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Special Section:
The Future of Critical Zone Science: Towards Shared Goals, Tools, Approaches and Philosophy

Backed-Up, Saturated, and Stagnant: Effect of Milldams on Upstream Riparian Groundwater Hydrologic and Mixing Regimes

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Key Points:

- Milldams raise riparian groundwater levels, decrease hydraulic gradients, and cause reversals in groundwater flow
- Milldam legacies contribute to reduced groundwater mixing in near-stream sediments
- Altered groundwater regimes due to milldams could affect riparian water quality processes

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

How milldams alter riparian hydrologic and groundwater mixing regimes is not well understood. Understanding the effects of milldams and their legacies on riparian hydrology is key to assessing riparian pollution buffering potential and for making appropriate watershed management decisions. We examined the spatiotemporal effects of milldams on groundwater gradients, flow directions, and mixing regime for two dammed sites on Chiques Creek, Pennsylvania (2.4 m tall milldam), and Christina River, Delaware (4 m tall dam), USA. Riparian groundwater levels were recorded every 30 min for multiple wells and transects. Groundwater mixing regime was characterized using 30-min specific conductance data and selected chemical tracers measured monthly for about 2 years. Three distinct regimes were identified for riparian groundwaters—wet, dry, and storm. Riparian groundwater gradients above the dam were low but were typically from the riparian zone to the stream. These flow directions were reversed (stream to riparian) during dry periods due to riparian evapotranspiration losses and during peak stream flows. Longitudinal (parallel to the stream) riparian flow gradients and directions also varied across the hydrologic regimes. Groundwater mixing varied spatially and temporally between storms and seasons. Near-stream groundwater was poorly flushed or mixed during storms whereas that in the adjacent swales revealed greater mixing. This differential groundwater behavior was attributed to milldam legacies that include: berm and swale topography that influenced the routing of surface waters, varying riparian legacy sediment depths and hydraulic conductivities, evapotranspiration losses from riparian vegetation, and runoff input from adjoining roads.

Plain Language Summary

Riparian zones can buffer streams from upland nitrogen pollution and are thus considered as important water quality management practices. How the presence of milldams affects groundwater flow paths and their buffering capacity is not known. This study showed that milldams back up stream water above dams, reduce the groundwater gradients from the upland to the stream, and also result in their reversal during summer dry conditions and floods. Milldams reduced the mixing of groundwaters for near-stream sediments. This response was attributed to the topographic and sediment conditions associated with the milldams.

1. Introduction

Damming waterways has substantially affected the hydrology and nutrient cycling of riverine ecosystems (Belletti et al., 2020; Maavara et al., 2020; Van Cappellen & Maavara, 2016). Water-powered mills and associated low-head milldams were ubiquitous in the United States, United Kingdom, and Europe, leaving extensive legacies long after these structures ceased to serve their original purpose (Brown et al., 2018; Brykala & Podgorski, 2020; Johnson et al., 2019; Walter & Merritts, 2008; Wegmann et al., 2012). There are an estimated 2.4 million dams that are too small to be listed on the National Inventory of Dams and many others that are unmapped and unidentified (Brewitt & Colwyn, 2020; Buchanan et al., 2022). Human-made dams fragment stream ecosystems (Fencl et al., 2015); are detrimental to riverine wildlife (Bellmore et al., 2019; Henley et al., 2000); and can contribute heavily to suspended sediment and nutrient loads in streams when breached (Cashman et al., 2018; Gellis et al., 2017; Jiang et al., 2020). However, few studies have addressed how milldams alter riparian hydrology and mixing regimes and how this could affect riparian zone water quality processes and functions (e.g., Lewis et al., 2021).

Riparian zones are critical ecotones between uplands and streams that provide valuable water quality services and benefits and are therefore promoted as important landscape management practices (Lowrance et al., 1997; Pinay & Haycock, 2019; Vidon et al., 2010). One of the most important water quality functions of riparian zones is denitrification—a process that converts nitrate-nitrogen (N) in groundwater to inert nitrogen gas (Gold et al., 1998; Groffman et al., 1992; Hill, 2019; Lowrance, 1992), and acting as an important natural filtering process to remove excess groundwater N. Denitrification typically occurs under wet, saturated, anoxic soil conditions with near-surface groundwater levels (Hill, 2019; Lowrance et al., 1997; Lutz et al., 2020), similar to those observed in riparian zones upstream of milldams. However, how milldams influence riparian groundwater hydrology with subsequent consequences for denitrification and nitrogen buffering is not known and a critical knowledge gap. This knowledge gap becomes especially important given that milldams are being increasingly removed across the US mid-Atlantic and the northeast (Bellmore et al., 2019; Foley et al., 2017).

While less is known about how milldams affect riparian hydrology, there have been multiple studies investigating the effects of smaller, less permanent, beaver dams (Fanelli & Lautz, 2008; Gold et al., 2016; Hill & Duval, 2009; Janzen & Westbrook, 2011; Larsen et al., 2021; Shuai et al., 2017; Smith et al., 2020; Wang et al., 2018). Beaver dams can elevate stream and groundwater levels upstream of the dam and decrease the lateral hydraulic gradient of upland/riparian groundwaters toward the stream (Hill & Duval, 2009; Janzen & Westbrook, 2011; Wang et al., 2018). Decrease in hydraulic gradients can also increase the residence time of groundwater in the riparian zone (Hill & Duval, 2009). Elevated stream water levels can redirect stream water laterally into the riparian zone resulting in the surficial and sub-surficial flows through the riparian zone (Smith et al., 2020; Wang et al., 2018; Westbrook et al., 2006). Depending on the hydraulic conductivity and texture of the riparian soils, this lateral hyporheic flow has been shown to loop around the dam with emergence downstream of the dam (Hill & Duval, 2009; Lautz et al., 2006; Wang et al., 2018). Whether similar groundwater exchange patterns and dynamics also extend to riparian zones above milldams is not known. The direction of the riparian flow paths (toward or away from the stream) and associated residence times of water could influence nitrogen processing and the concentrations of nitrate-N and ammonium-N in riparian soils (Hill & Duval, 2009; Wang et al., 2018).

Here, we assessed the effects of milldams on riparian groundwater hydrology upstream of two relict milldams in Pennsylvania (PA) and Delaware (DE). The Roller milldam (2.4 m tall) is located on Chiques creek, PA and drains an agricultural watershed while the Cooch milldam (4 m tall) is on Christina River, DE and drains a mixed land use watershed. Key questions we addressed were: How do milldams affect riparian groundwater hydrology and mixing regime upstream of the dam? How does the groundwater regime vary with high and low stream flows? What factors and site conditions influence the groundwater regime? Are milldam effects on riparian hydrology similar to those from beaver dams? and What are the broader implications of the altered groundwater regime for riparian water quality functions?

We hypothesized that: (a) riparian groundwater levels upstream of the dam would be close to the soil surface and riparian hydraulic gradients would be low; (b) typically, riparian groundwater flow direction would be from the uplands to the stream, but reversals could occur during peak stream flows; and (c) stream-riparian groundwater mixing would be enhanced by the backup and lateral gradients created by milldams. To test these hypotheses, stream and riparian groundwater levels and specific conductance were monitored using high-frequency, water level and specific conductance loggers installed in the stream and riparian groundwater wells. Stream and riparian groundwaters were also sampled monthly for selected cations and anions that were used as conservative tracers. The riparian groundwater mixing regime was characterized using the specific conductance and chemical tracer data.

2. Materials and Methods

2.1. Study Sites

Roller Milldam (built circa 1730) on Chiques Creek near Manheim, PA (40.1082, −76.4431) stands about 2.4 m tall and 30 m wide, extending across the local valley (Figure 1a). Forest covers 26% of the watershed, 20% is developed land, and 54% of the watershed is devoted to agriculture (Homer & Barnes, 2012). The watershed is in the Piedmont region of the USA and approximately 40% of the watershed is underlain by carbonate bedrock,

