Setting objectives for hydrologic restoration: from site-scale to catchment-scale

Objectifs de restauration hydrologique : de l'échelle de la parcelle à celle du bassin versant

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RÉSUMÉ

Afin de protéger, voire restaurer, les fonctions et valeurs écologiques des cours d'eau urbains, les récentes approches de gestion des eaux pluviales visent à restaurer un régime fluvial proche de l'état naturel en rétablissant les processus hydrologiques à diverses échelles. La mise en pratique de ces objectifs de gestion est cependant entravée par l'absence de critères applicables à l'échelle locale, identifiables pour une parcelle donnée. Nous proposons ici un cadre pour ces objectifs à l'échelle locale, définis à partir des contributions de la parcelle au bilan hydrologique du bassin versant. Ces objectifs concernent la part du volume de pluie qui doit être perdue, par évapotranspiration ou réutilisation, et celle qui doit être infiltrée. Le concept de perte initiale équivalente, mesurant la probabilité de ruissellement de surface produit par un événement pluvieux, est également introduit afin de rétablir le phénomène de rétention naturelle d'un bassin versant. L'identification de ces objectifs à l'échelle locale semble indiquer que la rétention des eaux pluviales (suivie de pertes par évapotranspiration ou réutilisation) et la restauration du ruissellement souterrain sont nécessaires à petite échelle, soulignant le rôle essentiel des techniques de récupération et d'infiltration à la source.

ABSTRACT

The protection and eventual restoration of natural ecological functions and values in urban streams requires approaches to stormwater management that restore natural hydrologic processes at small scales, with the ultimate goal of returning catchment-scale flow-regimes towards their pre-development behaviour. Adoption of such approaches is however, currently limited by a lack of stormwater management design objectives applicable at the site-scale. In this paper, we outline a conceptual framework for setting such objectives based on the role that an individual site plays in delivering catchment-scale hydrologic outcomes. Objectives are provided for the proportion of rain falling on impervious areas that should be lost (evapotranspired and/or harvested) and infiltrated. We also propose an objective for equivalent initial loss, which characterizes the probability of surface runoff from a given rain-event, with the aim of restoring natural catchment-scale retention of storm events. It is apparent that the management of flow-regimes at small scales will require both retention (and loss through use or evapotranspiration) of stormwater and restoration of baseflow processes. Stormwater harvesting and infiltration-based techniques are thus required to manage stormwater at small scales.

KEYWORDS

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

1 INTRODUCTION

The ecological function and structure of streams is inevitably degraded when urban stormwater runoff is conveyed directly to receiving waters via conventional drainage systems (Walsh and Kunapo, 2009). This occurs as a consequence of both altered flow-regimes (with consequent geomorphic changes) and reduced water quality (Walsh et al., 2005). Burns et al. (2012) showed the hydrologic consequences of conventional drainage systems, and proposed an approach to stormwater management known as flow-regime management. This approach aims to restore natural hydrologic processes (e.g. evapotranspiration and infiltration) at small scales with the goal of returning catchment-scale flow-regimes to as close as practicable to their pre-developed condition. In the pre-development context, the majority of catchment-scale rainfall is evapotranspired, with remaining rainfall infiltrated. There is usually little surface runoff from undeveloped catchments. This water balance likely results in catchment-scale flow-regimes that could support healthy streams. Thus, mimicking evapotranspiration and infiltration at small scales, is likely to restore ecologically important elements of pre-development flow-regimes (Poff et al., 1997).

To achieve the goals of flow-regime management, stormwater managers require new stormwater management objectives, applicable at the land-parcel (or site) scale, since restoration of flow regimes requires application at a range of scales, with a primary focus being at or close to the source of runoff (Argue, 2011; Burns et al., 2012). In this paper, we develop such stormwater management objectives—for use by municipal stormwater managers, and developers. Numeric targets for these objectives are calculated using Melbourne, Australia as a case study.

We demonstrate that the management of flow-regimes at small scales will require both retention of stormwater runoff and restoration of baseflow processes.

