Restoring natural flow regimes: the importance of multiple scales

La restauration d'un régime d'écoulement naturel : la mise en œuvre à plusieurs échelles

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RÉSUMÉ

L'urbanisation induit de fortes modifications du régime d'écoulement avec des conséquences négatives pour l'écologie, la qualité de l'eau et la géomorphologie des milieux aquatiques. La restauration d'un régime plus naturel est indispensable pour un bon état écologique des cours d'eau urbains. Cette étude a pour objectif d'évaluer les performances hydrologiques d'un bassin d'infiltration à l'échelle du quartier et de récupérateurs d'eau à l'échelle de la parcelle. Notre évaluation a utilisé une série constante de mesures de débit d'un cours d'eau naturel de référence se situant à proximité, afin de comparer les performances des ouvrages en termes de leur reduction du volume ruissellé et de sa fréquence, de la durée et de la magnitude du débit de pointe, en parallèle de leur restauration du débit d'étiage. Les différentes techniques différaient en termes de leur impact sur le régime hydrologique : les récupérateurs d'eau à l'échelle de la parcelle semblent capables de restaurer un volume de ruissellement similaire à celui du cours d'eau naturel, alors que le bassin d'infiltration met en valeur la restauration du débit d'étiage. Cette étude démontre qu'une combinaison de différentes techniques, mise en place à toutes les échelles, est nécessaire pour restaurer tous les différents aspects du débit d'écoulement avant aménagement, étant donné que la performance des récupérateurs d'eau est limitée par la demande pour l'eau stockée, alors que la performance du bassin d'infiltration est souvent contrainte par la surface disponible pour sa mise en place.

ABSTRACT

Urbanisation changes flow regimes which negatively impact the ecology, water quality and geomorphology of receiving waters. These flow regimes need to be restored to more natural levels to improve stream health. We measured the performance of precinct scale (infiltration basin) and household scale (water tanks) stormwater retention systems against flow objectives developed from a nearby reference stream. Continuous flow data was used to determine their performance in restoring total volume, frequency, duration and magnitude of high flow events and baseflows. The different systems varied in their ability to meet flow objectives; the infiltration system was able to restore baseflows through filtration, exfiltration and attenuation, while other metrics were reduced but not to predeveloped levels. The tanks reduced runoff volume and event frequency. The individual systems studied could not meet all flow objectives, demonstrating the need for a combination of systems at different scales. We conclude that certain aspects of the flow regime are easier to restore than others and that working at multiple scales is required and that in residential urban areas, the performance of stormwater harvesting systems is limited by demand, while information system performance is commonly limited by space.

KEYWORDS

Harvesting, Infiltration, Monitoring, Rainwater tanks, Retention, Stormwater, Streams, Urban

1 INTRODUCTION

Urban stormwater runoff results in reduced water quality (Hatt et al., 2004), changes to the flow regime (Burns et al., 2012b) and channel morphology (Tillinghast et al., 2011) and destruction of habitat (Vietz, in prep.), leading to a reduction of biodiversity and delivery of ecosystem services (Walsh et al., 2005). Attempts to address these factors often involve riparian and in-stream restoration, or the use of stormwater control measures such as swales, wetlands, ponds and biofiltration systems to attenuate flows and reduce pollutant concentrations. However, these approaches do not necessarily always address the fully range of hydrologic impacts of urbanization (Burns, et al., 2012b), while those that do, are often focussed on managing peak flows and flooding. Booth (2005) highlights the importance of hydrology as a primary stressor, suggest that this needs to be addressed to restore the health of the stream ecosystem (Konrad & Booth, 2005). Importantly, water quality improvement and habitat restoration should not be neglected, particularly as their impact will be amplified as hydrology is managed.

When impervious runoff is conveyed directly to streams via hydraulically efficient drainage paths (e.g. pipes and constructed channels), all aspects of the natural flow regime are altered. Commonly observed effects include:

- Increased total runoff volume. Around 70-90% of rainfall in a natural catchment is evapotranspired (Zhang et al., 2001). As impervious surfaces replace forested areas, evapotranspiration and infiltration decrease, resulting in increases in total runoff volume typically by a factor of five (Fletcher et al., 2007).
- Increased frequency and magnitude of high flows, particularly for frequent events, which while not producing any runoff response in the natural catchment, generate hydraulic stress and delivering polluted waters, in urbanised catchments (Fletcher et al., 2011).
- A reduction in baseflows, brought about by reduced infiltration (Price, 2011). While this can be offset by irrigation or infrastructure leakage, impervious areas must necessarily reduce natural baseflow processes (Walsh et al., 2012)

