



# Stream and floodplain restoration impacts riparian zone hydrology of agricultural streams

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**Abstract** While the influence of stream restoration on vertical and lateral hyporheic exchange has been documented, impacts on broader riparian zone hydrology have not been thoroughly investigated. We quantified riparian water table dynamics, hydraulic gradient, and groundwater flow paths and fluxes across a range of hydrologic conditions following natural channel design restoration (riparian regrading, in-channel cross-vane structure installation). Water table measurements were collected at least once per season for 2.5 years to capture water levels during baseflow conditions from networks of wells and piezometers at sites with different stream morphology (created riffle-cross-vane-scour pool complexes versus natural pools and riffles), restoration status (agricultural restored, unrestored, forested reference), and riparian characteristics (slope, soils, topography) in North Carolina, USA. The regraded riparian zone had higher near-stream water tables (< 0.5 m below ground surface) than the unrestored site.

Riffle-cross-vane complexes induced a zone of low hydraulic gradient that spanned 30–40% of the riparian area, similar to groundwater dynamics near beaver dams. This effect persisted regardless of hydrologic condition (wet or dry) or scour pool status (functioning or filled-in). Riffles also promoted a lower near-stream hydraulic gradient at the forested site. Conversely, the influence of stream features on riparian groundwater was minimal at the unrestored site, where groundwater fluxes were controlled by hillslope inputs and riparian geomorphology. Overall, restoration enhanced stream-riparian zone hydrologic interaction beyond the immediate hyporheic zone. Our work stresses that cross-vanes, even when partially buried by sediments post-restoration, impact whole floodplain hydrology in a more significant way than shown by prior stream restoration studies.

**Keywords** Aquatic restoration · Riparian hydrology · Cross-vane · Natural channel design

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## Abbreviations

F Forested reference site  
NCD Natural channel design  
R Agricultural restored site  
U Agricultural unrestored site with forested buffer

## Introduction

Agricultural activities often lead to aquatic ecosystem degradation, notably through stream channel modification,

altered flows, and nutrient loading (Blann et al. 2009). Channel incision inhibits exchange of water and dissolved solutes between the stream and floodplain, while land disturbance, erosion, and compaction can disrupt surface water–groundwater interactions by blocking interstitial hyporheic spaces (Hancock 2002; Kroes and Hupp 2010). In response, stream restoration is becoming increasingly common, particularly in the USA and Europe (Bernhardt et al. 2005). Aquatic restoration projects often involve significant manipulation of the near-channel floodplain, including riparian zone reconstruction (regrading, widening, re-vegetation). Current stream restoration natural channel design (NCD; Rosgen 2007) approaches often implement grade control structures that are anchored into the streambank (e.g., channel spanning boulder cross-vanes, weirs), which form the foundation of riffle-step-pool sequences (Kauffman et al. 1997). Downward hyporheic exchange may increase adjacent to in-stream restoration structures (Hester and Doyle 2008; Gordon et al. 2013; Daniluk et al. 2013; Zimmer and Lautz 2014), and patterns of upwelling and downwelling near restoration structures are often consistent with those of natural riffle-pool sequences (Crispell and Endreny 2009). Many restoration design elements, including geomorphic structure size and type, groundwater discharge rate, slope, and sediment hydraulic conductivity, influence the magnitude of surface water–groundwater exchange (Hester and Doyle 2008).

Despite the influence of restoration on floodplain morphology and knowledge that hyporheic flow paths can occur across a range of scales (from cm to km, Boulton et al. 2010), most research regarding the impact of restoration on hydrology involves quantifying hydrologic interactions in the immediate hyporheic zone (e.g., surface water–groundwater mixing adjacent to and underneath the stream channel) and does not more broadly assess the impact of restoration on riparian hydrology. Enhancing hyporheic exchange beyond the immediate wetted perimeter is nevertheless a key component of restoring ecological functioning of streams, as the near-stream zone affects aquatic biology (e.g., macroinvertebrate habitat, temperature buffering) and biogeochemistry (e.g., cycling of oxidation-reduction sensitive elements) (Boulton et al. 1998). Therefore, it is critical we improve our understanding of how restoration influences hydrology across the aquatic-terrestrial interface, as understanding changes in hydrology provides insight into post-restoration physical, chemical, and ecological responses.

Though research has not directly investigated the influence of in-stream restoration structures on far-reaching surface water–groundwater interactions, other studies have demonstrated that stream impoundments (e.g., beaver dams) can exert considerable influence on riparian zone hydrology (Burchsted et al. 2010). For example, Hill and Duval (2009) observed a dominant flow gradient from the channel to a riparian zone in Ontario, Canada, induced by water ponding behind a beaver dam. The dam's influence on the hydraulic gradient ultimately enhanced riparian zone inundation and flooding. Similarly, Westbrook et al. (2006) showed beaver dams increase stream-floodplain connectivity by enhancing the depth and extent of overbank flooding. Even when valley floors are not flooded because of beaver dams, groundwater levels can rise over 1 m (Giriat et al. 2016) and remain elevated during low flow conditions (Westbrook et al. 2006). Human-created dams have also been shown to alter riparian hydrology, impacting surface water–groundwater hyporheic exchange several meters into the riparian aquifer and influencing water table fluctuations up to 30 m from the dam (Sawyer et al. 2009). Small dams and microdams (2.5–20 m in height) create a rise in river stage, increasing lateral seepage of river water into groundwater, leading to enhanced groundwater recharge and shallower water tables in adjacent and downstream riparian areas (Ashraf et al. 2007; Nedaw and Walraevens 2009; Chen et al. 2012; Berhane et al. 2016). Riverbed hydraulic conductance also impacts groundwater head and influences regional groundwater table variations in conjunction with aquifer hydraulic conductivity (Chen et al. 2012). In addition, riparian geomorphology may influence hyporheic flow paths beyond the immediate streambed. For example, convex riparian topography and steep slopes promote deeper water tables with subsurface flows influenced by upland inputs, while concave riparian zones with gentler slopes have shallower water tables more susceptible to stream influence (Lowrance et al. 1997; Hill 2000; Vidon and Hill 2004).

Though studies suggest stream impoundments and riparian topography influence groundwater dynamics, our understanding of how stream and floodplain restoration directly influences riparian zone hydrology remains relatively qualitative to date. To address this concern, this study aims to quantify the impact of stream and floodplain restoration on riparian hydrology by answering the following three questions: (1) To what

