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Review papers

Stormwater infiltration and the 'urban karst' – A review

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A B S T R A C T

The covering of native soils with impervious surfaces (e.g. roofs, roads, and pavement) prevents infiltration of rainfall into the ground, resulting in increased surface runoff and decreased groundwater recharge. When this excess water is managed using stormwater drainage systems, flow and water quality regimes of urban streams are severely altered, leading to the degradation of their ecosystems. Urban streams restoration requires alternative approaches towards stormwater management, which aim to restore the flow regime towards pre-development conditions. The practice of stormwater infiltration—achieved using a range of stormwater source-control measures (SCMs)—is central to restoring baseflow. Despite this, little is known about what happens to the infiltrated water. Current knowledge about the impact of stormwater infiltration on flow regimes was reviewed. Infiltration systems were found to be efficient at attenuating high-flow hydrology (reducing peak magnitudes and frequencies) at a range of scales (parcel, streetscape, catchment). Several modelling studies predict a positive impact of stormwater infiltration on baseflow, and empirical evidence is emerging, but the fate of infiltrated stormwater remains unclear. It is not known how infiltrated water travels along the subsurface pathways that characterise the urban environment, in particular the 'urban karst', which results from networks of human-made subsurface pathways, e.g. stormwater and sanitary sewer pipes and associated high permeability trenches. Seepage of groundwater into and around such pipes is possible, meaning some infiltrated stormwater could travel along artificial pathways. The catchment-scale ability of infiltration systems to restore groundwater recharge and baseflow is thus ambiguous. Further understanding of the fate of infiltrated stormwater is required to ensure infiltration systems deliver optimal outcomes for waterway flow regimes.

Contents

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1. Introduction

In most temperate climates, streamflow generation in natural catchments is dominated by subsurface processes (Kirkby, 1988), and a large proportion of rainfall is lost to evapotranspiration (Zhang et al., 1999). Streamflow is typically dominated by 'pre-event' water (Fiori, 2012; Tetzlaff et al., 2014) i.e. water that has been stored in the catchment before the rainfall event. Urbanization seals native soils with impervious surfaces (e.g. roofs, roads and pavement), substantially changing the hydrologic cycle (Fletcher et al., 2013). It modifies the way rainfall travels to receiving waters, altering both surface and subsurface pathways.

Initial losses of rainfall from impervious surfaces are typically small (0.5–4 mm, from depression storage or fissures) (Amaguchi et al., 2012; Burns et al., 2015a) and so most rainfall events in urban catchments generate surface runoff. The common way to manage this excess runoff is through the use of hydraulically efficient stormwater drainage networks, which are connected directly to receiving waters. A major consequence of this stormwater management approach is severely altered flow regimes: increased frequency, magnitude and volume of surface runoff (Barron et al., 2013; Braud et al., 2013; Paul and Meyer, 2001). Urban streamflow displays a dominance of contributions from 'event' water, i.e. water from rainfall events (Jacobson, 2011; Miller et al., 2014).

Alterations to the flow regime of urban streams are not limited to high flows. Urban streams may also have greatly impacted baseflow (Bhaskar et al., 2015a; Price, 2011), which is here defined as the groundwater contribution to streamflow. The construction of impervious areas drained by stormwater networks reduces infiltration and groundwater recharge (Sharp and Garcia-Fresca, 2003), and this typically reduces baseflows, although in some cases baseflow in urban streams may be increased by anthropogenic sources, such as leakage of imported water (Lerner, 2002).

