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Impact of Preferential Flow Paths on Alluvial Groundwater Flow Patterns and Phosphorus Transport

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Abstract. *While surface runoff is considered to be the primary transport mechanism for phosphorus (P), subsurface transport through coarse subsoil to gravel bed streams may be significant and represent a source of P not alleviated by current conservation practices (e.g., riparian buffers). Previous research has documented P transport in a preferential flow path (PFP) identified as a buried gravel bar. It is hypothesized that PFPs, if connected to the soil surface, provide a rapid and efficient method of transporting P, and that these alluvial features are transient storage zones for nutrients, acting as a sink during high flow and a source during baseflow. The objectives of this project were to document the impact of PFPs on groundwater flow patterns on a field scale and to quantify potential P transport capacity through PFPs. Long-term monitoring was performed at floodplain sites adjacent to Barren Fork Creek and Honey Creek in northeastern Oklahoma. Based on results from subsurface electrical resistivity mapping, observation wells were installed both in PFPs and in non-PFP subsoils. Water levels and temperature in the wells were monitored real-time using pressure transducers for four months, which included multiple high flow events. Also, P samples were obtained from the observation wells and in the stream to document P concentration gradients over time. Contour plots showing direction of flow were generated based on water table elevation data. Results indicated spatial heterogeneity in hydraulic conductivity and zones of groundwater convergence and divergence. The activity of PFPs depended on the elevation of the water table and the interaction between the stream and the groundwater. The PFPs that rapidly transported P had groundwater total P concentrations that mimicked the stream and exceeded 0.20 mg/L during some high flow events. The pathways with rapid P transport did not necessarily correlate to subsurface zones of high hydraulic conductivity. Pathways of high hydraulic conductivity must be connected to the surface water source and be hydraulically activated for preferential transport to occur.*

Keywords. Alluvial Groundwater, Ozark Ecoregion, Preferential Flow, Stream-Aquifer Interaction, Subsurface Transport, Alluvial Floodplain

Introduction

The Ozark ecoregion of Missouri, Arkansas, and Oklahoma is approximately 62,000 km^2 and is characterized by karst topography, including caves, springs, sink holes, and losing streams. The erosion of carbonate bedrock (primarily limestone) by slightly acidic water has left a large residuum of chert gravel in Ozark soils, with floodplains generally consisting of coarse chert gravel overlain by a mantle (1 to 300 cm) of gravelly loam or silt loam. Karst topography adds complexity to the potential pathways for contaminant transport in the Ozark ecoregion (Neill et al., 2003; Davis et al., 2005).

Increased nutrient loads result in several adverse impacts on surface water quality, including excessive algal growth, fish kills, polluted drinking water, and taste and odor issues. Scientists and engineers need to identify critical nutrient source areas and transport mechanisms within a catchment in order to protect and enhance drinking water systems, recreation activities, and aquatic ecosystems. Nitrogen is a concern, but phosphorus (P) is generally considered the most limiting nutrient in most surface water systems (Daniel et al., 1998). In addition, excessive soil P concentrations can increase potential for P transport to surface waters or leaching into the groundwater, exacerbating the problem.

Countries throughout the world have spent billions of dollars restoring and protecting riparian buffer zones adjacent to stream systems to reduce sediment, nutrient, and pesticide transport to streams from upland areas and alluvial floodplains. Buffer strip effectiveness becomes an issue if a transport pathway through the subsurface is significant (Cooper et al., 1995; Lacas et al., 2005), since buffers primarily address the commonly observed and more easily understood surface runoff transport mechanism (Lacas et al., 2005; Popov et al., 2005; Reichenberger et al., 2007; Poletika et al., 2009; Sabbagh et al., 2009). Subsurface transport may be important due to local or regional conditions (Lacas et al., 2005), even for a highly sorbing contaminant such as P (Turner and Haygarth, 2000; Fuchs et al., 2009).

Subsurface P transport is a less studied and understood transport mechanism compared to transport by surface runoff, although numerous studies have reported subsurface P transport, including fields with tile drainage (Turner and Haygarth, 2000; Djodjic et al., 2004; Kleinman et al., 2004; Nelson et al., 2005; Andersen and Kronvang, 2006; Hively et al., 2006). For example, Kleinman et al. (2004) noted that P leaching is a significant, but temporally and spatially variable transport pathway. Djodjic et al. (2004) suggested that soils with high infiltration rates, e.g. due to macroporosity, possess reduced buffer capacity for P and therefore studies should not depend on soil test P or soil P sorption estimates alone to determine leaching potential. From research on four grassland soils, Turner and Haygarth (2000) documented that subsurface P transport, primarily in the dissolved form, can occur at concentrations that could cause eutrophication. When assessing long-term risk of P loss from waste-amended soils, Nelson et al. (2005) indicated that P leaching and subsurface transport should be considered. Andersen and Krovang (2006) developed a Danish P Index that incorporated leaching and tile drains as potential P transport pathways. Developing a model for total dissolved P (TDP) in a dairy farm watershed, Hively et al. (2006) considered transport in both baseflow and surface runoff. In addition, other researchers are beginning to emphasize colloidal P transport in the subsurface, as P adsorbs to small particles capable of being transported through soil pore spaces.

There have been several studies conducted in which observation wells were used to monitor the flow of nutrients in alluvial floodplains (Vanek, 1993; Carlyle and Hill, 2001; Fuchs et al., 2009; Heeren et al., 2010a,b). A study by Cooper et al. (1995) showed a high P availability for groundwater transport due to saturation of the riparian zone. Monitoring 12 wells in a lake riparian zone, Vanek (1993) noted groundwater P concentrations ranging from 0.4 to 11 mg/L with an average of 2.6 mg/L. Thompson and McFarland (2010) observed high soil P levels in streambank sediments near the water table, thought to have been transferred there by flow from the surface water into the alluvial aquifer. Carlyle and Hill (2001) monitored the behavior of P in the subsurface in a river riparian zone and suggested that riparian areas can become saturated with P. They documented higher soluble reactive P (SRP) concentrations (0.10 to 0.95 mg/L) in areas having soils with higher hydraulic conductivities buried under topsoils. Due to the increased redox potential, they suggested that riparian areas might actually be contributing to the release of P.