The relative importance of these hydrologic factors in terms of ecological consequence is still being debated. For example, Steuer *et al.* (2010) found high flow event frequency to be the most ecologically relevant, with average flow magnitude (volume?), high flow magnitude and duration and rate of change of flow also consistently associated with changes in aquatic communities in metropolitan areas across the US. Similarly, Clausen and Biggs (1997) found flood frequency the most useful ecological flow variable in New Zealand streams, with average flow conditions and some measure of variability also significantly related to many biological variables used.

Regardless, the importance of restoring flow regimes to address stream health is increasingly being recognised (DeBusk et al., 2011; Poff et al., 1997; Walsh, et al., 2012). Burns et al. (2012) suggest that this can be achieved by focussing control strategies at-source which promote the harvesting, evapotranspiration and infiltration of stormwater runoff. It is argued that such an approach can help restore the natural levels of infiltration, evapotranspiration and runoff.

Many stormwater control measures are flexible in terms of scale of application (Wong, 2007) and application at multiple scales helps to mitigate against risk of failure (Bertrand et al., 2010; Sénéchal et al., 2010). Small-scale systems have the advantage of minimising catchment area, thus ensuring the flows being dealt with are manageable. Systems at small scale also deliver benefits in terms of integration into the private landscape, as well as facilitating the harvesting of water at the household scale. However, larger systems, implemented at precinct scale, are necessary to capture both runoff from public impervious areas and to deal with overflows from systems located upstream. It is thus implementation at a combination of scales that is likely necessary to be successful in mitigating changes to the flow regime from urbanisation.

In this study, therefore, we examine the performance of household scale systems (rainwater tanks), and a precinct scale system (a vegetated infiltration basin) in terms of their impact on the flow regime. We compare these flow regimes with reference conditions from a nearby healthy stream. We also discuss improvements to these systems and suggest that, in time, it may be possible to restore some or even all of the hydrologic indicators of predeveloped flow regimes, through careful application of stormwater control measures at a range of scales.

2 METHODS

We measured the performance of (i) precinct scale and (ii) household scale stormwater retention systems against flow objectives developed from a nearby reference stream. The **precinct scale** system was a 100m^2 infiltration system, treating runoff from a 9,800 m^2 catchment, while two **household scale** sites comprised rainwater tanks collecting roof runoff (Figure 1). Continuous flow data was obtained from upstream and downstream of these systems and the performance of these systems was then assessed using a range of flow metrics; runoff volume, frequency and magnitude of event flows, along with baseflow rate. Continuous flow data from the reference stream provided target values for these flow metrics. All sites monitored were located in the Dandenong ranges on the urban fringe, approximately 35km East of Melbourne, Australia (Figure 1). This area is a low mountain range with an average annual rainfall of between 1000-1500mm (www.bom.gov.au).

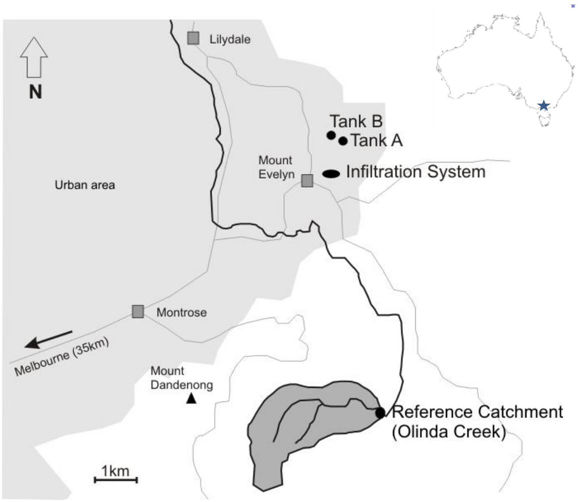

Figure 1. Location of study area. Study sites located within Little Stringybark Creek catchment.