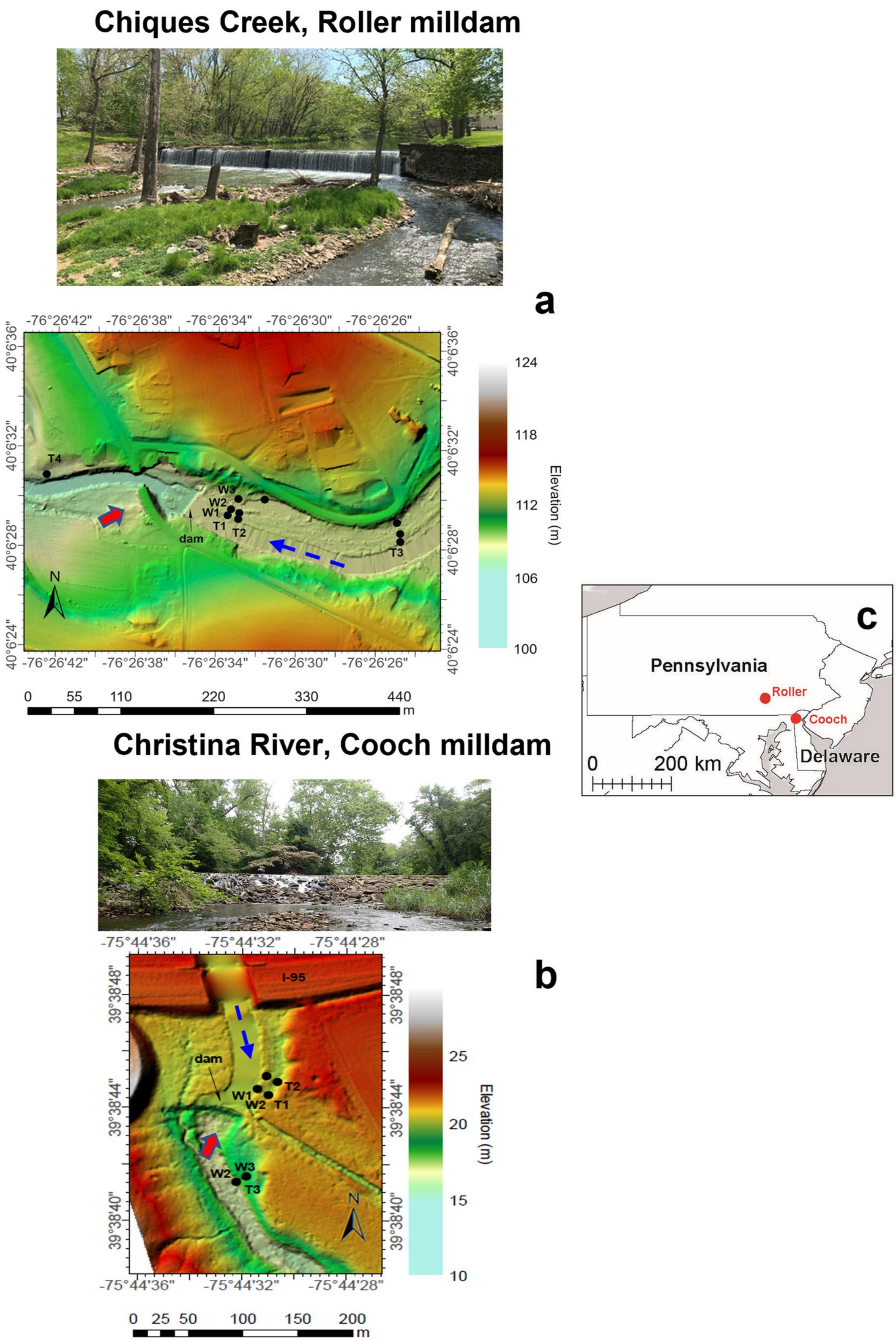

Figure 1. Photos and LIDAR DEM images of milldam sites indicating groundwater well transects upstream (T1–T3 with wells W1–W3) of the dam at (a) Roller milldam on Chiques Creek in Pennsylvania, USA; (b) Cooch milldam on Christina River, Delaware, USA; and (c) locations of the two sites in Pennsylvania and Delaware, respectively. Thick red arrows indicate the photo view directions.

and the balance consists mainly of gently folded sedimentary and lightly-metamorphosed rock types. The soils in the Chiques Creek watershed are predominantly silt loams, but the riparian soils are classified as Hagerstown silt loam (HaB) and silty clay loam (HbD) (Soil Survey, 2021). Roads and houses are located along the creek and riparian zones. Based on accessibility and permissions, three groundwater monitoring transects (T1–T3) were established upstream of the dam along the north riparian zone with three wells each (W1–W3), resulting in a total of nine upstream wells (Figure 1a and Figure S1 in Supporting Information S1). A downstream well in transect T4 was also established but remained dry for most of the year, except for occasional flood conditions. However augering these wells was difficult due to coarse sediments and presence of gravel and rocks and the wells could only be augered to about 1 m before refusal (rock or gravel layer at the bottom).

Cooch's Milldam (built circa 1792) on Christina River in Newark, DE (39.6455, −75.7423), stands about 4 m tall and 40 m wide, also spanning the width of the local valley (Figure 1b). Forest covers 30% of the watershed, 23% is pasture and cropland, and developed land covers 47% (Homer & Barnes, 2012). The Cooch's Mill area is in the Piedmont physiographic province with the primary geologic unit being Iron Hill gabbro, a deeply weathered rock rich in iron oxides (Ramsey, 2005). Soils in the Christina River watershed are predominantly silt loam with the poorly drained Hatboro-Codorus Complex (Hw) and the moderately well drained Keyport (KpB) and Mattapex (MtaB) silt loams (Soil Survey, 2021). Two groundwater well transects (T1–T2) were established upstream of the dam along the eastern riparian zone with two wells (W1–W2) each, for a total of four upstream wells (Figure 1b and Figure S2 in Supporting Information S1). Two downstream wells (W2 and W3) were also established at transect T3 but similar to Chiques, remained dry expect for flood conditions.

2.2. Riparian Terrace Topography, Sediment Thickness and Characteristics

Both dams span the local valley (Figures S1, S2, S3c, and S3d in Supporting Information S1) which results in fine-grained upstream riparian terraces that are as tall as the dam and coarse-grained floodplains downstream that are shorter. At both sites upstream riparian topography is shaped by legacy sediment deposition (James, 2013; Johnson et al., 2019; Merritts et al., 2011) with: (a) riparian terrace elevations immediately upstream of the dam higher than further upstream; (b) a sediment berm along the stream edge (Figure S3a in Supporting Information S1) because of overbank flooding and deposition; and (c) a swale in the middle of the riparian terrace parallel to the stream (Figures S1, S2, and S3b in Supporting Information S1). There is ponded water in the swale for most of year (Figure S3b in Supporting Information S1), except during the driest parts of the year in July-September (Figure S3d in Supporting Information S1). Visual observations over the study period indicated that the depth of ponded water in the swale increased during storm events and floods and the water moved longitudinally down the swale in the direction of streamflow and the dam. The ponded water in the swale originated from rainfall interception, stream overbank flows, and surface runoff from adjoining roads (Figures S1 and S2 in Supporting Information S1). At Chiques, surface runoff from Old Auction Road entered the riparian zone upstream of transect T3 along a gravel path that led to a former dock on the creek (Figure S1 in Supporting Information S1). The riparian terrace elevation was also closest to the stream level at this former dock location. At Christina, surface runoff from interstate 95 entered the eastern riparian swale via two storm pipes located upstream of transect T2 (Figure S2 in Supporting Information S1). A former raceway is also located at the Christina site immediately downstream of transect T1 (Figure S2 in Supporting Information S1). In contrast to storm conditions, during storm recession and summer dry periods, swale surface water was observed to drain in the direction opposite of stream flow dictated by the surface topography (note arrows in Figures S1 and S2 in Supporting Information S1).

Surface topography for upstream riparian terraces was characterized using LIDAR DEM whereas coordinates (easting and northing) and surface elevations for groundwater wells were determined using a real-time kinematic (RTK) GPS and a total station survey instrument. At Chiques, all W1 wells were on the sediment berm, well W3 in transect T1 was located on a riparian bench at the upland edge, while well W2 from transect T1 and wells W2 and W3 from transects T2 and T3 were in the swale depression (Figure 1 and Figure S1 in Supporting Information S1). At Christina, both W1 wells were located on the near-stream sediment berm while wells W2 were in the swale (Figure 1 and Figure S2 in Supporting Information S1).

Hand augering for groundwater wells until refusal at the Chiques site indicated that legacy sediments were thicker for the near-stream wells (W1) (∼3–4 m deep, Figure S4 in Supporting Information S1) and decreased in thickness at the swale and further upslope (∼1–1.5 m for wells W2 and W3, Figure S3 in Supporting Information S1). This transect pattern was also observed at the Christina site with near-stream sediments being thicker (∼4 m) than those in the swale (~1–1.5 m). Particle size analysis for the upstream riparian sediments using the standard hydrometer method (Ashworth et al., 2001) indicated that the sediments were predominantly silty clay to silty clay loam in texture. At Chiques, the average % sand, silt and clay contents were 16%, 48%, and 35% ($n = 24$), respectively, while at Christina the corresponding values were 11, 58, 33% ($n = 12$), respectively. The average soil bulk density across the sites was 1.12 ± 0.14 g cm^{-3}. Based on these textural values, the average saturated hydraulic conductivity based on the Jabro (1992) pedotransfer function (which has been validated for soils from southeastern Pennsylvania) was estimated to be 91 ± 16 and 86 ± 17 cm d^{-1} for the Chiques and Christina sites, respectively.

2.3. Hydrologic and Specific Conductance Monitoring

Hydrologic monitoring was initiated in November 2019 and continued until September 2021. Each groundwater well was made up of 5-cm diameter screened PVC pipes which were screened for the full length below the soil surface.Non-vented pressure transducers (U20L HOBO) were installed in all groundwater wells and in the streams to continuously record water table elevations every 30 min. Additional sensors were placed above ground at each site to record atmospheric pressure for barometric correction. Water table elevations were referenced against the soil surface elevations for the wells (Figures S1 and S2 in Supporting Information S1) and the stream so that water levels could be directly compared. Monthly depth-to-water measurements were taken manually using an electric water-level sounder (Solinst 102M) for verification. In addition to water level loggers, specific conductance sensors (HOBO U24) were mounted in both streams and all wells, taking measurements at 30-min intervals. Manual well and stream depth-to-water and specific conductance measurements were taken monthly for verifying the sensor readings.

Pump tests using the Hvorslev water recovery method (Freeze & Cherry, 1979) were performed for selected near-stream (W1) and swale (W2) wells at both sites to determine the in-situ hydraulic conductivity. Pump tests could not be completed for some of the swale wells because water filled the wells too rapidly during pumping and the wells could not be drained.