2 METHODS

2.1 Conceptual objectives for flow-regime management

To restore natural streamflow regimes for a catchment, the water fluxes of impervious areas within urban land-parcels need to be restored towards those of undeveloped land-parcels. This means increasing (i) volumetric losses (i.e. rainfall lost from the catchment) and (ii) infiltration (filtered-flow), and decreasing the (iii) frequency and (iv) volume of surface runoff. Volumetric losses could include evapotranspiration and harvesting (i.e. water supplied to end-uses that are exported from the catchment via constructed [sanitary] sewers). Water that is infiltrated or adequately filtered and released to streams through pipes, at an appropriate rate, can be regarded as filtered-flow. The probability of surface runoff occurring can be characterized by equivalent initial loss—a random variable expressed in mm of rainfall retained before surface runoff occurs.

Volumetric loss and infiltration (filtered-flow)

For undeveloped land-parcels, most rainfall is transpired or evaporates (lost from the catchment), and only a small amount infiltrates into local soils to ultimately reach streams as subsurface (filtered) flows (Figure 1). Surface runoff is occasionally generated following large rainfall events, but is typically resorbed into downslope soils (Burch et al., 1987; Davis et al., 1996) before it can reach the stream as surface runoff. Some land-parcels within riparian zones or other saturated areas of catchments (partial area contributions) (Dunne and Black, 1970) will contribute surface runoff directly to streams, but only rarely.

Undeveloped land-parcels become urban when some (or all) natural soil and vegetation is replaced with impervious surfaces (e.g. pavement, roads and roofs) and this significantly alters the water balance (Figure 1). This problem is often exacerbated during construction, when the topsoils of vegetated areas are removed and/or compacted, reducing soil water storage.

A proportion of an urban land-parcel is typically made impervious (although this proportion may be high), and any remaining vegetated areas (albeit with pre-existing vegetation likely replaced by garden) would be expected to behave hydrologically similarly to the undeveloped condition (although perhaps with lower runoff storage potential due to soil modification; Konrad and Booth 2005); the proportion of impervious areas will obviously increase with urban density.

Most rain that falls on impervious surfaces becomes surface runoff, with only a small amount evaporated. None of this rain falling on impervious surfaces infiltrates into local soils; meaning subsurface (and thus filtered) flows are reduced downstream. Surface runoff from impervious areas is often conveyed directly to streams via conventional drainage systems, carrying with it high levels of pollutants.