Even though surface runoff has shown higher concentrations in many field studies, subsurface flow with low P concentrations but occurring over a long time period may still significantly contribute to the total nutrient load of a surface water body. The above findings show that there is a potential for focused subsurface nutrient transport through preferential pathways, also called paleochannels. Exchange of water and P between the stream and the gravel subsoils is distributed across the entire river channel but enhanced in these preferential pathways (Malard et al., 2002). There is a need for additional studies devoted to understanding both groundwater flow patterns and P transport capacity through the subsurface of alluvial floodplains.

The objectives of this project were to document the impact of the PFPs on groundwater flow patterns on a field scale and to quantify potential P transport capacity through PFPs. Long-term monitoring was performed at floodplain sites adjacent the Barren Fork Creek and Honey Creek in northeastern Oklahoma, and it is hypothesized that similar hydrogeologic conditions exist in gravel bed streams and their associated shallow alluvial aquifers worldwide.

Materials and Methods

Alluvial Floodplain Sites

The alluvial floodplain sites were located in the Ozark region of northeastern Oklahoma. The Barren Fork Creek site (Figure 1a, latitude: 35.90°, longitude: -94.85°) was immediately downstream of the Eldon Bridge U.S. Geological Survey (USGS) gage station 07197000. With a watershed size of 845 km^2, the Barren Fork Creek site had a median daily flow of 3.6 m^3 s^{-1}. The Honey Creek site (Figure 1b, latitude: 36.54°, longitude: -94.70°) was also located immediately downstream of a USGS gage station (07189542). As a smaller order stream, the Honey Creek site had a 0.54 m^3 s^{-1} median daily flow and a 150 km^2 watershed.

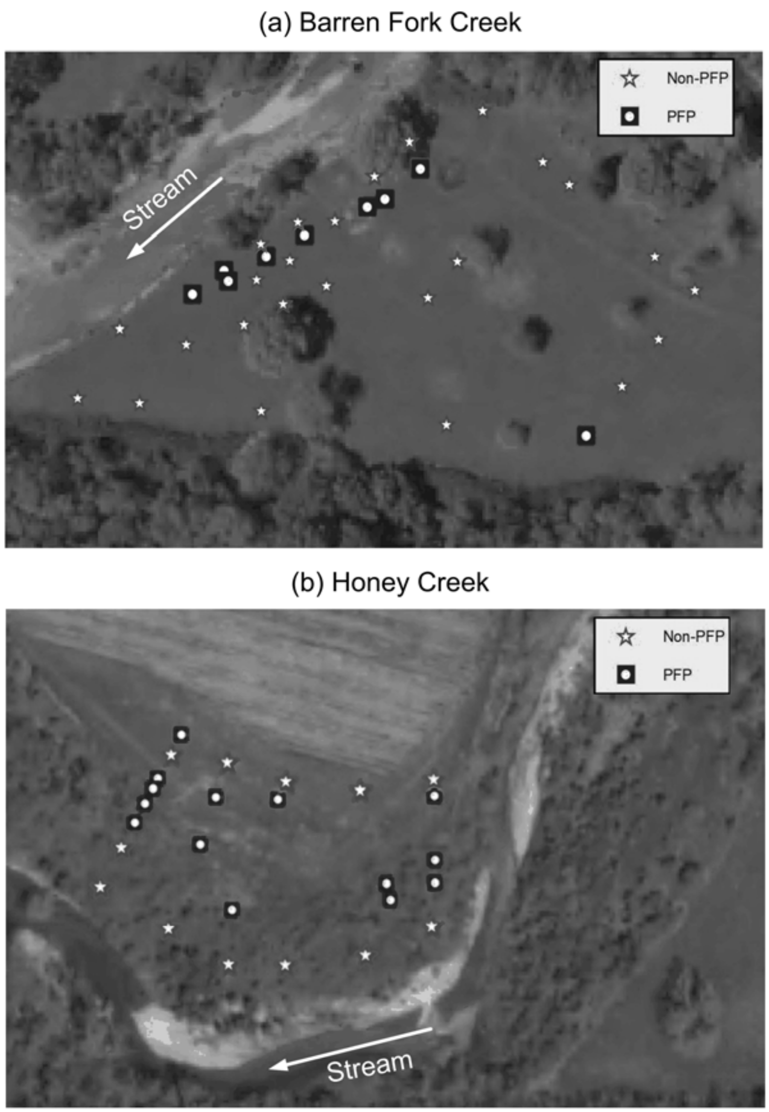

Figure 1. (a) Barren Fork Creek site, located near Tahlequah, OK, with observation well locations. (b) Honey Creek site, located near Grove, OK, with observation well locations.

The Barren Fork Creek site was a hay field with a soil test P (STP) of 33 mg/kg and had not received fertilizer for several years. The Honey Creek study site was composed of both forest and grassland. Adjacent to a tree farm, the area had received fertilizer in the past resulting in an STP of 60 mg/kg. The riparian area on Honey Creek was located on the inside of a meander bend, an area likely to aggradational. The study area at the Barren Fork Creek was located on the outside of a meander bend and was being eroded away by the stream. The soils of both floodplain sites were classified as Razort gravelly loam underlain with alluvial gravel deposits. Topsoil thickness ranged from 0.5 to 1.0 m at the Barren Fork Creek site and from 0.1 to 0.5 m at the Honey Creek site. Soil hydraulic studies on these soil types have shown that subtle morphological features can lead to considerable differences in soil water flow rates (Sauer and Logsdon, 2002). Fuchs et al. (2009) described some of the soil and hydraulic characteristics of the Barren Fork Creek floodplain site, including estimates of hydraulic conductivity for the gravel subsoil between 140 and 230 m d^{-1} based on falling head trench tests.

Observation Well Installation

Assuming a positive correlation between electrical resistivity and hydraulic conductivity, observation well locations were located in PFPs and in non-PFP subsoils (Figure 1), based on previous electrical resistivity results (Heeren et al., 2010a,b; Miller et al., 2010a,b). Using a Geoprobe Systems drilling machine (6200 TMP, Kejr, Inc., Salina, KS), observation wells were installed in the alluvial floodplains with a 2 to 3 m screened section at the base. Depth to refusal ranged from 4.0 m to greater than 5.0 m at the Barren Fork Creek site and from 2.5 to 3.5 m at the Honey Creek site.

