To be refereed

New generation stormwater management objectives for stream protection: implementation at multiple scales to restore a small stream.

Christopher J Walsh,

Department of Resource Management and Geography, The University of Melbourne

Tim D. Fletcher, Belinda E. Hatt, Matthew Burns

Centre for Water Sensitive Cities, Department of Civil Engineering, Monash University

Correspondence: cwalsh@unimelb.edu.au

Abstract:

Urban stormwater runoff is increasingly being recognized as an environmental flow problem for stream ecosystems, with combined effects of reduced dry-weather flow resulting from lost infiltration contributions to groundwater, increased frequency of hydraulic and water quality disturbances resulting from direct hydraulic connection of stormwater drainage systems, and a substantial increase in total runoff volume resulting from lost evapotransipiration from pre-urban vegetation. To date, stormwater management objectives have not adequately addressed these complex environmental flow problems. We therefore developed four metrics that can be

applied to stormwater retention devices at multiple scales, and can form the basis of objectives for stormwater management aimed at protection of stream ecosystems.

Quantifying the metrics for a particular catchment first requires assessment of a) the total volume of runoff from a unit of impervious surface and b) the total volume of streamflow that would have been generated from the same unit area when the catchment vegetation was in its natural state. General indicative values of these volumes can be estimated from mean annual rainfall, using published models of impervious and forest (or other appropriate pre-development vegetation type) runoff. Alternatively, the runoff coefficient of an appropriate reference catchment can be used. For the major Australian cities, the volume of impervious runoff is typically 5-10 times the runoff from pre-urban forested catchments, representing a large volume of urban runoff that should be kept out of streams entirely if environmental flows are to be achieved.

The four metrics measure change in: 1) frequency of surface (piped) flows to the stream; 2) the volume (and implicitly the temporal pattern) of subsurface (filtered) flows; 3) the median concentrations of P, N, and TSS in water flowing to the stream; 4) the total volume of water flowing to the stream. With minor variations among metrics, the value for each variable (X) is calculated for the area of interest (A): i) if it was covered by pre-urban vegetation and drained to the stream along pre-urban drainage lines (X_n) ii) if it was impervious and drained by conventional, piped stormwater drainage (X_u); and iii) if it was impervious and drained to the proposed treatment (X_t). The metric, standardized to a unit area of 100 m^2 is calculated as:

$$I = 1 - \max\left(\frac{(X_t - X_n)}{(X_u - X_n)}, 0\right) \times A / 100$$

The four metrics can be combined as a mean and used as a general measure of environmental protection.

We describe the use of these metrics in the design and prioritization of stormwater treatment measures in the catchment of a small urban stream that is the subject of a restoration study. The metrics permitted a standard for comparing the efficacy of a diverse range of treatments across several scales for stream protection, which could be compared against cost. The outcomes of the project will be a new set of stormwater management objectives matched to stream ecosystem requirements.

Introduction

New approaches to urban stormwater management developed in the 1990s were largely driven by concerns about the health of coastal embayments such as Melbourne's Port Phillip Bay (Harris *et al.* 1996; Victoria Stormwater Committee 1999), Brisbane's Moreton Bay (Moreton Bay Waterways and Catchments Partnership and Ecological Engineering 2006) or NE USA's Chesapeake Bay (Palmer 2004). The initial focus on large receiving water bodies, with a large capacity to buffer inflows, led to a dominant perception that stormwater is a water quality problem, which can be solved by limiting pollutant loads. Loads have therefore become the focus of objectives for management of stormwater.

However, the widespread, severe degradation of stream and river ecosystems in urban catchments remains a well known problem, and the primary cause of the degradation in modern cities is urban stormwater runoff (Walsh *et al.* 2005b). Although much of what has been written about new approaches to stormwater management has suggested that protection of urban streams and waterways is an aim (e.g, Melbourne Water 2005), evidence of protection or improvement of stream health as a result of new stormwater management approaches is wanting. A major contributor to the failure of new stormwater management approaches to protect stream ecosystems is that urban stormwater is demonstrably not only a water quality problem, but also a complex environmental flow problem. Streams and rivers, by their nature, are more susceptible to degradation from changes to flow regime than are large coastal water bodies, so there is an urgent need to reassess objectives for stormwater management to include retention or restoration of important elements of the flow regime (Arthington *et al.* 2010).

With recent growing interest in Australia in stormwater harvesting, the lack of recognition of stormwater as an environmental flow problem and a lack of understanding of the nature of the problem by urban water resource managers has become apparent. On one hand, policy documents have sought to limit the volume of harvestable stormwater on the spurious premise that uncontrolled stormwater flows have some environmental flow benefit (e.g., Victorian Government: Department of Sustainability and Environment 2006). On the other, a range of large-scale projects designed to extract water from large urban drains or waterways have been proposed and funded, under the rubric of 'stormwater harvesting', even though the water harvested from such schemes is most likely from a mix of sources. A surprisingly large proportion of such projects extract dry-weather flows from drains, which obviously cannot be considered stormwater (Knights and McAuley 2009). While extraction of dry-weather flows from large urban drains can only exacerbate low-flow-related impacts of urban stormwater, the ability of such schemes to significantly reduce the impacts of increased storm flows are generally limited by their ability to abstract sufficient volumes during storms.

