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Land cover controls on summer discharge and runoff solution chemistry of semi-arid urban catchments

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SUMMARY

Recharge of urban runoff to groundwater as a stormwater management practice has gained importance in semi-arid regions where water resources are scarce and urban centers are growing. Despite this trend, the importance of land cover in controlling semi-arid catchment runoff quantity and quality remains unclear. Here we address the question: How do land cover characteristics control the amount and quality of storm runoff in semi-arid urban catchments? We monitored summertime runoff quantity and quality from five catchments dominated by distinct urban land uses: low, medium, and high density residential, mixed use, and commercial. Increasing urban land cover increased runoff duration and the likelihood that a rainfall event would result in runoff, but did not increase the time to peak discharge of episodic runoff. The effect of urban land cover on hydrologic responses was tightly coupled to the magnitude of rainfall. At distinct rainfall thresholds, roads, percent impervious cover and the stormwater drainage network controlled runoff frequency, runoff depth and runoff ratios. Contrary to initial expectations, runoff quality did not vary in repose to impervious cover or land use. We identified four major mechanisms controlling runoff quality: (1) variable solute sourcing due to land use heterogeneity and above ground catchment connectivity; (2) the spatial extent of pervious and biogeochemically active areas; (3) the efficiency of overland flow and runoff mobilization; and (4) solute flushing and dilution. Our study highlights the importance of the stormwater drainage systems characteristics in controlling urban runoff quantity and quality; and suggests that enhanced wetting and in-stream processes may control solute sourcing and retention. Finally, we suggest that the characteristics of the stormwater drainage system should be integrated into stormwater management approaches.

1. Introduction

Groundwater recharge of urban runoff has gained importance as a potential strategy to offset municipal water demands in arid and semi-arid regions (Chralowicz et al., 2001; Crowley et al., 2005; Decook and Foster, 1984). In these regions, water resources are scarce, and population growth and urban expansion are expected to continue to increase (Berling-Wolff and Wu, 2004; Norman et al., 2009). Moreover, projected climate changes are likely to increase the uncertainty of future water resources with higher temperatures and more extreme patterns in rainfall (Gelt et al., 1999; Serrat-Capdevila et al., 2007); thus, municipalities are seeking alternatives to enhance groundwater recharge and encourage water resources conservation.

Recharge in arid and semi-arid regions typically occurs along mountain fronts and via infiltration in ephemeral stream channels during the summer months, when high intensity rainfall generates most of the annual runoff (Gochis et al., 2006; Goodrich et al., 1997; Resnick et al., 1983). Because runoff quantity increases with increasing rainfall magnitude and percent impervious cover in some semi-arid catchments (Gallo et al., 2012), urbanization may enhance runoff recharge in ephemeral waterways and augment localized water resources. Indeed, recent work using groundwater age tracers by Carlson et al. (2011) indicates recharge of new waters in ephemeral channels and increases in groundwater nitrate in an urban semi-arid basin. Questions remain about the sources of these new waters, the quality of urban runoff for potential recharge, and how land cover controls urban hydrology and

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hydrochemistry, information that is critical for management of groundwater quality.

Numerous studies across a wide range of geographic locations and climates show that urbanization can alter catchment hydrologic responses and negatively impact surface and downstream waters (for example: Athayde et al., 1983; EPA, 1997; Maestre and Pitt, 2006; Shuster et al., 2005; Smullen et al., 1999; Walsh et al., 2005a; Wenger et al., 2009; Zampella et al., 2007). Early urban runoff monitoring efforts such as Nation Wide Urban Runoff Program (NURP, Smullen et al., 1999), the National Water Quality Assessment Program (NAWQA, Brown et al., 2009) and the National Stormwater Quality database (NSQD, Maestre and Pitt, 2006; Pitt et al., 2008) aimed to identify urban runoff responses from distinct urban land uses. However, the data showed mixed responses to land use, indicating more complex controls on urban runoff responses. Some conceptual models suggest that both, urban runoff quantity and quality, are primarily controlled by percent impervious cover (Arnold and Gibbons, 1996; Paul and Meyer, 2001; Schueler, 1994), while others indicate that urban runoff quality and quantity are largely controlled by the extent of catchment connectivity and the characteristics of the stormwater drainage system (Carle et al., 2005; Hatt et al., 2004; Meierdiercks et al., 2010; Ogden et al., 2011; Walsh et al., 2009). However, few studies have specifically addressed how urbanization alters runoff responses in semi-arid regions (for example: Asaf et al., 2004; Ishaq and Alassar, 1999; Jiries et al., 2001; Lewis and Grimm, 2007) where runoff and subsequent streamflow occur only in response to rainfall. A recent study by Gallo et al. (2012), for example, showed that short term (hours) partitioning of rainfall controls the temporal patterns of urban hydrologic responses in semi-arid study catchments in Tucson, AZ. In contrast, the temporal patterns in runoff quality were controlled by the magnitude, frequency and timing of rainfall. However, the role of land cover and its configuration in controlling runoff hydrology and hydrochemistry remains unclear.