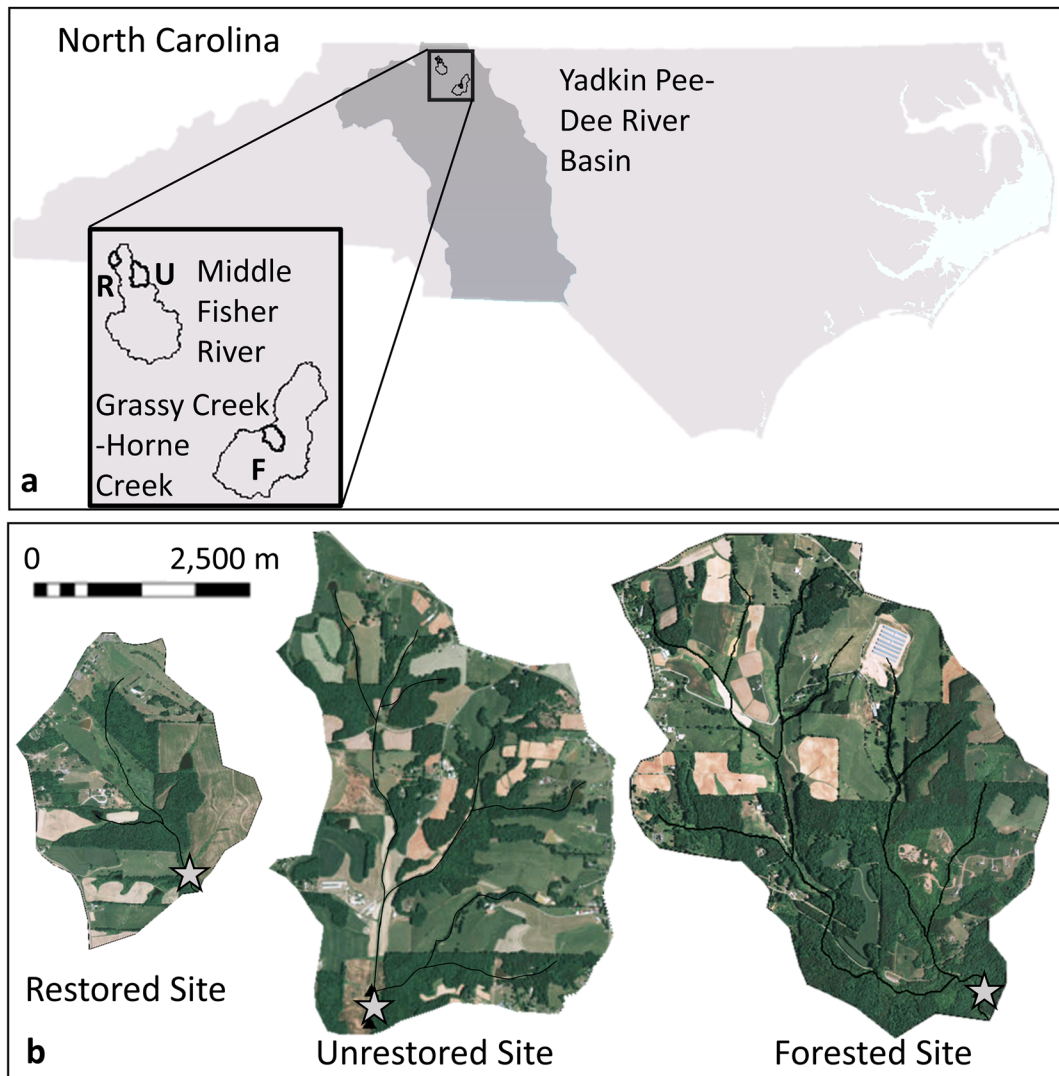
extent do geomorphic changes induced by NCD restoration impact water table height in the riparian zone relative to unrestored sites? (2) How does NCD restoration impact riparian hydrology and does the area of influence of restoration structures change seasonally (wet vs. dry conditions) or with cross-vane functional status (filled in scour pool beneath cross-vane)? (3) What is the relative importance of stream vs. riparian geomorphology at controlling riparian groundwater flow at the sites? To address these questions, we studied the hydrological functioning of three riparian zones in North Carolina, USA with contrasting stream morphology (e.g., riffle-cross-vane complexes with created scour pools vs. natural pools, runs, and riffles), restoration status (agricultural restored, agricultural unrestored with forested buffer, forested reference), and riparian characteristics (slope, soils, topography) over a span of 2.5 years.

### Study region

Stream-riparian field sites were located in the Upper Yadkin Pee-Dee River Basin in the Piedmont region of North Carolina, USA (Fig. 1a). The region has a temperate climate with a mean annual 30-year precipitation of 1188 mm and temperature of 12.9 °C (National Oceanic and Atmospheric Administration [NOAA] Climate Data Online, 1981–2010 Normals Annual Data, Mt. Airy, Station ID: GHCND: USC00315890, NOAA 2016). Soils in the area are shallow and comprised of saprolite derived from gneiss and schist or alluvium and colluvium developed from igneous and metamorphic rock. This region in North Carolina is largely agricultural, comprised of combined row crops (tobacco, corn, and soybeans), pasture, and hog/chicken farming. Field sites included headwater streams that span a gradient of agricultural influence and restoration (Fig. 1b), including one stream that runs through a forested state park with agricultural activity in the headwaters (Home Creek, F), an unrestored agricultural stream with a 10 to 15-m mixed herbaceous-forested buffer that experiences some incision but has in-stream complexity (riffles, point bars, meanders) (Jackson Creek, U), and a restored agricultural stream with a 27-m herbaceous buffer (Cook's Creek, R) (Fig. 2). Cook's Creek and Jackson Creek are located in the Middle Fisher River watershed, with drainage areas of 1.42 km<sup>2</sup> and 4.43 km<sup>2</sup>, respectively, while Home Creek is located in the Grassy-Creek Home Creek watershed,

with a drainage area of 5.03 km<sup>2</sup> for the stream segments of interest (Fig. 1a, b). Drainage areas were delineated in ArcGIS (ESRI 2016) using topographic maps, satellite imagery, and the National Hydrography Dataset (Multi-Resolution Land Characteristics Consortium 2011; USGS 2014). Dominant soil series in the Middle Fisher River watershed near Cook's Creek and Jackson Creek include Fairview cobbly sandy loam, Fairview sandy clay loam, Colvard and Suches, Clifford sandy clay loam, Braddock fine sandy loam, and Woolwine-Fairview-Westfield complexes. Depth to bedrock in these soils often exceeds 1.5 m but can range from 0.5 to 1.5 m. Bedrock outcroppings were visible at the unrestored stream, but depth to bedrock was generally greater than 1.5 m in the riparian zone. The forested site also exhibited bedrock outcroppings in the stream channel, though the depth to bedrock was also over 1.5 m in the riparian zone. Soils in this part of the Grassy Creek-Home Creek watershed included Brevard-Greenlee complexes, Fairview-Poplar Forest complexes, Hayesville-Sauratown complexes, and rock outcrop-Ashe complexes, and many soil map units in this area contain "stony" and "bouldery" modifiers. Soil types were derived using the United States Department of Agriculture – Natural Resources Conservation Service (USDA-NRCS) Web Soil Survey (Soil Survey Staff 2019).

