Land use controls on the water quality and flooding responses of suburban streams: A case study of Deer Creek at the Litzsinger Road Ecology Center

Monitoring Report for July 6, 2017 to September 7, 2018

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1. Introduction and project background

Urban streams often experience problems with water quantity and quality due to high levels of impervious surface area (ISA) in their watersheds. High watershed ISA reduces infiltration, leading to rapid delivery of runoff from precipitation events. This can cause shorter lag times between precipitation events and stream peak flows, higher peak flows, degraded stream channel morphology from erosion or deposition, and reduced water quality (Brun and Brand, 2000; Paul and Meyer, 2001). Despite these dramatic changes in the flood responses of urban streams, surprisingly few studies attempt to resolve the extent to which "new" event water (i.e., recent precipitation) and "old" pre-event water (i.e., baseflow) contributions are altered in developed watersheds.

To address urban stream response, our research group has monitored water quality, quantity, and sourcing for Deer Creek at the Litzsinger Road Ecology Center (LREC) from June 22, 2015 to September 12, 2015 and September 2, 2016 to present. Our efforts have yielded both interesting and puzzling results regarding the short-term (flood and daily) and long-term (seasonal) geochemical and hydrologic responses of Deer Creek. A particularly surprising result from our monitoring efforts was our finding of high baseflow inputs to Deer Creek during flooding events, despite relatively high ISA in the watershed (i.e., 28.0% of the basin area). Similar to previous studies (Buttle et al., 1995; Gremillion et al., 2000; Buda and DeWalle, 2009; Meriano et al., 2011), our research (Deeba et al., 2017; Hasenmueller et al., 2017; Deeba and Hasenmueller, 2018) efforts to understand stream flood response in Saint Louis, Missouri, have shown that high watershed ISA leads to higher flood peak flows from recent precipitation events. We have also found that highly urbanized streams in Saint Louis have larger event water contributions during floods than rural or suburban streams. However, our assessment of flood flow components at Deer Creek (Hasenmueller and Shaughnessy, 2016; Deeba et al., 2017; Hasenmueller, 2017; Deeba and Hasenmueller, 2018) and other nearby streams with variable land use in their catchments (i.e., Fox Creek, Grand Glaize Creek, Black Creek, and the River des Peres; Hasenmueller et al., 2017) showed that the relationship between baseflow contributions and ISA in local watersheds is not linear. Instead, the baseflow inputs during floods at suburban streams are very similar to rural streams, despite suburban stream systems having significantly more ISA in their watersheds (up to ~30% more ISA than rural watersheds). Our findings suggest that although impervious surfaces can considerably decrease baseflow contributions to highly urbanized streams, suburban streams like Deer Creek are less impaired than might be predicted by land cover.

While flow component delivery during floods is less impacted than expected at Deer Creek, this stream still features many of the same water quality issues observed in highly urbanized basins. For example, chloride contamination at Deer Creek and a nearby suburban stream, Grand Glaize Creek, are similar to or greater than the highly urbanized River des Peres watershed (Deeba, 2017; Hasenmueller et al., 2017; Deeba and Hasenmueller, 2018). Indeed, the chloride levels for both suburban and urban watersheds are, on average, above the United States Environmental Protection Agency (USEPA) chronic limit for aquatic life (USEPA, 2018) and are highly variable. This suggests that suburban basins may be more impaired for specific water quality parameters than predicted by their land cover.

In light of the seemingly opposite water quality and sourcing responses to ISA in the Deer Creek watershed, we seek to build on the previous work by our group (Hasenmueller and Shaughnessy, 2016; Deeba et al., 2017; Hasenmueller, 2017; Hasenmueller et al., 2017; Deeba and Hasenmueller, 2018) and others (Intuition and Logic, 2005; Lopez, 2009; Haake, 2011; Chott, 2013; Rinne, 2013) to understand the role of land use variables in controlling the unique chemical and physical responses in the suburban Deer Creek watershed at the LREC site. These efforts will help us describe why Deer Creek features uniquely high groundwater contributions to flood events, but also high levels of chloride and other contaminants. To give context to our results at Deer Creek, we compared water sourcing results from the LREC site to nine other watersheds in the Saint Louis metropolitan area that lie along a gradient of increasing ISA (from 7.1 to 35.3% of the catchment area). All the watersheds feature similar climate (humid subtropical), geology (mostly Paleozoic carbonates), soil (silt loams), and vegetation (temperate deciduous forests). Understanding baseflow inputs to urbanized watersheds is critical for maintaining ecosystem health as groundwater contributions reduce both the physical and chemical variability of streams. This will become increasingly important as urbanized areas expand and climate becomes more variable and extreme.