2.1 Site descriptions

Precinct scale

The infiltration system treats runoff from a 9800m^2 impervious catchment comprising of roads (6170m^2), roofs (3050m2) and some other paved areas (580m^2). The system has a surface area of 100m^2, thus being only 1% of the catchment area (due to space constraints on the site). It is vegetated with indigenous sedges and shrubs and is not lined, allowing exfiltration of water. The extended detention depth is 300mm while below the surface there is 400mm of filter media (loamy sand), a 200mm transition layer (sand and fine gravel) and 400mm of coarse aggregate (scoria) at the base. Riser pipes control filtered flow from the bottom of the system, allowing water to drain to 100mm below the surface, to prevent long ponding periods (Figure 2). Point infiltration rates of the surrounding soil ranged from 2 to 17 mm/hr.

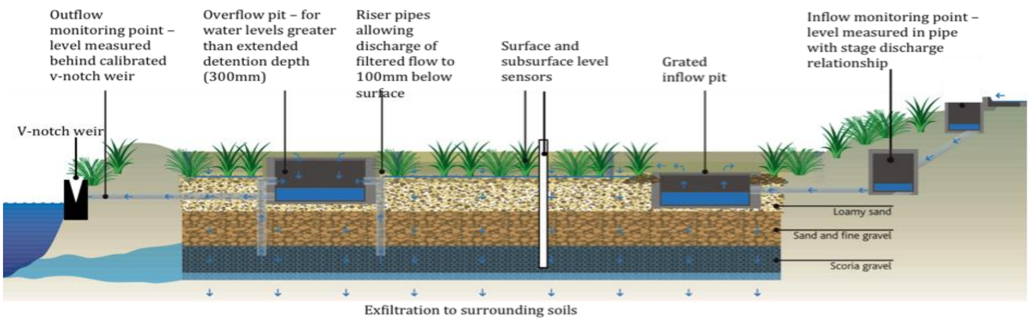

Figure 2. Cross-section of the infiltration system treating the precinct scale catchment.

Household scale

The two tanks monitored are on residential properties. Household A has a 5500 L tank connected to 90 m^2 of a 253 m^2 roof. Household B has a 9000 L tank connected to 316 m^2 of a 327 m^2 roof. It is important to note that flow from parts of the roof (163 m^2 and 11 m^2, respectively) do not drain to the tanks. These flows are thus ignored in study, as our aim was to assess the performance of the tanks in relation to their catchment areas. Mean daily use from the tanks was measured at 134 L/day for tank A (toilet, laundry and hot water) and 323 L/day for tank B (all internal uses) (Burns et al., 2012a).

Reference catchment

The reference stream, Olinda Creek, has a catchment area of just over 9 km^2, most of which is forested. While 3.9% of the catchment is impervious, only 0.12% is connected directly to the stream, meaning that its flow regime is essentially natural. The catchment is approximately 5km south of the experimental sites, making it an effective reference.

2.2 Monitoring setup

Precinct scale

At the infiltration system, inflow and outflow were measured, as well as water level above and below the vegetated surface. The inflow was calculated from measured water level in the inlet pipe and a stage discharge relationship developed from manual discharge measurements. These manual discharges were volumetrically calibrated during the monitoring period, while the water level in the inlet pipe was continuously measured using an ultrasonic level sensor (Microsonic pico100WKI). High flow rates beyond our stage discharge curve were extrapolated using both modelled flows and theoretical flow estimates as a guide. The outflow was calculated using a compound v-notch weir in the outlet pipe (Figure 2). This weir had been calibrated in the laboratory and the water level in the outflow pipe was measured with an ultrasonic level sensor (Microsonic mic35IUTC), just upstream of the weir. The water levels above and below the infiltration basin were measured and recorded by Odyssey water capacitance probes (Figure 2). All data was collected at 1-minute intervals.

Household scale

Flow rates into and out of the tanks studied were modelled using MUSIC software, from the roof area (and an assumed initial loss of 0.6 mm) and 6-minute rainfall data collected approximately 1 km south of the study sites and daily water use measured from the tanks by Burns et al. (Burns, et al., 2012a).

Reference catchment

Water level was continuously measured (6-minute timestep) in Olinda Creek from early 2009 by an Odyssey water capacitance probe. A rating curve developed from 19 manual discharge measurements made during 2012 (with Sontek Flowtracker) was used to estimate flows. Rainfall in the Olinda Creek catchment was obtained using rainfall data from the nearest rain gauges (Melbourne Water gauges 586090 and 229690 and Bureau of Meteorology gauges 086372 and 086266), and Thiessen polygons to estimate the rainfall within the catchment.