The Cook's Creek stream-floodplain restoration project consisted of installation of cross-vanes (i.e., channel-spanning boulder grade-control structures; Fig. 3) within the straightened channel. Incision at the site prior to restoration (underbank cutting, crumbling stream banks) was consistent with erosion observed at agriculturally influenced streams. Cross-vanes were constructed to redirect flow from the banks toward the center of the channel; high velocities during high flow maintain pool depth through scouring of bed sediments. River rock from the site was used to create riffles immediately upstream of each cross-vane, followed by a deep scour pool that transitioned to a run before the next riffle began, creating riffle-step-pool geomorphology (Fig. 3). Cross-vanes were located every 15–20 m along the restored reach (Fig. 2d). Restoration also impacted the riparian zone. The streambanks were lowered and regraded (near-stream bank dimensions transitioned from approximately 2:1 to 3:1), which removed existing vegetation and topsoil. Following construction, erosion control netting was installed and trees (mix of potted and live stakes) and herbaceous vegetation (seed) were planted. Stream restoration using NCD (e.g., cross-



**Fig. 1** The stream-riparian field sites are located in the Upper Yadkin Pee-Dee River basin in Surry County, North Carolina (a). The agricultural restored (R) and unrestored (U) sites are located in the Middle Fisher River watershed, while the forested (F) site is

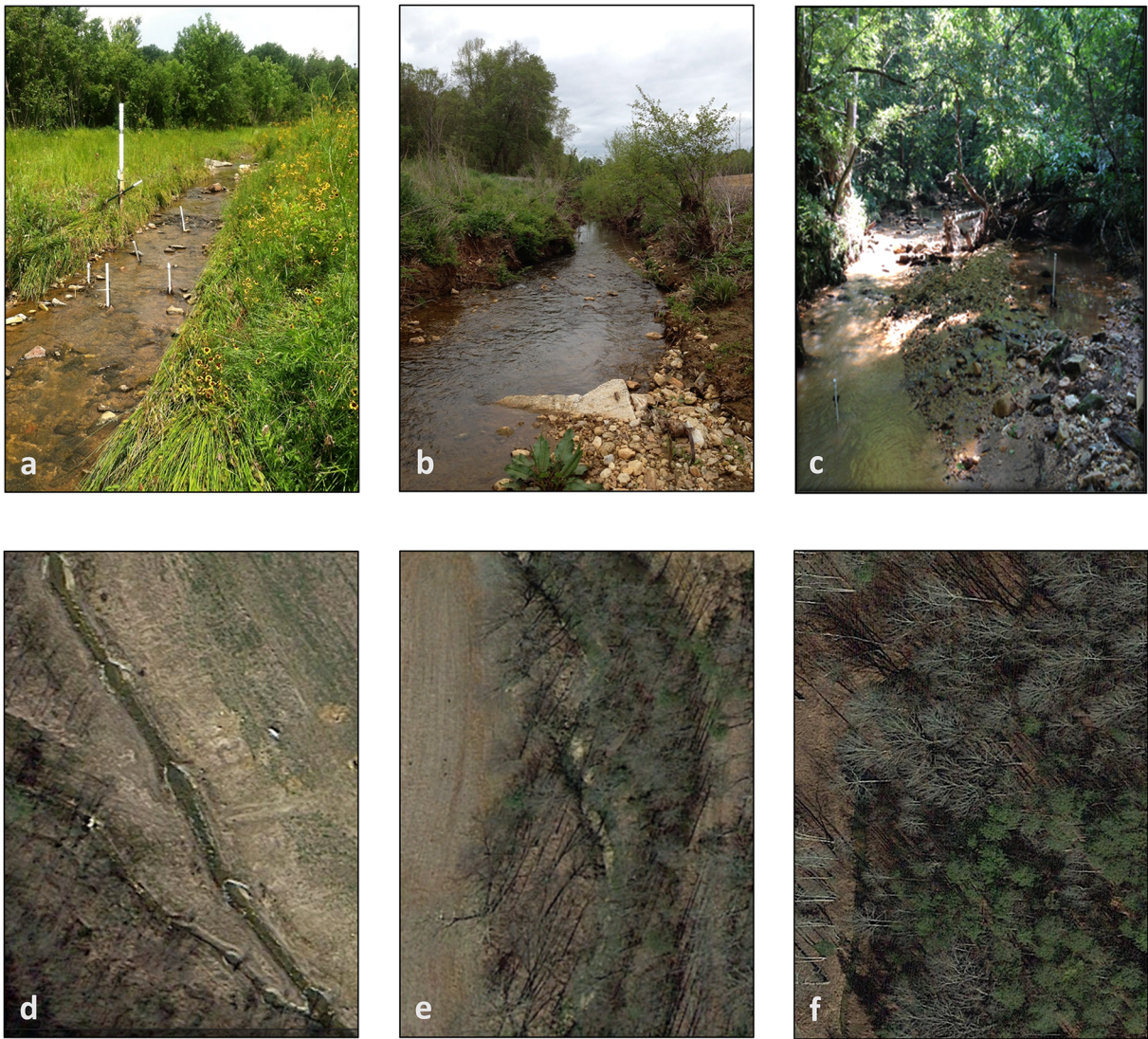
located in the Grassy Creek-Horne Creek watershed (a). Aerial views of the contributing drainage area for the restored, unrestored, and forested sites are shown in panel b. The study area for each site is marked with a star symbol

vane installation, riparian regrading and re-vegetation) was completed in 2012 and sampling began during the spring of 2013. Specific field-measured soil texture and topography data for each site are presented in the “Results” section.

## Materials and methods

Piezometers were installed in transects through representative stream features (pools, riffles, runs) and in nests in different areas of the riparian zone (near-stream,

mid-riparian, near-agricultural field/hillslope) at each of the study sites (Fig. 4). A network of 9 to 11 riparian piezometer nests was installed per site, to encompass the landscape geomorphic positions within each riparian area. Each nest consisted of one well and 2–3 piezometers located at depths of approximately 50-cm increments, ranging from 50 to 275 cm below ground surface. Piezometers had screen lengths of 20 and 10 cm in the riparian zone and stream, respectively, and were constructed from 1.27 cm inner diameter (ID) polyvinyl chloride (PVC) pipe. Wells were constructed from 5.1 cm ID PVC pipe and slotted throughout their length.



**Fig. 2** Field site pictures (a–c) and aerial imagery (d–f) for the three sites of interest—restored (a, d), unrestored (b, e), and forested (c, f). Aerial images taken during leaf-off conditions in 2013 (restored and unrestored) and 2017 (forested site), courtesy

of Google Earth. Please note configuration of cross-vane structures at the restored site in aerial photograph; cross-vanes are spaced approximately 15 to 20 m apart along the stream reach (d)

Wells and piezometers were capped when not sampled. Well and piezometer locations and at least three representative geomorphic cross-sections from the stream to the hillslope were surveyed at each site using a Trimble M1 total station (Westminster, CO, USA) to develop site topographic maps. In early summer 2013, the cross-vane nearest the network of riparian piezometers and wells failed and quickly began filling with sediment. Two additional riparian zone nests (9 and 10) were added in the near-stream zone adjacent to a cross-vane located approximately 20 m downstream from the cross-

vane experiencing sedimentation. Whenever piezometers were installed, soil samples were collected throughout the depth of the piezometers and assessed for texture using the Natural Resources Conservation Service hand texture methodology (Burt 2014). Dominant soil type and topography of each site is described in the “Results” section.