2. Methods

2.1. Analyses for Deer Creek at LREC

2.1.1. Field methods

To address the impact of land use on water quality, quantity, and sourcing for Deer Creek at the LREC site, we combined continuous in situ water quality monitoring, weekly field sampling, and high frequency sampling during storm perturbations from July 6, 2017 to September 7, 2018. We continuously measured (5-minute data intervals) water quality, including temperature, specific conductivity, chloride, turbidity, dissolved oxygen (DO), and pH at the LREC site using a YSI 6600 V2 sonde from July 6, 2017 to February 21, 2018. However, the instrument had ongoing issues with biofouling and silt build up, which, unfortunately, rendered the data for many water quality parameters unusable. So, we replaced the YSI 6600 V2 sonde with a newer model of the same type of instrument, the YSI EXO2, which has a specialized wiper brush to remove biofilms and debris from the sensors' surfaces. The YSI EXO2 was used to measure the same water quality parameters from February 21, 2018 to September 7, 2018.

In addition to our continuous monitoring efforts, we made approximately weekly field visits from July 6, 2017 to September 7, 2018 that included point measurements of the same water quality parameters with handheld meters (i.e., YSI Professional Plus Multiparameter Instrument and Hach 2100P turbidity meter) and collection of grab samples for lab analyses. Additional physical samples were collected using an automatic sampling device (i.e., an ISCO 6712) to understand stream flood response; generally 10-50 samples were obtained to characterize these events. Selected samples were analyzed for stable isotopes. In addition to physical samples collected from the stream, precipitation samples were also collected for chemical and isotopic analyses to determine the proportion of "new" water contributed to stream flow during floods using the same methods reported by Hasenmueller and Shaughnessy (2016) and Hasenmueller (2017). We also archived discharge data measured by United States Geological Survey (USGS) gaging station 07010075, which is located only 300 m downstream of our monitoring site (USGS, 2018).

2.1.2. Lab methods

Selected physical samples of stream water (collected during field visits or by the autosampler) and precipitation were measured for stable water isotopes (2-hydrogen and 18-oxygen) using an isotope ratio infrared spectrometer (Picarro L2130i). Isotope values are reported in the conventional manner as δ^2H and δ^{18}O values relative to V-SMOW; precision is respectively ± 1.0‰ and ± 0.1‰.

2.1.3. Basin characteristics

We also assessed land use metrics (e.g., ISA and forest coverage), geology, and soil type in the Deer Creek watershed using ArcMap 10.4.1. Land use and land cover characterization results were used to understand the unique hydrologic response in the Deer Creek catchment over both short and long timescales.

2.2. Comparison of Deer Creek with other watersheds in the Saint Louis region

To give context to our results from Deer Creek, we monitored nine other watersheds in the Saint Louis region (Fig. 1) that lie along a gradient of increasing urbanization, from forest-dominated watersheds west of the city (minimum ISA = 7.1%) to highly urbanized watersheds near the city center (maximum ISA = 35.3%). This transect also reduces meteorological differences between the studied catchments as the predominant storm path in this region is from southwest to northeast. To avoid the confounding factor of variable lithology, we picked watersheds that were dominated by carbonate lithologies, ranging from Ordovician dolostones to Mississippian limestones (Missouri Spatial Data Information Service, 2017). The Deer Creek watershed features some Pennsylvania shales (<50% of the catchment area).

At each of these watersheds, in situ probes (HOBO Freshwater Conductivity Data Loggers) that continuously measure (i.e., 5-minute data intervals) specific conductivity and temperature were installed. All of these sensors were collocated with USGS gauging stations (USGS, 2018). The specific conductivity, temperature, and discharge data have been collected since November 2017.