Long-Term Monitoring for Groundwater Flow Patterns

At each site, twenty-four observation wells were instrumented with automated water level loggers (HoboWare, Onset Computer Corp., Cape Cod, MA) to monitor water pressure and temperature at five minute intervals from April to July, 2009 (Figure 1). One logger was placed above the water table at each site to account for changes in atmospheric pressure. Reference water table elevations, obtained with a water level indicator, were then calculated. The logger data were processed with HoboWare Pro software, which accounted for changes in atmospheric pressure as well as changes in water density due to temperature.

Water table elevation data were analyzed with Matlab (The Mathworks, Natick, MA). Using 30-minute intervals, a cubic interpolation was performed to determine the head for grid points in the two-dimensional well field. Contour maps were plotted with equipotential lines using 2-cm spacing. Streamlines were calculated as everywhere-tangent to the gradient, or perpendicular to contour lines. Patterns in groundwater contours and streamlines were investigated at both baseflow conditions and also during storm events.

Phosphorus Sampling and Testing

Water samples from observation wells were collected during multiple high flow events (Figure 2) from the top of the water table (i.e., upper 10 cm) using a peristaltic pump. High flow events were of particular interest because stream P concentrations generally increase with streamflow in these watersheds (Storm et al., 2009). Samples were stored on ice and transported back to the laboratory for analysis. Samples were digested with the sulfuric acid-nitric acid method (Pote et al., 2009). Total P concentrations were determined colorimetrically (Murphy and Riley, 1962; EPA Method 365.2) with a spectrophotometer (Spectronic 21D, Milton Roy, Ivyland, PA). Contour plots of total P concentration were generated with Matlab (The Mathworks, Natick, MA). A cubic interpolation was performed to determine the P concentration for grid points in the two-dimensional well field with a contour interval of 0.01 mg/L P. Data from the local USGS gage stations were also used in the analysis.

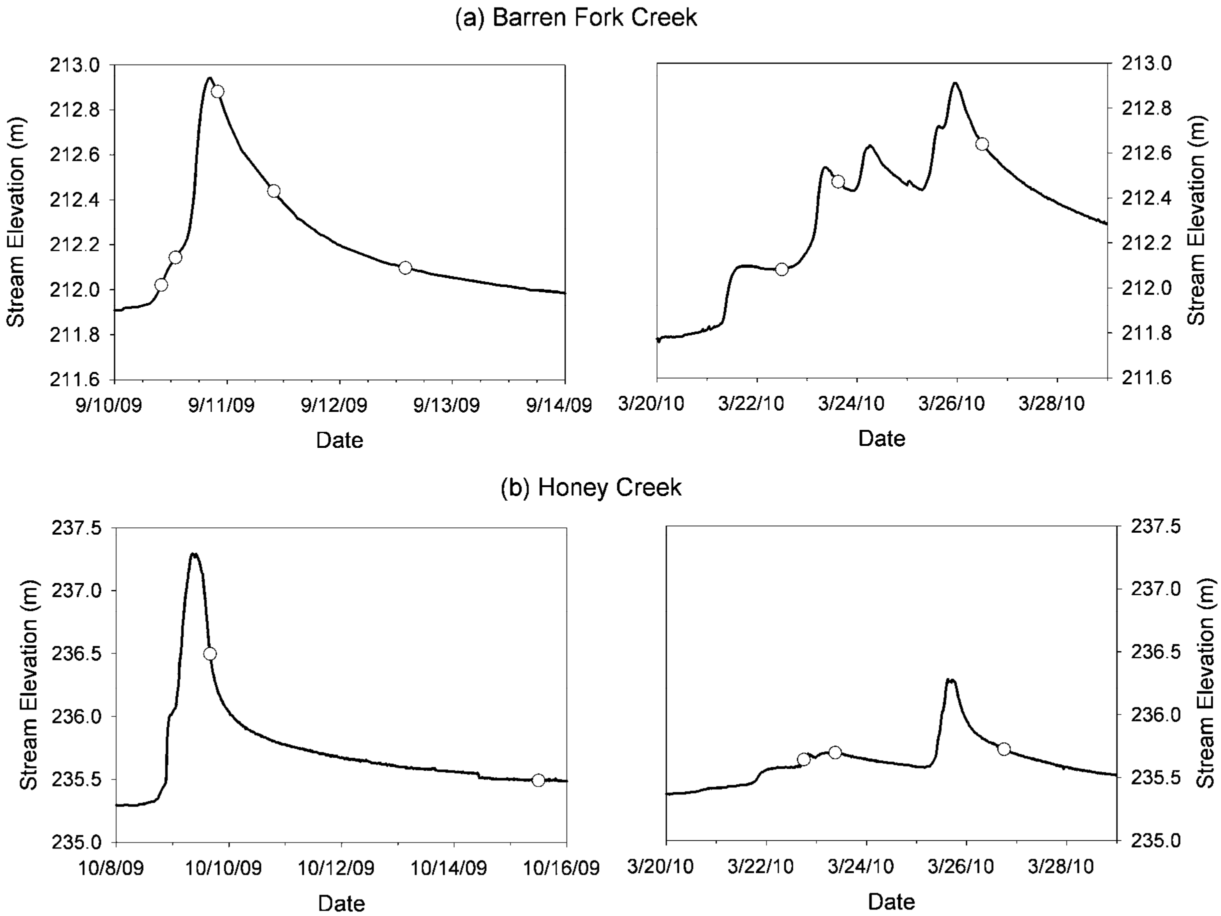

Figure 2. Hydrographs for the Barren Fork Creek (a) and Honey Creek (b) field sites. Circles designate dates of P sampling from the observation wells and creeks.