Water level was measured at least once per season to capture water table dynamics at baseflow in each piezometer and well from March 2013 to July 2015 using a Solinst Mini Water Level Meter, Model 102M (Solinst

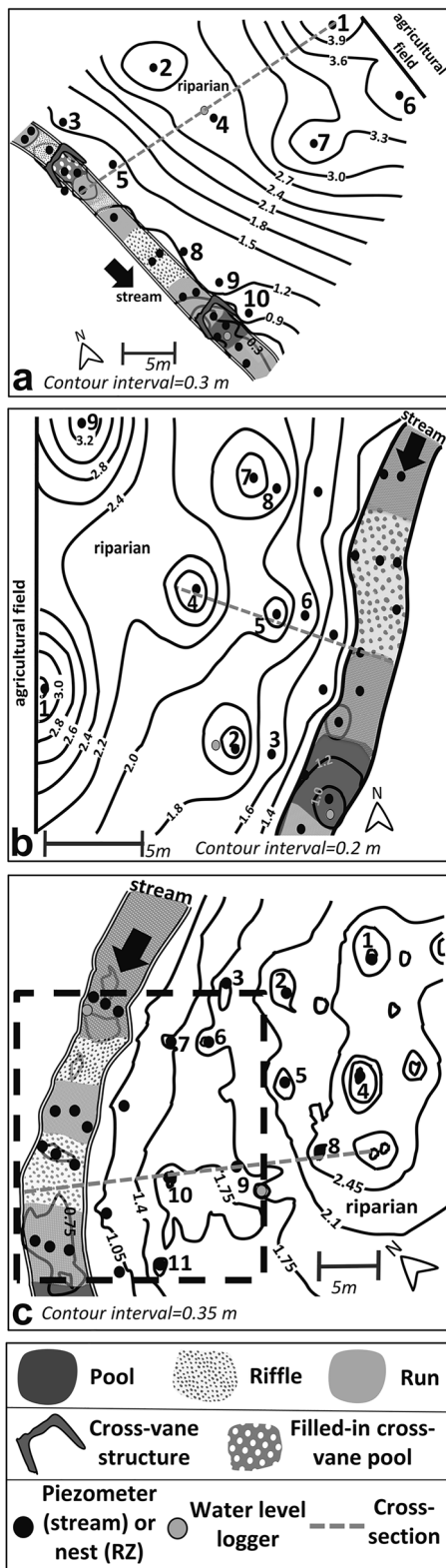
**Fig. 3** The riffle-cross-vane complex installed at the restored site in 2012, pictured slightly after regrading and re-seeding (a) and following growth of herbaceous vegetation (b). Note the presence of large boulder structures that span the channel, concentrating flow in the center of the stream to reduce erosion



Canada Ltd., Georgetown, ON, Canada). Although higher sampling frequency may be needed to capture water table response to storms as in Welsh et al. (2019), lower sampling frequencies for a large number of piezometers and wells as in this study offer the opportunity to capture high spatial resolution data that cannot be captured otherwise during baseflow conditions when the water table is relatively static (Vidon and Smith 2007; Liu et al. 2014; Williams et al. 2014). Water table measurements are expressed above a site-specific common datum, which was set to the lowest point, or thalweg, of the streambed. Hydraulic head was calculated as the sum of pressure head plus elevation head at each location. Site groundwater flow maps and cross-sectional hydraulic head transects were generated using Grapher (Version 10, Golden Software, Golden, CO).

Flow lines were visually assessed to determine if a zone of low hydraulic head was present next to the stream which diverged from a hillslope-dominated groundwater flow pattern. Such a zone of low hydraulic head and elevated water tables downstream of impoundments would signify an impact by stream features on near-stream hydrology. To quantify the areal extent of impacted hydraulic head, we delineated the zone with groundwater levels similar to those observed adjacent to the geomorphic feature of interest (i.e., a zone of influence). To derive this zone of influence, we calculated the average absolute difference in water levels between near-stream wells directly above and below each cross-vane-riffle complex (i.e., well 3 versus 5 [upstream cross-vane] and well 9 versus 10 [downstream cross-

vane]) across all seasons. The average difference between wells 3 and 5 was 13 cm, while the average difference between wells 9 and 10 was 7 cm. Overall, the absolute difference in water levels upstream and downstream of cross-vane structures averaged 10 cm across all seasons, with a relative percent difference of less than 5%. We compared this value to the average difference between the near-stream well not located in the immediate vicinity (e.g., within 2.5 m) of either cross-vane (well 8) and all other near-stream wells surrounding the cross-vane structures across all sample dates; this average difference in water levels equated to 22 cm. Therefore, to quantify the influence of the cross-vane on water levels in the riparian area, we set our cross-vane zone of influence as  $\pm 10$  cm of the interpolated water level directly next to each cross-vane structure. This captures natural variability in water levels measured in wells influenced by high water tables and low hydraulic head around the cross-vane structures (average difference, 10 cm). This criterion also limits the zone of influence to exclude changes  $> 20$  cm in water levels, a threshold supported by the average difference (22 cm) between wells adjacent to cross-vanes and the well not in the vicinity of cross-vanes along the same relative elevation and near-stream landscape position. We applied this same criterion of  $\pm 10$  cm to the zone next to riffles at the forested and unrestored sites for consistency in determining the zones of influence of stream geomorphic features among sites. This zone of influence graphically represents the area of the site where hydraulic gradient differs from a hillslope



◀ **Fig. 4** Topography of the agricultural restored (R: a), agricultural unrestored with forested buffer (U: b), and forested reference (F: c) field sites, expressed in meters (m) above a site-specific datum. Sites were instrumented with a network of piezometers and wells; each black dot represents the location of a piezometer nest (numbered in riparian zone [RZ]) or the location of an individual piezometer (in-stream). Gray dots denote locations of water level loggers. Wetted channel geomorphic features (pools, riffles, and runs) are displayed in each stream. Location of hydraulic head cross-sectional profile is displayed via a dashed gray line. The portion of the forested site (c) where water table is displayed in Fig. 6 is denoted with a dashed black box

dominated field-to-stream gradient and therefore delineates the zone of impact of in-stream features on groundwater flow (Westbrook et al. 2006). The total study areas of interest for the restored site, unrestored site, and forested site were approximately 820 m<sup>2</sup>, 270 m<sup>2</sup>, and 330 m<sup>2</sup>, respectively. The zone of influence of stream features on groundwater flow was expressed as a percentage of the total area for each site.

Groundwater fluxes along selected transects of wells and piezometers at the sites were determined using the one-dimensional form of Darcy’s Law for a 1-m<sup>2</sup> section of riparian zone at each site (Vidon and Hill 2004; Liu et al. 2014). To this end, hydraulic conductivity was measured in each riparian nest using the Hvorslev water recovery method (Freeze and Cherry 1979). Lateral hydraulic gradients through the riparian zones were determined via the change in hydraulic head over the distance between piezometers in each cross-section. Nonparametric statistical tests (Wilcoxon rank sum and Steel-Dwass post hoc tests) to account for differences in groundwater fluxes among sites were run in JMP, Version 10 (SAS Institute Inc., Cary, NC, USA), as data were not normally distributed (Shapiro-Wilk W test).

Seasonal water level measurements in all wells and piezometers were complemented with continuous water level and temperature measurements (5 to 15-min recording intervals) at one location in each stream and riparian zone using HOBOWare level loggers in order to suitably identify baseflow periods for seasonal water level measurements throughout the sites (model #U20-001-02-Ti, Onset Computer Corporation, Bourne, MA, USA). Stream water level loggers were located in relatively deep, low-velocity areas, while riparian zone loggers were located approximately 5 to 10 m away from the stream in each riparian zone in a 5.1 cm ID PVC well (Fig. 4).