In this study, we address the question: How do land cover characteristics control storm runoff quantity and quality in semi-arid urban catchments? We monitored runoff quantity and quality in five small (<4.7 km^2) urban catchments in Tucson, Arizona during the summer rainfall seasons of 2007 and 2008. We identified instances of collinearity among land cover variables, and quantified the effect of summertime rainfall and land cover characteristics on urban runoff responses. We expected runoff quantity to increase and runoff quality to decrease with increasing urbanization, specifically in response to impervious cover and the characteristics of the stormwater drainage system. We show that the effects of land cover on some aspects of urban hydrology vary with the magnitude of rainfall; that runoff quality does not vary directly with urban land cover; and we highlight mechanisms controlling runoff quality.

2. Study region and study period overview

The study catchments are located in the Tucson Metropolitan area in southern Arizona, USA within an alluvial basin bounded by the Tucson, Santa Catalina and Rincon mountains to the west, north and east, respectively (Hoffmann et al., 2007). The Tucson Mountains are primarily Late Cretaceous to Early Tertiary andesite and dacite, and alluvium from this range is constrained to the west of the Santa Cruz River and does not underlay our study catchments (Ludington et al., 2007). The Catalina and Rincon Mountains are primarily composed of Late Cretaceous to Early Tertiary granite and pegmatite, and to a lesser extent early Proterozoic to Tertiary gneiss and mylonite. Late Pliocene to early Pleistocene alluvial fans comprise the Catalina and Rincon Mountain foothills, and quaternary granitic alluvium derived from these two ranges makes up the basin fill east of the Santa Cruz River (Ludington et al., 2007). The major Santa Cruz River tributaries, the Canada del Oro, Rillito Creek, Pantano Wash and Tanque Verde Creek are ephemeral waterways that flow to the northwest of the basin (Wilson et al., 1998), and have been identified as areas of focused groundwater recharge (Eastoe et al., 2004).

The regional climate is semi-arid; mean annual precipitation is approximately 310 mm, potential evapotranspiration exceeds 1960 mm yr^{-1} (Gelt et al., 1999; Wilson et al., 1998), and evaporation can exceed 250 mm yr^{-1} (Unland et al., 1996). The Tucson Metropolitan Area is located within the Sonoran Desert Ecoregion, the wettest North American Desert (Arizona Game and Fish Department, 2006). Precipitation in the Sonoran Desert is bimodally distributed with approximately 48% of rainfall occurring during the summer months as thunderstorms (i.e. the North American Monsoon, Gelt et al., 1999) that follow an extended period (2–3 months) of hot and dry conditions. Atmospheric convection generates monsoonal rainfall (Gelt et al., 1999; Hoffmann et al., 2007), which is characterized by its short duration, high intensity and high spatial heterogeneity (Garcia et al., 2008; Morin et al., 2006; Syed et al., 2003). Data from Morin et al. (2006) indicate that monsoonal thunderstorms can be spatially isolated to a radius as small as 2 km. In contrast, winter precipitation events are longer in duration, lower in intensity, spatially widespread, and evenly distributed. Winter rainfall accounts for most mountain front recharge in non-urban settings (Coes and Pool, 2007; Eastoe et al., 2004); however, a significant proportion of recharge occurs via stream channel infiltration of runoff generated in response to monsoonal rainfall (Baillie et al., 2007; Goodrich et al., 2004). Therefore, urban rainfall–runoff responses may significantly impact ephemeral channel recharge. This study was conducted between June 15th and September 30th of 2007 and 2008, the official span of the summer monsoon (Guido, 2008), when infiltration excess overland flow of monsoonal rainfall generates most of the annual runoff (Gochis et al., 2006; Goodrich et al., 1997; Stone et al., 2008).

3. Methods

3.1. Catchment characterization

We monitored urban runoff responses from 5 hydrologically isolated catchments, each dominated by a specific type of urban land use: (1) low density residential (LD), (2) medium density residential (MD), (3) high density residential (HD), (4) mixed land use (MX), and (5) commercial land use (CM, Fig. 1). The catchments were delineated in ArcMap 9.0 using the stormwater drainage system, which does not share any infrastructure with the sewer system, and using 0.65 m elevation data provided by the City of Tucson's Office of Conservation and Sustainable Development (Tucson OCSD) and the Pima County Department of Transportation (http://www.dot.co.pima.az.us/gis/maps/). The percent low, medium and high density residential housing, the percent commercial development (commercial + roads), and the percent open space (parks + undeveloped land + agricultural land) for each catchment were determined from December 2006 parcel-level hydrologic land use data provided by Tucson OCSD as follows:

$$fa_{LCx} = 100 \cdot \frac{a_{LCx}}{a_c} \quad (1)$$

where fa_{LCx} is the catchment proportion of land cover x, a_c is the catchment size or area in km^2 and a_{LCx} is the area in km^2 of land cover x. Areas were calculated using the "Area Calculation by Gauss" method in ArcMap 9.0. Percent impervious cover (IC) within the catchments was determined as follows:

$$IC = \sum_{x=i}^{n} fa_{LCx} \cdot fIC_{LCx} \quad (2)$$