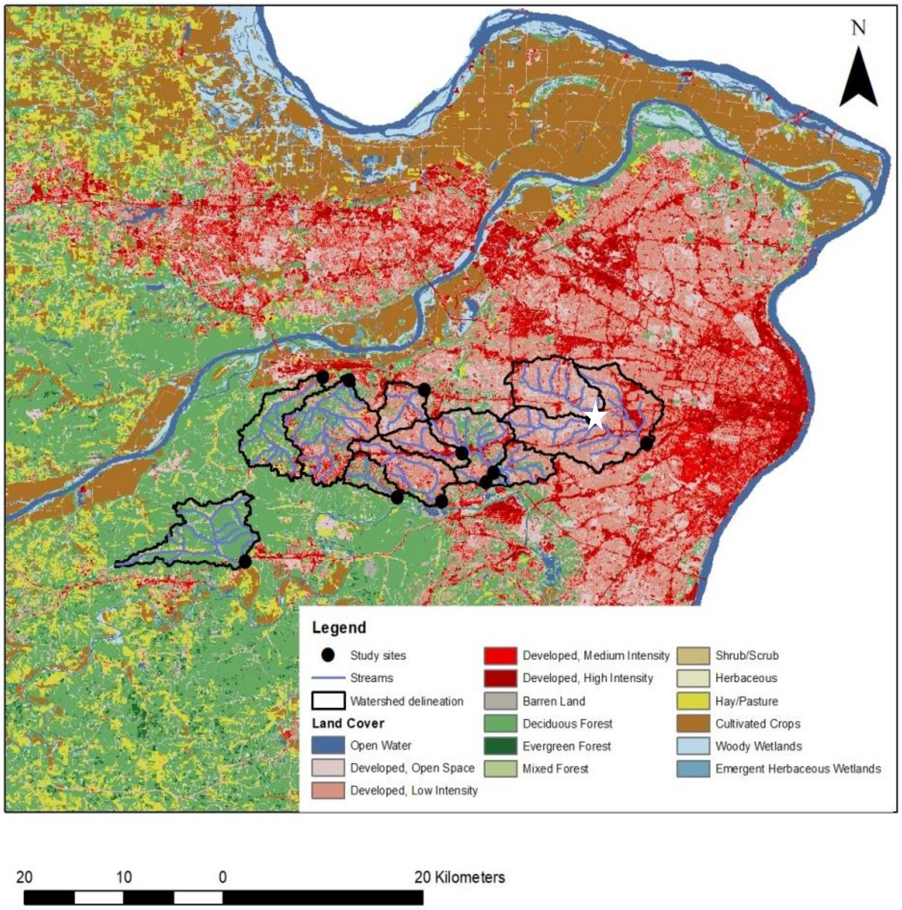

Figure 1. Stream study sites are shown on a land use/land cover map (Multi-Resolution Land Cover Characteristics Consortium, 2017). Deer Creek at the LREC site is indicated with a white star, while other sampling locations are indicated with black circles. The watershed area that drains to a particular sampling location is delineated with a black line.

2.3. Hydrograph separations

To determine the relative contributions of baseflow and event water to Deer Creek at LREC and the other regional streams, we used two-component hydrograph separations, which can be described by the equations:

$$Q_t = Q_b + Q_e \tag{1}$$

$$Q_t C_t = Q_b C_b + Q_e C_e \tag{2}$$

$$X_b = \frac{C_t - C_e}{C_b - C_e} \tag{3}$$

where Q is the discharge, C is the tracer value (specific conductivity or stable isotopes), the subscripts represent the total (t), baseflow (b), or event water (e) discharge or tracer value, and X_b is the baseflow fraction. In this study, baseflow is defined as the specific conductivity measurement in the stream 48 h prior to the precipitation event, with the exception of rapid, consecutive storm events, in which case baseflow specific conductivity values are those recorded 48 h before the first flood event occurred.

Multiplying the baseflow fraction (X_b) for a given point in the flood by the total discharge at that same point (Q_t) provides the volume of the total flow that is made up of groundwater (Q_b):

$$Q_b = X_b Q_t \tag{4}$$

Individual Q_b values can be plotted over time with Q_t values to observe the variations in baseflow over the course of a flood event. The summation of all Q_b values during a flood event, divided by the summation of all Q_t values, results in the weighted average for the baseflow fraction, $X_{b\ avg}$, for an individual flood event:

$$X_{b\ avg} = \left(\frac{\Sigma Q_b}{\Sigma Q_t}\right) 100\% \tag{5}$$

Individual flood responses for a specific stream can be averaged for an entire study period to determine the overall hydrologic response at a given site.

3. Results and discussion

3.1. Water quality at Deer Creek

Our monitoring results for Deer Creek are outlined in the following sections and illustrated in Fig. 2. These efforts captured the stream's physical and geochemical responses from July 6, 2017 to September 7, 2018. Our observations highlight the variations in water quality at Deer Creek over both short and long timescales.