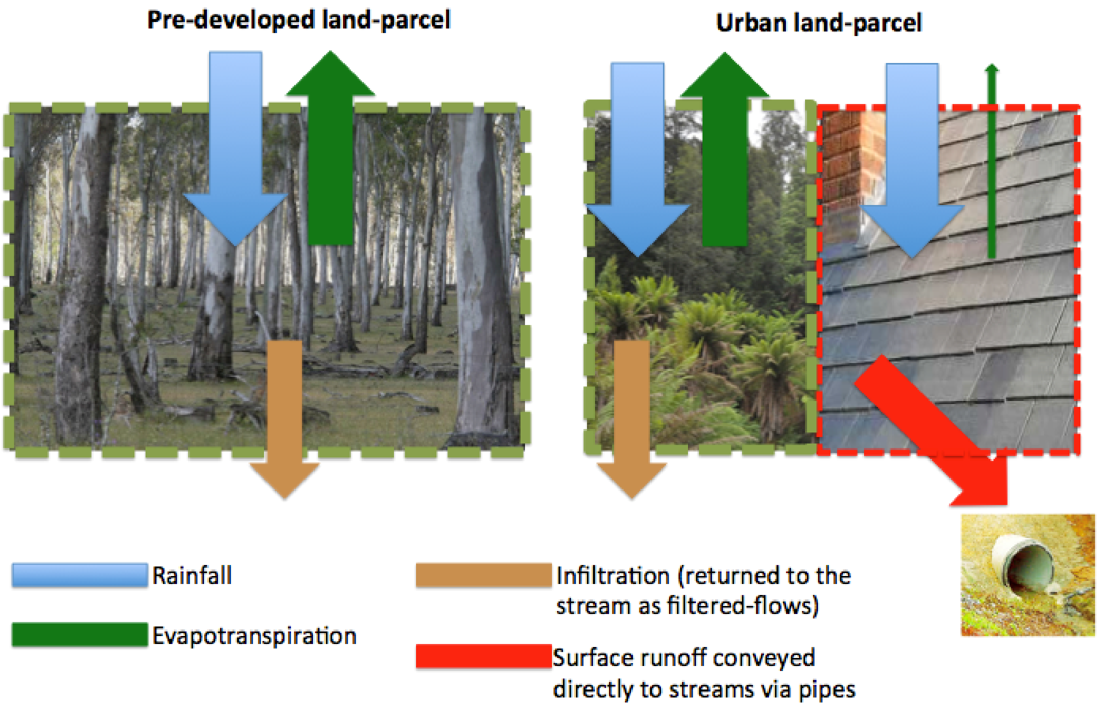

Figure 1 – Conceptual water balance diagrams for pre-developed (left) and urban (right) land-parcels. The size of each arrow is indicative of the magnitude of each flux. Replacing forest or grassland with impervious surfaces significantly increases the frequency and volume of surface runoff whilst reducing the amount of rainfall lost out of the catchment and infiltrated into soils.

Equivalent initial loss

We mentioned above that in the pre-development condition, there would be infrequent occasions following large rainfall events when surface runoff is generated at small scales. The amount of rainfall required to initiate surface runoff is often defined as the initial loss. This is a random variable that will vary over time with climatic conditions. Many hydrologists have therefore determined initial loss values for undeveloped catchments. Importantly, such a loss value is indicative of the amount of rainfall required to initiate surface runoff in the catchment, but it does not reveal where in the catchment surface runoff occurs. It is therefore difficult to quantify or predict the amount of surface runoff generated from undeveloped land-parcels in a particular location within a catchment.

However in urban catchments, surface runoff conveyed from impervious areas within urban land-parcels (via pipes) simplifies the runoff process, bypassing the influence of spatial arrangement and location within the catchment. Therefore, the frequency and volume of surface runoff delivered to streams from impervious areas, regardless of their location within the catchment, can be reliably predicted. Even impervious areas on distant hillslopes will contribute surface runoff directly to streams if they are connected via a constructed drainage system. The challenge is therefore to manage impervious areas to mimic the natural initial loss of the catchment, such that the hydrologic influence of connected impervious areas to the catchment will be much closer to the undeveloped condition than the urban state. Thus, it is suggested that an appropriate equivalent initial loss target for connected impervious areas, is the median initial loss (per rain-event) of nearby (reference) undeveloped catchments.

In the next section, we take these conceptual objectives of 1) volumetric loss, 2) infiltration (filtered-flow), and 3) equivalent initial loss, and use a case study to illustrate how numeric targets can be derived for each objective.

2.2 Setting numeric targets

We used Melbourne, Australia as a case study to express the conceptual objectives as numeric targets. Melbourne has a temperate climate, with a mean annual rainfall of 650 mm (distributed relatively uniformly throughout the year), and mean annual daily maximum temperature of 20°C (station 086071; www.bom.gov.au).

Numeric targets for the amount of rainfall to be lost (evapotranspired and/or harvested) and infiltrated were determined using studies concerning the water balance of undeveloped catchments. Because these studies used catchment-scale data, we investigated the transferability of these studies to the site-scale. To determine a numeric target for equivalent initial loss, we used initial loss values for nearby undeveloped catchments.

Volumetric loss and infiltration targets

Zhang et al. (2001) used a global data set of catchment-scale water balances to develop relationships between mean annual evapotranspiration and mean annual rainfall for forested and grassland catchments (Figure 2 and Equation 1). Annual runoff volume can be estimated from these relationships by subtracting annual evapotranspiration from annual rainfall, and assuming that changes in soil water storage are negligible, which is reasonable over the long term (Equation 2). After Walsh et al. (2012), we denote the annual runoff volume predicted by the Zhang relationships as filtered-flow, since its origin would be primarily subsurface (Kirchner, 2003). In the undeveloped state, most of the annual flow volume will reach the stream through subsurface runoff pathways.

$$ET = \left[f \frac{1 + 2\frac{1410}{P}}{1 + 2\frac{1410}{P} + \frac{P}{1410}} + (1 - f)\frac{1 + 0.5\frac{1100}{P}}{1 + 0.5\frac{1100}{P} + \frac{P}{1100}} \right] P \qquad [1]$$

Where: ET is mean annual evapotranspiration, in mm, f is the fraction of forest cover (f is 0 for grasslands) and P is mean annual rainfall, in mm (Zhang et al., 2001).

$$FF = P - ET \qquad [2]$$

Where: FF is mean annual filtered flow, P is mean annual rainfall and ET is mean annual evapotranspiration (all in mm) (Zhang et al., 2001).