Results and Discussion

Groundwater Flow Patterns

Patterns in the water table elevation contour plots and streamlines at each site remained relatively similar during baseflow conditions, but changed during high flow events. Plots for baseflow conditions and during a high flow event at each site (Figures 3-4) were selected to illustrate the range of flow patterns in these data. The highest gradients in the alluvial aquifer occurred during the rising limb of the hydrographs, when the stream stage was rising most quickly. A PFP can be seen along the Barren Fork Creek (Figure 3b) providing an inlet for stream water to enter the groundwater system. This area of focused recharge appeared to be at point (80 m, 60 m) which was the location of the PFP that was studied previously (Fuchs et al., 2009; Heeren et al., 2010b). At other times, the contour patterns indicated flow convergence zones (bottom center of Figure 3d,f), where a PFP appeared to be draining a large area of groundwater. At the Honey Creek site, there was a PFP that activated during the rising limb of flood events (Figure 4b), acting as a convergence zone that drained a large area of groundwater to the northwest. The location of this PFP was consistent with previous electrical resistivity research at this site (Miller et al., 2010a,b).

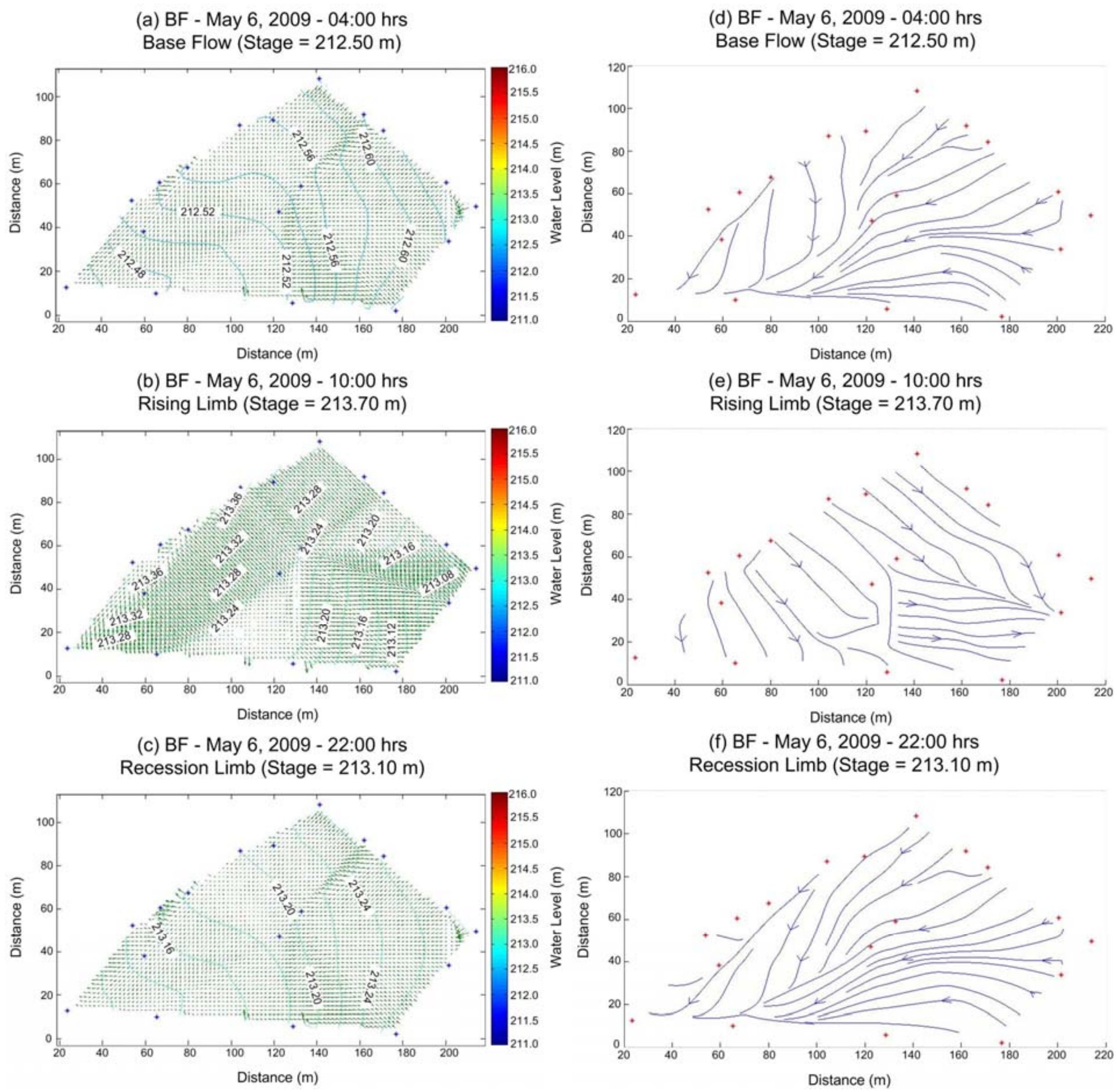

Figure 3: Water table elevation contour plots (a-c) and streamlines (d-f) for the Barren Fork (BF) Creek site during baseflow (a and d), the rising limb (b and e), and the recession limb (c and f) of a streamflow hydrograph. For scale, the May 6, 2009, event had a peak flow of 250 $m^3 s^{-1}$, a 1.3-yr recurrence interval event. Arrow vectors in the background (a-c) indicate the magnitude and direction of the water table gradient.

