Empirical evidence of dynamic hydrogeomorphic feature inundation in a lowland floodplain

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Abstract

Floodplains along low-gradient, meandering river systems contain diverse hydrogeomorphic features, ranging from isolated depressions to hydrologically-connected channels. These ephemerally-flooded features inundate prior to river water overtopping all banks, enhancing river-floodplain connectivity during moderately high flow stages. Predicting when and where ecological functions occur in floodplains requires understanding the dynamic hydrologic processes of hydrogeomorphic features, including inundation and exchange. In this study, we examined storm event-scale inundation and exchange dynamics along a lowland, meandering river system in central Illinois (USA). We monitored surface water presence/absence, surface water level, and groundwater level across floodplain hydrogeomorphic feature types (i.e., isolated depression, backwater channel, and flow-through channel). Using these data, we evaluated inundation onset and recession characteristics, drivers of groundwater-surface water interactions, and direction of hydrologic exchange with the river channel. Surface water presence/absence patterns suggested inundation onset timescales were primarily controlled by microtopography and recession timescales were correlated with floodplain elevation. Employing a novel hysteresis approach for characterizing groundwater-surface water interactions, we observed distinct patterns indicating differences in water sources across hydrogeomorphic units and event characteristics. Finally, differences in hydraulic head along floodplain channels revealed that channels with multiple inlets/outlets (i.e., flow-through channels) conveyed down-valley flow and channels with single inlets primarily functioned as sinks of river-derived water to the floodplain with short source periods. These results highlight the heterogeneity of hydrologic processes that occur along lowland, meandering river-floodplains, and more specifically, point to the important role hydrogeomorphic features play in controlling dynamic connectivity within the river corridor.

Key words: River corridor exchange, floodplain inundation, perirheic zone, groundwater-surface water interactions, intermittent, ephemeral

1. INTRODUCTION

Far from pipes that passively convey water and solutes downstream (Bencala, 1993; del Giorgio & Pace, 2008), rivers are complex systems in which spatial and temporal variations in channel characteristics (e.g., topographic features, land surface gradients, variable hydraulic conductivity) and dynamic forcing (e.g., discharge, lateral and longitudinal hydraulic gradients, groundwater inflows and outflows) interact to yield complex 3-dimensional and time-variable connectivity (Findlay, 1995; Malard, Tockner, Dole-Olivier, & Ward, 2002; Wohl, 2017). The resulting material and energy exchanges between rivers and off-channel surface and subsurface waters define the river corridor (National Research Council, 2002; Harvey & Gooseff, 2015), a concept which expands the frame of reference of river systems beyond their banks, underscoring the influence of rivers on surrounding environments as well as the influence of adjacent landscapes on downstream waters.

Floodplains are recognized as key components of river corridors (Amoros & Bornette, 2002; Wohl, 2021), with river-floodplain connectivity (i.e., exchange of water and materials between river channel and adjacent floodplain) an important factor regulating downstream water quality and sustaining river-floodplain ecosystems (Larsen, Harvey, & Maglio, 2015; Poole, 2010; Tockner, Lorang, & Stanford, 2010). Like river channels, floodplains themselves exhibit variation in form and dynamics (Hughes, 1980), where their hydrologic functioning (i.e., water storage, flow pathways, and residence times) is the result of interactions between regional hydrometeorological forcings (e.g., the timing, duration, and magnitude of precipitation; Hirschboeck, 1988), watershed position (e.g., stream order; Scott, Gomez-Velez, Jones, & Harvey, 2019), and local hydrogeomorphic features (e.g., ridges, sloughs, and secondary channels; Hupp, 2000). Just as there are numerous physical processes that govern the pathways and transport times of precipitation through hillslopes to streams, floodwaters are subject to a host of processes that influence transport and fate during floodplain inundation and flood recession. Although floodplains are recognized as ecologically important interfaces between the terrestrial and aquatic environments (Gordon, Dorothy, & Lenhart, 2020; Opperman, Luster, McKenney, Roberts, & Meadows, 2010; Tockner & Stanford, 2002), we have limited understanding of hydrological processes occurring at floodplain reach-scales. Consequently, we have a limited ability to predict when and where important ecological functions occur. Thus, the objective of this study is to characterize the spatial and temporal variability of inundation dynamics across hydrogeomorphic features and between storm events in a low-gradient floodplain system.

