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Research papers

The impact of urbanization on subsurface flow paths – A paired-catchment isotopic study

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ABSTRACT

Urbanization disturbs groundwater flow through the sealing of native soils with impervious surfaces and through modifications to the subsoil by constructed drainage and other infrastructure (trenches and excavations, e.g. water supply). The impact of these disturbances on groundwater contributions to urban streams (i.e. baseflow) is poorly understood. While high flows caused by impervious runoff to streams are a common focus of urban studies, the route taken by groundwater to become streamflow in urban landscapes is not generally considered. To assess the impact of urbanization on groundwater sources to streams, both rainfall and baseflow were sampled weekly for stable isotopes of water in two nearby streams—one draining a *peri*-urban catchment and the other draining a forested, natural catchment. In addition, to study the rate of groundwater discharge to the stream, monthly baseflow recession behavior was investigated. We found that baseflow in the forested catchment was constant in stable isotope values ($\delta^{18}O = -5.73‰ \pm 0.14‰$) throughout the year. Monthly baseflow recession constants were close to 1 and had little variation (ranging 0.951–0.992), indicating a well-mixed groundwater store and long residence times. In contrast, the urban baseflow isotopic composition featured distinct seasonal variations ($\delta^{18}O = -3.35‰ \pm 1.20‰$ from October to March and $\delta^{18}O = -4.54‰ \pm 0.43‰$ from April to September) and high week-to-week variability in summer, reflecting a contribution of recent rainfall to baseflow. Recession constants were lower (ranging 0.727–0.955) with pronounced seasonal variations, suggesting shorter residence times and the likely presence of a variety of stores and pathways. These results provide evidence that the urban catchment has diversified groundwater pathways, and its groundwater storage is drained faster than that of the forested catchment. It highlights some of the subsurface hydrological consequences of urbanization. Restoring low-flow aspects of the flow regime through nature-mimicking stormwater management requires careful consideration of how the behavior of natural groundwater pathways can be restored or replicated using innovative stormwater control measures.

1. Introduction

Urbanization substantially modifies the water balance in catchments. The sealing of native soils with impervious surfaces causes surface runoff to increase, whilst decreasing evapotranspiration and infiltration. Flow pathways are modified, as the excess surface runoff is commonly routed directly to receiving waters via hydraulically efficient drainage systems (Burns et al., 2012). The dominance of surface flow paths and the complexity of groundwater systems has led to the overlooking of subsurface processes in urban catchments (Cizek and Hunt, 2013). In contrast, in non-urban, temperate catchments, subsurface pathways have been identified as dominant contributors to streamflow (Buttle, 1994; Tetzlaff et al., 2015). While the importance of subsurface waters to urban streams is increasingly apparent (Bhaskar and Welty, 2015; Gabor et al., 2017), understanding baseflow responses following urbanization is still very uncertain (Price, 2011; Bhaskar et al., 2015), as reduced groundwater recharge caused by impervious surfaces (Barron et al., 2013; Braud et al., 2013) is countered by increased recharge through leakage from utilities (Lerner, 2002), and require a better understanding of processes.

The presence of drains, sewers, telecommunication and gas lines potentially impact shallow groundwater pathways. Fractured pipes can

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intercept groundwater flow (Wittenberg and Aksoy, 2010) and pipes are usually surrounded by highly permeable sand or gravel trenches which can become preferential flow pathways for groundwater and pollutants (Sharp et al., 2013). Conceptually identified as the 'urban karst' (Vázquez-Suñé et al., 2004; Kaushal and Belt, 2012), this network of large macropores can impact streams relying on shallow groundwater stores (Perera et al., 2013). This could also in theory accelerate the transport of infiltrated water, thus affecting groundwater discharge to streams and reducing subsurface storage (Bhaskar et al., 2015).

Streamflow at a given time is composed of a mix of water coming from past and new rainfall reaching the stream through a range of pathways. Rapid pathways include overland flow (Hewlett and Hibbert, 1967; McDonnell, 2009) and soil macropores (Sidle et al., 2001; Beven and Germann, 2013), while slower ones include the soil matrix or deeper groundwater flow paths (Perrin et al., 2003). Regional groundwater can be decades old, and produce old baseflow (Katsura et al., 2008; Kosugi et al., 2008). The time taken by rainfall to become streamflow (i.e. transit time) has been quantified using tracers (Maloszewski and Zuber, 1982; Maloszewski and Zuber, 1996; Etcheverry, 2002), such as the conservative stable isotopes of water. Catchment mean transit times can range from months to years in forested, natural catchments, (Vitvar et al., 2002; McGuire and McDonnell, 2006; McDonnell et al., 2010), primarily controlled by climate, topography, catchment shape and soil cover (McGlynn et al., 2003; McGuire et al., 2005; Rodgers et al., 2005). The role of vegetation and climate are variable. For example, vegetation cover was not found to be a primary driver of groundwater residence time in the Europeans Alps (Mueller et al., 2013). In contrast, evapotranspiration rates during recharge periods are thought to control mean transit times in the Australian Alps (Cartwright and Morgenstern, 2015); and can also control the rate of groundwater discharge to streams (Tallaksen, 1993; Wittenberg, 2003).