2.3 Data analysis

Total volume

Inflow and outflow volumes from the tanks and infiltration system were calculated. Infiltration and evapotranspiration rates from the infiltration system were estimated using the sub-surface level data during dry weather periods (when there was no inflow or outflow from the system). To calculate the infiltration rate, the overnight (10pm to 5am, when evapotranspiration could be assumed to be minimal) level change was recorded for almost 100 nights and plotted against water level in the system. The additional dry weather level change during the daytime (9am to 4pm) of the same period was attributed to evapotranspiration.

Event flow frequency and duration

A threshold of three times the median daily flow was used to distinguish high flow events, following Clausen & Biggs (1997). From this threshold, a number of variables could be calculated including; the number of times the threshold is exceeded or the flood frequency (FRE3), the mean duration (DUR3) of these events, and the total time flows were above this threshold (TIM3). For both the precinct and household scale catchments, the median daily flow was 0. Therefore, the threshold for these catchments was based on the scaled daily median flow from the reference stream. The threshold for the reference stream was 480 L/sec (0.19 L/hr/m^2). The scaled threshold for the infiltration system and households A and B was 0.52L/sec, 0.005L/sec and 0.017L/sec respectively.

Peak flows

Mean, median, 90th, 95th and 99th percentile peak flows were calculated upstream and downstream of treatment systems and for the reference stream. For events where no outflow was recorded a peak flow of 0 was used in the analysis.

Base flows

The contribution of low flows below the defined high-flow threshold was also investigated. Both the total volume and duration of these low flows were calculated, as were the periods of 0 flow.

Data was analysed from all sites during the 265 days from 23rd November 2011 to 14th August 2012. During this period 997mm of rain was recorded in the Mt Evelyn rain gauge near the infiltration system and tank treatment systems, and 928mm fell in the Olinda Creek catchment (reference stream).

3 RESULTS

The urban catchments (Tank A & B and the infiltration system) are much more responsive to rainfall, even downstream of the stormwater control measures, and with much lower baseflows (Figure 3).