At the reach-scale, floodplains have historically been conceptualized as flat, featureless expanses which exist in a binary state of either dry or flooded above some threshold river stage (Rhoads, 2020; Riley, 1972; Williams, 1978; Wolman & Leopold, 1957). More recently, the availability of high-resolution remotely sensed topographic data has led to a recognition that contrary to our oversimplified historical depiction, a diversity of hydrogeomorphic features span low-gradient floodplains (Czuba, David, Edmonds, & Ward, 2019; David, Edmonds, & Letsinger, 2017; Dunne & Aalto, 2013; Jones, Poole, O'Daniel, Mertes, & Stanford, 2008; Lewin & Ashworth, 2014; Trigg, Bates, Wilson, Schumann, & Baugh, 2012). Here, we define floodplain hydrogeomorphic features as distinct topographic elements such as swales, point bars, scroll bars, and sloughs that generally occur in episodically inundated topographic lows. These features occur along a gradient of hydrologic connectivity, ranging from closed depressions to morphologically connected linear elements (Lewin & Ashworth, 2014). At one end of this continuum are depressional wetlands, which provide ecosystems services largely dependent on their relative lack of connectivity to permanent water bodies (Cohen et al., 2016), including the provision of breeding habitats to support local biodiversity (Colburn, Weeks, & Reed, 2008; Semlitsch & Skelly, 2008) and water quality benefits as effective biogeochemical reactors (Marton et al., 2015). Although depressional wetlands lack permanent surface water connections, these variably inundated wetlands are by no means hydrologically or biogeochemically disconnected from nearby waters (Cohen et al., 2016). In addition to forming episodic surface connections with other hydrogeomorphic features and the river channel during some flood events (Leibowitz & Brooks, 2008), such isolated pools can provide groundwater recharge as well as receive groundwater discharge (Winter & LaBaugh, 2003).

On the other end of the river-floodplain connectivity continuum are ephemerally flooded secondary channels. These hydrogeomorphic features are prevalent along meandering river-floodplain systems (David et al., 2017; Xu et al., 2020) and often inundate prior to river water overtopping all banks, thus increasing the duration and magnitude of river-floodplain connectivity (Lindroth et al., 2020). On an annual basis, river-floodplain connectivity along floodplain channels can persist for weeks (e.g., Czuba et al., 2019) to months (e.g., Hupp, 2000), highlighting the role floodplain channels play in transport and fate beyond extreme events. Here, we refer to two distinct types of floodplain channels: (i) backwater channels have a single well-defined morphologic connection to the main river channel and lose morphological definition as they traverse the floodplain and drain into depressions or complexes of poorly defined sloughs, and (ii) flow-through channels extend from a point of origin along the main river channel to a point of reconnection with the main river channel, remaining well-defined morphologically as they traverse the floodplain.

