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Source-control stormwater management for mitigating the impacts of urbanisation on baseflow: A review

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SUMMARY

While infiltration source-control technologies are increasingly used to manage the volume, rate and quality of stormwater runoff, there is little guidance on their role and impact on baseflow. This review addresses the impacts of urbanisation on baseflow in peri-urban catchments, with the aim to better understand the potential role of stormwater infiltration source-control technologies in restoring pre-development baseflows. We analyse the physiographic and anthropogenic factors that affect the baseflow response to urbanisation. We also suggest that observed uncertainties in these baseflow responses may arise from inconsistencies in site assessment methodologies, including measurement techniques and selection of indicators. We use the natural flow paradigm to propose catchment-scale baseflow objectives and illustrate potential barriers in translating these catchment-scale objectives to the site scale. Finally, we examine the function of source-control stormwater infiltration techniques in light of both design and environmental parameters (e.g. climate, soil properties). Although we conclude that source-control technologies have potential to mitigate the impact of urbanisation on baseflow hydrology, the complexity of subsurface flow processes makes it difficult to model the effects of the implementation of several stormwater management techniques on catchment baseflow. We thus suggest that the adoption of a clear framework for baseflow assessment in pre- and post-development states, along with fundamental research on the translation from site-scale processes to catchment-scale effects, are essential research steps to guide future stormwater management for baseflow in peri-urban catchments.

1. Introduction

Urbanisation has long been recognised as an important stressor to stream ecosystems; the disturbances to flow regimes, the alteration of water quality, and direct habitat modifications affect the health of many streams around the world, even at very low levels of urbanisation (Walsh et al., 2005a; Wenger et al., 2009). While much attention has been paid to the influence of urbanisation and stormwater management practices on peak flows, impacts on baseflow and low flow have been much less studied, with only broad reviews found in the literature without a specific focus on stormwater management impacts (e.g. Price, 2011; Smakhtin, 2001). The smaller body of literature on the impact of stormwater management on baseflow and low flow may be in part explained by the complexity of the subsurface flow generation processes in urban catchments, where multiple modifications of the water balance are caused by increased imperviousness, external water inputs, and potentially long-term climate changes (O'Driscoll et al., 2010).

Similar to Price (2011), we note the inconsistent usage of the terms baseflow and low flow in the literature. We define baseflow as the "portion of streamflow coming from groundwater or delayed sources" (Hall, 1968), while low flow designates "flow that occurs during prolonged dry weather" (Smakhtin, 2001). The term baseflow thus pertains to the *source* of flow, while low flow pertains to the flow rate; however, the two are closely linked and in some sense overlapping. Their use depends on the perspective of the studies: while baseflow pertains to the net outcome of subsurface flow mechanisms, low flow commonly refers to baseflow during the dry season and is used when the emphasis is on environmental flows, i.e. on the flow regime necessary to maintain aquatic ecosystems and their benefits. The focus of this paper is on baseflow, but the term low flow will be used occasionally when addressing dry season flow, ecological issues, and when citing studies that have specifically used that term.

The alterations of baseflow by urbanisation have two potential consequences on stream ecosystems. Firstly, they may affect the

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water quality of receiving waters, as the possible decrease in baseflow due to urbanisation may accentuate the impact of pollutant inputs to the stream because of higher concentrations (Menció and Mas-Pla, 2010). Secondly, changes in the baseflow regime directly impact instream and riparian ecosystems by modifying their habitat (Rolls et al., 2012). The strength of the relationship between baseflow regime and ecological integrity is still debated (Arthington et al., 2006; Roy et al., 2009), with some eco-hydrological studies reporting no correlation between biological and baseflow indicators (Kennen et al., 2008; Steuer et al., 2010). Yet, many studies suggest that the degradation of stream ecosystems is indeed correlated with changes in baseflow characteristics (Clausen and Biggs, 1997; DeGasperi et al., 2009; Finkenbine et al., 2000). At their greatest extent, these alterations may involve a change in stream type, from intermittent to perennial or *vice versa*, with major consequences for habitat availability (Bond and Cottingham, 2008; Levick et al., 2008).

The broader recognition of the ecological issues related to alterations of streamflow regime has led to the emergence of the *natural flow paradigm* (Richter et al., 1996; Walsh et al., 2005a). This paradigm postulates that "the ecological integrity of river ecosystems depends on their natural dynamic character" (Poff et al., 1997) and suggests that hydrological objectives for water resources management should be based on the flow regime in its natural, pre-urbanised state "over recent historical time" (Poff and Zimmerman, 2010). In particular, the management of stormwater in an urban catchment should aim to mimic the pre-development hydrograph. The development and subsequent interest in the natural flow paradigm has been paralleled by the development of stormwater management strategies based on innovative technologies, comprising various types of infiltration or stormwater harvesting systems. Initially designed with a focus on runoff volume reduction and water quality improvement (Argue et al., 2009; TRCA & CVCA, 2010; US-EPA, 2009), such technologies include source-control techniques, which receive and deal with stormwater runoff at or close to its source. They have been increasingly used to (i) reduce hydrologic and water quality disturbance to urban waterways, and (ii) make use of stormwater as an alternate water resource. This approach to stormwater management are often collectively termed Water Sensitive Urban Design (WSUD; Wong, 2007), Low Impact Development (LID; Davis, 2005) or Sustainable Urban Drainage Systems (SUDS; CIRIA, 2000; Fletcher et al., 2008; Mikkelsen et al., 1996).