2.4. Water Chemistry and Laboratory Analyses

Monthly stream and groundwater well samples were collected starting November 2019 with sampling twice a month before Covid-19 (March 2020) and monthly thereafter. No water sampling was performed in March–April 2020 due to Covid-19 travel constraints. Water samples were collected in 250 mL polyethylene bottles and field rinsed twice with the sample before being filled (groundwater samples were recovered using low disturbance balers). Within 48 hr of collection, water samples were vacuum filtered using 0.7 μm glass fiber filters (Grade F Sterlitech) and acidified to pH 2 with concentrated hydrochloric acid. Stream and groundwater samples were analyzed by the University of Delaware Soils Laboratory for Al, B, Ca, Cu, Fe, K, Mg, Mn, Na, P, S, and Zn concentrations using inductively coupled plasma optical emission spectroscopy. Concentrations of dissolved organic carbon (DOC) were determined by the Soils Laboratory using thermal combustion on an Elementar total organic carbon/total nitrogen analyzer.

2.5. Data Analysis

High-frequency (30 min) specific conductance (μS cm^{-1}) and select elemental tracers were used to characterize the extent of mixing between stream water and riparian groundwater. Elemental tracers were selected based on simple conservative behavior (S. Inamdar et al., 2013) and included B, Ca, K, Mg, Na, and DOC. Correlation-based principal component analysis (PCA) in JMP Pro 15 was used to characterize the spatial and temporal variability of conservative solutes for stream water, riparian groundwater, and precipitation in the PCA mixing space (S. Inamdar et al., 2013). Surface runoff and ponded water collected at Chiques and Christina were also added to the multivariate analysis. Separate PCAs were conducted for data from Chiques Creek and Christina River because of the large differences in water chemistry for these watersheds. Samples that fell outside of the 95% confidence interval were excluded from the analysis.

2.6. Determination of Groundwater Hydraulic Gradient, Flow Directions and Regimes

Groundwater hydraulic gradients and flow directions were determined by comparing the georeferenced groundwater and stream water elevations. Based on these comparisons, three distinct riparian groundwater hydrologic

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Table 1
Saturated Hydraulic Conductivity (cm d^{-1}) Values for Roller/Chiques and Cooch/Christina Sites Using the Hvorslev Method

Site	T1W1	T1W2	T1W3	T2W1	T2W2	T2W3	T3W1	T3W2
Chiques (Roller)	97	468	237	108	85	–	86	76
Christina (Cooch)	–	78	na	59	262	na	na	na

Note. Dashes indicates locations where data was not available. na—not applicable.

regimes were identified: "dry," "wet," "transition," and "storm" regimes. Specifically, regimes were categorized based on the criteria described below (details in Sherman, 2022). Dry regime occurred when water level in at least one riparian well was lower than stream water level and water level in the near-stream wells (W1) was greater than the mid-riparian or swale wells (W2). Wet regime occurred when water level in all riparian wells was greater than stream water level. Storm regime occurred when water level in at least one riparian well was lower than stream water level and a spike in stream water level rather than a drop in riparian water level differentiated it from the dry regime. Storm regime included only the largest storms and overbank flooding events while small storms without overbank flooding were classified under the wet regime. Conditions that did not fall within the dry, wet, or storm regimes were classified as transition.

2.7. Selected Events for Within-Event Specific Conductance Variations

Five events of varying precipitation magnitude were selected to investigate the within-event changes in the 30-min specific conductance data to investigate the mixing of riparian groundwaters during these events. These events included: a small storm on 9 July 2021 (30 mm precipitation at Christina and 26 mm at Chiques site); a medium storm on 25 December 2020 (52 mm at Christina and 46 mm at Chiques); a large storm associated with Hurricane Ida on 9 September 2021 (111 mm at Christina and 127 mm at Chiques); a dry period in summer 2021, and a specific conductance spike at Christina River in winter 2021. Precipitation data for Christina were available from the University of Delaware Agricultural Farm Weather Station in Newark (DEOS, 2022) located 2.5 km from the Cooch milldam site. Precipitation data for the Chiques site were obtained from the Millersville University Weather Information Center (Millersville University, 2022) located about 10 km from the Roller milldam site.

3. Results

3.1. Hydraulic Conductivity of Riparian Sediments

Pump test data obtained using the Hvorslev method for selected wells (Table 1) indicated that hydraulic conductivity for riparian sediments varied between 76 and 468 cm day^{-1} at the Chiques site and between 59 and 262 cm d^{-1} for the Christina site. While the lowest hydraulic conductivities for both sites were measured for the near-stream berm wells (W1) and the highest values were recorded for the swale wells (W2), the number of measurements were not sufficient to make clear distinctions between the berm (near-stream) and swale locations. Overall, the measured values encompass the range of saturated hydraulic conductivities derived from soil textural data using the Jabro (1992) pedotransfer function mentioned earlier (91 ± 16 and 86 ± 17 cm day^{-1} for Chiques and Christina sites, respectively).

3.2. Riparian Groundwater Elevations, Flow Directions, and Gradients for the Three Hydrologic Regimes

Groundwater elevations, flow directions, and hydraulic gradients varied across the wet, dry, and storm hydrologic regimes as described below.

Wet Regime: The wet regime was dominant at both sites, comprising 75.7% of the recorded time at Chiques Creek and 60.7% at Christina River sites (Figure 2 bottom). Riparian groundwater elevations were typically higher than the stream water level for this regime (Figures 2 and 3). Other than well T1W1 at Christina, wells adjacent to the stream had lower mean water levels than wells farther from the stream along the same transect. Overall, near-stream groundwater levels (wells W1) varied less than wells further upslope (wells W2 and W3; Figure S5 in Supporting Information S1).

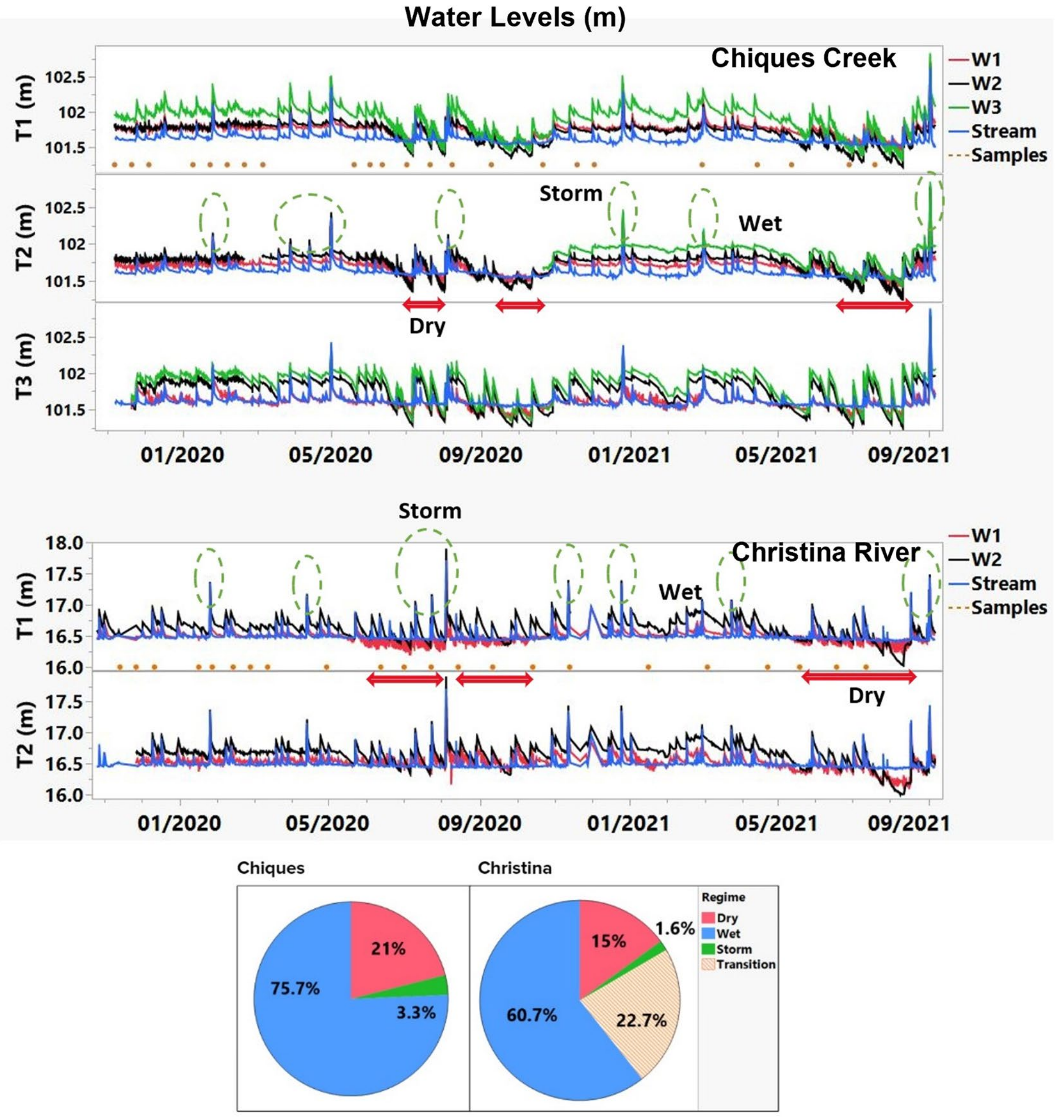

Figure 2. (top): Time series of water level elevations (*m* AMSL) for Chiques Creek (above) and Christina River (below) with the three hydrologic regimes identified: Dry regimes are denoted by red arrows, storm events (peak flows) with green dashed ovals, and the remaining data into the wet and transition regimes. Dates when water samples were taken are marked by orange dots. (bottom): Percentage of time in each hydrologic regime at Chiques (left) and Christina (right). Blue represents the wet regime, red dry, green storm, and the beige shaded area represents the transitional regime between wet and dry conditions.