Regardless of feature type, increased interest in the connectivity and function of floodplain hydrogeomorphic features coincides with a concerted effort to understand the influence of transient hydrologic connectivity on ecosystem functioning more broadly. For example, estimated to comprise more than 50% of the global river network, intermittent and ephemeral streams can be hotspots of biogeochemical transformation but have only been rigorously studied in recent decades (Burrows et al., 2017; Datry, Larned, & Tockner, 2014; Gómez-Gener et al., 2021). Likewise, river network expansion via episodic floodplain channel inundation may have basin-scale biogeochemical effects, but ephemeral floodplain channels are under-studied, even compared to their perennial counterparts in larger floodplain systems (e.g., Mertes, Dunne, & Martinelli, 1996; Trigg et al., 2012). In another example, recent work has highlighted the outsized role of small ephemeral wetlands (i.e., geographically isolated wetlands) in maintaining downstream water quality (Cheng, Park, Kumar, & Basu, 2022; Marton et al., 2015). Although overlooked with regards to legal protections due to their small size and apparent geographic isolation (e.g., Creed et al., 2017; Tiner, 2003; Wade, Kelleher, Ward, & Schewe, 2022), these studies emphasize the importance of periods of disconnectivity in the enhanced ability of geographically isolated wetlands in retaining nutrients. Similarly, considering both transient hydrologic dynamics and geomorphic connectivity is key to understanding nutrient and pollution retention patterns across floodplain hydrogeomorphic features characterized by intermittent and ephemeral inundation, as well as their relative importance to other aquatic systems.

Understanding the mechanisms by which floodplains retain, export, and transform water and solutes requires consideration of how feature morphology, antecedent conditions, and storm event characteristics interact to control both water sourcing and subsequent transport processes. Commonly, river-sourced water comprises only a portion of floodwaters on floodplains. Groundwater, direct precipitation, runoff from nearby slopes, antecedent water from prior floods, and local tributary water can also contribute floodplain water (Mertes, 1997; Pinel et al., 2020). The area where differentially sourced floodwaters mix, termed the perirheic zone, can have steep chemical and sediment concentration gradients and thus can influence nutrient transformation and hydrogeomorphic patterns. Recent studies have emphasized temporal (Jones, Scott, Edwards, & Keim, 2014) and spatial (Berezowski, Partington, Chormański, & Batelaan, 2019) dynamics of the perirheic zone. Given their varied topographic positions and role in conveying flow, hydrogeomorphic features are expected to influence both the timing and location of perirheic zone formation. For example, floodplain channels convey river-derived water to more isolated depressional regions of floodplains, likely to contain differentially-sourced or antecedent floodwater. Inundation mechanisms, and thus water-sourcing, in floodplain channels themselves may vary with antecedent conditions (e.g., groundwater table elevation, the presence of antecedent floodwater) and position on the floodplain (e.g., elevation, proximity to river or valley sides that convey runoff).

In this study, we use empirical evidence from a lowland meandering river-floodplain system in central Illinois to investigate spatial and temporal patterns of inundation across floodplain hydrogeomorphic features that span a gradient of hydrologic connectivity, including isolated depressions, backwater channels, and flow-through channels. Specifically, we ask: (i) how does inundation onset and recession vary by location and hydrogeomorphic feature type?; (ii) how do location, antecedent wetness, and event characteristics impact groundwater-surface water (GW-SW) interactions across different hydrogeomorphic features?; and (iii) how does floodplain channel flow direction vary within events and across hydrogeomorphic features? To answer these questions, we use a network of surface water and groundwater level monitoring supplemented with high spatial frequency monitoring of the presence or absence of floodwater within hydrogeomorphic features. Together, these data provide a comprehensive depiction of the spatiotemporal patterns of inundation dynamics and associated linkages between groundwater and surface water levels. Such observations are a first step towards understanding the hydrologic functioning of floodplain hydrogeomorphic features and ultimately aggregating their influence across larger spatial scales to predict transport and transformation through river-floodplain networks.