Given that urban stormwater is inconsistently defined among different contexts, we will begin by classifying the different components of flows that might flow through urban waterways, with the aim of identifying those components that are damaging to stream ecosystems, and those that might provide environmental benefit. Then, given the lack of universal understanding of stormwater as an environmental flow problem, we will review the hydrologic impacts of urban stormwater on stream ecosystems. With this theoretical basis, we propose four objectives for stormwater management, and demonstrate how partial attainment of these objectives can be calculated as an index and used to prioritize and implement stormwater retention works.

Components of the flow regime in urban drains and waterways

We first define an ***urban waterway*** as a stream or drain that receives water from an urban stormwater drainage system, as well as subsurface flow from pervious parts of its catchment through natural flow paths. ***Streams*** are topographic flow paths that have not been sealed for flood conveyance, and might include ephemeral drainage lines. Drains that are classed as urban waterways will most likely have once been small streams, and have been sealed (and possibly buried e.g., Elmore and Kaushal 2008) for flood conveyance. The important feature shared by such systems is their conveyance of subsurface flows. They thus retain some elements of non-stormwater flows that could provide environmental flow benefits, either to the waterway itself, or to downstream waters.

Impervious runoff is the water that runs off impervious surfaces. We maintain that this source of water should be the primary definition of ***urban stormwater runoff***. It has been argued that runoff from compacted pervious surfaces can also contribute to urban stormwater runoff, but we argue that such surfaces are not routinely connected to stormwater drainage systems, and even if they are, they produce over-surface runoff much less frequently and in much smaller volumes than do impervious surfaces. Thus, while we acknowledge that there is potentially a small contribution from pervious surfaces that have been compacted to some extent, almost all urban stormwater runoff is generated from impervious surfaces such as roofs and pavement. Impervious runoff can only be physically separated from other flow types when it is intercepted at or near source (or in pipes and drains that receive no other water source). The distinction of this water before it reaches an urban waterway is important because retention of upland impervious runoff, before it becomes mixed with other water sources, also permits the use of this water to restore filtered dry-weather flows.

Rainwater is often used to describe runoff from roofs that can easily be harvested in tanks at source. This can be a useful distinction from more general impervious runoff for harvesting purposes, as it is usually of better quality than runoff from pavement. However, if rainwater is not harvested, it becomes an inseparable part of the larger problem of impervious runoff.

Storm drainage flow is runoff flowing in urban waterways during and soon after a rain event that was large enough to produce upland impervious runoff (typically > 0.5 mm/d from roof surfaces: Hollis and Ovenden 1988; Ragab *et al.* 2003). This flow will be dominated by impervious runoff in most urban drains and small urban waterways, but might also include:

a) overland flow from pervious land that is permitted to flow into an urban drain. For instance, overland flow from turf in parks is often permitted to drain into stormwater pits. However, such overflows are only likely in rare, large events, and this water will constitute only a very small proportion of the total flow except in extremely large events;

b) interflow and other subsurface flows originating from pervious land (delayed delivery of storm flows through natural hydrologic pathways); and

c) leakage or overflows from water supply or wastewater sewerage systems.

Dry-weather drainage flow, the flow in urban waterways in dry weather, consists only of subsurface flows from pervious land delivered through natural topographic flow paths, or leakage from water supply and wastewater sewerage systems. If a significant part of this flow is from wastewater leaks, then this is an environmental and health problem that needs to be addressed, preferably through upland actions to prevent the leaks. However, there are examples of intractable leakage problems, such as in the Prahran main drain in Melbourne, where a short-medium term solution amounted to dry-weather sewer mining (Melbourne Water 2007, who incorrectly portrayed this activity as "targeting stormwater"). With the exception of wastewater leaks, dry-weather drainage flows likely serve important environmental flow functions either to the waterway itself or to its receiving water, as discussed below.

In summary, water flowing in urban waterways combines several water sources, which constitute different threats and benefits to receiving waters. In most urban contexts, the most damaging component is impervious runoff, which we argue should be the definition of stormwater. Impervious runoff presents a complex environmental flow problem for urban streams which needs to be tackled before it reaches the stream.

Urban stormwater as an environmental flow problem

The changes to stream hydrology resulting from urban stormwater runoff are well documented, and include increased frequency, magnitude, and annual volume of storm flow, with reduced recession (Leopold 1968), increased total volume of runoff (Cuo *et al.* 2009), and reduced baseflows in winter and summer(Konrad and Booth 2005; Kauffman *et al.* 2009). Such effects are clearly evident by comparing similar streams with differing levels of catchment urbanization (Fig. 1).

The sustained baseflows with only minor fluctuations in flow after most storms (Fig. 1a) that are typical of streams in forested catchments provide a relatively stable habitat, with infrequent hydraulic disturbances to stream biota and channel substrate. A critical element of the catchment hydrology of forested streams that is rarely emphasized is that virtually all of the water that flows into the stream reaches it through subsurface flow paths. Delivery of flows through subsurface flow paths – either deep groundwater flows, or shallow interflow following storms- is the norm, even for many streams that have relatively flashy hydrographs (Kirchner 2003). Upland subsurface flow paths provide both a sustained, slow delivery of water to streams and a natural filter to maintain water quality.