Based on groundwater elevations, transverse/orthogonal flow direction (indicated by arrows in Figure 3) was primarily from the riparian zone to the stream. Longitudinal flow direction was in the direction of streamflow—downstream (Figure 3). Groundwater hydraulic gradients generally decreased moving away from the dam, both transversely within each transect and longitudinally with the transects (Figure 4 and Table 2). The well closest to the dam and the stream (T1W1) exhibited the steepest hydraulic gradients for both sites (0.048 m m^{-1} at Chiques and 0.0247 m m^{-1} at Christina, Table 2). In general, the hydraulic gradients were smaller than topographic gradients (Table 2).

Dry Regime: The dry regime composed 21% of recorded data at Chiques and 15% at Christina (indicated by red arrows in Figure 2). For Christina, about 22.7% of the time fell into a transitional regime between wet and dry conditions (Figure 2). During the dry regime (typically, non-storm conditions in June through October), some of the riparian groundwater elevations, and swale wells (W2) in particular, dropped below stream level (Figures 2 and 3). The dry conditions also revealed pronounced diurnal water table fluctuations with swale wells (W2) drying out faster than other wells across both sites (Figure S6 in Supporting Information S1).

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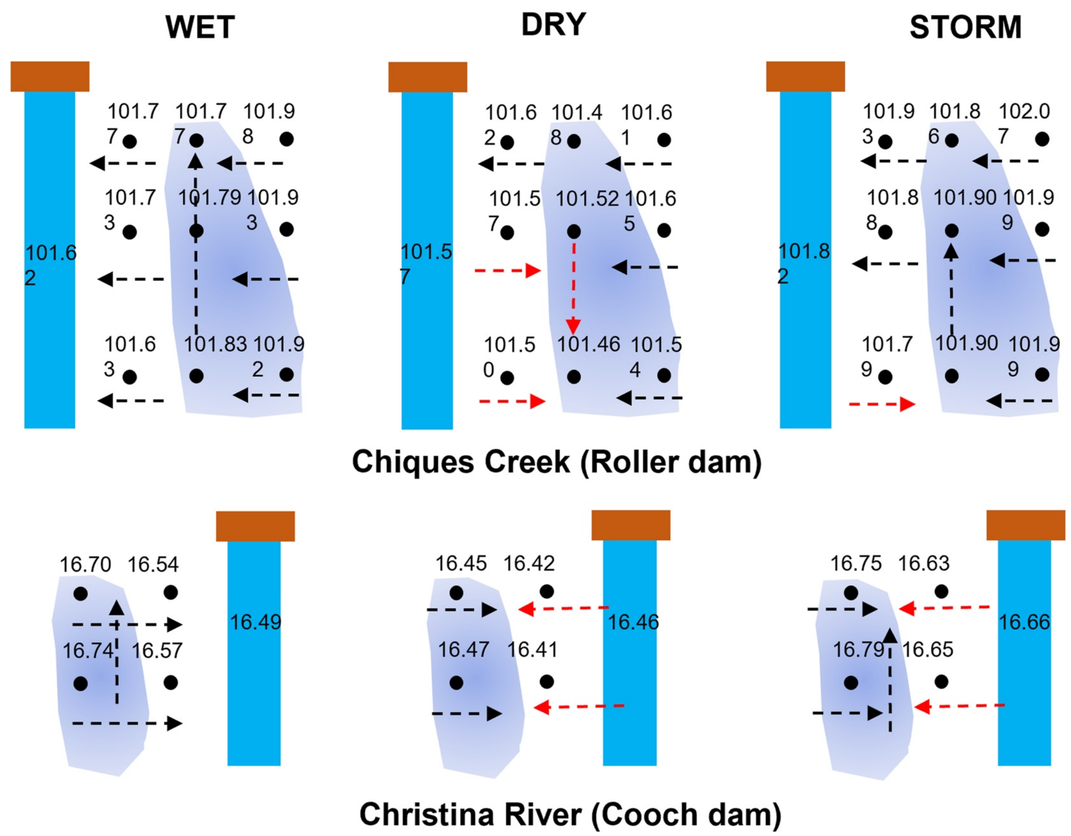

Figure 3. Plan view of groundwater elevations (m AMSL) and flow directions for wells during the three hydrologic regimes (wet, dry, and storm) at Chiques Creek (top) and Christina River (bottom) milldam sites. Elevation values are averages for the regimes. The approximate swale extent on the riparian terrace is indicated by shaded blue areas. The dams are indicated by brown rectangles and the streams are in light blue. Stream flow is toward the dam in all cases. Groundwater flow reversals are indicated by red arrows.

Low riparian groundwater elevations during the dry regime resulted in a reversal of flow directions from the stream toward the riparian zone (Figure 3). This was also reflected by the negative hydraulic gradients during this time (Figure 4 and Table 2). Stream-to-riparian hydraulic gradients were pronounced for the swale W2 positions and transect T3 at Chiques but occurred for all Christina wells (Table 2). Longitudinal groundwater gradient in the mid-riparian swale was from transect T2 to T3 at Chiques, which was a reversal of the direction from those during wet conditions (Figure 3). The reversal in the longitudinal direction at Christina was however not apparent (Figure 3).

Storm Regime: The storm regime accounted for only 3.3% of time at Chiques and 1.6% at Christina (Figure 2). Storm regime conditions occurred when stream water levels exceeded riparian groundwater levels during peak flows/floods (circled in Figure 2). These sharp increases in stream levels resulted in overbank flooding, especially for riparian locations that were lower in elevations (e.g., transect T3 at Chiques and upstream of transect T2 at Christina). Groundwater flow directions were more complex for this regime with flow toward the riparian zone in transects closer to the stream surface (e.g., T3 at Chiques) versus those higher and closer to the dam (Figure 3). Lateral hydraulic gradients were reversed during rapid rises in stream stage, illustrated by sharp but brief negative spikes in hydraulic gradient, particularly at near-stream locations (Figure 4).

Ponded water (0 to ∼30 cm) during storms was common at the swale locations (e.g., wells W2; Figure S3b in Supporting Information S1) at both sites but was rarely observed in near-stream locations (wells W1) because of the berm (Figure S3a in Supporting Information S1). Water levels rose past the soil surface less than 1% of recorded time at W1 locations for both sites while ponded water was observed 15%, 9%, and 54% of the time at Chiques T1W2, T2W2, and T3W2, respectively. This trend was also observed at Christina, where water ponded at T1W2 19% of the time and 25% of the time at T2W2.

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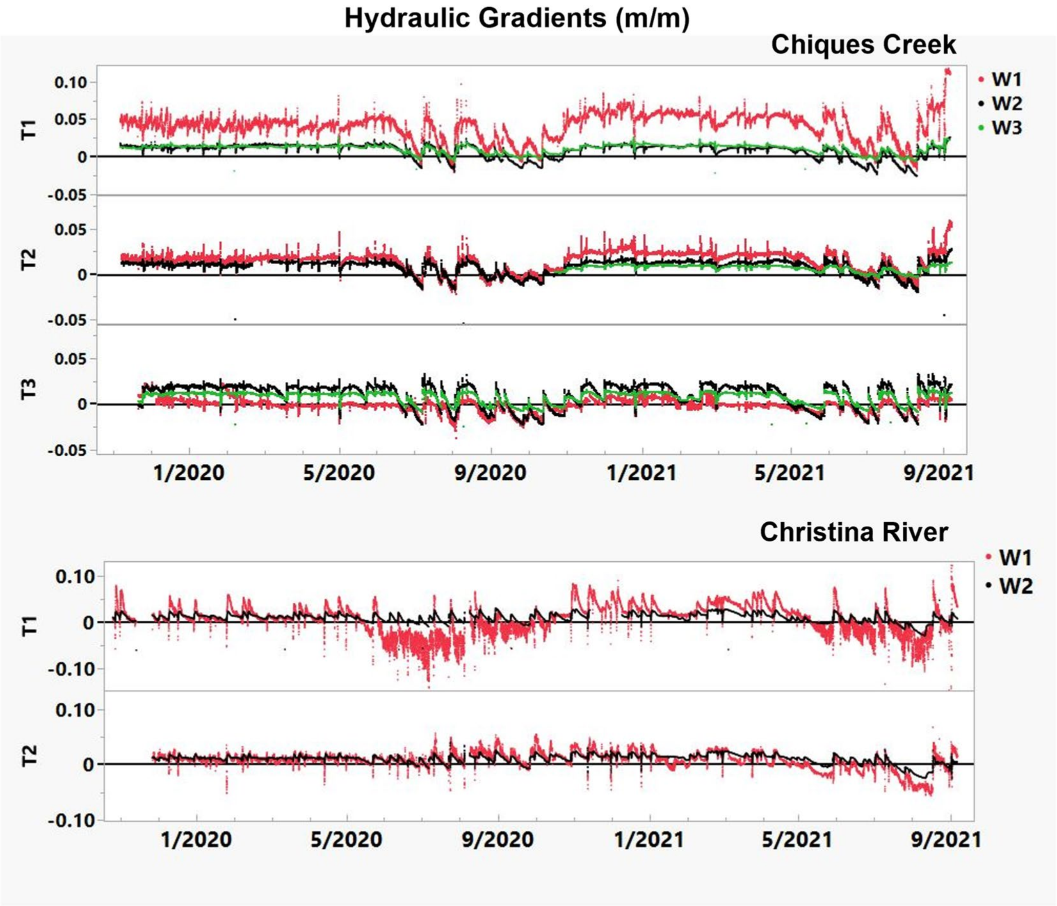

Figure 4. Full time series of hydraulic gradients at Chiques (above) and Christina (below). Positive values indicate flow from the riparian zone to the stream, while negative gradients indicate flow from the stream to the riparian zone.

