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Continuous and event-based time series analysis of observed floodplain groundwater flow under contrasting land-use types

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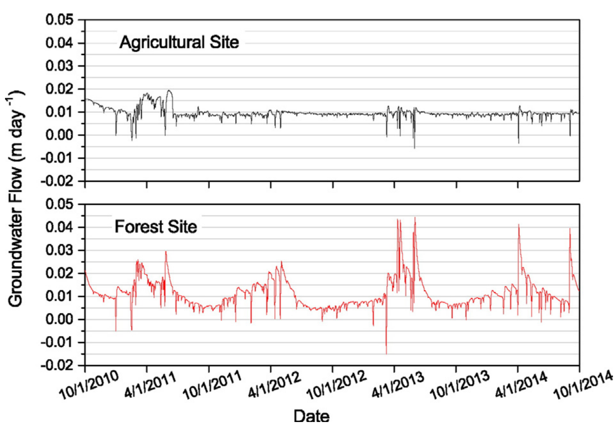
HIGHLIGHTS

- Applied high-resolution groundwater monitoring at a forest and agricultural field
- Forest exhibited a more dynamic groundwater flow regime than the agriculture site.
- The forest displayed greater stream-to-aquifer flows, relative to the Ag site.
- Event-based analyses showed a more seasonally responsive flow regime at the forest.
- Results highlight importance of floodplain forest ecosystem services.

GRAPHICAL ABSTRACT



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ABSTRACT

There is an ongoing need to improve quantitative understanding of land-use impacts on floodplain groundwater flow regimes. A study was implemented in Hinkson Creek Watershed, Missouri, USA, including equidistant grids of nine piezometers, equipped with pressure transducers, which were installed at two floodplain study sites: a remnant bottomland hardwood forest (BHF) and a historical agricultural field (Ag). Data were logged at thirty minute intervals for the duration of the 2011, 2012, 2013, and 2014 water years (October 1, 2010–September 30, 2014). Results show significant ($p < 0.001$) differences between Darcy-estimated groundwater flow at the two study sites. Although median flow values at the two sites were similar (0.009 and 0.010 m day^{-1} for the Ag and BHF sites, respectively), the BHF displayed a more dynamic flow regime compared to the Ag site. Maximum flow values were 0.020 and 0.049 m day^{-1} for the Ag and BHF sites, respectively. Minimum flow values were −0.018 and −0.029 m day^{-1} for the Ag and BHF sites, respectively. The BHF showed greater magnitude, longer duration, and more frequent negative flows, relative to the Ag site. Event-based analyses indicated a more seasonally responsive flow regime at the BHF, with higher flows than the Ag site during the wet season and lower flows than the Ag site during the dry season. Notably, the seasonal pattern of relative site flow differences was consistent across a wide range of precipitation event magnitudes (i.e. 8–45 mm). Results are by majority attributable to greater rates of plant water use by woody vegetation and preferential subsurface flow at the BHF site. Collectively, results suggest greater flood attenuation capacity and streamwater buffering

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potential by the BHF floodplain, relative to the Ag, and highlight the value of floodplain forests as a land and water resource management tool.

1. Introduction

Land use changes like forest removal can impact a variety of physical, chemical, and biological natural processes. Studies have repeatedly and conclusively shown that land use change modifies hydrologic regimes in response to altered mass and energy flux (Booth and Jackson, 1997; Brezonik and Stadelmann, 2002; Twine et al., 2004; Konrad and Booth, 2005; Hubbart et al., 2007; Karwan et al., 2007; Hubbart et al., 2015). Land-use impacts on hydrologic regimes are particularly important in floodplain landscapes. As a function of their location at the groundwater-surface water interface, floodplains can provide numerous ecosystem services such as biogeochemical transformation and remediation of nutrients and pollutants, runoff regulation, and floodwater mitigation (Krause et al., 2007). However, land-use practices such as urbanization have been shown to degrade floodplain condition and function, impairing natural ecosystem service potential and in extreme cases transforming floodplains into sources of water pollution (Gooddy et al., 2014).

Floodplain forests in particular are important ecotones, regulating energy and nutrient fluxes between surface water and groundwater reservoirs (Sanchez-Pérez and Trémolières, 2003). Recent research highlighted the benefits of floodplain forests, including but not limited to filtering runoff/groundwater, reducing overbank flow velocity, functioning as a source of coarse woody debris to streams (an important component of in-stream habitat), and providing diverse habitat essential to biodiversity (Naiman et al., 1993; Piegay, 1997). Floodplain forests can also function as zones of nutrient (e.g. nitrate) retention, influencing groundwater chemistry and reducing nutrient loading to adjacent streams (Jordan et al., 1993). Additionally, floodplain soils and vegetation management are central to the flood water attenuation capacity of floodplains (Hubbart et al., 2011). Floodplains attenuate floods by retaining water and decreasing velocity, thereby slowing and reducing flood wave impacts (Wheater and Evans, 2009). Thus, downstream flood risk mitigation can be achieved by permitting the natural attenuation (i.e. inundation, infiltration, retention, evapotranspiration) afforded by floodplains (Wheater and Evans, 2009). However, research indicates that <25% of native bottomland hardwood forest remains in various regions of the U.S., and that the majority of forest removal has been due to agricultural conversion (Abernathy and Turner, 1987; Carter and Biagas, 2007).