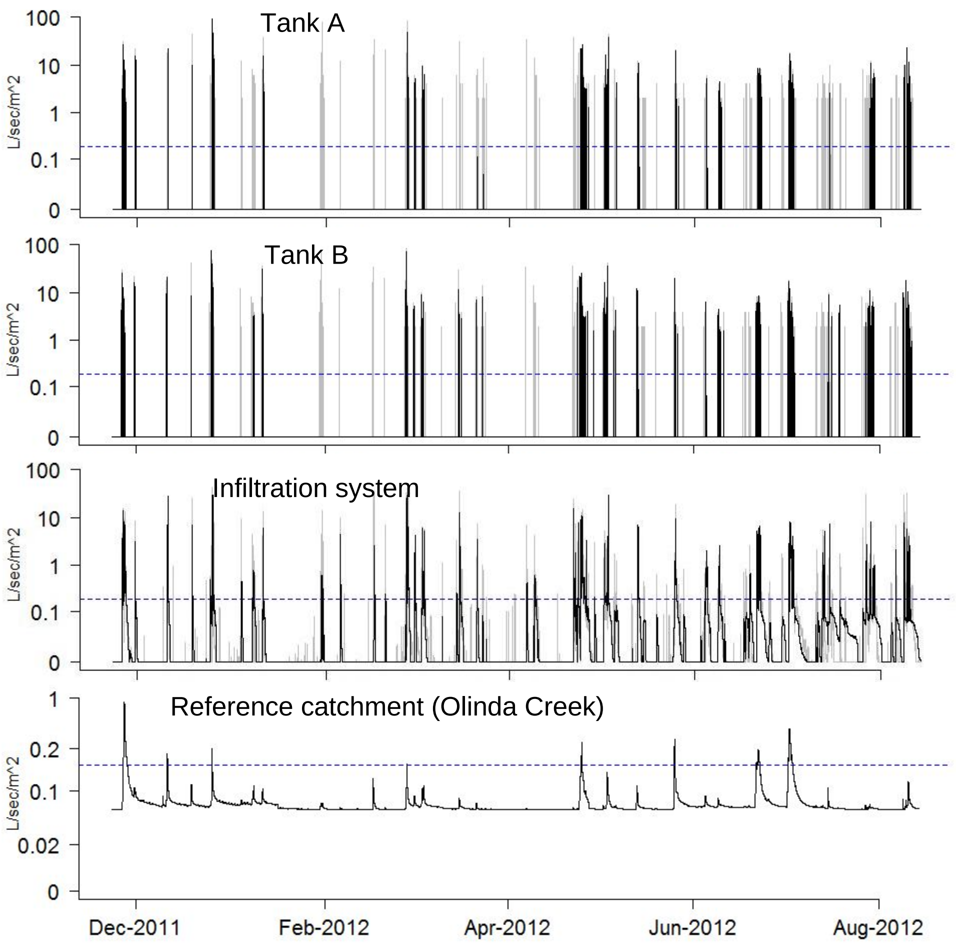

Figure 3. Hydrographs of all catchments (Nov 2011 to Aug 2012). For the catchments with treatment systems, inflows are grey and outflows are in black. The blue dashed line is the threshold (3 x median flow) used to separate event flows. Flows normalised by catchment area to L/hr/m^2 (or mm/hr). Note different scale on y-axis for reference catchment.

Total volume

Total runoff volumes were reduced by all systems to varying degrees - tank A 43%, tank B 31% and infiltration system 8% (Table 1). However, runoff as a percentage of rainfall was still much higher than the reference catchment (Table 1 - percentages in bold), even after treatment. Volumes for the infiltration system did not include two very large events that were unable to be measured (with flows above the rating table range). The rainfall for these 2 events was also removed for calculations.

Table 1 - Runoff from reference stream and urban catchments upstream and downstream of treatment systems.

Catchment	Flux volume (m^3)	Flux/area (mm)	Flux (% of rainfall)	Recorded rainfall (mm)
Reference (Olinda Creek)	600740	66.3	**7.1%**	928.1
Runoff household A upstream	80	885.6	89%	997.0
Runoff household A downstream	45	495.6	**50%**	
reduction	*44%*			
Runoff household B upstream	275	869.3	87%	997.0
Runoff household B downstream	190	600.9	**60%**	
reduction	*31%*			
Infiltration system upstream*	6598	673.3	77%	879.6
Infiltration system downstream*	6039	616.2	**70%**	
Exfiltrated by system	873	89.1	8.9%	997.0
Evapotranspired by system	133	13.6	1.4%	
reduction	8%			

*2 extreme events removed

Event frequency and duration

Table 2 describes several event measures and their change as a result of the control measures. The number of events above the threshold (FRE3) from the urban catchments were reduced by 50-60%, but still far more than the 9 recorded in the reference stream. The total time of event flow (TIM3) and the volume of event flow (VOL3) were also reduced by treatment, but fell well short of the reference catchment. Interestingly, the mean duration of events (DUR3) actually increased, a consequence of flow detention.

Table 2. Event frequency and duration from reference stream and urban catchments upstream and downstream of treatment systems (* = 2 extreme events omitted, due to measurement error).

Catchment	FRE3 (events > threshold)	DUR3 (mean duration > threshold, hrs)	TIM3 (total event time, days)	VOL3 (total event vol, mm)
Olinda creek	9	12.6	4.7	35.4
Household A upstream	876	0.24	8.6	885.6
Household A downstream	337	0.41	5.8	495.6
difference	*62%*	*-71%*	*33%*	*44%*
Household B upstream	876	0.24	8.6	869.3
Household B downstream	407	0.43	7.2	600.9
difference	*54%*	*-79%*	*16%*	*31%*
Infiltration system upstream*	196	2.5	21	604.7
Infiltration system downstream*	84	5.2	18	525.4
difference	*57%*	*-108%*	*13%*	*13%*

Event peak flows

Although peak flows were reduced by the treatment systems, many were still an order of magnitude higher than the reference stream (Table 3). A 100% reduction in median flows (Table 3) highlights the removal of small peaks altogether, while lower reductions for the higher percentile peak flows demonstrate the inability of the systems to reduce very high peak flows from large events. In these cases the systems were filled to capacity and the peak flow rates thus often unaffected.

Table 3 - Peak flows upstream and downstream of treatment systems and peak flow reduction (* = 2 extreme events omitted, due to measurement error).