3.3. Riparian Groundwater Specific Conductance

Specific conductance (μS cm^{-1}) varied significantly among the study sites, well locations and transects, and over the year (Figure 5). At Chiques, the highest specific conductance was recorded for upland edge well W3 in transect T1 while the lowest values were observed for swale wells W2 and W3 located in transect T3 (Figure 5). Transect T3 at Chiques was closest to the gravel road which routed surface runoff during storms from Old Auction Road into the riparian area. Specific conductance for T3 wells—W2 and W3 was even lower than that recorded for Chiques stream water (Figure 5). For Christina, swale wells W2 had higher specific conductance compared to near-stream W1 wells (Figure 5). Typically, across both sites, near-stream W1 wells had lower variability in specific conductance compared to the other wells (Figure 5 bottom).

Storm flow conditions typically diluted both streams and riparian groundwater specific conductance, but dilution patterns varied with individual storm events and local conditions (Figure 6). Specific conductance During the small 9 July 2020 storm, there was a dilution at Chiques well T1W3 (Figure 6a), but no notable response was observed for the other wells. Similarly, for the larger 25 December 2020 storm, T1W3 exhibited increased dilution, with little change in the W1 and W2 well conductivities (Figure 6c). During the largest storm on 1 September 2021—T1W3 displayed an initial increase in specific conductance followed by slight dilution (Figure 6e); both T1W1 and the stream were diluted; but T1W2 showed no response. This September storm was large enough to cause overbank flooding at Chiques which was evident by sediment deposition and marks on vegetation following the storm. Specific conductance at Christina well T2W1 increased slightly during the small July 9 storm and decreased for the other wells (Figure 6b). During the December 25, storm, a sharp drop in specific conductance at well T2W2 occurred with small changes at the other well locations (Figure 6d). While the September 1 storm produced a significant dilution for well T2W2, the same was not observed for the transect T1 wells at Christina (Figure 6f).

Table 2
Comparison of Topographic (From Soil Surface) and Groundwater Hydraulic Gradients ($m\ m^{-1}$) From Individual Wells to the Stream Water Surface by Hydrologic Regime (Wet, Dry, Storm, and Transition) at Chiques Creek (Above) and Christina River (Below)

Chiques Creek	Topographic	Wet	Dry	Storm
T1W1	0.1794	0.0480	0.0096	0.0357
T1W2	0.0139	0.0122	−0.0082	0.0056
T1W3	0.0288	0.0131	0.0013	0.0115
T2W1	0.1127	0.0199	0.0002	0.0147
T2W2	0.0146	0.0124	−0.0038	0.0071
T2W3	0.0037	0.0094	0.0022	0.0056
T3W1	0.0411	0.0023	−0.0098	−0.0058
T3W2	0.0122	0.0161	−0.0072	0.0017
T3W3	0.0086	0.0110	−0.0007	0.0039
Christina River		Wet	Dry	Storm
T1W1	0.4745	0.0247	−0.0279	−0.0219
T1W2	0.0168	0.0149	−0.0044	0.0055
T2W1	0.0791	0.0137	−0.0177	−0.0053
T2W2	0.0122	0.0140	−0.0047	0.0059

Note. Gradient values are averaged over the regime periods.

Values and changes in specific conductance for Christina River site were particularly notable during winter storms in 2021 (Figure S7 in Supporting Information S1). Occurring during or soon after precipitation events, specific conductance spikes were observed for stream water, followed by wells T2W2 and T1W2 (Figure S7 in Supporting Information S1). However, groundwater specific conductance spikes were much greater than those for stream water and with peak values as high as 20,982 $\mu S\ cm^{-1}$ for well T2W2 (Figure S7 in Supporting Information S1). Well T2W2 was the swale well closest and immediately downstream of storm drains that discharged road runoff from interstate 95 into the riparian area (see Figure S2 in Supporting Information S1 for storm drains). These specific conductance spikes followed a cold winter period that required deicing road salt applications for interstate 95.

3.4. Riparian Groundwater Mixing Regime From Conservative Solutes

PCA for selected solutes for the two sites further illustrates the mixing patterns for riparian groundwaters and the chemical similarity or differences with stream water (Figure 7). The first two principal components at Chiques accounted for 71.8% of total variability while at Christina they accounted for 76.4% of total variability (Figure 7). Ca, Mg and Na were the key solutes determining the distribution of sites along component 1 (x axis) while DOC (as indicated by the eigen vectors) dictated the distribution for component 2 (y axis). For both sites, the low solute end-members (precipitation and surface runoff) were positioned in the left quadrants while riparian groundwaters were generally in the right quadrants. Stream water was located in the lower left quadrant, but closer to the axis origins. Among the groundwater values, there were important differences. Wells W1 were chemically similar to the stream water but were shifted to the right. In comparison, W2 wells that were diluted by road runoff (e.g., swale wells for transect T3 at Chiques) were shifted to the left and top in the PCA space. On the other hand, the upland-edge well T1W3 at Chiques was shifted furthest to the right in the PCA space indicating a chemistry very different from the other wells.

4. Discussion

This study provided important insights into riparian hydrology and groundwater mixing regimes upstream of the milldams. High-frequency water level data supported our hypotheses that riparian groundwater elevations were close to the soil surface; hydraulic gradients from the riparian zone to the stream were low; and gradient rever-

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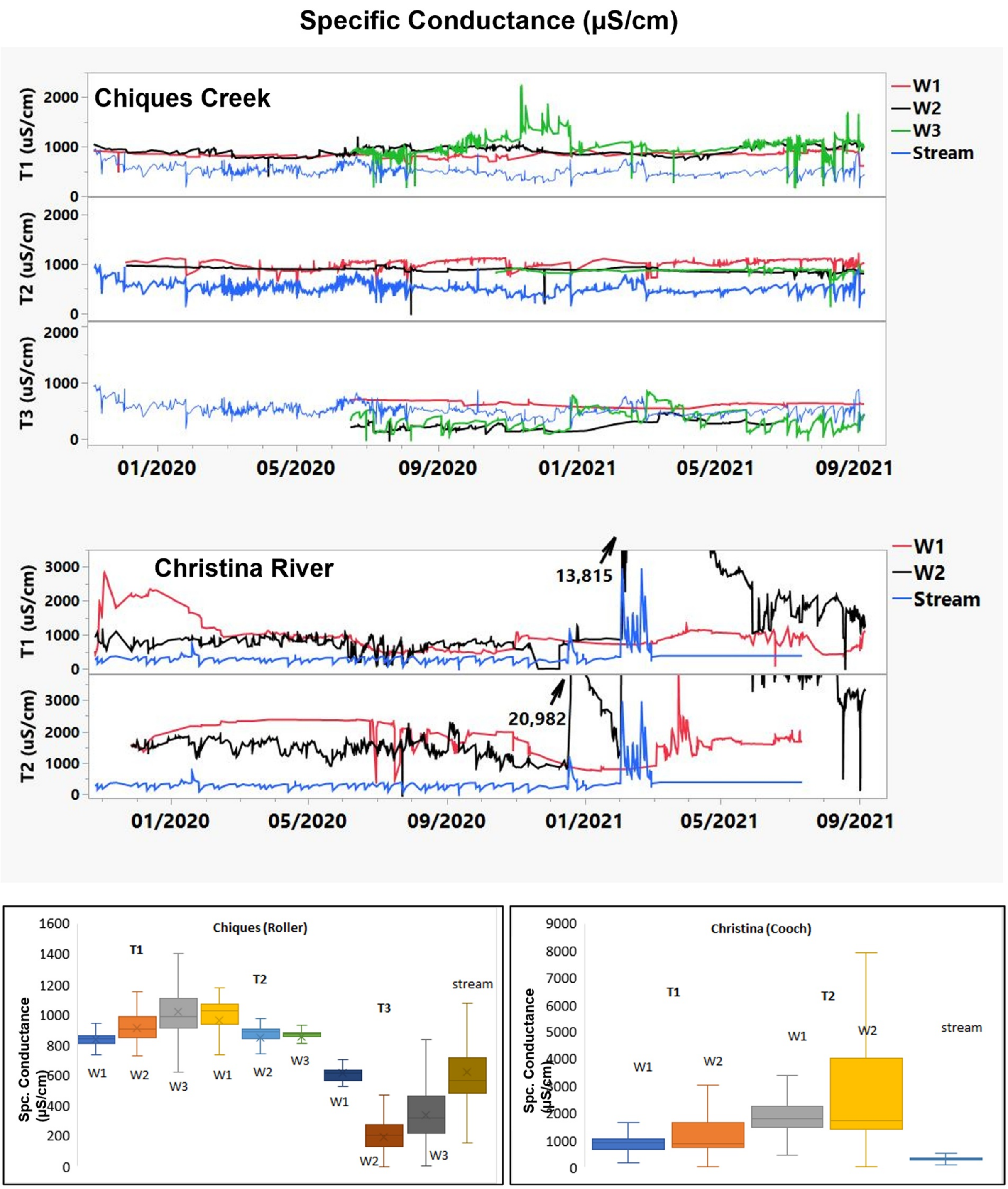