2. DATA AND METHODS

2.1 Site description

The study site is a 4-km reach of the upper Sangamon River, a tributary of the Illinois River, and adjacent floodplain (Figure 1a). The monitored area covers about 1 km^2 of floodplain and river corridor. The site is located within Allerton Park, a protected natural area near Monticello, Illinois, USA which contains lowland (floodplain) and upland forest, and is a core research site of the of the Critical Interface Network (CINet) and the preceding Intensively Managed Landscapes Critical Zone Observatory (Kumar et al., 2023). The region has a humid continental climate with hot summers and cold winters. Monticello receives an annual average precipitation of 1,020 mm. Illinois, and the Midwest generally, experiences a wide variety of storms in all seasons (Changnon & Kunkel, 2006). Thunderstorms (i.e., convective storms) account for 50–60 percent of annual precipitation (Angel, 2003), with the majority of thunderstorms occurring in warmer months (May–July). These storms typically produce heavy rain for a brief period of 30 minutes to an hour. They can occur individually or in clusters or lines, with multiple thunderstorms occurring in a day or over several days.

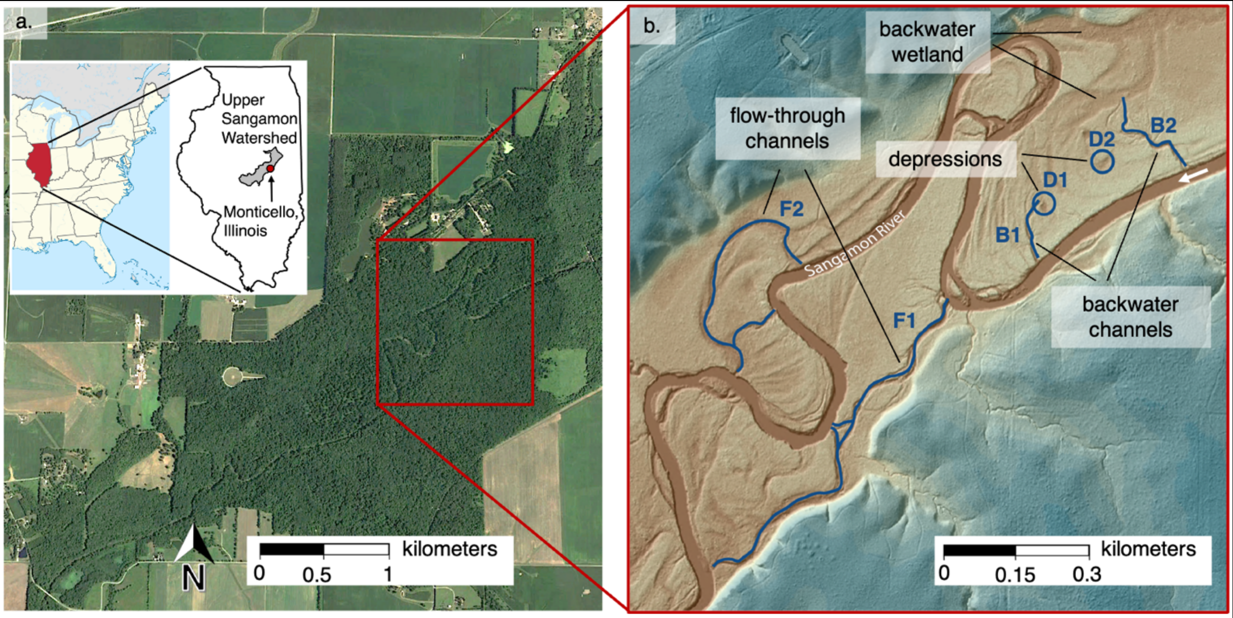


Figure 1. Field site location along the Sangamon River near Monticello, IL (a). Aerial photograph depicts forested landcover of immediate study region and primarily agricultural land use of surrounding watershed. Monitored floodplain hydrogeomorphic features outlined and labeled (b): depressions (D1 and D2), backwater channels (B1 and B2), and flow-through channels (F1 and F2).