With stormwater management strategies beginning to consider impacts on flow regimes in a more holistic manner (Burns et al., 2012), questions arise about the urbanisation-induced alterations to baseflow. To what extent does urbanisation affect the baseflow regime? What role should and could stormwater management, and in particular source-control techniques, play in mitigating these effects? The focus of our review is mainly on peri-urban catchments, defined by their relatively low density of development, where the space and pervious area available for the implementation of source-control techniques enhancing stormwater infiltration and retention could be exploited for restoration to a more natural, pre-development hydrologic cycle. We start the review with an analysis of the impacts of urbanisation on baseflow, stressing the limitations of the methodologies used to measure the resulting changes. Then, we identify catchment-scale objectives for the mitigation of baseflow alteration, highlighting the difficulties in their translation at the scale of source-control techniques. Finally, we present the functions and design options of source-control infiltration techniques and examine how their combined effects may be modelled at the catchment scale. We conclude with a synthesis of knowledge gaps and subsequent priorities for future research.

2. Assessment and interpretation of baseflow alterations by urbanisation

2.1. Influence of urbanisation on baseflow generation processes

Since subsurface flows result from the complex interactions between vegetation, climate, soil and topography, it is difficult to generalise the effects that urbanisation might have on catchment baseflow (see review by Price, 2011). For example, the baseflow index (ratio of baseflow to total streamflow) of natural catchments may range from 20% to 90% within a region, depending on the particular catchment geology (Bloomfield et al., 2009; Lacey, 1996). Catchments with low-permeability soils, which limit infiltration in the natural state, may thus have a less pronounced baseflow response to urbanisation than those with more free-draining soils (Meyer, 2005). Similarly, vegetation and rainfall characteristics influence the amount of evapotranspiration, affecting the amount of water available for both surface runoff and baseflow (Calder, 2000; Hickel and Zhang, 2003; Zhang et al., 2001). Therefore, the characteristics of the subsurface flow processes in the pre-development state will affect the nature and extent of baseflow response to urbanisation.

In addition to catchment physiography, four main characteristics of urban development influence alterations of the baseflow regime: catchment imperviousness, connectivity between impervious surfaces and the receiving waters, spatial distribution of impervious surfaces in the catchment, and anthropogenic water inputs and outputs. Catchment imperviousness has been widely used to characterise the impact of urbanisation, especially in relation to runoff quality, and increased runoff volumes and peaks (see reviews in Jacobson (2011) and Shuster et al. (2005)). *Effective* (or *directly connected*) imperviousness, which only includes "impervious areas that are hydraulically connected to a drainage system" (Shuster et al., 2005), is usually distinguished from *total* imperviousness, and is seen as a better predictor of rainfall-runoff response and stream health (Walsh et al., 2005a). However, consideration of the catchment effective imperviousness alone is unlikely to wholly explain the alterations to baseflow by urbanisation. Firstly, modifications to pervious areas may also result in altered infiltration and rainfall-runoff behaviour (Gregory et al., 2006; Mueller and Thompson, 2009; Shuster et al., 2005), due to compaction and structural modification of urban soils. While the significance of these effects is likely to be dependent on site-specific building practices (Boyd et al., 1994; Goldshleger et al., 2009), the presence of areas with different levels of compaction potentially precludes the prediction of baseflow alteration using impervious areas alone. Secondly, with a focus on baseflow, total imperviousness may better predict the gross disturbance to infiltration and evapotranspiration fluxes, and thus to net baseflow contributions. Indeed, sealed surfaces that drain to pervious areas are discarded in the calculation of effective imperviousness, but these areas are still likely to change the catchment baseflow regime. The change from homogeneous recharge to localised recharge between impervious areas may induce smaller losses by evapotranspiration than in the pre-development state (Ku et al., 1992), or alter the magnitude and timing of subsurface flow processes producing baseflow (Brandes et al., 2005; O'Driscoll et al., 2010). The sole consideration of *connected* impervious areas thus potentially ignores some changes in baseflow generation processes induced by urbanisation.

In addition to its area, the spatial distribution of imperviousness may also impact baseflow generation processes significantly. Recent laboratory studies confirmed the influence of alternating patterns of bare soil and impervious areas on the total amount of infiltrated water (Pappas et al., 2011; Shuster and Pappas, 2011),