Figure 5. (top) Full time series of riparian groundwater specific conductance (μS cm^{-1}) at Chiques (above) and Christina (below). Large specific conductance spikes at Christina were truncated to show long-term variation at the site. (bottom) Box plots of specific conductance (μS cm^{-1}) by location at Chiques (left) and Christina (right) separated by transect.

sals (from stream to riparian) occurred during summer high evapotranspiration periods and for peak stormflow conditions. On the other hand, specific conductance data along with PCA of selected tracers revealed a complex pattern in riparian groundwater and stream water mixing that differed across storm event and seasonal scales. This mixing pattern did not support our original hypothesis that dams would universally enhance groundwater mixing in upstream riparian zones. Near-stream riparian groundwaters (W1 wells) were similar to the stream

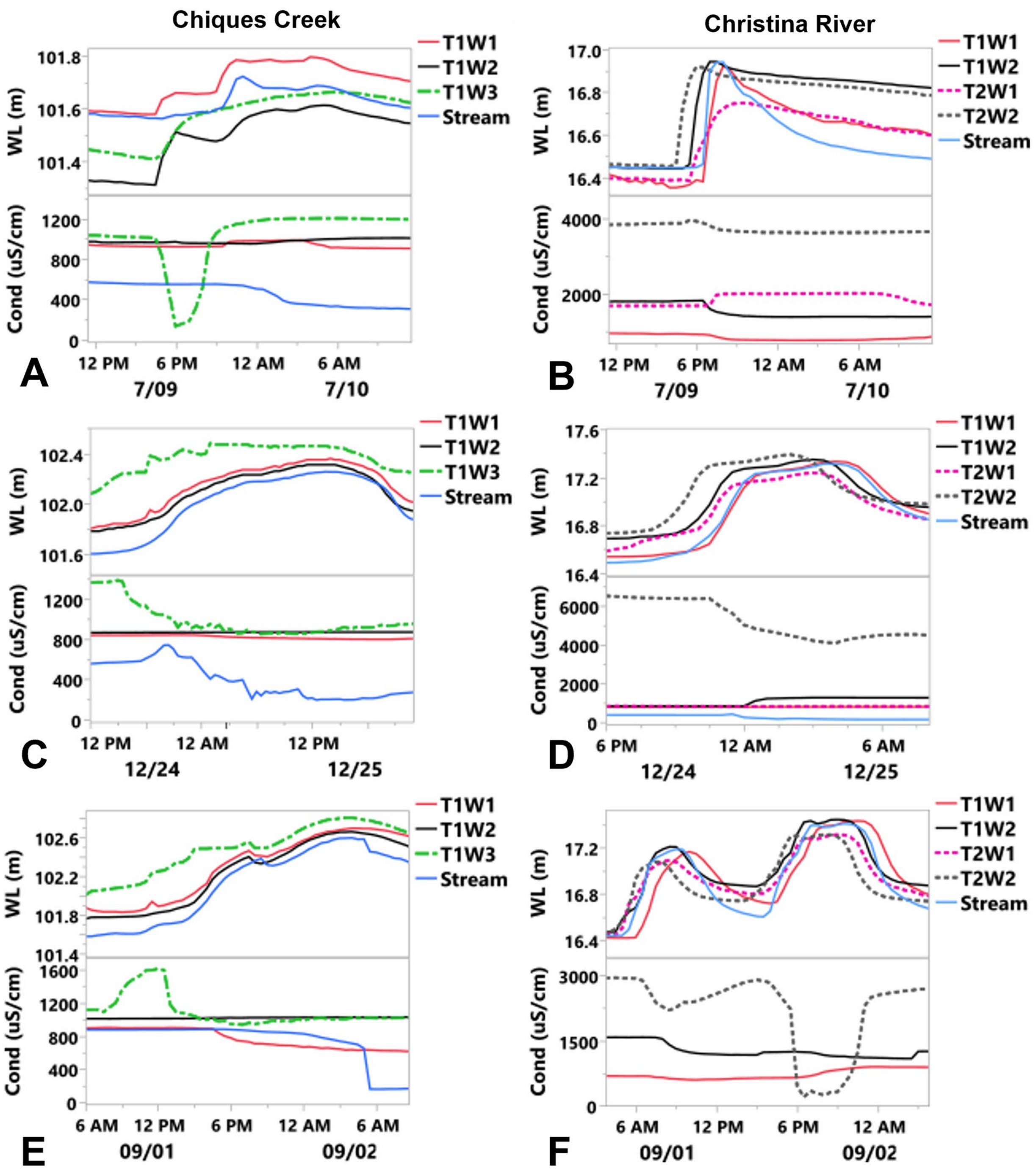

Figure 6. Riparian groundwater levels (*m*) and specific conductance plots (μS cm^{-1}) for individual events highlighting the changes in specific conductance across the well locations for Chiques Creek (left panel: a, c, and e) and Christina River (right panel: b, d, and f). Near stream wells (W1) displayed minimal variations in specific conductance.

water chemistry at seasonal scales but did not display the large chemical variations during storms that occurred in the streams. On the other hand, swale groundwater chemistry showed greater chemical variations during storm events. We attribute these responses to site conditions and legacies associated with milldams that include: (a) transverse and longitudinal variation in riparian surface (berm and swale) topography; (b) thickness, texture and conductivity of the riparian sediment profile; (c) influence of riparian vegetation on the hydrologic budget; and (d) hydrologic effects of anthropogenic artifacts such as roads and other impervious surfaces in vicinity of

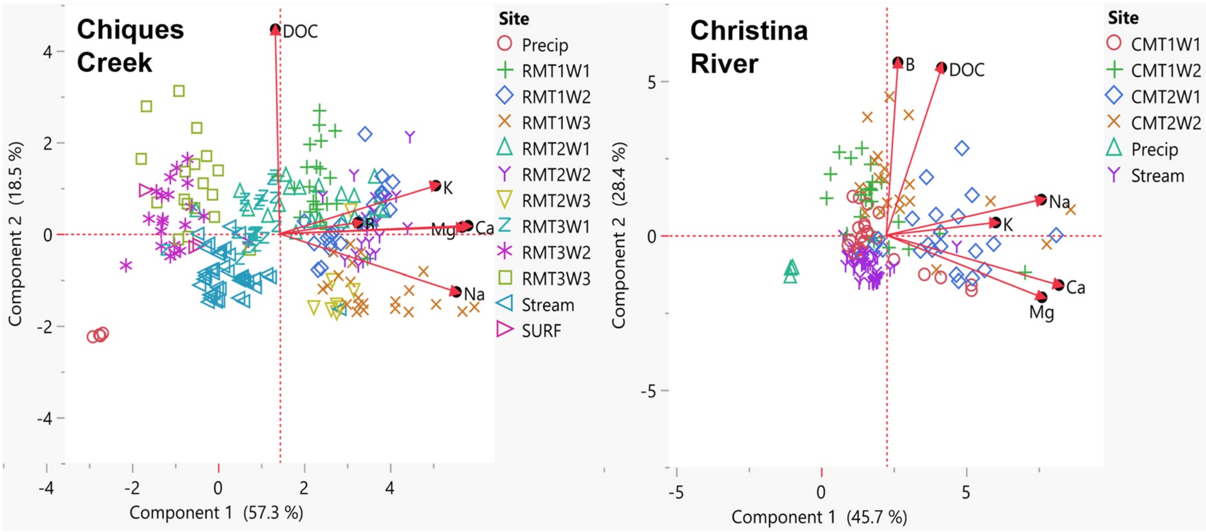

Figure 7. Principal component analysis biplot (loading plot superimposed onto score plot) of conservative tracers (B, Ca, K, Mg, Na, and DNPOC) at Chiques Creek (left) and Christina River (right).

the dams. Our results also highlight interesting similarities and differences between hydrologic responses from beaver and milldams, all of which are elaborated further below.

4.1. Effects of Milldams and Their Legacies on Riparian Groundwater Hydrology

Similar to observations made for beaver dams (Hill & Duval, 2009; Janzen & Westbrook, 2011; Larsen et al., 2021; Lautz et al., 2006; Wang et al., 2018) riparian groundwater levels were close to the soil surface upstream of the dam and are attributed to the backup and rise of stream water levels upstream of the dam. However, this study also showed that riparian groundwater elevations, gradients, and flow directions varied in space and time. These differences and their driving factors are highlighted through a conceptual model presented in Figure 8. During the wet regime, which occurred for most of the year, transverse hydraulic gradients and flows were from the riparian terrace toward the stream while groundwater in the mid-riparian swale flowed down-valley (Figure 3). This pattern was essentially determined by the surface and groundwater inputs and local topography of the riparian zone. During wet periods of the year, runoff inputs into the riparian areas occurred from the upland aquifer as well as storm runoff from adjacent roads (Old Auction road at Chiques and I-95 at Christina River, Figures S1 and S2 in Supporting Information S1) and other adjacent impervious surfaces. At the Chiques site, upland subsurface flows occurred in the vicinity of well T1W3 (indicated by a coupled water level rise and rise in specific conductance) whereas dilute storm runoff was funneled along the gravel road and into the swale at transect T3 (indicated by the sharp increases in water levels for W2 and W3 at this transect coupled with low specific conductance values, Figures 2 and 5). These surface runoff inputs are likely responsible for the downstream gradient recorded in the swale during the wet conditions.