Over time, land use/land cover changes (e.g. forest removal, agricultural cultivation) can result in alterations to subsurface hydraulic processes such as infiltration rate, percolation, and soil water retention (Hubbart et al., 2011; Wahren et al., 2009). Recent studies identified numerous impacts of land use on subsurface hydrology. Wahren et al. (2009) showed that afforestation resulted in increased infiltration, soil water retention, and hydraulic conductivity, particularly in the upper soil horizons. It was further noted that subsurface flow in forested sites can be dominated by preferential flow via macropores created by decayed roots (Wahren et al., 2009). Similarly, Gonzalez-Sosa et al. (2010) quantified land-use impacts on topsoil hydraulic properties in France, showing that bulk density values were lowest and hydraulic conductivity values were highest for forest soils, relative to pasture and cropland. In a study comparing soil characteristics of a remnant bottomland hardwood forest and a former agriculture field, Hubbart et al. (2011) reported mean infiltration at the forest site to be 61% greater than the agricultural site. Given that subsurface hydraulic properties can influence groundwater flow regimes, land-use impacts on subsurface hydraulic properties could impair floodplain ecosystem services (i.e. flood wave attenuation, streamwater filtering) by altering groundwater flow patterns.

Previous studies have reported land-use impacts on groundwater flow patterns. For example, Scanlon et al. (2005) noted that rangeland cultivation resulted in an alteration of subsurface water flow direction, from primarily upward under rangeland, to primarily downward under cropland. Using a coupled land use/groundwater model, Dams et al. (2008) predicted a regional reduction in baseflow of up to 2.3% in the Kleine Nete Catchment, Belgium. Similarly, Batelaan et al. (2003) predicted complicated changes to groundwater discharge rates and the spatial extent of discharge areas associated with a land use development plan in Belgium. Cho et al. (2009) found MODFLOW-simulated reductions in groundwater hydraulic head and streamflow corresponded to the intensity and spatial distribution of land use changes (e.g. forest removal, urbanization) for a subwatershed of the Upper Roanoke River Watershed in the United States. It is worth noting that the majority of previous studies utilized episodic or opportunistic sampling to inform reductive modeling methods. While the financial and labor savings provided by numerical modeling methods (e.g. MODFLOW) rationalize their widespread application in groundwater hydrology, such methods incorporate critical assumptions (e.g. steady-state conditions) and often produce results based on conceptualized field conditions. Few studies can be found in the literature utilizing continuous, automated, in situ sampling methods to analyze groundwater flow regimes. Such methods can produce high-resolution quantifications of groundwater flow responses to land use/land cover changes, and can confirm or challenge conclusions based on theory and/or predictive modeling.

Improving the understanding of groundwater-surface water interactions generally, and floodplain response to anthropogenic landscape alteration specifically, is crucial to improving the management of multi-use urbanizing watersheds containing floodplains (Sophocleous, 2002). The objective of the current work was to investigate land-use impacts, specifically historic forest removal, on floodplain shallow groundwater flow regime utilizing continuous, automated, in situ monitoring. Such information will improve water resource management by informing decision-makers and stakeholders about the long-term hydrologic results of floodplain land use change.

2. Methods

2.1. Site description

This research was conducted in the Hinkson Creek Watershed (HCW) located in central Missouri, USA (Fig. 1). The project is nested within an experimental watershed study implemented in 2008. The HCW contains approximately 60% of the city of Columbia, a city with a population of approximately 116,000 (USCB, 2015). Land use in the HCW is approximately 34% forest, 38% agriculture, and 25% urban (Hubbart et al., 2011), making it a regionally representative location for studying the effects of different land use types on floodplain shallow groundwater. According to a 64 year climate record of Columbia, Missouri (station ID #231790, 231791), average annual temperature and precipitation within the watershed were 12.5 °C and 991 mm yr^{-1}, respectively (Missouri Climate Center, 2014). Two floodplain reaches of Hinkson Creek with contrasting land use histories were selected for data collection: a remnant (i.e. no previous harvest) bottomland hardwood forest (BHF), and a historical (i.e. currently fallow) agricultural field (Ag). The Ag site was continuously cropped for the majority of