Directing impervious runoff into stormwater drainage systems reduces the opportunity for water to reach receiving waters through these natural flow paths. Reduced infiltration therefore has the dual effect of reducing the volume of dry-weather flows, and increasing the volume and frequency, and reducing the quality of wet-weather flows. These combined hydrologic and water quality changes to stream hydrology have been widely implicated in the severe degradation of stream ecosystems (Roy *et al.* 2005; Walsh *et al.* 2005a; Kennen *et al.* 2008).

A major aspect of hydrologic change wrought by urban stormwater runoff that has received little attention from ecological studies is the large overall increase in total volume of discharge. Urban land increases runoff volume because the removal of vegetation for impervious surfaces, together with the disconnection of natural flow paths that could allow uptake of water by soils and vegetation downslope, reduce the volume of water that is lost to the air through evapotranspiration. As the proportion of rainfall that becomes streamflow in vegetated catchments, and the proportion of rainfall that runs off impervious surfaces are well known, it is a simple task to estimate the volume of new, excess water that is generated by impervious surfaces (Fig. 2). In most cities, at least 60-90% of impervious runoff is water that would never have reached the stream in the pre-urban catchment.

While it is not necessarily a problem of direct ecological relevance, the excess volume of stormwater aggravates the challenge of retaining and treating stormwater adequately to provide filtered flows that could mimic lost subsurface-fed dry-weather flows. The problem of excess runoff also presents an environmental flow problem unlike any other (too much water rather than not enough), that could easily help to solve other problems (provision of urban water supplies, that could reduce the volume harvested from distant rural rivers, thus also addressing their environmental flow requirements; increase urban evapotranspiration to attenuate the urban heat island effect, helping cities to adapt to a warming climate (Coutts *et al.* 2007), reduce flood mitigations costs).

Environmental flow objectives for urban stormwater management

New approaches to environmental flow management seek to maintain elements of the natural flow regime that are of greatest importance to stream ecosystems (Poff *et al.* 2010). Having identified the critical elements of the hydrograph that are likely to be the primary drivers of urban stream degradation, we determined four objectives that effective stormwater management should target.

1. Minimize uncontrolled storm flows. The increased frequency of hydraulic and pollutant disturbance from stormwater drainage flows has been identified as a primary driver of ecological degradation in streams (Walsh *et al.* 2005a). While a natural forested stream might receive one or two substantial floods a year that are associated with increased hydraulic disturbance and delivery of increased contaminant concentrations, streams receiving urban runoff receive such flows every time it rains enough to elicit impervious runoff in the catchment: over 100 days/year in Melbourne. A primary objective of stormwater management is therefore the retention of as much stormwater flows in the catchment as possible to reduce the frequency of piped flows as close to the pre-urban frequency as possible (Walsh *et al.* 2009). Such objectives have recently been mandated for federal projects in

the US (US Environmental Protection Agency 2009), expressed as a requirement to retain the 95th percentile rain event on site. The emphasis of the US legislation is on infiltration, but further guidance is required if environmental flows are to be protected.

2. Infiltration flows must be delivered to the stream through treatment measures that ensure flow rates do not exceed pre-urban subsurface flow rates. This objective aims to restore lost dry-weather flows. Appropriate maximum flow rates can be estimated from baseflow separation analysis in reference streams, or by assessment of infitration capacities of native soils in the catchment (or a combination of these two techniques).

3. Infiltration flows should aim to meet water quality concentration objectives close to standard objectives for ecosystem protection of freshwaters (ANZECC and ARMCANZ 1999). For some variables, such as nitrogen, ANZECC objectives might be unattainable in treatment systems with collection pipes, in which case pragmatic acceptance of best attainable concentrations is appropriate. Wherever possible, exfiltration systems, and systems that allow overflow or infiltration flows to drain to pervious land, will help to achieve improved water quality, as well as increasing loss through evapotranspiration.

4. In almost all locations, the attainment of the first three objectives will require substantial retention and loss of stormwater runoff, either for indoor use and export to the wastewater stream, or for irrigation and loss to evapotranspiration. Therefore harvesting of a large proportion of

stormwater runoff is a central objective for restoration or protection of environmental flows. Our knowledge of the wide difference between natural and impervious runoff coefficients (Fig. 2) allow clear guidelines for the volumes of stormwater that should be kept out of receiving waters altogether (Fig.3). The predicted annual streamflow coefficients for grassland and forest catchments derived by Zhang *et al*. (2001) serve as useful bounds for the appropriate volume of runoff that should be allowed to reach the stream, primarily through infiltration systems. Using the curves of Fig. 3., in a region with an average rainfall of 800 mm/y, of the 8 ML/y that would fall on a 1-ha roof, ideally 1.5–2 ML/y should be allowed to reach the stream through filtration, infiltration and natural topographic flow paths. Around 4–5.5 ML/y should be harvested and retained in the catchment. Across a city such as Melbourne, with around 95,000 ha of impervious surfaces, the total volume of excess stormwater runoff that should be kept out of receiving waters for environmental flow benefit is approximately equal to the volume of water imported into the city for its water supply.