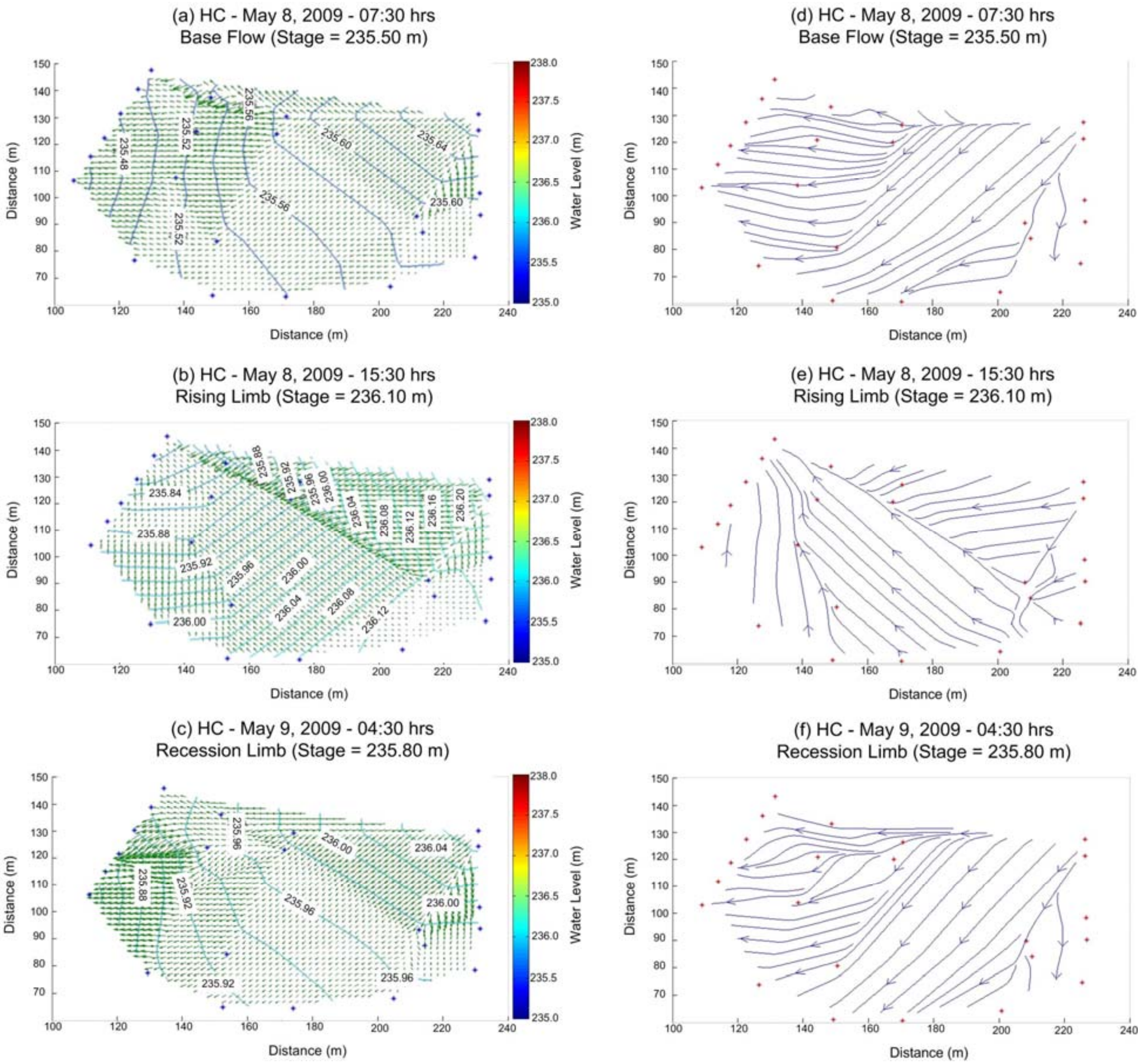

Figure 4: Water table elevation contour plots (a-c) and streamlines (d-f) for the Honey Creek (HC) site during baseflow (a and d), the rising limb (b and e), and the recession limb (c and f) of a streamflow hydrograph. For scale, the May 8, 2009, event had a peak flow of 18 m^3 s^{-1}, a 1.7-yr recurrence interval event. Arrow vectors in the background (a-c) indicate the magnitude and direction of the water table gradient.

An interesting observation based on the water table elevation data was that the Barren Fork Creek was a losing stream at this field site even during baseflow and falling limb conditions. This indicated the complexity of stream-aquifer interactions in these coarse gravel alluvial aquifers. We hypothesize a flow pattern where water regularly left the stream at one point within the study area, traveled through the aquifer, and reentered further downstream outside the study area. This would be equivalent to a large-scale hyporheic flow path, with its activity dependent on stream stage. It is also possible that a sinkhole exists in the aquifer, drawing water out of the stream-aquifer system. Schlottmann et al. (2000) report that water from Cave

Springs Branch (also in the Eastern Oklahoma Ozarks) may flow underneath a large surface divide to Honey Creek.

Phosphorus Concentrations

Contour plots of stream and groundwater total P concentrations at the Barren Fork Creek and Honey Creek field sites are shown in Figures 5-7 for two high flow events. During baseflow conditions, groundwater P concentrations were typically 0.01 to 0.04 mg/L and 0.02 to 0.06 mg/L at the Barren Fork Creek and Honey Creek field sites, respectively. The P concentrations were generally highest where stream water was entering the groundwater system, and decreased with distance down-gradient from the stream. This is likely due to sorption of the P onto the fine material in the gravel. Fuchs et al. (2009) reported a mass of P sorbed per unit mass of soil at complete surface coverage of 125 mg kg^{-1} and a binding energy of 0.048 L mg^{-1} for a Langmuir Isotherm performed on the fine material (i.e. < 2.0 mm) in the alluvial aquifer at the Barren Fork Creek site. Even though total P concentrations decreased as stream water moved through the aquifer due to sorption and dilution, transient storage was occurring in the alluvial aquifer as seen in the significant levels of P leaving the study area (and presumably re-entering the stream).

During high flow events, the maximum P concentrations measured in the groundwater were as high as 0.20 mg/L at the Barren Fork Creek site and 0.25 mg/L at the Honey Creek field site. In the groundwater adjacent to the creeks, a retarded migration of P into the alluvial groundwater was observed (Figures 5-7). However, in PFPs, rapid transport of P occurred in the groundwater system with concentrations at or near the P concentration in the creeks during larger storm events when the PFPs activated. For example, well 28 at the Barren Fork Creek site (in the southeast corner of Figure 1 and 5c,d), 100 m from the stream, had P concentrations similar to the stream P concentration. Well 28 was located adjacent to an abandoned stream channel that runs along the bluff; it is possible that the PFP is a buried lateral gravel bar. This would be consistent with Heeren et al. (2010b). Although only a fraction of the PFP wells had high P concentrations, high heterogeneity can result in situations where the main portion of the flow occurs in a few flow paths (Gotovac et al., 2009). It is hypothesized that high hydraulic conductivity combined with a high P concentration may result in a significant P load.