Allerton Park together with the adjacent Upper Sangamon River Land and Water Reserve comprise one of the largest remaining forests in central Illinois. The upland forest is primarily oak-hickory in composition (Boggess & Geis, 1967; Bretthauer, Gertner, Rolfe, & Dawson, 2007), and the bottomland forest is dominated by silver maple (Bell, 1974; Chueng & Brown, 1995). While the bottomland forest occupying the upper floodplain surface contains thick understory vegetation, including silver maple seedlings and herbaceous plant species like stinging nettle and giant ragweed, the topographically low hydrogeomorphic features have little groundcover most of the year. Although the study site is located within minimally disturbed, old-growth floodplain forest, the surrounding landscape has undergone significant anthropogenic changes in recent centuries (Kumar et al., 2018). Prior to European settlement, the Upper Sangamon River Basin was 90% prairie and 10% forest (IDNR, 1999), with the forests primarily in riparian zones. Today 90% of land use is row crop agriculture. Consequently, floodwaters are nutrient-rich due to high fertilizer inputs in the watershed (Brown & Peterson, 1983). Further, anthropogenic intervention has altered the landscape's drainage network.

Subsurface drainage (commonly “tiles” or “tile drainage”) installed beneath agricultural fields maintains an artificially lowered water table and rapidly conveys water from the landscape to streams (Cain, Woo, Kumar, Keefer, & Ward, 2022). Stream channels have been straightened and widened, and channel networks extended into the headwaters, increasing drainage density and efficiency compared to pre-disturbance conditions (Rhoads, Lewis, & Andresen, 2016).

Within the study area, the Sangamon River is a 5th-order stream (Stall & Fok, 1968) ranging 20–30 m wide and meandering through a valley about 0.5 km wide. Although changes in land use and climate have undoubtedly altered peak discharges and sediment loads in the upper Sangamon River, low stream power and cohesive, tree-lined riverbanks have limited changes in channel planform since at least the 1940s (Rhoads et al., 2024; Rhoads et al., 2016). Floodwaters typically exceed riverbanks within the park several times per year, with most flooding occurring during the winter and spring (January–June). Floodwaters are constrained by distinct valley sides separating the floodplain from the adjacent uplands. Floodplain soils are primarily Sawmill silty clay loam (NRCS, 2022), deep and poorly drained soils formed in alluvium. Prominent topographic features at the site include floodplain channels, both those with single and multiple morphologic connections with the main river channel, and closed depressions (Figure 1b). Evidence that active scour is occurring in the hydrogeomorphic features (Arnott, 2015; Shukla, Salas, Pankau, & Rhoads, 2024) and that they formed within alluvium deposited on the floodplain after European settlement (Grimley et al., 2017; Rhoads et al., 2024) suggest that they are relatively contemporary features and resulted from differential erosion associated with flow across the floodplain.

2.2 Field monitoring

The hydrologic dynamics of floodplain hydrogeomorphic features of varying morphologies and topologies were monitored using a combination of intermittency loggers and water level loggers (Figure 2). While hydrologic connectivity of hydrogeomorphic features varies through time, surface water connectivity at moderate flood stages—when floodplain hydrogeomorphic features are inundated but floodwaters have not overtopped all banks—provides a geomorphically-relevant method for characterizing feature archetypes. Instrumented features include depressions, backwater channels, and flow-through channels (Figure 1b). Depressions are not hydrologically connected to the river via surface water under moderate flood levels (Features D1 and D2, Figure 1b); backwater channels have one surficial connection to the main river channel at moderate flood stages and drain into a backwater wetland (Features B1 and B2, Figure 1b); and finally, flow-through channels have multiple surficial connections with the main river channel at moderate flood stages (Features F1 and F2; Figure 1b).