Catchment	**Mean peak flow ($L/m^2/hr$)**	**Median peak flow ($L/m^2/hr$)**	**90th percentile peak flow ($L/m^2/hr$)**	**95th percentile peak flow ($L/m^2/hr$)**	**99th percentile peak flow ($L/m^2/hr$)**
Olinda creek	0.4	0.3	0.6	0.7	0.9
Household A upstream	4	2	8	12	35
Household A downstream	2	0	5	8	21
difference	*58%*	*100%*	*37%*	*29%*	*39%*
Household B upstream	5	2	10	15	42
Household B downstream	3	0	7	12	26
difference	*50%*	*100%*	*30%*	*21%*	*39%*
Infiltration system upstream*	4	1	11	26	36
Infiltration system downstream*	2	0	6	8	29
difference	*52%*	*100%*	*47%*	*68%*	*19%*

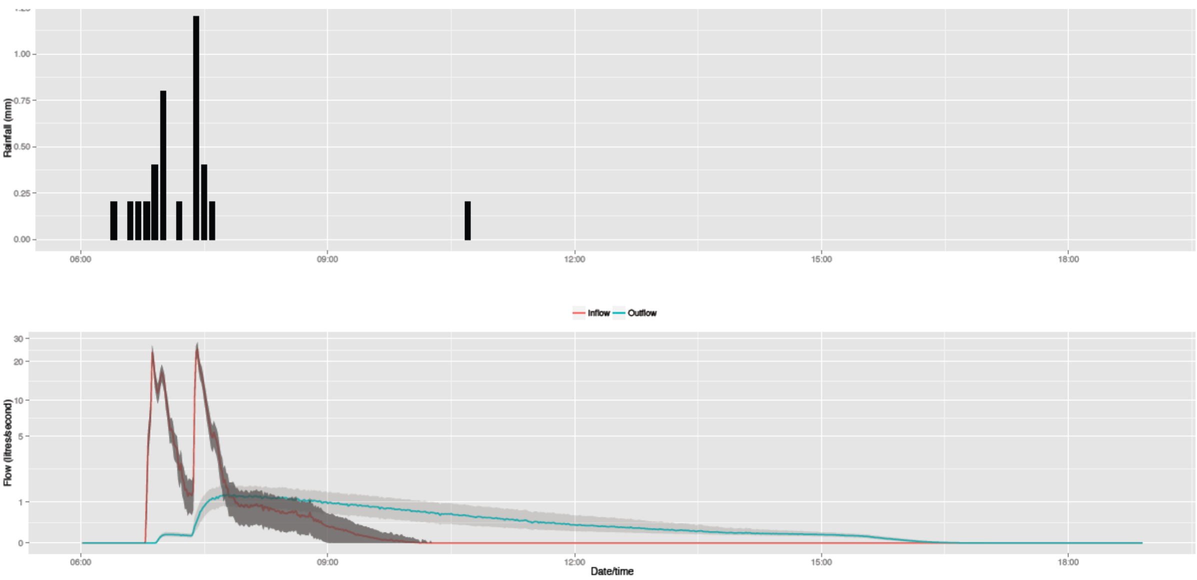

Figure 4. Hydrograph infiltration system, showing flow attenuation. The dark grey peaks of the inflow are reduced at the outflow (light grey). The error bounds (based on calculated uncertainties in flow measurement) are shown as the shaded area around each hydrograph.

Baseflow contribution

At the infiltration system, the volume of runoff delivered below the defined event threshold was increased by 32% at the outlet. This consists of 15% of the total outflow volume, while 53% of the reference catchment runoff is delivered below the threshold. However, this does not include a similar volume (13% of inflow volume) exfiltrated by the system which occurred constantly at a very low rate. The period of no flows was also increased (21%) by the infiltration system at the outlet. Again, it is assumed that a large proportion of the exfiltrated flows would have contributed to baseflow most of the time. Evidently, the tanks did not contribute any flows at or below the threshold, increasing the duration of 0 flows.

4 DISCUSSION

4.1 Ability to deliver natural flow regimes

Volume reduction targets appear to require a combination of harvesting and infiltration, with infiltration systems alone unable to retain the required volume of water. However, the infiltration system in this case study, despite being small, was effective in meeting baseflow restoration objectives. Conversely, rainwater tanks, serving only as retention systems, can only contribute to meeting flow volume, magnitude and frequency reduction objectives, servicing no benefit in terms of restoring the timing or amount of baseflows.

At the precinct scale, the volume exfiltrated (13%) was within the recommended range (of 10-30% of rainfall) provided by Walsh et al. (2012). In the situation where a larger amount of infiltration was required, design modifications such as an increased area or ponding volume would be required. In this case study, the system was relatively small (1% of its impervious area), being much smaller than other systems in the area (Hamel et al., 2012), given the relatively low permeability soils in the area. However, the low permeability soils in this area served a benefit, in ensuring that the system never dried out, thus returning a perennial baseflow contribution to the stream. Runoff frequency (FRE3) was reduced by over 50% in the precinct-scale infiltration system, despite its small size, but it is important to note that this frequency was still greatly above the reference condition, meaning that the frequency of disturbance to the receiving water would still be considerably greater than natural. However, the total duration of event flow was slightly reduced (with almost all events of less than 5 mm completely retained by the system). We estimate that in this catchment – *without any upstream retention systems* – this infiltration system would have been required to be around 5% of its catchment to completely return high flow metrics to their natural level.