Urbanization accelerates the transport of water to the stream, due to the contribution of rapid impervious drainage. In a study of temperate, wet Scottish catchments, Soulsby et al. (2014) found a total streamflow (i.e. including impervious runoff) Mean Transit Time (MTT) of around 10 days, 1 year, 2–3 years and 4 years, for, respectively, 100%, 63%, 13% and 0% urbanized catchments, respectively. In the same part of the world, Soulsby et al. (2015) confirmed the result by comparing an urban catchment with a MTT of 171 days against 456 days for a non-urban stream. McGrane et al. (2014) compared transit times in eight catchments (ranging in area between 104 and 488 km^2), but anthropogenic factors such as storage, groundwater abstraction and runoff disturbed the isotopic signal and caused the observations not to be considered reliable.

The catchment-scale impact of urbanization on the baseflow MTT has rarely been quantified in field studies. Burns et al. (2005) quantified baseflow transit times across a gradient of urbanization in low density catchments (0.38–0.56 km^2 with land-use ranging from non-developed to 11.1% imperviousness) but did not observe differences between catchments (MTT of around 30 weeks). Their findings could be related to the very low level of disturbances in the urban catchments. They did observe that the non-developed catchment had higher subsurface storage, but whether this was due to land-use or soil characteristics is unknown. Quantifying how groundwater travels in the urban environment is important: doing so could help in the management of groundwater contaminants which pose a threat to urban water quality (Roy and Bickerton, 2012; Gabor et al., 2017). It could also improve the effectiveness of stormwater infiltration as large investments are made worldwide on stormwater infiltration structures (Moura et al., 2007; Melbourne Water, 2013; Blecken et al., 2015), without yet a strong understanding of the fate of infiltrated stormwater.

This study aims to improve our understanding of the complexity of 'urban hydrogeology' (Schirmer et al., 2013). We investigate the impacts of low-density urbanization on groundwater pathways and baseflow using a hydrologically paired-catchment approach. We hypothesize that urbanization creates multiple, poorly mixed stores, connected by a shallow network of preferential groundwater flow paths, leading to a more rapid transfer of rainfall to the stream in comparison to the flow pathways in an undisturbed catchment. To test this hypothesis, two sub-humid streams - one in a forested catchment and the other in an urban catchment – were studied through two research questions:

- How does urbanization impact groundwater mixing processes and the source of baseflow? A sampling campaign of stable isotopes (^{18}O and ^{2}H) in both rainfall and baseflow was conducted in both catchments to investigate sources (old water/recent water) of baseflow. The forested baseflow had a stable isotopic composition while the urban baseflow isotopic composition reflected contribution of recent water.
- How does urbanization impact the timing of groundwater discharge to streams? Recession hydrographs characteristics were calculated to investigate residence and transit time of baseflow in both catchments. The forested baseflow was dominated by long transit times while the urban baseflow had shorter transit times.

2. Study catchments

Two streams, Lyrebird Creek (hereafter referred to as the forested stream) and Little Stringybark Creek (urban stream), were selected. Both are located east of Melbourne, Australia (Fig. 1) and share the same geology (Vandenberg, 1997): Devonian felsic igneous bedrock which has weathered into clayey soils. In the urban catchment, saturated hydraulic conductivities average $\sim 10^{-6}$ m s^{-1} (measured at the surface and at 0.5 m deep at several locations across the catchment with air-entry permeameters). Alluvial deposits occur in stream valleys of both catchments. The monitored outlets of the catchments are ~10 km from each other. The shape and area of both catchments are similar: Gravelius indexes (a ratio of catchment perimeter and area) are 1.41 and 1.34 (Supplementary Table 1).

The forested catchment drains a Eucalpyt-dominated landscape of 7.2 km^2 in size. The catchment is within the Dandenong Ranges National Park, with no agricultural land use and only a negligible amount of urbanization (total imperviousness < 1%, with less than a dozen permanent residents and no stormwater drainage infrastructure). The flow regime at the outlet is representative of pre-urban streams in the area (Walsh et al., 2015). Elevation ranges from 581 m AHD (Australian Height Datum, expressed in m) down to 213 m, mean annual rainfall is 1270 mm (Fig. 2) and average annual areal potential evapotranspiration (PET) is around 1100 mm (BoM, 2016).

The urban catchment is 4.5 km^2 in area and drains a *peri*-urban landscape comprising medium-density development in the headwaters, with larger rural properties in the lowlands. The catchment's population is around 2500 people. Most impervious surfaces (14.2% of the catchment, including 5.4% drained by a stormwater network) are drained to the stream using conventional stormwater drainage systems. The catchment is currently the subject of an experiment which is testing alternative approaches towards stormwater management. To date, the experiment has implemented hundreds of infiltrated-based stormwater control measures throughout the catchment (Walsh et al., 2015). The catchment does not have any deep underground structures (such as tunnels), and the only disturbances to groundwater pathways are shallow infrastructure—pipes, cables, and utility trenches. Elevation ranges from 266 m down to 136 m, mean annual rainfall is 1034 mm (Fig. 2) and average annual PET is around 1100 mm (BoM, 2016).

One year of streamflow data (May-2015 to May-2016) for the catchments was obtained from a database maintained by the Waterway Ecosystem Research Group (Walsh et al., 2015; WERG, 2018). In the forested catchment, stream water level was measured upstream of a culvert with a capacitance probe and converted to streamflow with a rating curve. In the urban catchment a pressure sensor was used to