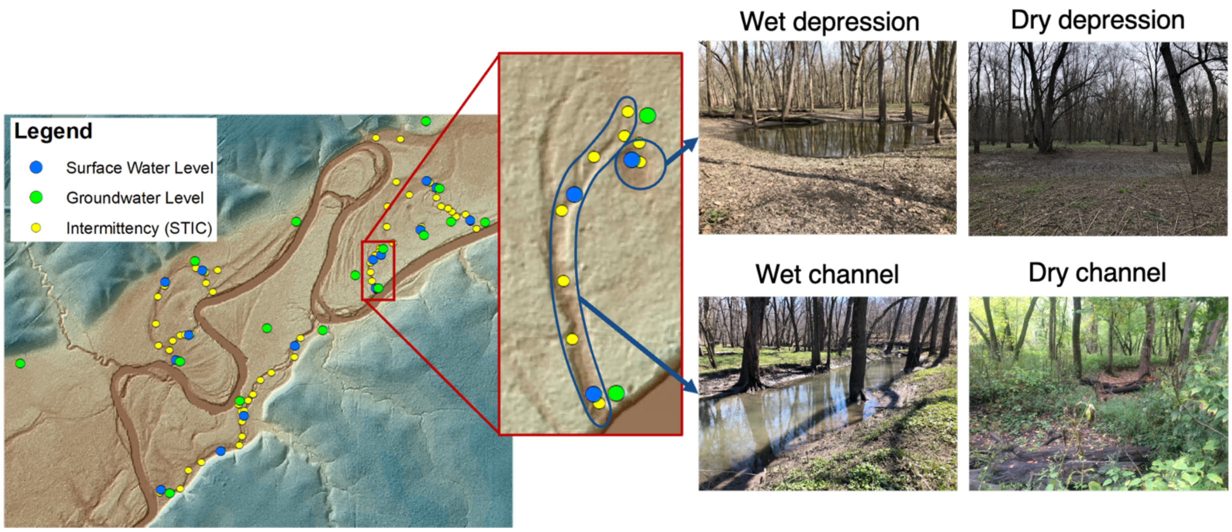


Figure 2. Monitoring network of surface water level (blue), groundwater level (green), and floodwater presence/absence (STIC loggers, yellow). Inset shows features B1 (backwater channel) and D1 (depression) with examples photos of wet and dry conditions.

Stream Temperature, Intermittency, and Conductivity (STIC) loggers were installed to monitor the occurrence of surface water at 60 discrete locations on the floodplain every 10 min over a 2.5-year period (June 2018–December 2020). Built by modifying HOBO Pendant Temperature/Light sensors (following Chapin, Todd, & Zeigler, 2014), STICs provide electrical conductivity measurements that are used as proxies for water presence/absence at the sensor elevations (here, slightly above the ground surface). For this study, STIC locations were considered inundated when electrical conductivity measurements diverged from the dry response (raw signal ≈ 0). Inundation was characterized by a sustained signal above zero, clearly distinguished from sporadic fluctuations of electronic noise or direct precipitation/moisture on the sensor. Examples of raw STIC electrical conductivity data are provided in Supplemental

Information (Figure S1). STICs were deployed primarily along the centerline of the floodplain channels and bottom of depressions. Given the placement of STIC sensors along the ground surface, STIC data were used to characterize spatial and temporal patterns of the initial presence of surface water on parts of the floodplain during flooding onset (i.e., wet-up), the timing of the last presence of floodwater during late flood recession (i.e., dry-down), and the duration of flooding at each location. While STIC loggers occasionally malfunctioned or were inaccessible due to flooding, inundation data were available for at least 50% of the study period for the 60 locations used in this study.