Implementing new stormwater management objectives

We argue that new stormwater retention objectives such as those described above are required if the health of Australia's urban streams, waterways and coastal waters are to be protected and restored. While some Australian organizations are moving towards such objectives, there is a long way to go before they could be considered mainstream. For now the challenge is to find ways to measure and demonstrate the benefits of such objectives. To demonstrate the efficacy of such objectives in restoring stream health, they need to be trialled at a whole-of-catchment scale. We are currently attempting to do this for the Little Stringybark Creek catchment, on the eastern fringe of Melbourne, where we are working with the community and the local council (Yarra Ranges), to build dispersed stormwater retention systems throughout the catchment. This project also offers an opportunity to quantify other benefits, such as the augmentation of the potable water supply through stormwater harvesting, the private benefits of an unrestricted water supply and greener garden, and microclimate amelioration. We are also testing whether the application of dispersed stormwater harvesting systems throughout the catchment (at the allotment and precinct scale) has a net energy cost or benefit.

To assess the true economic value of these multiple benefits to the community, we are implementing dispersed stormwater treatment measures using a market-based instrument (Nemes *et al.* 2010). Underlying the market-based instrument is an environmental benefit index that measures the extent of attainment of the four objectives described above (see www.urbanstreams.net/Rpad/EBcalc.html). The index is the mean of four sub-indices corresponding to each objective, all of which are standardized by impervious catchment area: one unit measures the environmental benefit of removing the stormwater impact of 100 m^2 of impervious area.

The ***flow-frequency sub-index*** (after Walsh *et al.* 2009) assumes, for our study area, that runoff is generated from impervious surfaces 121 days/year, and that overland flow would have been generated from the pre-urban forest floor 12 days/year (a likely overestimate). Furthermore, it is assumed that any impervious areas that are not connected to the formal (piped) stormwater drainage system do not contribute to increased runoff frequency (while this is unlikely to be the case, the finding that such areas currently have no detectable environmental impact compared to the directly connected impervious areas (Walsh and Kunapo 2009) means they are not considered a high priority for treatment). The flow-frequency sub-index is calculated as:

$$\text{FF} = 1 - \max\left(\frac{R_g - R_n}{R_u - R_n}, 0\right) \times A/100 ,$$

where A = the area (m^2) of currently connected roof to be drained by the tank; R_g = number of days of runoff per year from A following treatment by tank (or garden, see below); R_n = frequency of runoff from A in pre-urban state (12 d/y; R_u = frequency of runoff from A before treatment (121 d/y).

The ***filtered flow volume sub-index***, FV. calculated as:

$$\begin{aligned}
&\text{if } FV_g < FV_{forest,} \\
&\qquad FV = \left(\frac{FV_g}{FV_{forest}}\right) \times A/100 \\
&\text{if } FV_g > FV_{pasture,} \\
&\qquad FV = \max\left(0, 1 - \frac{FV_g - FV_{pasture}}{FV_{forest}}\right) \times A/100 \\
&\text{Else,} \\
&\qquad FV = 1 \times \text{A}/100 ,
\end{aligned}$$

where FV_g = the volume of filtered water flowing out of a retention system, both through an outlet pipe (if present), and through exfiltration to the surrounding soils. FV_{forest} and $FV_{pasture}$ represent the bounds of ideal filtered flow volume. The bounds correspond to the two curves derived by Zhang *et al*. (2001), as described above (Figs. 2, 3). This formulation assumes that if the volume of runoff is limited, then systems must be designed to limit the rate of filtered flows to mimic pre-urban subsurface flows. Future formulations might more directly define desired filtered flow patterns.

The ***water-quality sub-index***, WQ, is calculated as the mean of the following three sub-sub-indices:

$$1 - \max(\frac{[N]_g - [N]_t}{2.2 - [N]_t}, 0) \times A/100$$
$$1 - \max(\frac{[P]_g - [P]_t}{0.35 - [P]_t}, 0) \times A/100$$
$$1 - \max(\frac{[TSS]_g - [TSS]_t}{150 - [TSS]_t}, 0) \times A/100$$
,

where *[N]*, *[P]*, *[TSS]* are concentrations of total nitrogen, total phosphorus and total suspended solids, respectively. $[X]_g$ is the median (or other defined percentile) concentration of element X flowing from the system, and $[X]_t$ is the target concentration (P 0.05 mg/L, N 0.6 mg/L, TSS 20 mg/L, derived from a pragmatic combination of the best achievable for treatment systems and guidance from the State Environment Protection Policy: Government of Victoria 1999). The first number in each denominator is the assumed concentration of untreated stormwater in mg/L (after e-Water Cooperative Research Centre 2010). *A* is the impervious catchment area, as defined above for the other sub-indices.

The ***volume reduction sub-index*** ,VR is somewhat redundant with FV, but is included as a sub-index because it reinforces the fact (not yet widely understood) that impervious surfaces generate large volumes of new, nuisance stormwater, and it implicitly puts a value on keeping this volume of water out of receiving waters entirely. VR is calculated as:

$$\mathrm{VR} = 1 - \frac{V_e - V_c}{V_e} \times A/100$$
,

where V_e = the excess volume of water generated by impervious surface *A* (i.e. the difference between the volume of runoff from an area of forest equivalent to A and the volume of runoff from the impervious surface: Figs. 2, 3); V_c = the volume of water harvested or lost from a rain-garden through evapotranspiration. For our study catchment, we chose to encourage as much extraction as possible from tanks, because it will be impossible to lose the target volume of runoff in our catchment from rain-gardens alone. Therefore, if a tank system uses all runoff that drains to it, it is possible for this sub-index to be as high as 1.36.