Transferability of catchment-scale loss & infiltration targets to the site-scale

Hydrologists have long held the view that hydrologic processes at small scales do not necessarily scale linearly to the catchment scale (Freeze, 1972; Pilgrim et al., 1982; Dunne et al., 1991; Cerdan et al., 2004). For example, it is likely that the evapotranspiration for a site closer to the stream (i.e. with greater groundwater availability) will be higher than that on the hillslopes (lower groundwater availability). To examine potential differences between land-parcel and catchment-scale evapotranspiration, we plotted undeveloped land-parcel scale measurements of evapotranspiration (derived from Benyon et al., 2012) on the catchment-scale Zhang et al. relationships (Figure 2). In these data, land-parcels that likely had access to groundwater (designated as those where groundwater was within 6 m of the surface; shown by red dots; pers. comm. Richard Benyon, The University of Melbourne) tended to exhibit evapotranspiration higher than annual rainfall. The evapotranspiration for sites that probably did not have access to groundwater (blue triangles) tended to be similar to that predicted by the Zhang et al. (2001) relationships. In all, these data show that land-parcel evapotranspiration is variable, but commonly higher than catchment-scale levels.

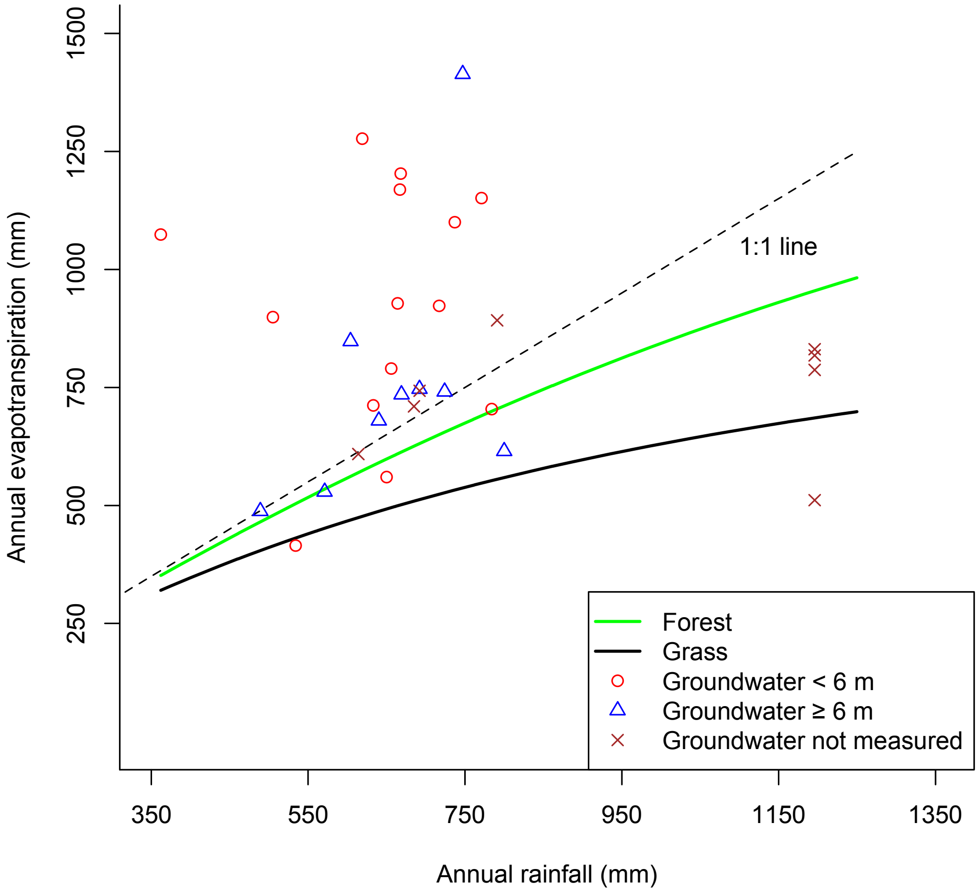

Figure 2 – Curves showing evapotranspiration as a function of rainfall, for forested (green) and grassland (black) catchments (based on the catchment-scale study of Zhang et al., 2001). The relationship between annual rainfall and evapotranspiration for individual land-parcel sites is also shown by points (i.e. all less than or equal to 900 m^2), based on the study of Benyon et al., (2012).