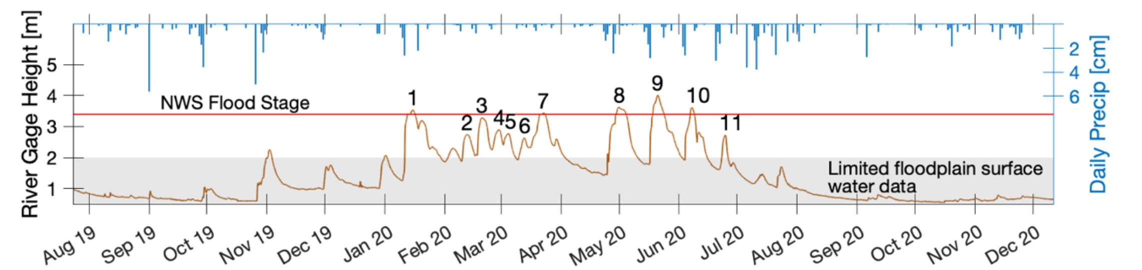
Surface water and shallow groundwater levels were analyzed for a 1.5-year period (July 2019–December 2020) of 15-min interval data collected using HOBO U20 Water Level Loggers. Sixteen shallow wells (3–6 m deep) were installed at higher floodplain elevations near hydrogeomorphic features to monitor changes in the near-surface water table, with the lower 1.5 m screened for all wells. Surface water was monitored at several locations along the centerline of each floodplain channel and at the bottom each depression, totaling 15 floodplain surface water monitoring locations. Co-located groundwater and surface water loggers at 11 sites were used to inform hydrologic dynamics and exchange processes within and between features. Whereas the high spatial frequency STIC sensor wet/dry data reveal spatial patterns of initial inundation timing and duration within a horizontal plane, water level data provides additional information on vertical flooding dynamics. Surface water level measurement locations were several centimeters above near-ground surface STIC measurements. Thus, water level and STIC data provide complimentary information on flooding dynamics over the course of a flood.

River stage in the main channel was monitored 0.4 km upstream of the study reach using a HOBO U20 Water Level Logger to relate floodplain dynamics to pre-storm and peak river stage. A Trimble S6 Robotic Total Station was used to record the relative elevations of monitoring equipment. Precipitation was measured 2-km from the study site using a Texas Electronics TR-525I tipping bucket rain gage through May 2020. Due to vandalism of instrumentation at that time, we use precipitation measured with a Meter ECRN-100 rain gage at a site near Champaign, IL, about 30-km away from the floodplain site, for remainder of the study.

2.3 Flood event selection and characterization

To compare spatial and temporal variation in inundation dynamics, 11 distinct flood events were identified over the 1.5-year water level monitoring period (Figure 3a). Only events which resulted in a floodplain surface water level response were considered in the analysis. Metrics of event characteristics and antecedent conditions were calculated for each identified event, including gross event precipitation, peak event river stage, antecedent river stage, change in river stage over the event, and antecedent inundation (Figure 3b). We consider gross event precipitation to be the total precipitation between a start time identified via visual inspection of precipitation and river stage timeseries and the time of peak event river stage. Antecedent river stage was identified as the river stage immediately preceding an increase in river stage for each event. Change in river stage was calculated as the difference between peak river stage and antecedent river stage. Antecedent inundation was calculated as the percentage of STIC locations with antecedent floodwater present prior to the start of the event.

a.



b.

Event Number	1	2	3	4	5	6	7	8	9	10	11
Gross Event Precip [cm]	4.0	0.9	1.2	0.6	0.0	0.8	1.2	6.3	5.4	4.5	5.3
Peak River Stage [m]	3.54	2.74	3.28	2.90	2.77	2.63	3.44	3.63	4.01	3.61	2.73
Antecedent River Stage [m]	1.35	1.97	2.16	2.35	2.50	2.02	2.42	1.55	1.88	2.01	1.71
Δ River Stage [m]	2.28	0.87	1.22	0.65	0.37	0.71	1.12	2.18	2.24	1.70	1.12
Antecedent Inundation (% STICs activated)	9	50	66	80	89	59	80	9	30	45	14