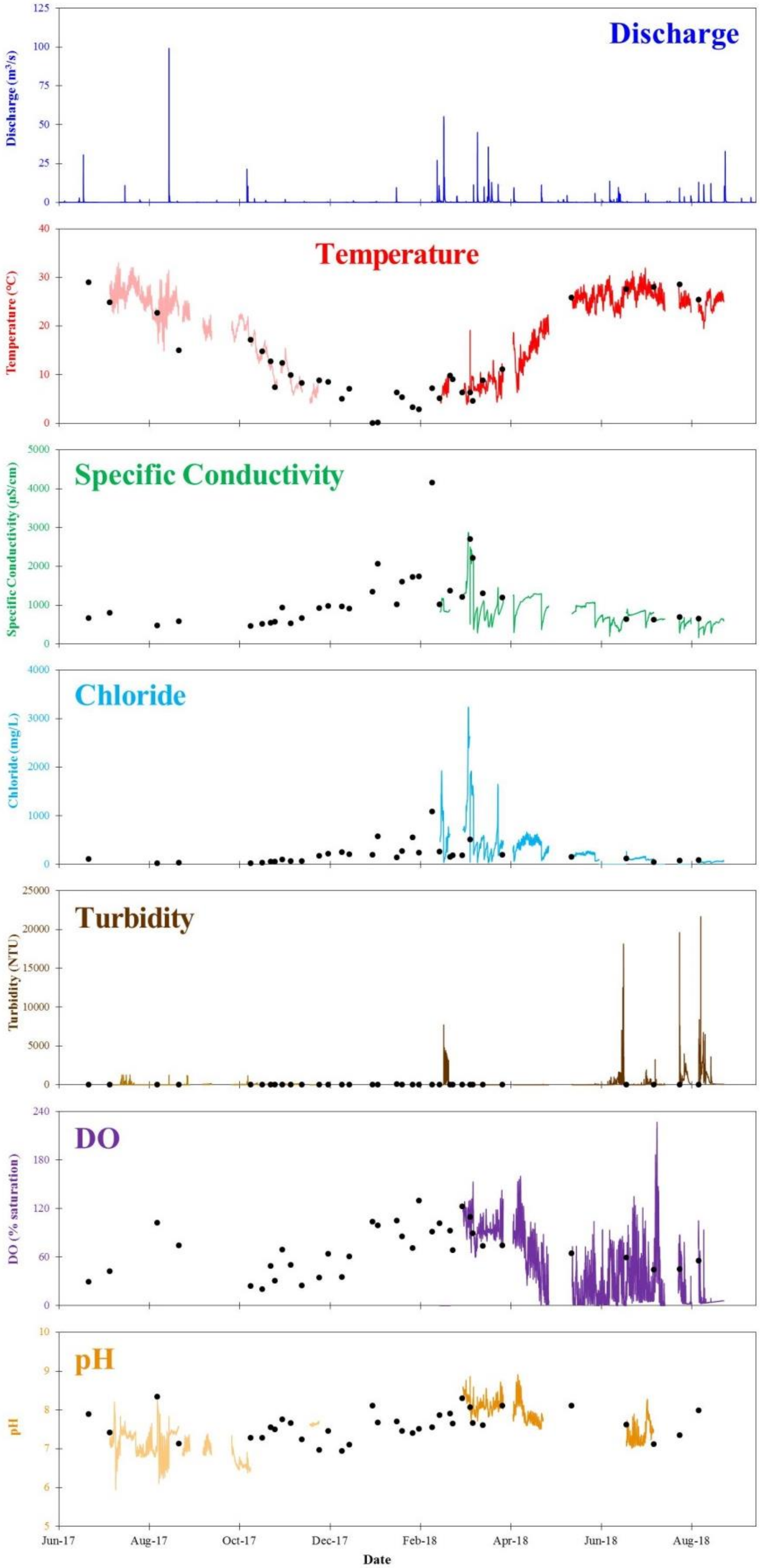

Fig. 1. Deer Creek discharge (USGS, 2018) and water quality data from July 6, 2017 through September 7, 2018 at the LREC site. Measured water quality parameters include temperature (ºC), specific conductivity (µS/cm), chloride (mg/L), turbidity (NTU), DO (% saturation), and pH. Continuous monitoring data are indicated by solid, colored lines; the lighter colors represent data from the YSI 6600 V2 sonde, while the darker colors represent data from the YSI EXO2 sonde. Due to equipment malfunctions, there is not a complete record for all water quality parameters. Black circles show point measurements of water quality parameters collected during field visits. These point data were used to correct any drift in the monitoring sensors.