Using the indices to prioritize stormwater management for stream health

To date, we have installed ~80 stormwater retention systems in private properties, and received proposals for an additional 30 systems, with a range of impervious catchment areas. Interestingly, the efficacy of the proposed systems at maintaining runoff hydrology and water quality from properties was unrelated to the area of surface requiring treatment, up to an area of 2650 m^2 (Fig. 4). However, systems that relied on harvesting alone performed consistently more poorly than systems that combined harvesting and infiltration. Indeed, the only systems that performed perfectly (i.e. achieved the maximum potential environmental benefit) were those that combined harvesting and infiltration (Fig. 4). Generally bioretention or infiltration systems alone could not achieve a perfect result as the space required to restore pre-urban evapotranspiration losses is usually prohibitive. However, in two properties, infiltration systems alone did achieve a near-perfect score, because they were allowed to overflow to large vegetated areas that ensured complete infiltration and take-up and loss by downslope forest trees in most rain events.

The challenge for harvesting and infiltration becomes ever more prodigious as the impervious catchment area increases. Therefore large end-of-pipe harvesting systems are unlikely to score highly on any of the sub-indices for stream protection. Such systems would require very large storages that would allow complete capture of approximately up to a 1-in-2-month recurrence interval flows (a 15-20 mm/d rain event in Melbourne), and permit a slow release of filtered water to the stream in order to approximate pre-urban hydrology. As an example, a harvesting and infiltration systems on a drain with an impervious catchment area of 1 km^2 would require the storage capacity to retain 19 ML of runoff following a 20-mm storm.. Whilst space constraints would likely preclude such a solution, a 7 kL tank on each house within that same catchment (assuming an imperviousness of 50% and a typical housing density of 15 per hectare, and each tank being half-full before the storm) would provide 10.5 ML of storage, leaving a deficit of only 8.5 ML to be achieved in storages in public open space areas, and infiltration/retention systems that could be in both private and public land.

Achieving environmental flow objectives for the protection of stream ecosystems will therefore only be feasible if stormwater retention and infiltration systems are applied at a range of locations and scales across the catchment, with a strong emphasis on application at or near source. This is not only because the catchment area and flow volumes are more manageable in these upstream locations, but because the first three objectives simply cannot be delivered by (for example) stormwater harvesting systems which extract directly from urban waterways. The catchment itself must be used to restore natural subsurface flows. Downstream treatments might then be used to deal with any deficits between what is required and the systems applied at and near source.

References

ANZECC, and ARMCANZ (1999). 'Draft Australian Water Quality Guidelines for Fresh and Marine Waters.' (Australian and New Zealand Environment and Conservation Council: Canberra, Australia.)

Arthington A. H., Naiman R. J., McClain M. E., and Nilsson C. (2010). Preserving the biodiversity and ecological services of rivers: new challenges and research opportunities. *Freshwater Biology* **55**, 1-16.

Coutts A. M., Beringer J., and Tapper N. J. (2007). Impact of Increasing Urban Density on Local Climate: Spatial and Temporal Variations in the Surface Energy Balance in Melbourne, Australia. *Journal of Applied Meteorology* **47**, 477—493.

Cuo L., Lettenmaier D. P., Alberti M., and Richey J. E. (2009). Effects of a century of land cover and climate change on the hydrology of the Puget Sound basin. *Hydrological Processes* **23**, 907–933.

e-Water Cooperative Research Centre (2010). 'MUSIC (Model for Urban Stormwater Improvement Conceptualisation) Version 4.' e-Water Cooperative Research Centre. http://www.toolkit.net.au/music

Elmore A. J., and Kaushal S. S. (2008). Disappearing headwaters: patterns of stream burial due to urbanization. *Frontiers in Ecology and the Environment* **6**, 308-312.

Government of Victoria (1999). Variation to state environment protection policy (Waters of Victoria): insertion of Schedule F7, Waters of the Yarra Catchment. The Craftsman Press, Victoria Government Gazette No. S89, Melbourne, Australia.

Harris G., Batley G., Fox D., Hall D., Jernakoff P., Molloy R., Murray A., Newell B., Parslow J., Skyring G., and Walker S. (1996). 'Port Phillip Bay Environmental Study Final Report.' (CSIRO: Canberra, Australia.)

Hollis G. E., and Ovenden J. C. (1988). One year irrigation experiment to assess losses and runoff volume relationships for a residential road in Hertfordshire, England. *Hydrological Processes* **2**, 61-74.

Kauffman G. J., Belden A. C., Vonck K. J., and Homsey A. R. (2009). Link between impervious cover and base flow in the White Clay Creek Wild and Scenic Watershed in Delaware. *Journal of Hydrologic Engineering* **14**, 324-334.

Kennen J. G., Kauffman L. J., Ayers M. A., Wolock D. M., and Colarullo S. J. (2008). Use of an integrated flow model to estimate ecologically relevant hydrologic characteristics at stream biomonitoring sites. *Ecological Modelling* **211**, 57-76.