Urban stormwater runoff conveyed directly to streams via conventional man-made drainage systems and the depletion of sustained low-flows are recognised as primary degraders of urban stream ecology (King et al., 2005; Vietz et al., 2014; Wright et al., 2011). Mitigation of the stormwater impacts on flow and water quality requires stormwater management approaches that return catchment-scale hydrology towards its natural condition (Walsh et al., 2012). Burns et al. (2012) hypothesized that flow and water-quality regimes can be restored at the catchment-scale by mimicking the natural water balance at small scales (i.e. the scale of each parcel or precinct). The objectives of such approaches are to return fluxes of infiltration and evapotranspiration towards the pre-development condition (Walsh et al., 2015), using a range of stormwater control measures (SCMs). A wide range of SCMs has been developed, including stormwater wetlands, ponds, infiltration systems, stormwater harvesting systems and even vegetated roofs and walls. Among the many SCMs, stormwater infiltration has been used widely as a tool to mitigate flow regime disturbances and restore more natural flow regimes (Hamel et al., 2012). Stormwater infiltration systems include rain-gardens, pervious pavement, infiltration trenches, basins and wells. One important underlying assumption behind stormwater infiltration is that increasing infiltration will recharge groundwater, thereby restoring baseflow (Hamel et al., 2013).

Despite the increasing popularity of stormwater infiltration, very little is known about the fate of infiltrated stormwater beyond the small scales (~10 to ~100 m^2: typically the size of infiltration systems and their vicinity). The temporal and spatial variability of the contributions of infiltrated stormwater to groundwater recharge and consequently baseflow remains unclear. Such uncertainty could potentially undermine efforts to restore the health of urban stream ecosystems through flow regime restoration, leading to degradation and loss of biodiversity and ecosystem services (Walsh et al., 2015). While the alteration of baseflow by urbanization and the mitigating potential of infiltration-based stormwater management has been investigated by others (e.g. Bhaskar et al. (2015a), Hamel et al. (2013)), no attempt has yet been made to review the literature to identify the fate of infiltrated stormwater and to provide a basis for future research on the question.

In this review paper the assumption that stormwater infiltration recharges the phreatic water store is therefore explored and possible pathways of this water are considered. The review is structured in two principal parts. In the first part, the hydrologic performance of infiltration-based stormwater management techniques is reviewed, i.e. their ability to attenuate high flows and restore baseflow from the site scale to the catchment scale. It is concluded that the current lack of understanding of the conversion of site-scale stormwater infiltration to catchment-scale baseflow is primarily due to insufficient knowledge of groundwater pathways in the urban context.

In the second part, the potential for man-made, high-permeability trenches, such as gravel surrounding underground pipes, to impact urban subsurface water pathways is evaluated. The 'urban karst' is an important concept identified by Kaushal and Belt (2012). It has been defined as the network of constructed pipes influencing groundwater flow, through leaks, cracks and fissures (sewers, stormwater) but also through associated high-permeability trenches surrounding these pipes (telecommunications, water supply). It can create preferential flow paths for infiltrated stormwater and associated pollutants and has the potential to be a driver of hydrological processes in urban catchments. The article, inspired by the concept proposed by Kaushal and Belt (2012), aims to provide a foundation for future research to better understand the catchment-scale impacts of stormwater infiltration. Without such understanding, stormwater management strategies based on infiltration may fail to perform as intended, or indeed may have perverse effects.

2. Impact of stormwater infiltration

2.1. Site-scale: piped inflow vs. piped outflow

At the scale of stormwater infiltration systems themselves (i.e. the size of systems, usually ranging around ~10 m^2 to ~100 m^2), the hydrological performance is well documented. Water budgets of infiltration systems are calculated as a comparison between piped inflow and outflow (Fig. 1, Marker 1). Infiltration systems have been found to be efficient at attenuating the frequency and the magnitude of peak flows, as well as decreasing the volume of stormwater runoff discharged to downstream drainage networks and thus receiving waters (Davis, 2008; Dietz and Clausen, 2008; Hunt et al., 2006; Li et al., 2009). Such findings are also true at the streetscape scale (~10 m^2 to ~10,000 m^2), as stormwater drains in streets with infiltration-based SCMs also see their overall volume of runoff and peak flows reduced (Jarden et al., 2015; Page et al., 2015; Wilson et al., 2014). These studies, though providing important information on the effects of infiltration systems on