3.1.1. Temperature

Temperature measurements from the YSI 6600 V2 sonde were unaffected by the issues with biofouling and silt build up, so we have a nearly complete record of temperature over the monitoring period. There is a small gap in the data during the winter of 2017-2018 when the continuous monitoring instrumentation was being replaced. Continuous measurements of temperature (Fig. 2) ranged from 3.8 to 32.0ºC (average = 19.9ºC). Lower values (down to 0.1ºC) were observed in point measurement data collected in January 2018 (Fig. 2). Analogously to previous observations by our research group, we saw both diurnal and flood-induced fluctuations in temperature. The changes in stream temperature as a result of flooding were often larger than the changes due to daily oscillations in air temperature.

3.1.2. Specific conductivity and chloride

Due to equipment failure, we were unable to monitor the dynamic changes in specific conductivity and chloride levels that occur during the winter road salting season. Nevertheless, we observed higher specific conductivity and chloride levels during the winter months in our grab sample data (Fig. 2; black circles). These high levels of specific conductivity and chloride persisted well into May 2018 before they were diluted, presumably because of cessation of salting activates and dilution by higher rainfall amounts in the spring. We also observed that chloride levels consistently exceeded the USEPA limits (USEPA, 2018) for chronic chloride contamination (230 mg/L) and, on several occasions, exceeded the acute contamination level (860 mg/L; Fig. 2).

Moreover, the specific conductivity at Deer Creek was highly variable and depended on flow conditions, with minimum values (down to 168 μS/cm) occurring at peak flooding (Fig. 2). During low flow periods in the non-road salting months, the average specific conductivity (660 μS/cm) observed at Deer Creek was above background levels for rural stream systems in the region (i.e., ~200-500 μS/cm; Winston and Criss, 2002; Hasenmueller et al., 2017), but not nearly as high as the specific conductivity levels that were recorded in the proceeding summer (i.e., average of 1,160 μS/cm). Persistently elevated specific conductivity during the summer months indicates that there is likely substantial contamination of the shallow groundwater in the watershed due incomplete flushing of winter deicing salts after application. However, changes in road salting practices or a milder winter may led to lower salt inputs to the stream during the winter.

3.1.3. Turbidity

The YSI 6600 V2 sonde's turbidity measurements (a proxy for total suspended solids in the stream water) were unaffected during deployment, providing a nearly complete turbidity record. Turbidity ranged from nearly zero to >20,000 NTU (Fig. 2). Turbidity was generally low (<10 NTU) during low flow conditions, but increased dramatically during flood events. Interestingly, high turbidity levels in response to flood events at Deer Creek were protracted compared to the flood-induced turbidity responses observed in other local streams (Hasenmueller et al., 2017). In other streams, high turbidity values were typically observed only on the rising limb of the flood hydrograph. In contrast, the LREC site exhibited high turbidity levels throughout most flooding events, including on the recessional limbs of the flood hydrographs. We suspect this response is due, in part, to the high erosion rates at the site where our monitoring equipment is deployed. The monitoring device is located on a cut bank that has experienced significant erosion due to progressive bank failure. We surmise that, even with lower discharge rates (like those that occur on the recessional limbs of flood hydrographs), there is still significant suspension of sediments occurring at this site as the bank erodes.

3.1.4. DO

Continuous DO data were affected by the biofouling and siltation issues for a portion of our monitoring period. The DO results are consequently only available after February 21, 2018 when we installed our new equipment. The DO ranged from nearly zero up to 227% saturation, with an average value of 45.3% (equivalent to 4.61 mg/L; Fig. 2). The average DO level is significantly lower than what would be expected if DO were equilibrated with the atmosphere (i.e., DO saturation equal to 100%).