To determine whether P concentrations varied with depth at the Barren Fork Creek site, low-flow sampling (with the peristaltic pump) was used on March 23, 2010, to collect samples at both the top of the water table and from 2.0 m below the water table. In most wells, P concentrations were similar at both depths. However, in well 28 (in the southeast corner of Figure 6b), the 2-m sample had a P concentration of 0.19 mg/L (compared to 0.04 mg/L at the top of the water table), which approached the level of P in the stream. These concentrations suggested that this PFP was at a particular elevation, near the bottom of the aquifer. The high concentrations in well 28 in Figure 5 were likely from the higher pumping rate that was used in 2009, resulting in mixing of groundwater from different depths within the observation well. Since the high flow events were similar in magnitude at the Barren Fork Creek site (Figure 2), this PFP was activated during both events. Honey Creek had significantly more activity in PFPs in 2009 due to the 6-yr recurrence interval event, compared to the less than 2-yr recurrence interval events in 2010.

Suspended colloids and sediment often possess particulate P; therefore high total P concentrations tended to correlate with samples that were visibly cloudy. Due to the shallow depth of water in the wells at the Honey Creek site, it was difficult to determine when the cloudiness was due to suspended colloids in the groundwater and when it was due to agitated sediment from the bottom of the well.

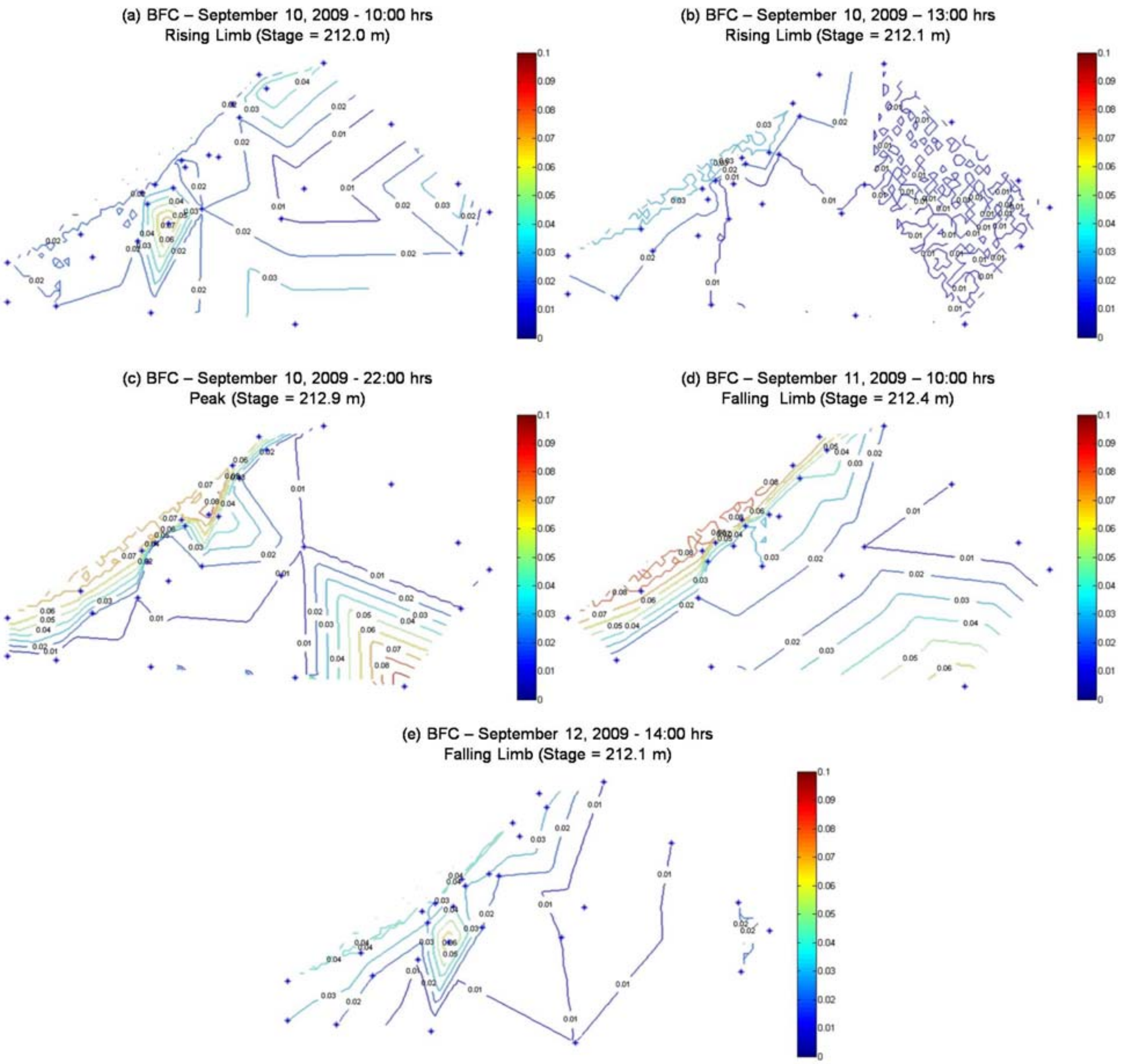

Figure 5. Total P concentration (mg/L as P) contour plots for the Barren Fork Creek (BFC) for the September 10, 2009, high flow event. Maximum flow was 86 m^3 s^{-1}, a 1.1-yr recurrence interval event.