Some of this variation is explained by the non-closed nature of some land-parcels; in other words, where annual evapotranspiration exceeds rainfall, there must be a contribution to the site water balance from groundwater, flowing from surrounding areas. Regardless of this variability, Figure 2 would suggest that the evapotranspiration of undeveloped land-parcels in the absence of groundwater is typically at least that predicted by the Zhang grassland relationship.

Thus, the grassland and forested relationships from Zhang et al. (2001) provide a basis to set lower and upper bound targets for both volumetric loss and infiltration (filtered-flow). These targets can be calculated using Equations 1 and 2. For our case study, these equations were used to calculate lower and upper bound volumetric loss and infiltration (filtered-flow) water flux restoration targets for Melbourne, Australia. The mean annual rainfall (1982-1991) for Melbourne (based on data from climate station: 086071) was used in Equation 1.

That water flux restoration targets lie within a range predicted by the Zhang relationships, allows some flexibility and enables natural variability (spatial and temporal) to be mimicked. It is hypothesized that if stormwater planners adopted such targets in an urban-catchment, the result would be a mosaic of different stormwater retention strategies that each perform somewhere within the target range. For example, some landowners might desire large rainwater tanks because they provide greater potable water substitution than smaller tanks. Larger tanks will generally result in greater harvesting losses from a site. Thus there is likely to be variation in the performance of stormwater retention strategies and this is consistent with the variation observed in undeveloped land-parcel water fluxes (Figure 2).

Equivalent initial loss target

Because Melbourne is within south-eastern Australia, we used the median initial loss of undeveloped catchments in the region (Hill et al. 1997) as our equivalent initial loss target. In reality, initial loss varies through time, as a result of climatic factors, and is thus influenced by seasonality. Whilst an ideal equivalent initial loss target could attempt to account for this variability (for example by having separate initial loss targets for summer and winter), this would introduce a degree of complexity (both in design and compliance evaluation) in both design and operation.

3 RESULTS

Volumetric loss and infiltration targets

We found that the volumetric loss target for impervious areas within a land-parcel in Melbourne, Australia, was 77-93% of mean annual rainfall (Figure 3). Thus, the matching infiltration (filtered-flow) target was 7-23% of mean annual rainfall (Figure 3).