Kirchner J. W. (2003). A double paradox in catchment hydrology and geochemistry. *Hydrological Processes* **17**, 871-874.

Knights D., and McAuley A. (2009). What makes a sustainable stormwater harvesting project? In 'Stormwater Industry Association of NSW and Victoria Joint Annual Conference. '. (Albury, NSW, Australia)

Konrad C. P., and Booth D. B. (2005). Hydrologic changes in urban streams and their ecological significance. *Amercian Fisheries Society Symposium* **47**, 157-177.

Leopold L. B. (1968). Hydrology for urban land planning - a guidebook on the hydrologic effects of urban land use. US Geological Survey, Geological Survey Circular 554, Washington, DC, USA.

Melbourne Water (2005). 'WSUD engineering procedures: stormwater.' (CSIRO Publishing: Melbourne, Australia.)

Melbourne Water (2007). Sustainability Report 2006/2007. Melbourne Water, Melbourne, Australia. http://www.melbournewater.com.au/applications/annual_report_2007/wways_riverhealth.htm

Moreton Bay Waterways and Catchments Partnership, and Ecological Engineering (2006). Water sensitive urban design: Developing design objectives for water sensitive urban development in South East Queensland Moreton Bay Waterways and Catchments Partnership, Brisbane, Queensland.

Nemes V., La Nauze A., Walsh C., Fletcher T., Bos D., Sharyn R., Plott C., and Stoneham G. (2010). Saving a creek one bid at a time: a uniform price auction for stormwater retention in urban catchments. In 'Australian Association of Agricultural and Resource Economics (AARES) National Conference'. (Adelaide, Australia.)

Palmer M. T. (2004). The Chesapeake Bay Restoration Act of 2000: New Requirements for Federal Agencies *WIliiam and Mary Environmental Law and Policy Review* **375**.

Poff N. L., Richter B. D., Arthington A. H., Bunn S. E., Naiman R. J., Kendy E., Acreman M., Apse C., Bledsoe B. P., Freeman M. C., Henriksen J., Jacobson R. B., Kennen J. G., Merritt D. M., O'Keeffe J. H., Olden J. D., Rogers K., Tharme R. E., and Warner A. (2010). The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. *Freshwater Biology* **55**, 147-170.

Ragab R., Bromley J., Rosier P., Cooper J. D., and Gash J. H. C. (2003). Experimental study of water fluxes in a residential area: 1. Rainfall, roof runoff and evaporation: the effect of slope and aspect. *Hydrological Processes* **17**, 2409-2422.

Roy A. H., Freeman M. C., Freeman B. J., Wenger S. J., Ensign W. E., and Meyer J. L. (2005). Investigating hydrological alteration as a mechanism of fish assemblage shifts in urbanizing streams. *Journal of the North American Benthological Society* **24**, 656--678.

US Environmental Protection Agency (2009). Stormwater Management for Federal Facilities under Section 438 of the Energy Independence and Security Act. http://www.epa.gov/owow/nps/lid/section438/.

Victoria Stormwater Committee (1999). 'Urban stormwater: best practice environmental management guidelines.' (CSIRO: Melbourne, Australia.)

Victorian Government: Department of Sustainability and Environment (2006). Sustainable Water Strategy, Central Region: Action to 2055. Department of Sustainability and Environment, Victoria, Melbourne, Australia.

Walsh C. J., Fletcher T. D., and Ladson A. R. (2005a). Stream restoration in urban catchments through re-designing stormwater systems: looking to the catchment to save the stream. *Journal of the North American Benthological Society* **24**, 690–705.

Walsh C. J., Fletcher T. D., and Ladson A. R. (2009). Retention capacity: a metric to link stream ecology and stormwater management. *Journal of Hydrological Engineering* **14**, 399-406.

Walsh C. J., and Kunapo J. (2009). The importance of upland flow paths in determining urban effects on stream ecosystems *Journal of the North American Benthological Society* **28**, 977-990.

Walsh C. J., Roy A. H., Feminella J. W., Cottingham P. D., Groffman P. M., and Morgan R. P. (2005b). The urban stream syndrome: current knowledge and the search for a cure. *Journal of the North American Benthological Society* **24**, 706–723.

Zhang L., Dawes W. R., and Walker G. R. (2001). Response of mean annual evapotranspiration to vegetation changes at catchment scale. *Water Resources Research* **37**, 701-708.

