lower than total pre-development runoff is released downstream. In Brisbane, this is not the case, again because the short-duration, high-intensity rainfall pattern results in regular spills of the stormwater harvesting pond. Similarly, pollutant loads can be reduced to at or below natural levels in both small and large catchments in Melbourne, but not in Brisbane. The presence of baseflow within a catchment generally makes the meeting of natural flow targets somewhat easier (Table 3), because the flow regime is more uniform, increasing the ability of the pond to detain water for distribution.

**Discussion**

These results provide confidence to urban water managers that stormwater harvesting can be applied in typical urban areas, and help in the dual objectives of (a) reducing demand on potable water resources, and (b) restoring flow and water quality to pre-development levels. However, it is clear that a simple “one size fits all” strategy will not be appropriate in all cases. For example, the standard “un-optimised” modelled stormwater harvesting scenario reduces total runoff too far (below pre-development levels) in the Melbourne peri-urban and high density scenarios, and not enough in the Melbourne traditional...
Table 3: Summary of selected environmental flow and pollutant load indicators for Brisbane and Melbourne. Table gives the ratio of the Developed and Developed with Harvesting cases to the Pre-Developed ('natural') level. Results are presented for (a) two catchment types - a small upland catchment with no permanent drainage line (and thus no baseflow), and a large lowland catchment, where all infiltration to groundwater becomes baseflow - and (b) three levels of urban density (identified by imperviousness). The 'target value' in each case is 1, which is the pre-developed level. Cases in **bold** represent cases where stormwater harvesting moved the indicator further away from natural; cases in *italics* represent cases where the indicators were reduced below natural by stormwater harvesting. The peak flow indicators for 1 and 3 month ARI have not been calculated, because at an hourly timestep for a catchment with no baseflow, they are zero for the pre-development case. Indicators for runoff frequency in catchments with baseflow have not been calculated, since no meaningful comparison can be made downstream of a stormwater re-use pond, where inflowing runoff and baseflow have become mixed.

<table>
<thead>
<tr>
<th>Imperviousness</th>
<th>City</th>
<th>Total runoff</th>
<th>Environmental flow indicators</th>
<th>Pollutant load indicators</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Frequency of runoff</td>
<td>1 year</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Devel’d Harvest</td>
<td>Devel’d Harvest</td>
<td>Devel’d Harvest</td>
</tr>
<tr>
<td>14</td>
<td>Brisbane</td>
<td>1.7</td>
<td>1.0</td>
<td>18.4</td>
</tr>
<tr>
<td></td>
<td>Melbourne</td>
<td>1.7</td>
<td>0.7</td>
<td>10.1</td>
</tr>
<tr>
<td>42</td>
<td>Brisbane</td>
<td>3.1</td>
<td>2.0</td>
<td>18.4</td>
</tr>
<tr>
<td></td>
<td>Melbourne</td>
<td>3.1</td>
<td>1.6</td>
<td>10.4</td>
</tr>
<tr>
<td>70</td>
<td>Brisbane</td>
<td>4.5</td>
<td>3.4</td>
<td>18.4</td>
</tr>
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<td></td>
<td>Melbourne</td>
<td>4.5</td>
<td>0.2</td>
<td>10.3</td>
</tr>
<tr>
<td>14</td>
<td>Brisbane</td>
<td>1.4</td>
<td>0.7</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td>Melbourne</td>
<td>1.4</td>
<td>0.7</td>
<td>n/a</td>
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<tr>
<td>42</td>
<td>Brisbane</td>
<td>2.1</td>
<td>1.4</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td>Melbourne</td>
<td>2.2</td>
<td>1.2</td>
<td>n/a</td>
</tr>
<tr>
<td>70</td>
<td>Brisbane</td>
<td>2.9</td>
<td>2.2</td>
<td>n/a</td>
</tr>
<tr>
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<td>Melbourne</td>
<td>3.0</td>
<td>0.2</td>
<td>n/a</td>
</tr>
</tbody>
</table>
suburban and all Brisbane scenarios. Moreover, the 3-month ARI peak flow is not ade-
quately reduced in most cases (particularly at higher levels of imperviousness).

This suggests that flow and water quality management need to involve a combination
of flow management measures (such as flow detention, infiltration and enhancement of
evapotranspiration) along with stormwater harvesting. Similarly, design and operation of
the stormwater harvesting system needs to be optimised to get the best mix of results,
across all flow and water quality indicators that are believed to be important. The sim-
plest approach would be to adjust the size of the stormwater harvesting pond, taking into
account the (perhaps conflicting) objectives of environmental flows, and security of
stormwater supply.

More sophisticated approaches may involve changing either the (a) configuration of
the stormwater pond, or the (b) harvesting regime. For example, the outlet of a storm-
water pond may be designed to replicate the pre-development peak flows for a range of
recurrence intervals. On the other hand, stormwater demand may be altered. For example,
harvesting rules could be established to allow stormwater to be taken only when it will
not stop environmental flow targets being met.

Future research will examine these possibilities, and attempt to optimise stormwater
harvesting regimes for various climates, catchment sizes and urban densities. One other
significant issue remains unanswered by this study; we have assumed that the pursuit of
the ‘natural’ pre-developed flow regime is the appropriate target. Given that in existing
urban areas, waterways are already grossly disturbed, and have most likely enlarged to
reflect the post-development flow regime, it may be that the ecologically-optimal flow
regime is now some hybrid between the pre- and post-development regime. In future
work, hydraulic analysis will be undertaken to determine the influence of channel mor-
phology on environmental flow requirements and the influence of changes in flow regime
on channel morphology.

Conclusions

Urbanization degrades waterways by changes to flow and water quality of runoff. Potable
water demand from urban areas also places pressure on water resources, which in turn
often impact on the health of aquatic ecosystems. Harvesting of urban stormwater has the
potential to address both impacts. Application of harvesting scenarios in both Brisbane
and Melbourne showed that flow and water quality indicators could be returned to near
pre-developed levels. Brisbane’s sub-tropical climate, with high rainfall intensities, made
this more difficult, particularly for total runoff and peak flow targets. On the other hand,
application in Melbourne revealed that over-extraction is possible for certain combi-
nations of development level and water demand, potentially starving the stream of the
required environmental flows. Careful consideration is therefore needed in designing a
stormwater harvesting scheme which optimises potable supply substitution benefits with
environmental flow targets. This may require stormwater harvesting to be implemented
within a suite of other flow and water quality management regimes.

References

1077–1090.

Booth, D.B. and Reinelt, L.E. (1994). Consequences of urbanization on aquatic systems-measured effects,