We note that both milldam sites were located in the Piedmont region (Cooch dam on Christina River was at the transition between Piedmont and Coastal plain region in Delaware) where the rolling terrain results in substantial elevational differences between the uplands and the stream (despite the increased legacy sediment infilling of the river valley upstream of the dam). We speculate that the temporal dominance of the wet regime (and riparian to stream gradients) at the annual time scale for our sites was likely a result of the steeper terrain coupled with the increased runoff from roads and other impervious surfaces in the immediate vicinity. However, despite the rolling landscape, both milldams were indeed effective in modulating the hydraulic gradients, with hydraulic gradients during the wet regime being lower than the measured topographic gradients (Table 2). Where the terrain is flatter (e.g., in the Coastal Plain) and the adjoining upland/riparian areas are free of impervious/anthropogenic surfaces (e.g., in rural settings), we would expect more subdued and/or variable riparian to stream hydraulic gradients (e.g., Hill & Duval, 2009). Lautz et al. (2006) also suggest that higher riparian water tables in relation to stream stage could limit the lateral hyporheic exchange with the riparian soils.

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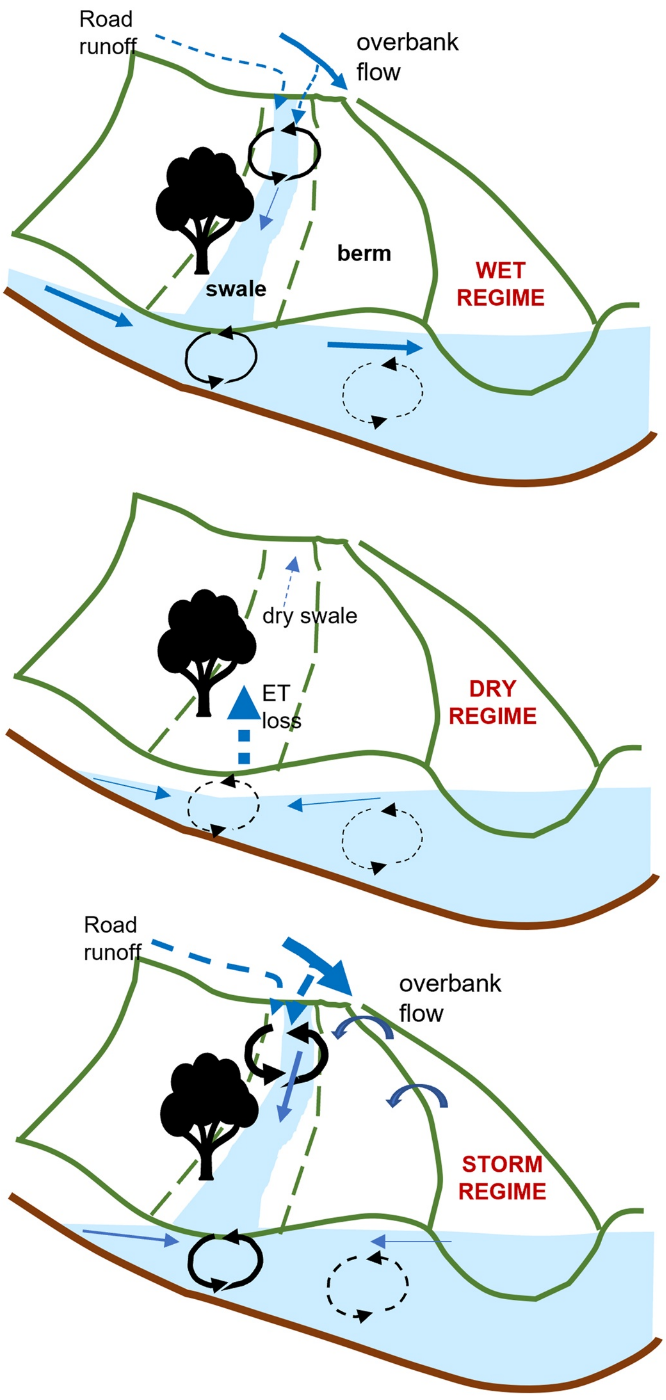

Potential factors and site conditions controlling hydrologic regime and groundwater mixing:

- Swale-berm surface topography (elevations transverse and parallel to stream)
- Riparian sediment depth (water storage) and hydraulic conductivity
- Stream overbank flows and surface runoff from roads
- Evapotranspiration losses from riparian vegetation

WET REGIME:

- Inputs from upland groundwater, road surface runoff and occasional overbank flow
- Groundwater levels are high and swale is wet
- Transverse groundwater flow is from riparian zone to stream.
- Swale flow downstream
- Groundwater mixing in swale is high and lower at the berm

DRY REGIME:

- Reduced water inputs
- Groundwater levels are lower and swale is dry
- Transverse flow is towards the swale from the stream
- Evapotranspiration losses are high
- Swale is draining upstream
- Groundwater mixing is low

STORM REGIME (Peak floods):

- Large inputs from stream overbank flows
- Groundwater levels are high and stream water levels are at peak
- Swale is flooded by road runoff and overbank flows
- Groundwater gradient is towards swale
- Swale flow is downstream
- Groundwater mixing in the swale is at its maximum

Figure 8. Conceptual model depicting the groundwater flow paths and directions and mixing potential for the three riparian hydrologic regimes: wet, dry, and storm. The groundwater table is shaded blue. Blue arrows depict groundwater flow, and the thickness of the arrows indicates the magnitude. The black circular arrows indicate the mixing potential, and the thickness indicates the strength of mixing or flushing.

While the wet regime and riparian-to-stream gradients were dominant, we did observe reversals in riparian groundwater flow (stream to riparian, Figures 2 and 3) for brief periods over the summer. Hydraulic gradients, which were already low due to the backup of impounded stream water, were flipped in the mid-riparian swale during the dry regime (conceptual model in Figure 8). The water table at all sites was lowered, but more so at the mid-riparian swale (corresponding to wells W2), allowing it to drop below stream water levels and reversing lateral hydraulic gradients (negative in Table 2). Furthermore, the longitudinal hydraulic gradient which was down-valley during the wet regime (Figure 3) was also reversed with drainage up-valley and following the topographic gradient (Figure 3).

Reversals of riparian-stream groundwater gradients have been reported in previous studies (dammed and undammed) and attributed to depression of riparian water tables because of high evapotranspiration losses from riparian vegetation (Duval & Hill, 2007; Hill & Duval, 2009; Kellogg et al., 2008). High evapotranspiration rates in the summer and early autumn similarly produced a stream-to-riparian hydraulic gradient in a beaver dam study located in the glaciated region of Ontario, Canada (Duval & Hill, 2007; Hill & Duval, 2009). Following these studies, we attribute the summer reversals on riparian groundwater to uptake and evapotranspiration by riparian vegetation in addition to the decreased inputs of precipitation and associated surface and road runoff. Vegetation evapotranspiration loss was also supported by the strong diurnal variations in groundwater elevations that we observed during the growing season at our sites, particularly in the swale wells (Figure S6 in Supporting Information S1). There was no ponded water in the swales during the summer periods and the soil surface was exposed and dry (Figure S3d in Supporting Information S1). It is very likely that due to the artificially raised stream water level upstream of mill dams and the riparian swale microtopography, gradient reversals at our dammed sites lasted longer than could occur in undammed locations and steeper valleys.

While our storm regime contrasted the dry regime in terms of soil wetness, it produced a similar hydrologic response—stream-to-riparian flows and gradients. The storm regime occurred during peak flows/floods when stream water levels rose sharply and resulted in overbank flooding along the riparian terrace. Lateral gradient reversals were more common for near-stream wells and wells located upstream and closer to the stream surface (e.g., transect T3 at Chiques and T2 at Christina where the berm wasn't as pronounced). It is also very likely that low hydraulic conductivity of the riparian sediments damped infiltration and contributed to the lagged response in riparian groundwaters to the flood event. The low sediment hydraulic conductivity coupled with the presence of the swale allowed for the floodwaters to be funneled downstream along the swale.

Some beaver dam studies have shown that the lateral stream to riparian flows and gradients could be significant enough to produce a looping pattern where stream water enters the riparian soils upstream of the dam, travels through the subsurface riparian profile around the dam, and then exists downstream of the dam (Hill & Duval, 2009; Janzen & Westbrook, 2011; Larsen et al., 2021; Wang et al., 2018). Janzen and Westbrook (2011) and Wang et al. (2018) reported this looping phenomenon for peatland soils while Hill and Duval (2009) observed this for glaciated terrain with permeable sand and gravel layers. We however, did not observe such a looping behavior at our riparian sites. Possible reasons, among others, could include: (a) unlike the river-spanning pervious beaver dams (made of wood and organic debris), our milldams were more impervious (made of rocks and gravel and in mid 1900s reinforced with concrete) and spanned the whole river valley and blocked any downstream flow through the riparian terrace; (b) contrary to the more permeable peatland and sand/gravel sediments at beaver dam sites, riparian sediments at our sites were fine-grained with low hydraulic conductivity that precluded significant and sustained flow through the sediments; and (c) the upland to riparian hydraulic gradient at our sites was large enough to overcome the gradient needed for the subsurface looping pattern to occur. However, it is possible that similar looping patterns may occur for milldams that are located in flatter terrain, are limited to the river width, and possess permeable riparian sediments or lenses of sand and gravel (e.g., in sandier terrain in the Coastal Plain). Valley-spanning milldams are also much taller and permanent than beaver dams and may have a greater long-term influence on the amount and nature of riparian sedimentation. Thus, valley-spanning milldams may have a different riparian groundwater and surface hydrologic regime compared to the more transient and river-spanning beaver dams.