## Results

### Site topography and soil characteristics

At the restored site, the influence of riparian regrading is observed 5 m from the stream, where the slope transitions from 12 to 5% on the stream bank (Fig. 4a). The near-stream riparian zone contains clay-based soils (clay, sandy clay, and sandy clay loam), which exhibit redoximorphic features (e.g., mottles, gleying) and frequently experience ponding following storm events. In contrast, soils near the agricultural field have a predominantly sandy loam texture. In the stream, the section of the channel studied here contains two cross-vane structures. The pool formed by the upstream cross-vane filled in with sediment during the summer of 2013, while the pool that formed under the downstream cross-vane did not experience the same degree of sedimentation and generally continued to function as expected.

The unrestored site (Fig. 4b), which is located adjacent to an agricultural field, does not have as much geomorphic complexity as the restored and forested sites and contains relatively homogeneous soils throughout the profile. Soils at this site are dominated by loam and fine sandy loam soils. The unrestored site has a slightly convex riparian zone shape and 12% overall slope. The forested reference riparian zone (Fig. 4c) has a slope of 10% and contains a large depositional point bar composed of cobble, gravel, and sand near the downstream section of the studied reach. This riparian site has high topographic heterogeneity and includes a depression located approximately 10 m from the stream, which intermittently experiences flooding. Both the depression and near-stream zone contain sand interspersed with cobbles and boulders. Soils in the mid and upper riparian zone are dominated by loamy sand and sandy loam soils.

### Stream and riparian water levels

Based on continuous stream and groundwater level data, the stream and riparian zone water levels peaked around the same time at the restored site (Fig. 5a). Additionally, manual water level measurements indicate the water table was frequently within 0.5 m of the ground surface in the area that was regraded (Fig. 5b). There was distinct separation between water levels in the near-stream, mid-riparian, and near agricultural field zones. Conversely, at

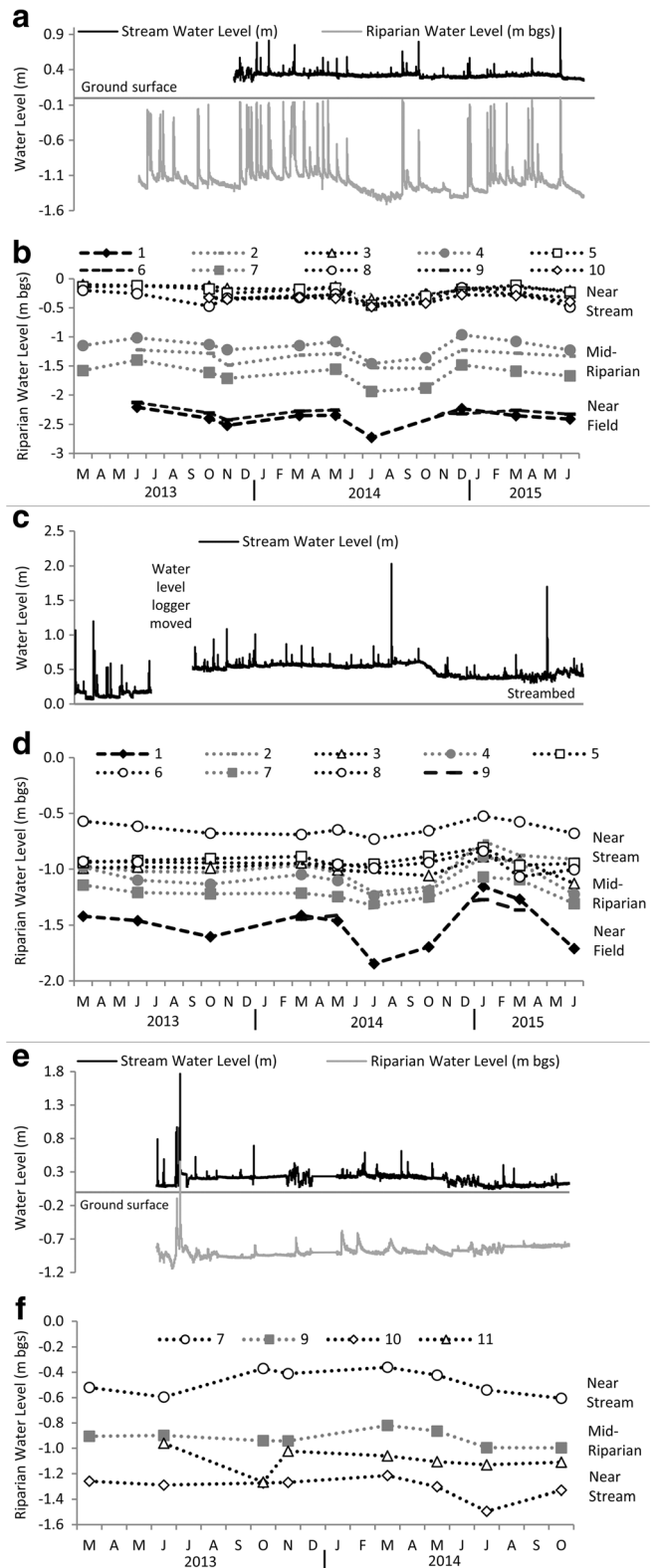
the unrestored site, the water table depth in the near-stream zone was greater than 0.5 m below ground surface (bgs), and there was less overall variability in water levels in the riparian zone at the unrestored site (range, 0.52 m to 1.85 m bgs; Fig. 5d) than at the restored site (range, 0.10 to 2.73 m bgs; Fig. 5b). At the forested site, where the riparian logger was located in the depression (nest 9), stream water level often peaked after the riparian zone water level (Fig. 5e). Near-stream riparian wells located in the riparian depression had a water table generally within 0.5 m from the ground surface. Conversely, wells located in the sand bar or in the upper riparian area had water table depths greater than 1 m bgs and 1.5 m bgs, respectively (Fig. 5f).

### Water table elevation and hydraulic head

Aerial contour maps of water levels and corresponding cross-sectional views of equipotential lines at the restored, unrestored, and forested sites during representative wet (spring) and dry (summer) conditions are displayed in Figs. 6 and 7. A cross-valley groundwater flow gradient exists at the restored site. The gradient is steeper from the near-field edge to the mid-riparian zone, then decreases from the mid riparian zone to the stream, coinciding with the presence of the cross-vane structures and regraded riparian area (Fig. 6a, b). During wetter conditions (Spring 2014, Fig. 5a, b), the zone of influence of the created riffle-cross-vane complex on the riparian groundwater table at the restored site accounted for approximately 35% of the area of the restored riparian zone (Fig. 6a, Table 1). During dry conditions (Summer 2014, annual minimum, Fig. 5a, b), the cross-vane zone of influence on riparian groundwater flow was equivalent to 42% of the riparian zone (Fig. 6b). Although only high and low water table conditions are represented here, the influence of the cross-vanes persisted throughout the year and was generally equivalent to 30–45% of the riparian zone area regardless of season and water table height (data not shown). The influence of cross-vanes on water table elevations and hydraulic head was also evident in measurements taken at 24 and 72 hours following storm events of various magnitudes in the summer of 2015 (Welsh et al. 2019). At the restored site, hydraulic head during the wetter period indicates that upwelling occurs in the mid-riparian zone, which is where the hillslope water meets the near-stream displaced water from the zone of



**Fig. 5** Restored (R: a), un-restored (U: c), and forested site hydrographs (F: e) for each stream (m above streambed) and riparian zone (m below ground surface [bgs]). Riparian water level data is not available for the un-restored site due to repeated malfunction of multiple deployed water level loggers. Manual seasonal well measurements (m bgs) are displayed in relation to hydrograph data for R, U, and F (b, d, f, respectively). Numbers 1–11 on each graph correspond to well locations, as depicted on Fig. 4. Location of water level loggers is also shown on Fig. 4



influence of the cross-vane (Fig. 7a). This created a small water table mounding effect downstream in the mid-riparian zone, at nest 7 (Fig. 6a, b). In the summer, when near-stream water table height declined, a flow reversal was observed from the stream to the near-riparian zone (Fig. 7b), inducing a down valley gradient immediately adjacent to the stream (Fig. 6b).