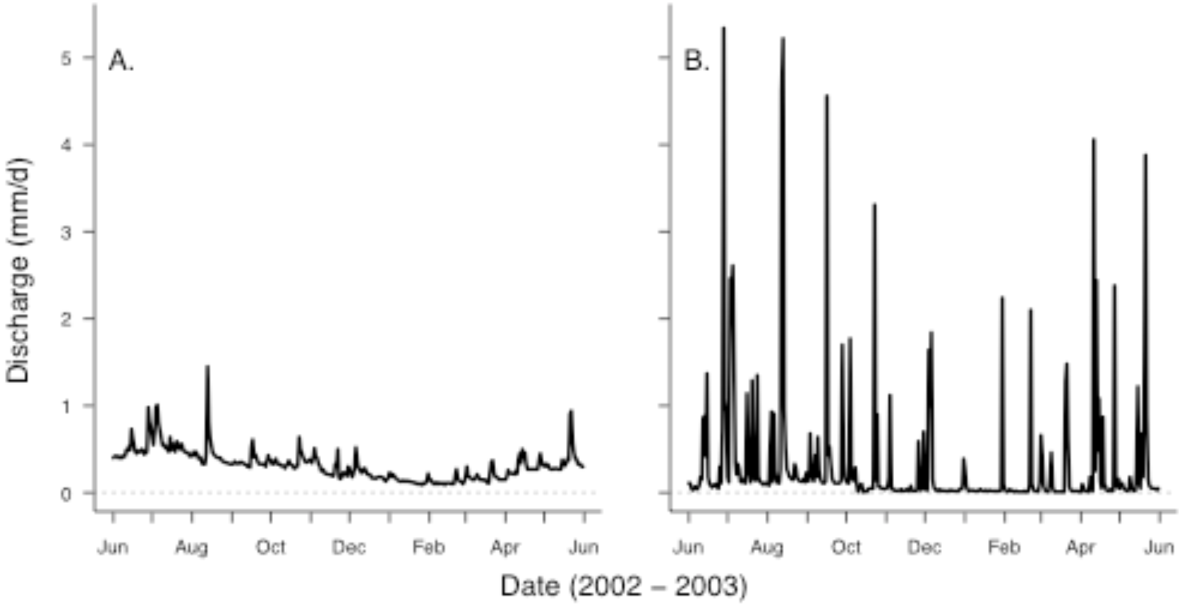

Fig. 1. Mean daily discharge in two eastern Melbourne streams of similar size, but with differing degrees of catchment urbanization. A Olinda Creek at Mt Evelyn, with effective catchment imperviousness near zero, B. Brushy Creek at Mooroolbark, effective catchment imperviousness ~20% (source, Melbourne Water, http:/melbournewater.com.au/).

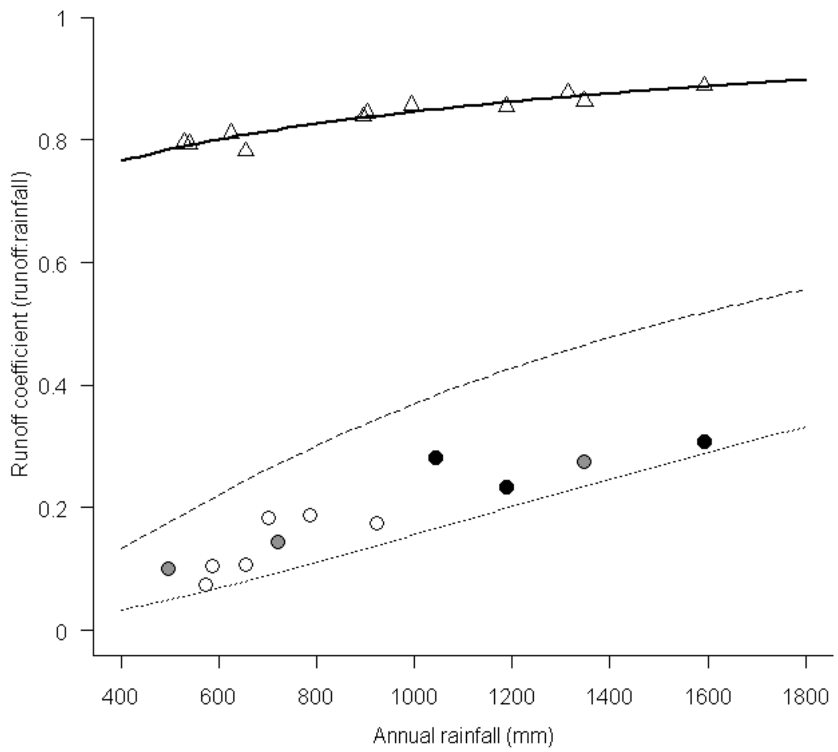

Fig. 2. Estimated annual runoff coefficients (C) from impervious surfaces (open triangles) from sites across the Melbourne region as a function of mean annual rainfall (R). Impervious runoff was estimated from daily rainfall data at each of 11 sites (3–45 years of data), assuming an initial loss of 1 mm/d. Regression line: C = 0.234 + 0.203*log10(R). R^2 = 0.90. Annual runoff coefficients from 12 streams with forested (closed circles), grassland (open circles) or mixed forested and grassland catchments (grey circles) across the Melbourne region as a function of mean annual rainfall. The lines surrounding these stream points are the relationship between streamflow derived by Zhang *et al*. (2001) for grassland (dashed curve) and forested catchments (dotted curve) of the world.