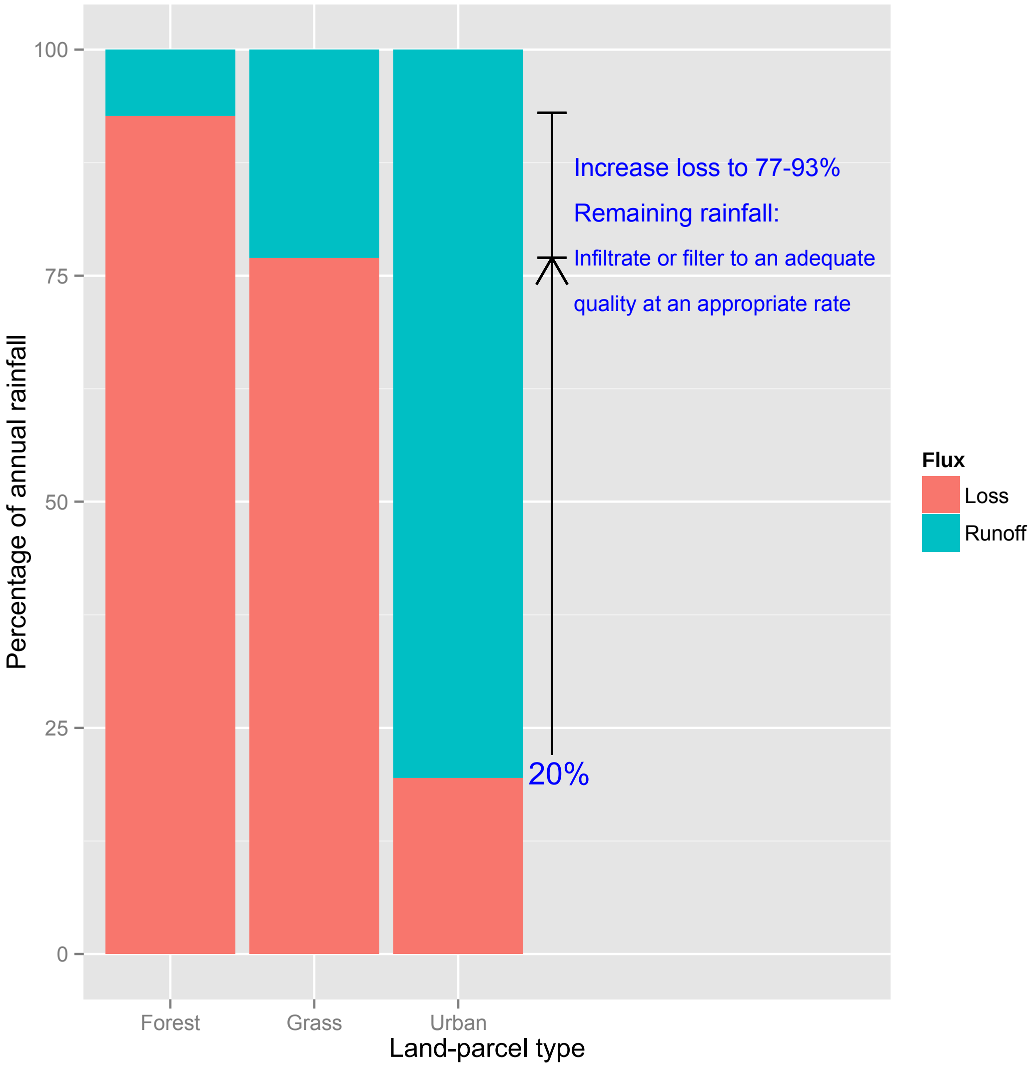

Figure 3 – Partition of mean annual rainfall (620 mm; 1982-1991) into water flux components, for three different urban land-parcel types (forest, grass and urban) in Melbourne, Australia. Loss = rainfall that is lost from the catchment because of evapotranspiration and harvesting (i.e. export to sewer). Runoff = rainfall that 1) is either infiltrated for forest and grassland land-parcels or 2) becomes impervious runoff for urban land-parcels. Impervious urban land-parcel water fluxes were calculated using an impervious runoff coefficient formula: Runoff = $[0.230 + 0.206*\log_{10}(\text{mean annual rainfall})] * 100$ (Walsh et al., 2012).

Equivalent initial loss target

We found that the median initial loss of 22 non-urban catchments (forested and rural) in south-eastern Australia was approximately 25 mm per rain-event (Hill et al., 1996). This result would suggest that stormwater control measures for a particular site should be designed to retain, on average, 25 mm of rainfall.

4 DISCUSSION AND CONCLUSION

The management of flow-regimes at the urban land-parcel scale will require both retention (through harvesting or increasing evapotranspiration) of urban stormwater runoff and restoration of baseflow processes. To achieve the suggested water flux restoration targets, the majority of rain falling on impervious areas needs to be lost, with remaining water infiltrated to local soils (or adequately filtered and released at an appropriate rate consistent with pre-development baseflow rates). This has important consequences for the selection and design of stormwater control strategies.

For example, large vegetated infiltration systems would be required to result in the volumetric loss targets we suggest because their evapotranspiration performance is primarily limited by surface area relative to the catchment area (Hamel et al., 2012). It is likely that without harvesting such systems would need to be sized to approximately the area of the impervious land-parcels they drain, which will rarely be feasible. Similarly, the use of rainwater tanks alone would be unlikely to achieve ideal performance because they capture only roof runoff, leaving other impervious surface runoff unaddressed.

We hypothesize that strategies to restore or protect pre-development flow-regimes at small scales are likely to require a combination of stormwater harvesting and infiltration. Burns et al. (2012) showed that a strategy comprising a rainwater tank (draining a detached households roof; connected to moderate demands) overflowing to a vegetated infiltration system (draining impervious pavement), was able to restore the flow-regime of a typical urban land-parcel to near-natural conditions.

There is, however, considerable uncertainty regarding the translation of hydrologic processes at these small scales to the catchment-scale, especially in urban landscapes (Burns et al., 2012). An important gap in our knowledge concerns the hydrologic processes that govern the movement of infiltrated water at small scales to the catchment-scale. For example, the capability to predict how much infiltrated water from a vegetated infiltration system at a given point within a catchment will reach the stream is currently limited (Hamel et al., 2013). Addressing these uncertainties will require detailed field experiments and modelling.

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