The average daily DO values generally decreased from the winter to the summer when water temperatures began to increase. This is a result of oxygen gas being less soluble in water at high temperatures and enhanced biological activity in the summer. We also observed extreme diurnal oscillations in DO (often nearly 100% variation in saturation) due to the dominance of photosynthesis during the daylight hours and respiration during the night. At times, photosynthetic activities were so high that they supersaturated the water with DO (i.e., >100% saturation). The largest variations in DO tended to occur during low flow periods and when water temperatures were warmest (Fig. 2), likely because aquatic photosynthesizes are more active when the stream water is clearer and temperatures are higher. These extreme DO variations are probably due to high levels of nutrients, like nitrogen and phosphorus species, enhancing biological activity in Deer Creek. The higher biological activity leads to more variability in DO (Lockmiller, 2018; Lockmiller and Hasenmueller, 2018). Water levels were relatively low during the period when the DO sensor was functional. Thus, we did not observe large variations in DO associated with flooding events as we had during previous monitoring periods (Hasenmueller, 2017).

3.1.5. pH

Over the monitoring period, we had several issues with biofouling, siltation, and damage to our pH sensor (Fig. 2). Thus, there are only intermittent periods when we have continuous pH data. Nevertheless, we still have weekly point data for pH (Fig. 2; black circles). Stream pH was near-neutral during the monitoring period, ranging from 5.9 to 8.9. We also observed diurnal oscillations in the pH data, as we had for DO. These oscillations are due to aquatic photosynthesizers taking up dissolved carbon dioxide (thereby causing the pH to increase) during the day. Higher dissolved carbon dioxide content and lower pH values occurred during the night when photosynthetic organisms were less active and respiration dominates. Similar to the DO response, these oscillations increased in amplitude during the warmer months.

3.2. Variations in baseflow contributions during flood events as a function of land use

We were able to capture multiple flood events at the LREC Deer Creek site (Fig. 2) over the monitoring period. We used a combination of specific conductivity and water isotope data to conduct hydrograph separations for the Deer Creek floods to determine the relative contributions of “older” groundwater and “newer” event water to the stream using the methods of Pellerin et al. (2008) and Hasenmueller et al. (2017). As observed in previous studies of Deer Creek (e.g., Hasenmueller and Shaughnessy, 2016; Hasenmueller, 2017), there were high inputs of baseflow to the stream during flood perturbations (i.e., ~90% of the total flow; Fig. 3A).

To determine why there were very high inputs of baseflow to Deer Creek during floods, we compared results from the LREC site with the nine other watersheds in the Saint Louis area. These watersheds featured a range of ISA (from 7.1 to 35.3%), but had similar climate (humid subtropical), geology (mostly Paleozoic carbonates), soil (silt loams), and vegetation (temperate deciduous forests) compared to Deer Creek. Our results show that, on average, all of the streams across the land use gradient had high baseflow inputs during floods (Fig. 3A-B). We found that there was a significant change in the weighted average of baseflow inputs during individual floods across the land use gradient ($p < 0.01$). However, baseflow inputs varied less than 15% between the least (ISA = 7.1%) and most (ISA = 35.3%) urbanized streams (Fig. 3A). During peak flow, there was no significant ($p = 0.07$) difference in baseflow contributions among the streams (Fig. 3B). These results indicate that land use in the Saint Louis region has a minimal effect on water partitioning during flood events. Nevertheless, when we analyzed the lag times between precipitation events and stream peak flows, we found that they were reduced substantially as a function of land use (~50% decrease; $p = 0.01$; Fig. 3C).

Our results imply a decoupling of the sourcing and timing of flow fraction delivery across a land use gradient. In other words, the water sources remain relatively unchanged across the land use gradient, but both flow fractions get to the streams much faster in urban areas than in rural areas. The faster delivery of groundwater in more urbanized streams implies enhanced water transport through preferential flowpaths. Our study streams overlie carbonate rocks with known conduit flow that could enhance groundwater delivery rates. Urban karst may also accelerate groundwater transport to streams. However, a study of proximal urban watersheds with ISA similar to the most developed sites explored in this study, but overlying shales, show low baseflow inputs during floods (~25% of the total flow; Hasenmueller et al., 2017). This suggests that lithology is a more important control on flow fraction delivery than enhanced permeability from urban karst.