At the unrestored site, a dominant cross-valley gradient exists from the agricultural field toward the stream (Fig. 6c, d). Though the water level throughout the riparian zone changes seasonally, the dominant hillslope gradient persists regardless of season. The equipotential lines displayed in the cross-sectional diagram also support this cross-valley gradient (Fig. 7c, d). The zone of influence (delineated as 10 cm above and 10 cm below the riparian water level adjacent to the geomorphic feature) of the riffle on near-stream groundwater flow encompassed 10% of the riparian zone study area in the wet season and 4% of the riparian area during the dry season (Fig. 6c, d, Table 1).

At the forested site, a cross-valley gradient occurred from the depression (nest 9), a concave area containing higher water tables and convergent flow, toward the stream. However, in the upper reach of the stream, the large riffle functioned in a similar fashion to the restored riffle-cross-vane complex in the near-riparian zone, leading to a lower hydraulic gradient that extended into the riparian zone. The area of influence of the riffle was 36% of the riparian zone in the wet season, and 37% in the dry season (Fig. 6e, f, Table 1). A small area of upwelling, similar to the subsurface flow patterns observed at the restored site, also occurred at the forested site, as evidenced by the cross-section equipotential lines (Fig. 7e, f).

#### Groundwater fluxes and hydraulic conductivity

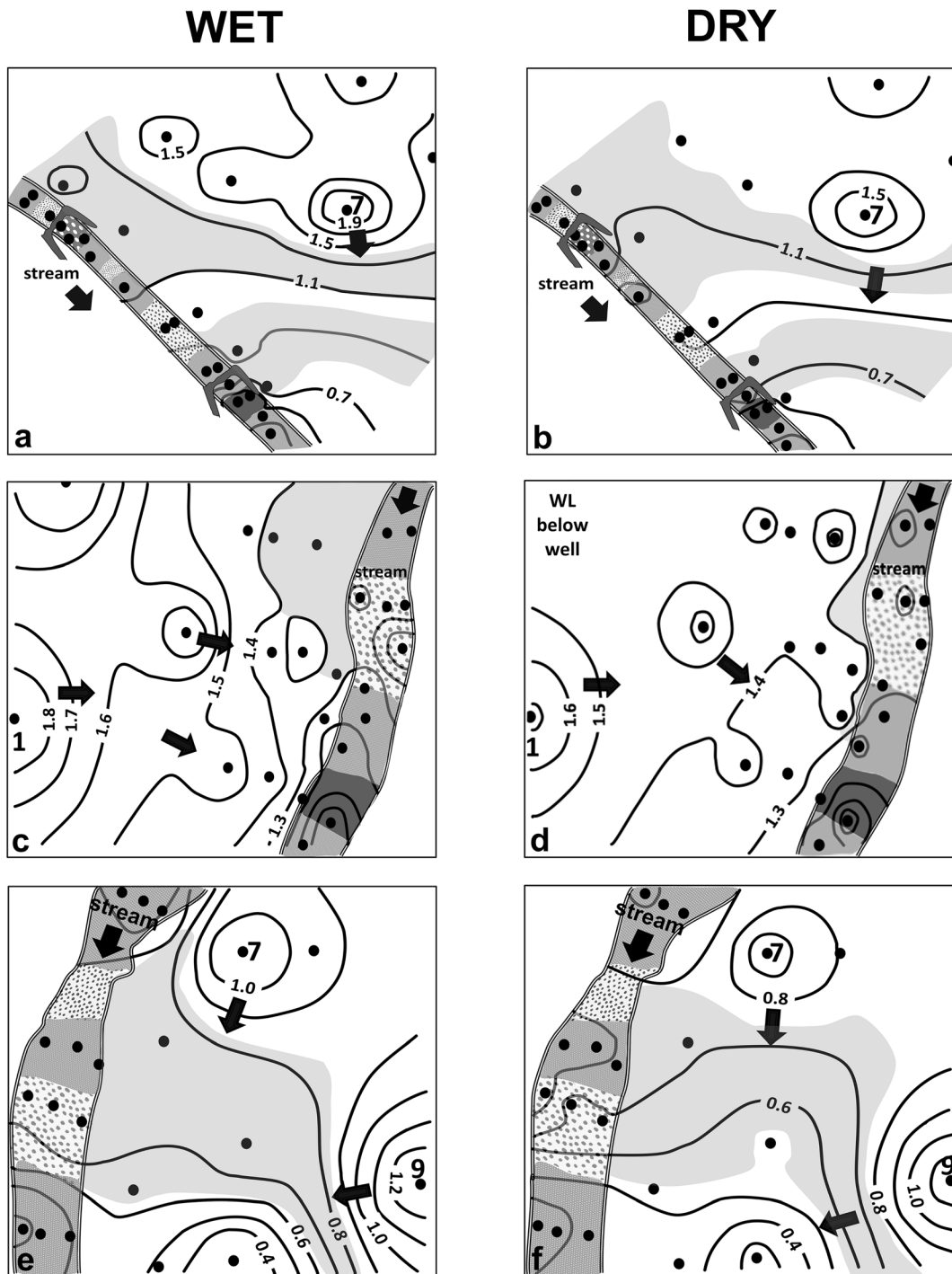
Groundwater fluxes were lowest at the restored site (mean  $6.5 \text{ L day}^{-1} \text{ m}^{-2}$ , median  $6.7 \text{ L day}^{-1} \text{ m}^{-2}$ ) and highest at the forested site (mean  $60.1 \text{ L day}^{-1} \text{ m}^{-2}$ , median  $60.6 \text{ L day}^{-1} \text{ m}^{-2}$ ). However, saturated soil hydraulic conductivities were of the same order of magnitude among sites (Table 1). When all seasons were combined, groundwater fluxes were significantly different among sites (Wilcoxon rank sum test,  $p < 0.0001$ ) and fluxes were higher at the forested site than at the restored and unrestored sites (Steel-Dwass post hoc test,  $p = 0.0021$  and  $p = 0.0022$ , respectively).

## Discussion

To what extent do riparian geomorphology and stream restoration influence riparian water table dynamics?