4.2. Milldam Effects on Riparian Groundwater Mixing

Specific conductance and chemical tracers revealed contrasting event and seasonal scale mixing patterns for riparian groundwaters. While near-stream riparian groundwaters (wells W1) were similar to stream waters on a seasonal scale (PCA, Figure 7), the specific conductance patterns for these wells were muted and did not reveal stream water and/or precipitation influence (dilution) during storm events. In contrast, swale wells, which were located further away from the stream edge indicated greater mixing and expression of event waters (precipitation and surface runoff). We also found that near-stream (W1) wells displayed lower variability in groundwater elevations (Figure S5 in Supporting Information S1) and specific conductance (Figure 5) compared to the other wells. This clearly suggests that groundwaters at the berm/near-stream locations are not very dynamic and are not mixing or getting flushed at the short event time scales. We attribute this behavior to the sediment thickness, hydraulic conductivity of the sediments, and the runoff routing of stream and event waters through the riparian swale. We speculate that the low hydraulic conductivity of riparian sediments (~50–100 cm day^{-1}) does not allow for quick transport and mixing of event waters at the time scales of minutes to hours and that any mixing, if it occurs, is further damped by the large storage of pre-event waters in the legacy sediment depths of ~3–4 m. In comparison, the sediment depths and thus the water storage at the swale wells is lower (1–1.5 m) and event waters are rapidly transferred to these locations as surface runoff via the swale (particularly at transects T2 and T3). The surface input of event waters and lower storage facilitates greater mixing of groundwaters at the swale locations.

Although the near-stream wells were unresponsive to event-scale specific conductance variations, we do not propose that the near-stream groundwater was hydrologically disconnected. On the contrary, the groundwater levels in the near-stream wells responded quickly and in tandem to variations in stream water levels (Figure 2). A similar behavior was also reported by Vidon (2012) for undammed riparian zones. Vidon (2012) attributed this response to a pressure wave phenomenon where the pressure associated with incoming event inflow displaces the pre-event water into the wells rapidly and without actual particle-to-particle mixing and transport of the waters. We hypothesize that a similar phenomenon is happening at our stream and near-stream regions upstream of the dam. Stream waters do affect the near-stream groundwater regime, but the mixing does not happen at the short time scale of the storm event, but rather at the longer seasonal scale as indicated by the PCA mixing diagrams.

These observations and interpretations suggest that sediment depth and hydraulic conductivity in riparian zones upstream of the dam represents an important first-order control on riparian groundwater response and mixing. While our current sediment textural (% sand, silt and clay) data associated with the wells was not of a resolution high enough to characterize the spatial variability, we speculate that there may be distinct variations in riparian sediment texture and hydraulic conductivity in the transverse, longitudinal, and vertical directions with distance upstream of the dam. Previous studies have reported distinct patterns in upstream sediment deposition in dam reservoirs with finer fractions closer to the dam and coarser fractions further away (Snyder et al., 2004). A similar stratification occurs with depth/vertically with coarsening of sediments toward the surface as the dam fills up (Snyder et al., 2004). If such sediment stratification occurs in riparian terraces, it could further accentuate poor flushing or non-mixing of groundwaters above the dam. In such situations, we would expect pockets of poorly flushed groundwaters close to the dam (transversally and longitudinally), with increased mixing and flushing further away from the dam.

4.3. Caveats and Future Research

While this study generated promising new information on milldam effects on riparian hydrology, we recognize that there are limitations to the study. Ideally, riparian zones on both sides of the stream should be instrumented and investigated. However, because of accessibility, permissions, and safety considerations we could monitor only one side of the riparian terrace at each milldam site. The southern terrace at Chiques was occupied by houses while the western terrace at Christina required crossing the Christina River and was infested with posion ivy (safety considerations precluded this option). Our study sites also revealed high contents of silt and clay in riparian sediments and spatial (transverse, longitudinal and vertical) variability could not be characterized because of limited augering/well sites. A more detailed spatial characterization of the texture and hydraulic conductivity of the sediments would allow for a better characterization of the groundwater flow regime. In addition, given the 200+ year history of milldams in the eastern US, riparian areas at many of the milldam sites have been subject to considerable disturbance and alterations– relict raceways, mill houses, and/or other structures. Unlike the conditions of beaver dams in natural landscapes, these relict anthropogenic legacies could also influence the hydraulic conductivity and groundwater flow patterns in milldam-associated riparian areas. Both of our study sites had valley-spanning dams and were located in the Piedmont region of USA with substantial topographic gradient between the upland and the stream. For more generalizable assessment of milldam effects on hydrology of riparian terraces, we should include sites where the dam is constrained to the channel (e.g., run-of-the-river dams) and the terrain has lower topographic relief.

Addition of piezometers could also help better characterize how milldams affect the vertical hydraulic gradients in riparian terraces (we did install a few piezometers but rigorous monitoring was limited by Covid19-related constraints). While we did install a few groundwater wells downstream of the dam in the lower coarser-grained floodplains, these wells remained dry for most of the time and did not provide meaningful information to characterize the downstream hydrologic effects of the dam. We speculate that similar to "rain shadow" effects of mountains, valley-spanning dams and their legacies (e.g., raceways) likely create a "dam shadow" effect downstream of the dam that influences groundwater flow paths and results in dry groundwater wells downstream of the dam. Additional studies should investigate this hypothesis.

4.4. Broader Environmental Implications

Raised groundwater levels, low hydraulic gradients and their reversals, differential mixing, and stagnation of groundwaters in the riparian zone due to milldams could amplify ("hot spots and hot moments") or dampen ("cold spots and cold moments") biogeochemical interactions and processing of nutrients and solutes in the riparian zones (Dwivedi et al., 2018; Gu et al., 2012; S. Inamdar et al., 2021; Vidon et al., 2010). In addition to directly influencing hydrologic flowpaths and residence times, sediment texture could also modulate redox conditions (Briggs et al., 2013; Shuai et al., 2017; Wallace & Soltanian, 2021a; Wallace et al., 2020). Although stream water infiltration into riparian hyporheic zones during peak flows can substantially increase redox potential, underlying sediment texture also significantly controls aquifer redox conditions, where high conductivity sediments can sustain areas of high redox potential for longer periods of time after a storm event than low conductivity sediments (Wallace & Soltanian, 2021b). Hydraulic conductivity at our sites was on the lower side and could have significant influence on the riparian redox regime and associated processes. Initial observations from our sites do indeed reveal hypoxic (<2 mg L^{-1} of dissolved oxygen; close to zero in many wells) conditions in riparian soils upstream of milldams and that groundwater hydrology was likely an important regulator (S. P. Inamdar et al., 2022).

Hill and Duval (2009) suggested that upland to stream groundwater gradients facilitated the entry of nitrate-rich upland groundwaters into the riparian zone and thus potentially enhanced denitrification loss of nitrate-N. On the other hand, reversals of groundwater flows from the stream into the riparian hyporheic zone have been shown to increase ammonium-N in soil pore waters (Covatti & Grischek, 2021; Hill & Duval, 2009). Elsewhere, reduced mixing potential, stagnation of groundwaters, and consequent low redox conditions have been shown to enhance ammonium-N production in soils through processes such as dissimilatory nitrate reduction to ammonium (DNRA; Pandey et al., 2020; Reverey et al., 2018). DNRA competes with denitrification under extremely reducing conditions (Pandey et al., 2020). Indeed, low dissolved oxygen coupled with elevated ammonium-N concentrations (as high as 30 mg N L^{-1}) have been observed in near-stream (W1) groundwater wells at our milldam sites and poor flushing or hydrologic stagnation is being investigated as an important hydrologic control (S. P. Inamdar et al., 2022). These observations clearly suggest that understanding how milldams alter riparian hydrology is critical to understanding their roles in influencing riparian nutrient source-sink behavior. If milldams increase nitrogen (i.e., ammonium-N) retention in riparian zones they could be undercutting valuable nutrient-removal ecosystem services (e.g., denitrification removal of nitrate-N) provided by riparian zones, which could be an important argument for their removal.

5. Conclusions

This study provided important first insights into how milldams alter upstream riparian zone hydrology. Beyond raising groundwater levels in riparian zones upstream of the dam, this study revealed that: (a) riparian to stream groundwater hydraulic gradients were low and could reverse during periods of high evapotranspiration losses and peak flows; (b) groundwater mixing potential varied significantly in space and time in the riparian zone with zones of minimal mixing in thick, low hydraulic conductivity, near-stream sediments; (c) milldam legacies including riparian microtopography (berm and swale) and sediment depths and texture were important determinants of riparian groundwater conditions; and (d) milldam effects on riparian hydrology were different from the observations reported for naturally-occurring, more pervious, beaver dams.

Observations from this study suggest that milldams could create zones or pockets of poor mixing or hydrologic flushing in riparian zones. Such pockets of poor hydrologic flushing could encourage persistent reducing conditions that could be detrimental to nutrient-removal ecosystem services (such as denitrification) provided by riparian zones. Thus, milldam alteration of riparian hydrology could have important consequences for watershed management and decisions on dam removals. This study also underscores how anthropogenic activities and their legacies alter the critical zone. Understanding these effects and alterations is a valuable opportunity for advancing critical zone science, evaluating new paradigms, and developing better solutions to manage our ecosystems.

Data Availability Statement

All water and chemistry data used in this manuscript is posted on Hydroshare and available via the link: http://www.hydroshare.org/resource/9d8690a7131c48c2a2f1488a2657dc7d.

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