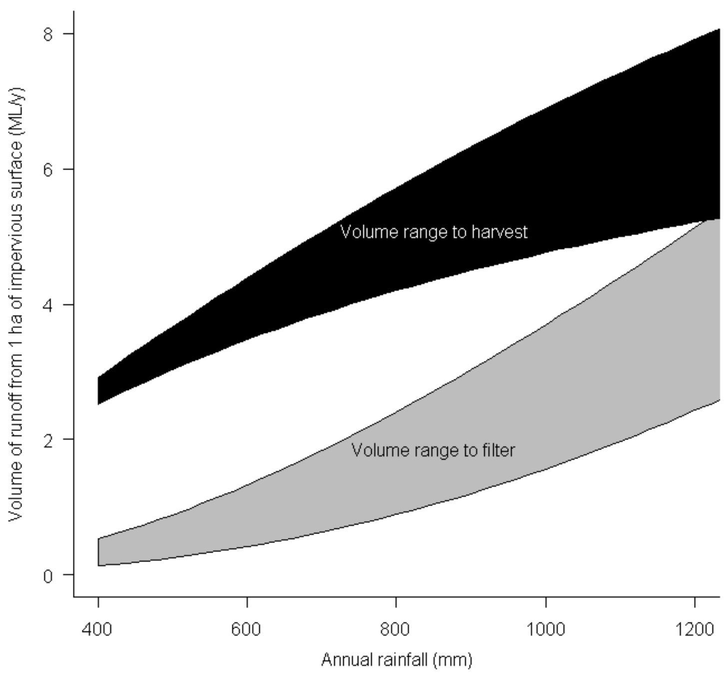

Fig. 2. Annual volume of runoff from 1 ha of impervious surface (from the relationship between impervious runoff coefficient and annual rainfall shown in Fig. 2), partitioned into two parts: the volume that needs to be passed through filtration systems to restore lost subsurface flows (grey polygon), and the volume that needs to be retained in the catchment and not delivered to the stream (through evapotranspirational loss or through use and export from the catchment through the wastewater stream). For each part, a range is indicated between situations in which the target streamflow is predicted by the grassland curve (more stream flow, less retention in catchment) or by the forest curve (less streamflow, more retention in the catchment) of Zhang *et al*. (2001; Fig. 1).

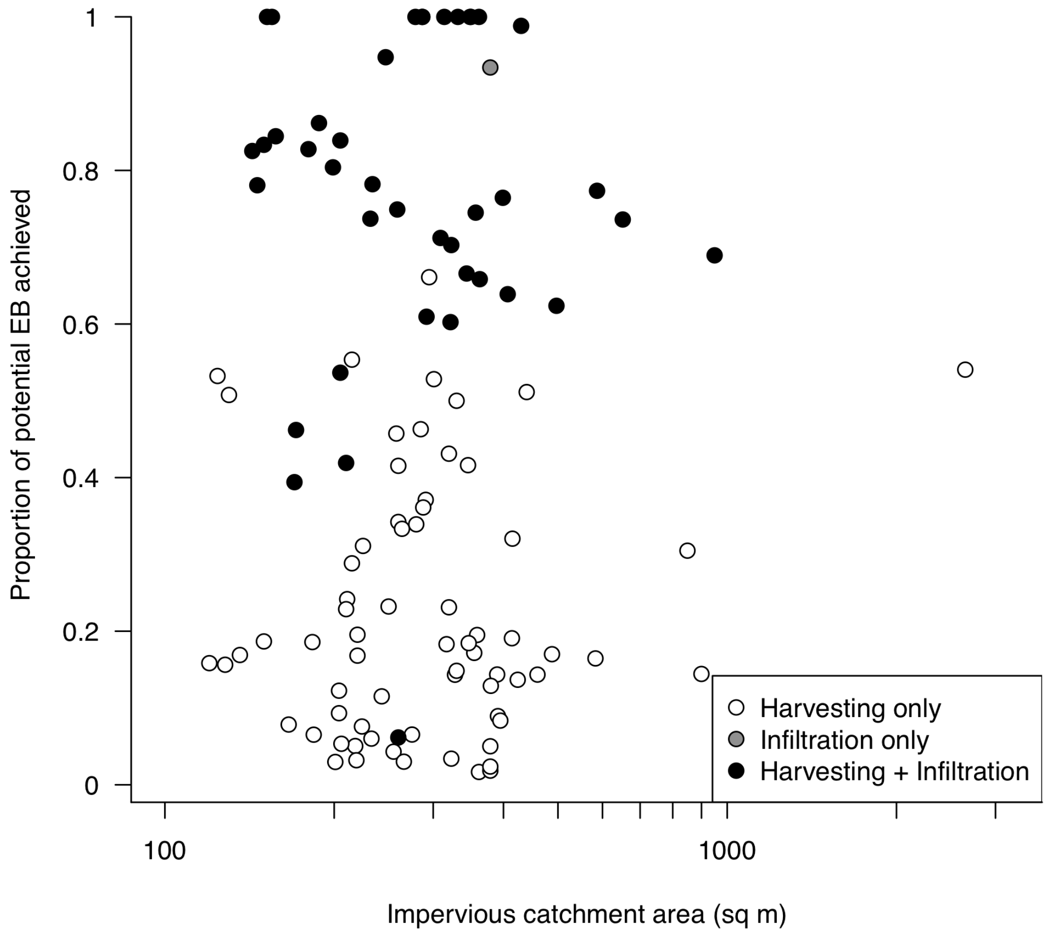

Fig. 4. Proportion of maximum feasible environmental benefit score achieved by 110 systems proposed or built on private properties the Little Stringybark Creek catchment study. While there was no relationship between impervious area being treated and the effectiveness of the treatment, systems that combined harvesting and infiltration systems consistently performed best.