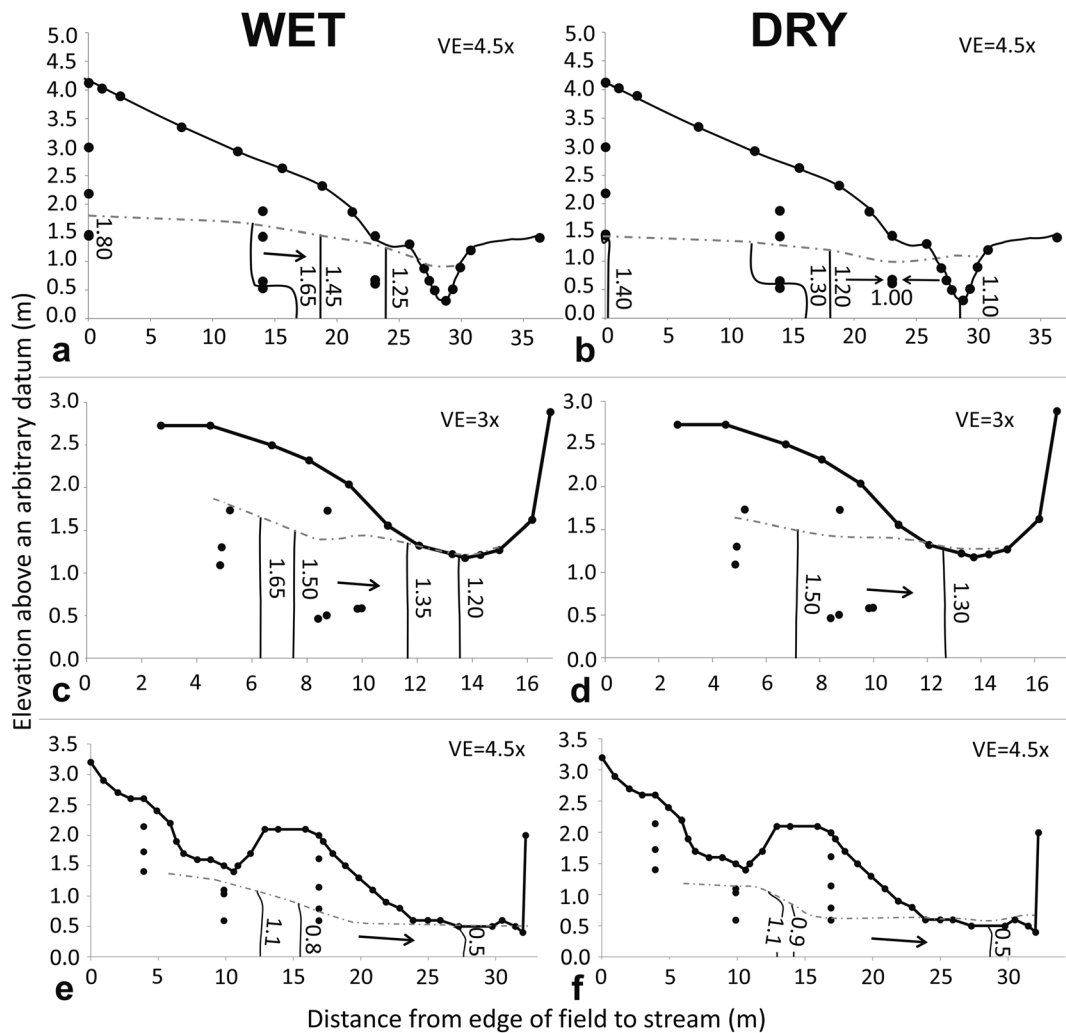
The restored riparian zone, which was regraded to lower the bank elevation and impacted by cross-vane structure boulders embedded in the near-stream area, had high near-stream groundwater tables ( $< 0.5 \text{ m}$  from the ground surface). Water table depth has been shown to correlate to elevation above the channel, and in this study the near-channel land surface was regraded, impacting near-stream restored elevation (Jansson et al. 2007). Similarly, Moorhead et al. (2008) observed high groundwater tables post-restoration within 50 m of a previously straightened stream that had been re-meandered with created pool-riffle sequences. Groundwater levels within 0.3 m of the ground surface in the area of influence of beaver dams were also reported by Westbrook et al. (2006). In this study, a water table within 0.5 m of the ground surface was also located in the upstream area of the forested site, where a gentle slope occurred at nest 7. Downstream, water tables were farther from the ground surface (nests 10 and 11) on account of the existence of an extensive gravel vegetated point bar creating locally convex topography. However, the depression area in the mid-riparian zone (nest 9) had groundwater levels that were closer to the ground surface than in the point bar. Other research has shown that concave topography, such as in the restored regraded section and in the depression in the forested site, can create hillslope hollows, which often experience saturation from below (Sophocleous 2002). Conversely, the unrestored site had convex topography and experienced incision, leading to lower near-stream water tables. Incision has been shown to alter riparian zone hydrology, leading to lower water tables 30 m into the riparian zone and development of an extensive unsaturated zone (Schilling et al. 2004). Overall, data indicate that riparian geomorphology drives variability in groundwater table depth at all sites.

Stream geomorphology (i.e., pool-riffle sequences, presence/absence of cross vanes), however, influenced water table dynamics in the area located immediately adjacent to the stream. For instance, data indicate that in-stream impoundments promoted higher groundwater tables that extended into the riparian area in the downstream direction as flow impediments, such as boulder cross-vanes, direct stream water laterally into the riparian zone. This leads to a lower hydraulic gradient near



**Fig. 6** Aerial view of water table elevations at the restored (R: a, b), unrestored (U: c, d), and forested sites (F: e, f), expressed in meters (m) above a site-specific datum, during wet (spring, left panel) and dry (summer, right panel) periods. Arrows represent the general direction of flow. A dominant cross-valley gradient is demonstrated at the unrestored site, while presence of riffles and cross-vanes lead to lower near-stream hydraulic gradients in the

forested and restored sites, respectively. The zone of influence of riffles and cross-vanes (gray-shaded area in each riparian zone) is expressed as the area that is 10 cm above and 10 cm below the water level next to the created structure (R) or natural geomorphic feature (U, F). Please refer to Fig. 4 for a detailed legend for in-stream features



**Fig. 7** Cross-sectional views of riparian and channel topography and hydraulic head equipotential lines (shown as vertical solid lines) at the restored (R: a, b), unrestored (U: c, d), and forested (F: e, f) sites during the wet (left) and dry (right) seasons,

expressed above a site-specific datum (m). The dashed line presents the water table surface. Arrows represent direction of flow. VE, vertical exaggeration of topographic profile. Note different x axes for each site

**Table 1** Groundwater fluxes ( $L day^{-1} m^{-2}$ ), hydraulic gradient ( $m m^{-1}$ ), geomorphic feature zone of influence (% of riparian zone), and hydraulic conductivity ( $m s^{-1}$ ) at the agricultural restored (cross-vanes, regrading, re-vegetation) (R), agricultural unrestored

(U), and forested reference (F) field sites during wet and dry periods. Geomorphic feature: stream cross-vane-riffle complex (R), natural riffles (U, F)

Site	Groundwater flux ( $L day^{-1} m^{-2}$ )		Hydraulic gradient ( $m m^{-1}$ )		Geomorphic feature zone of influence (% of riparian zone)		Hydraulic conductivity, $K_{sat}$ ( $m s^{-1}$ )
	Wet	Dry	Wet	Dry	Wet	Dry	
R	7.35	5.88	0.02	0.02	33	42	3.92E-06
U	11.42	8.57	0.01	0.01	10	4	9.16E-06
F	66.96	75.8	0.08	0.09	36	37	9.34E-06

the restored stream, spanning over 10 m into the riparian zone beyond the stream bank. Although such impacts of cross-vanes on riparian water table dynamics in the downstream direction are novel and have not been reported in the stream restoration literature thus far, this is consistent with the work of Westbrook et al. (2006) around natural beaver dams, where the authors show that beaver dams in Colorado altered groundwater flow paths and levels, creating a nearly flat groundwater surface for over 80 m into the riparian zone downstream of the beaver dam. In Wyoming, Lautz et al. (2006) also described interception of near-stream water by a large-scale flow path after diversion of stream water into the subsurface occurred in a losing reach surrounding a debris dam. At the restored site in this study, downwelling was often apparent above and immediately below the upper cross-vane (data not shown). Therefore, the upper section of the restored reach was losing in nature, and riparian hydrology was affected beyond the local hyporheic zone, primarily in a downstream direction.