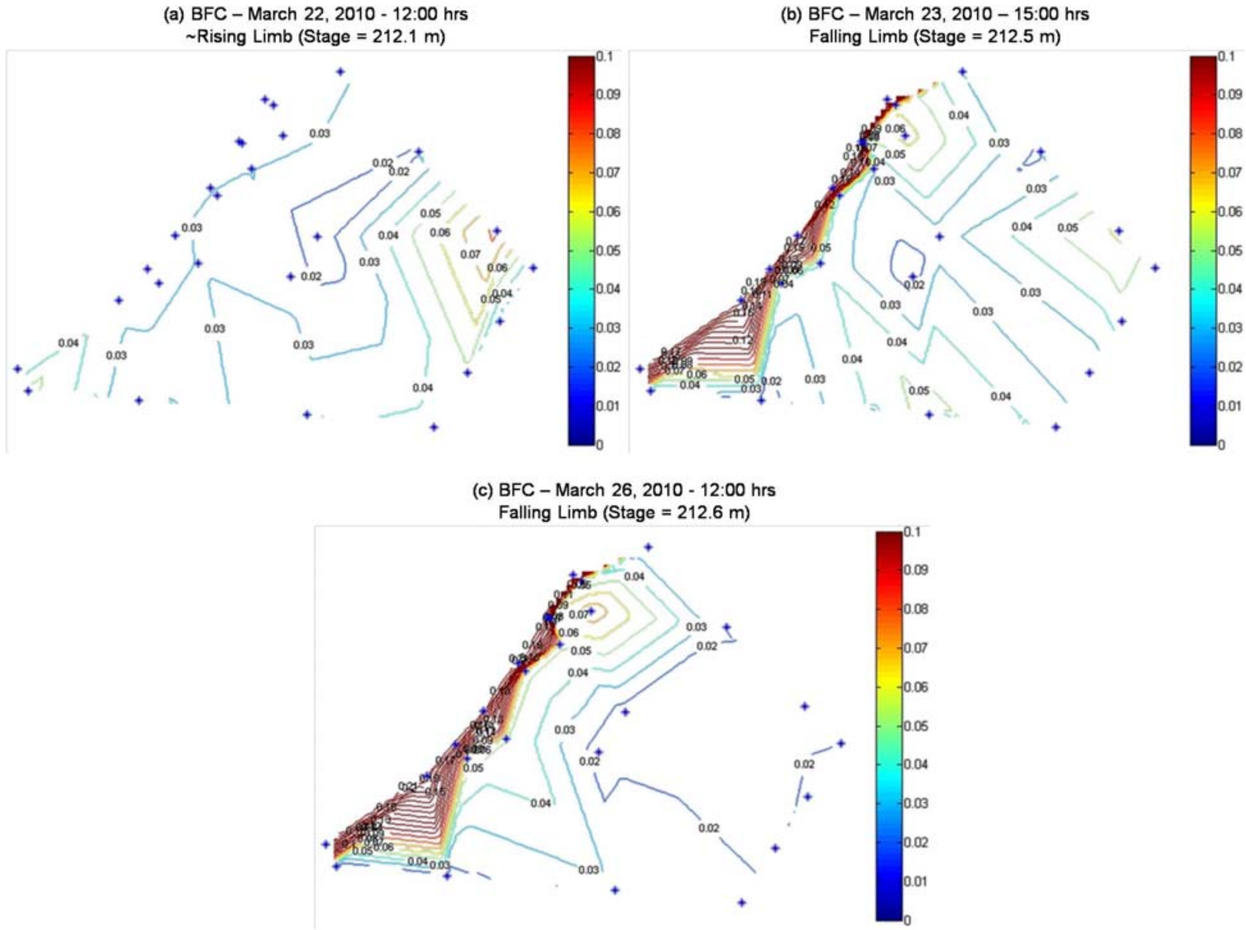

Figure 6. Total P concentration (mg/L as P) contour plots for the Barren Fork Creek (BFC) for the March 23 and March 25, 2010, flow events. The maximum flow for the March 23, 2010, event (a and b) was 48 $m^3 s^{-1}$, a 1.05 year recurrence interval event. The maximum flow for the March 25, 2010, event (c) was 85 $m^3 s^{-1}$, a 1.1-yr recurrence interval event.

Groundwater total P concentrations were also summarized by the median and interquartile range (Table 1). A general linear model was used to analyze differences between PFP and non-PFP wells, but the differences were statistically different in only one of the four datasets (Table 2). These results suggested that although the PFP wells were located in zones of high hydraulic conductivity, flow capacity was not the only condition necessary for significant P transport. Zones of high conductivity must be connected (i.e., not isolated by low conductivity material) and hydrologically activated (e.g., water table reaching a minimum elevation) for preferential flow to occur. Finally, the preferential flow must be connected to a P source (e.g., high concentrations in the stream or leaching from the soil surface) to be transporting P. Therefore, it is not surprising that only a fraction of the PFP wells had high P concentrations. The general linear model was also used to compare differences between wells close to the stream and wells far from the stream, and found the distance from the stream to be a statistically significant variable in two of the four data sets. This is consistent with the observation of P generally moving into the aquifer but with the movement retarded due to sorption.