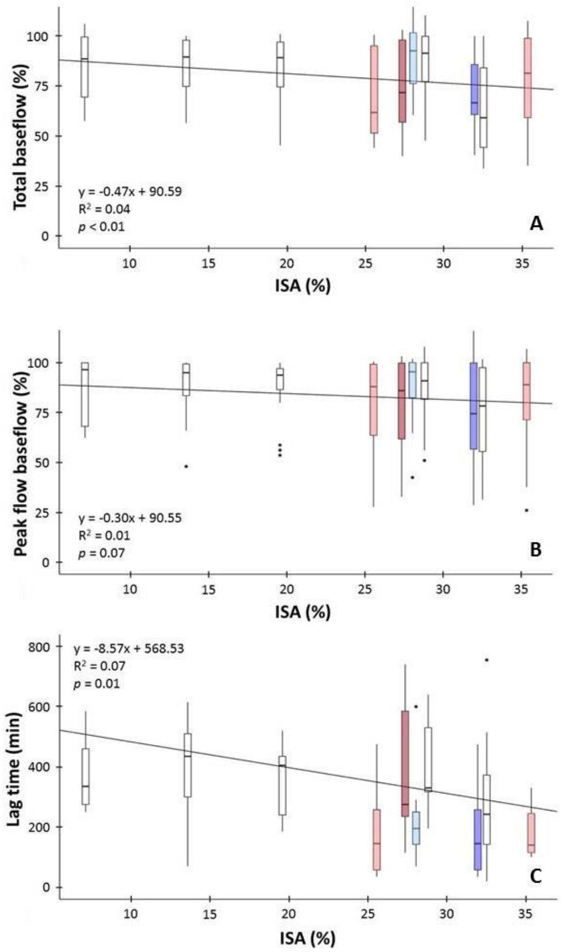

Fig. 3. Baseflow and lag time data for streams across a land use gradient: (A) total baseflow inputs over the course of entire flooding events, (B) baseflow inputs at peak flow, and (C) lag times plotted against ISA. The Deer Creek basin is denoted in blue, with the lighter shade representing the LREC monitoring site (ISA = 28.0%) and the darker shade representing lower Deer Creek at Maplewood, Missouri (ISA = 32.0%). Nested basin response at Deer Creek is compared with the nearby Grand Glaize Creek watershed (denoted in red). Here, the darker shade represents Grand Glaize Creek at Valley Park, Missouri (ISA = 27.4%), and the lighter shades represent the Sugar Creek (ISA = 25.6%) and Grand Glaize Creek at Weidman Road (ISA = 35.3%) tributaries.

4. Conclusions and need for future work

Our monitoring efforts for Deer Creek at the LREC site from July 6, 2017 to September 7, 2018 yielded significant water quality, quantity, and sourcing data. We collected point and continuous records for stream temperature, specific conductivity, chloride, turbidity, DO, and pH, in spite of equipment problems with our continuous monitoring device. We observed several persistent problems with water quality at Deer Creek. In the winter months, we observed elevated levels of specific conductivity and chloride. Chloride often exceeded USEPA regulatory limits for aquatic life. The high values for these parameters coincided with the winter road salting season, indicating that road deicing applications were the likely source. These salts were not completely flushed from the system after the winter. Thus, Deer Creek had elevated specific conductivity and chloride levels into the summer months. We also observed prolong periods of high turbidity levels following rainfall events. We suspect that these episodes of high turbidity are related to continuing failure of the bank where our monitoring equipment is situated. Additionally, we saw large fluctuations in DO and pH (as was also observed in our previous monitoring efforts) that are likely the result of biological activity in the stream. These fluctuations decreased in amplitude during the winter when aquatic organisms were less active.

In addition to examining the water quality conditions at Deer Creek, we also explored the sourcing and timing of flow components during flood events. As was previously documented, Deer Creek maintains relatively high baseflow inputs during floods (~90% of flow over the monitoring period). Other regional streams with similar basin and climate characteristics featured comparably high levels of baseflow during flood events, despite large differences in ISA among the basins. In contrast, we observed a sharp decrease in lag times as urbanization increased in the watersheds. Seemingly, there is a decoupling of sourcing and timing for the flow faction delivery across the land use gradient. We suspect this is the result of the carbonate lithology in this area, which may cause rapid transmission of groundwater through karst conduits. This implies that lithology is an important influence on flood timing and water sourcing. Nevertheless, additional analyses of land use and land cover as well as geologic metrics (such as the densities of various karstic features) in the studied watersheds are needed to understand this phenomenon. We hope to continue our monitoring of Deer Creek at the LREC site in light of these findings. In particular, we would like to obtain additional monitoring data to further assess the seasonal changes in water quality and baseflow responses for the stream. We also hope to characterize other basin metrics to determine the key drivers for Deer Creek's unique flood response.

5. Acknowledgements

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