At the household scale, the rainwater tanks reduced volume by around 30-40%, thus going a reasonable way to meeting the required reduction of 70-90% to meet natural levels (Walsh et al. 2012). The performance of the household-scale tanks was limited by demand, despite household B using their tank for all indoor uses. This case-study shows the difficulty in meeting flow reduction targets in lower density catchments, where the ratio of inhabitants: roof area is low (ie. due to large houses). In denser urban environments, where apartments and townhouses are more common, greater volumetric reductions could be achieved. However, other design modifications could also be effective, such as the use of the rainwater tank for passive irrigation (Burns, et al., 2012a), whereby a proportion of the tank 'leaks' to the garden, thus increasing the tank's effective storage volume, as well as contributing to baseflows, which are otherwise not helped by tanks. Overflow of the tank into an infiltration system at the allotment could be similarly effective.

4.2 Optimisation of multiple scales

The systems in this study showed different performances against different objectives. For example, tanks were better able to reduce runoff volume, while the infiltration system was able to exfiltrate and contribute to baseflow. This provides opportunities to use a variety of systems in a catchment to achieve pre-developed flow regimes. Reducing runoff volume is one of the biggest challenges to returning a more natural flow regime. With the loss of evapotranspiration causes by urbanisation, alternative approaches are required. Harvesting at the allotment-scale provides a sensible strategy, because the water is harvested close to where it is needed. Despite the highly distributed nature of such systems, recent studies suggest that the use of energy by distributed rainwater harvesting is relatively low (Gardner et al., 2006). However, harvesting at larger scales should not be ignored, provided it is undertaken before water gets to a waterway; extraction from a waterway will not result in protection of the waterway from pollution and flow change, and in many cases is likely to result in baseflows being extracted, unless careful consideration of this is made in the design (Knights & McAuley, 2009). Stormwater control at the precinct scale has the advantages of grouping multiple impervious surfaces. Indeed, meeting flow objectives with allotment scale measures alone will not be possible (Burns et al., 2010; Walsh et al., 2008), as impervious areas associated with roads and public spaces will remain untreated. A combination of measures is thus required, and this has the advantage of dispersing the many related benefits – such as biodiversity, landscape aesthetics (Van Roon, 2005) and microclimate amelioration (Endreny, 2008) throughout the urban landscape, thus maximising the benefit to communities. Based on the empirical investigation in this study, we hypothesise that a combination of allotment, streetscape and precinct-scale stormwater control measures should be to deliver a flow regime close to that of the pre-developed state. Hamel & Fletcher (*this volume*) investigate this hypothesis further in a modelling study.

4.3 Selection of metrics

In this study we have used metrics related to a number of components of the flow regime considered to be ecologically important (Poff, et al., 1997), including the frequency and duration peak flows, as well as the duration and volume of baseflows. Since achieving these only becomes possible once the volume of runoff is reduced (Walsh *et al.,* 2012), this metric is also important. We thus suggest that stormwater management strategies should be measured against a range of flow objectives. Lastly, we reiterate that other factors – particularly water quality – remain important drivers of ecosystem health. Stormwater strategies should thus be assessed against a suite of water quality and flow targets, if receiving waters are to be protected.

5 CONCLUSION

In this study we investigated the performance of different stormwater control measures at both allotment and precinct scale, in terms of their ability to return important aspects of the flow regime (total volume, peak flows, base flows) towards their natural level. The treatment systems studied were able to restore different aspects of the flow regime. The precinct-scale infiltration system was able to restore baseflows while the allotment-scale tanks were better able to reduce runoff volumes. Peak flows and event frequency and duration were also reduced, although not to the levels measured in the reference stream. We conclude that returning natural flow regimes – along with water quality – requires stormwater control measures applied at a range of scales, with a complementary mix of retention and infiltration-based techniques. We also conclude that stormwater strategies should be assessed against a range of flow and water quality metrics, rather than relying on singular measures, such as peak flow rates.

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