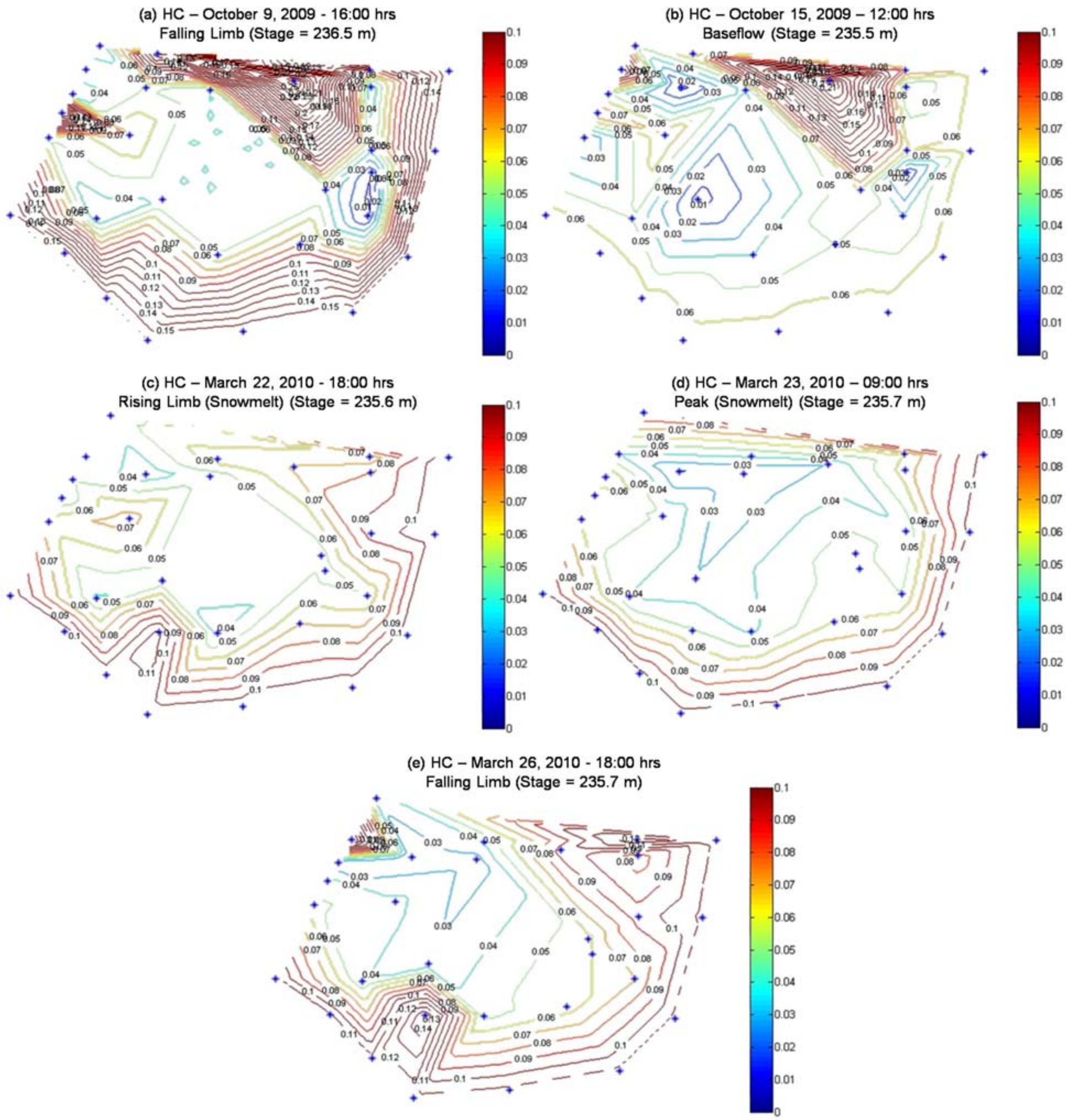

Figure 7. Total P concentration (mg/L as P) contour plots for Honey Creek (HC) for the October 9, 2009, and March 23 and March 25, 2010, flow events. The maximum flow for the October 9, 2009, event (a and b) was 81 $m^3 s^{-1}$, a 6 year recurrence interval event. The maximum flow for the March 23, 2010, event (c and d) was 6.1 $m^3 s^{-1}$, a 1.1 year recurrence interval event. The maximum flow for the March 25, 2010, event (e) was 24 $m^3 s^{-1}$, a 1.7-yr recurrence interval event.

Table 1. Total phosphorus concentrations (mg/L as P). Groundwater concentrations are characterized by the median and interquartile range (IQR).

Site	Date	Runoff Source	Hydrograph	Groundwater Median	Groundwater IQR	Stream
Barren Fork Creek	9/10/09A	Rainfall	Rising Limb	0.02	0.03	0.02
	9/10/09B	Rainfall	Rising Limb	0.01	0.01	0.03
	9/10/09C	Rainfall	Peak	0.01	0.02	0.07
	9/11/09	Rainfall	Falling Limb	0.02	0.03	0.08
	9/12/09	Rainfall	Falling Limb	0.02	0.02	0.04
	3/22/10	Snowmelt	~Rising Limb	0.03	0.01	0.03
	3/23/10	Snowmelt	Falling Limb	0.04	0.02	0.20
	3/26/10	Rainfall	Falling Limb	0.02	0.03	0.21
Honey Creek	10/09/09	Rainfall	Falling Limb	0.05	0.03	0.16
	10/15/09	Rainfall	Baseflow	0.05	0.03	0.07
	3/22/10	Snowmelt	Rising Limb	0.05	0.02	0.11
	3/23/10	Snowmelt	Peak	0.05	0.02	0.10
	3/26/10	Rainfall	Falling Limb	0.05	0.04	0.11

Table 2: Comparison of total phosphorus concentrations between PFP and non-PFP observation wells, and between wells close to the stream and wells far from stream. Probability (p) from a General Linear Model with $p<0.05$ being significant.

Site	Year	Probability: Distance From Stream	Probability: PFP v. non-PFP
Barren Fork Creek	2010	0.000	0.000
Barren Fork Creek	2009	0.528	0.169
Honey Creek	2010	0.006	0.532
Honey Creek	2009	0.285	0.161

Summary and Conclusions

Groundwater flow patterns in these alluvial floodplains changed dramatically during high flow events due to the activation of preferential flow pathways in the subsurface. During the rising limb of stream hydrographs, preferential flow pathways acted as focused recharge/discharge zones. Without properly locating observation wells within the pathways, general groundwater monitoring may have never indicated this preferential flow.

These pathways influenced P concentrations monitored in the groundwater. During baseflow conditions, groundwater P concentrations were typically 0.01 to 0.06 mg/L. During high flow events, the maximum P concentrations measured in the groundwater were as high as 0.20 mg/L at the Barren Fork Creek site and 0.25 mg/L at the Honey Creek site. In the general groundwater system adjacent to the creek, a slow migration of P into the alluvial groundwater was observed. However, in preferential flow pathways, rapid transport of P was possible in the groundwater system with concentrations at or near the P concentration in the streams during large storm events when the PFPs activated. The pathways with rapid P transport did not necessarily correlate to subsurface zones of high hydraulic conductivity. Pathways of high hydraulic conductivity must be hydraulically activated for preferential flow to occur and must be connected to the surface water source for preferential transport of P to occur. High P levels at the soil surface would be another possible source for preferential transport, but that transport mechanism was not studied in this project.

This research shows that PFPs can transport water and P rapidly from the stream through the groundwater system, but more work needs to be done to characterize runoff P leaching through the topsoil, its connectivity to the PFPs, and its rapid movement to the stream bypassing riparian buffers. Such results emphasize the sporadic nature of focused recharge/discharge in these systems and more work should be devoted to understanding the occurrence and activation of alluvial preferential flow pathways.

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