How does NCD restoration impact near-stream groundwater flow?

A flow reversal was observed in the regraded section of the restored site, where stream water was driven into the nearby bank and a near-stream down valley gradient was induced adjacent to the stream. Hill and Duval (2009) also report a stream to riparian zone flow gradient in an area adjacent to a beaver dam, with hillslope inflow only producing a gradient toward the stream in the upper riparian zone. Other gently sloping riparian zones have been shown to exhibit similar summer flow reversals (Vidon and Hill 2004). High stream water levels can also influence groundwater tables by creating local groundwater mounds, especially following high flow events (Jung et al. 2004; Vidon 2012). In a similar manner, a groundwater mound was observed at the restored site following storms as reported by Welsh et al. (2019), but also on a seasonal basis in this study downstream of the cross-vane in the mid-riparian area (nest 7). At this location, interactions of near-stream riparian water (in the zone of low hydraulic gradient) with upper riparian groundwater (flowing along a cross-valley gradient) created a groundwater mound. This was particularly evident during the flow reversal, which occurred in the drier summer months, suggesting that cross-vanes impact water table dynamics in the riparian

zone in a similar way to storms. The fact that cross-vanes do impact riparian water table dynamics in the riparian zone beyond the immediate hyporheic zone surrounding the cross-vanes on a seasonal basis (not only following storms) is novel and suggests that such structures have a greater impact on whole floodplain hydrology than initially reported in the stream restoration literature (Kasahara and Hill 2006; Hester and Doyle 2008).

Though the effect of cross-vanes persisted regardless of season, the percentage of the riparian zone influenced by cross-vanes at the restored site differed depending on time of year (33% wet spring period, 42% dry summer period). During the dry period, hillslope inputs decrease, riparian water table falls, and the stream becomes an important driver of water table dynamics at the restored site. In contrast, at the incised and less geomorphologically complex unrestored site, the zone of influence of riffles was greater in the wet season (10%) than during the dry season (4%), although it was approximately 60–90% less than at the other two sites (Table 1). At the forested site where lateral inputs were limited all year long, the area of influence of the riffle expectedly did not change seasonally (36–37%; Table 1). Ultimately, the differences in the size of the zone of influence between the sites indicate that at the unrestored site, groundwater flow dynamics are primarily influenced by lateral flow from the immediate upland environment, while at the restored or at the reference forested sites, stream geomorphology can significantly impact water table dynamics in the riparian zone. The differences in area of influence between the restored, forested, and unrestored sites also show that from a hydrological standpoint, the restoration was successful in bringing restored riparian hydrology closer to a forested reference condition.

Our data also indicate that the combined effects of near-stream regrading and cross-vane restoration structures impact riparian groundwater flow dynamics (i.e., water table, flow paths), even when in-channel cross-vane structures are not functioning as expected (e.g., filled in with sediment and cobble from upstream sources as is the case for the upstream cross-vane at the restored site). Although other studies have shown that post-restoration siltation and clogging of streambed pore spaces could inhibit in-channel vertical hyporheic exchange (Kasahara and Hill 2006), our study is the first to show that even cross-vanes experiencing burial by sediment continue to exert control on riparian zone

hydrology in a similar way to normally functioning cross-vanes, suggesting that cross-vanes may have a greater impact on riparian zone hydrology than initially expected based on past stream restoration studies (Kasahara and Hill 2006; Hester and Doyle 2008).

What is the relative importance of stream vs. riparian geomorphology at controlling groundwater flow at the sites?

Though the restored site had similar groundwater–surface water interactions to the forested site, groundwater fluxes were lower at the restored site than at the forested site (Table 1). In spite of potential soil compaction at the restored site during the restoration process, saturated soil hydraulic conductivities remain of the same order of magnitude at the restored, unrestored, and forested sites. Hydraulic gradient was however consistently higher at the forested site than at the restored or unrestored sites. Together, this suggests that hillslope hydraulic gradient (i.e., gradient beyond the area of the riparian zone influenced by in-stream features) and differences in soil hydraulic conductivities drove differences in groundwater flow between sites (Table 1). At the restored and forested sites, where a low gradient area formed near geomorphic features, a groundwater mound and a down valley gradient formed (see above), which is consistent with hillslope water “piling up” in the middle of riparian zone. So, although in the immediate vicinity (a few meters or in the area of influence) of in-stream features the groundwater flow may be reduced due to a low hydraulic gradient, the overall groundwater flow across the whole riparian zone remains primarily controlled by riparian saturated soil hydraulic conductivity and the overall water table gradient from field-to-stream. Of note, beyond specific controls on groundwater fluxes at the sites, groundwater flux values at the sites were consistent with fluxes reported in the literature for other riparian zone types with sandy loam to loamy clay soils, 2 to 6 m deep confining layers, and a range of topography types (i.e., straight, concave, convex) (Vidon and Hill 2006). Local controls on groundwater fluxes identified in this study (i.e., riparian saturated soil hydraulic conductivity and overall field-to-stream water table gradients) are also consistent with local controls (surficial geology/soil texture, upland inputs, and topography) reported in other studies (Sabater et al. 2003; Vidon and Hill 2004; Vidon et al. 2014).

## Conclusions

This study directly quantified how floodplain restoration (cross-vane installation, riparian zone regrading) exerted considerable influence over 30–40% of the riparian area. Restoration affected water table depth, hydraulic gradient, and flow direction immediately near and downstream of each in-stream structure on a seasonal basis in a similar way to how beaver dams impact riparian zone hydrology. Results also indicated that in-stream structures lead to riparian hydrological changes similar to those observed only following storm events in riparian zones located near streams without in-stream impoundments present. This study is therefore the first to show that cross-vanes may have a greater impact on riparian zone hydrology than initially expected based on past stream restoration studies (Kasahara and Hill 2006; Hester and Doyle 2008). Our study also showed that overall groundwater fluxes in the field-to-stream direction remain primarily driven by riparian zone characteristics and hillslope inputs (as opposed to in-stream structures) but that fluxes can be influenced in the near-stream area immediately surrounding each restoration structure (i.e., the area of influence). When compared with reference and unrestored site conditions, our data suggest that in-stream channel structures and riparian zone regrading to lower stream banks to reconnect floodplains is an effective strategy in moving site hydrology toward forested reference conditions, even when the cross-vanes quickly experience burial by sediment post-restoration. Our study is the first to show that even though cross-vanes experiencing burial by sediments post-restoration may have a limited impact on hyporheic flow (Kasahara and Hill 2006), they continue to exert significant control on water table at the riparian zone/floodplain scale, which ultimately may also affect near-stream biogeochemistry and water quality functions.

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## Compliance with ethical standards

**Conflict of interest** The authors declare they have no conflict of interest.

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