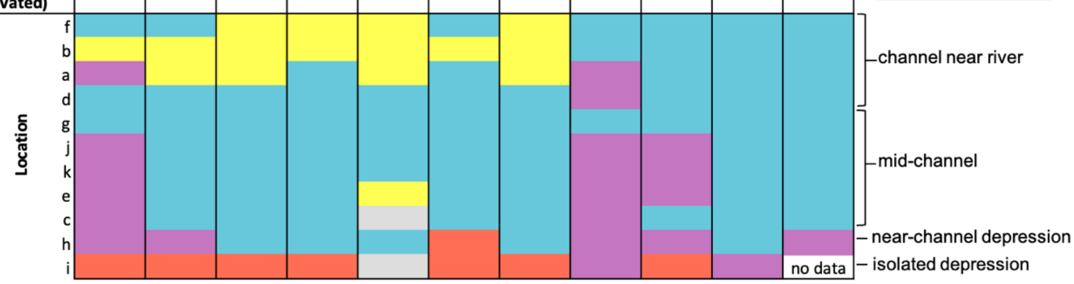


Figure 3. Monticello River gage height upstream of the monitored floodplain (brown) and precipitation (blue) over the monitored period (a). The National Weather Service (NWS) flood stage is indicated by the red line. Numbers designate the flood event number. Event characteristics and antecedent conditions with observed GW-SW hysteresis patterns in columns below (b). Locations in panel b correspond to labels in Figure 7.

2.4 Wet-up timescale and inundation duration analysis

For each event, we calculated the wet-up timescale as the time between initial increase in river water level and the time of inundation at each STIC location for each event. A total of 44 STIC sensor locations were used for the wet-up timescale analysis, selected for having continuous datasets across events. Because antecedent floodwater occurred at some floodplain locations prior to each event and some locations did not inundate during all events, the total number of wet-up timescale values calculated for each event varies between 8 and 40 locations. Kruskal-Wallis tests were performed to determine whether wet-up timescales differed between events using a significance threshold of 0.05. Wet-up timescale metrics were used to compare inundation timing across locations for the 11 events identified during the water level monitoring period.

Linear regression analysis was used to test for relationships between wet-up timescales within events and expected controls on inundation (i.e., elevation, distance from river connection, and distance from valley wall) at each location. Distance from the nearest river connection along the channel centerline was determined for locations with an evident channel flow path to the river (i.e., within floodplain channels and the near-channel depression D1), and thus excluded STIC locations in the more isolated depression D2 and the backwater wetland. Because large differences in mean wet-up timescales between events could obscure within-event trends, we use a normalized wet-up timescale, calculated as the difference between wet-up timescale and mean wet-up timescale across all sensors for a given event. While we report the r^2 value for all calculations, we proceed with interpretation of an $r^2 < 0.3$ to indicate no relationship, $0.3 \leq r^2 < 0.5$ to indicate a weak relationship, $0.5 \leq r^2 < 0.7$ to indicate a moderate relationship, and $r^2 \geq 0.7$ to indicate a strong relationship. We also used linear regression to test for relationships between the percent time each of the 60 STIC locations was inundated over the monitoring period and the expected inundation controls. Finally, Kruskal-Wallis tests were performed to test whether percent time inundated differs as a function of hydrogeomorphic feature type.

2.5 Water level analyses

Trends in groundwater and surface water levels have been used widely to interpret interactions between groundwater and surface water stores (Kalbus, Reinstorf, & Schirmer, 2006). In one study, Brookfield, Stotler, and Reboulet (2017) used temporal variations in river response functions, which indicate the relationship between the response of groundwater levels and a change in river stage, to interpret water sources and changes in flow mechanisms between a river and aquifer. Here, we use direct GW-SW level relationships for each pair of co-located water level loggers to characterize hydrologic dynamics and infer inundation mechanisms. Although analyzing hydraulic gradients between groundwater and surface water provides a direct method to infer groundwater-surface water exchange in one dimension, process interpretations in low-gradient environments can be sensitive to small inaccuracies in land surface and water level elevation measurements (Cain & Hensel, 2018). Given that differences in water levels between co-located monitoring locations were often very small, evaluating the relationship between temporal groundwater-surface water level variations offers an analysis technique less prone to inaccuracies in absolute vertical measurements. Thus, GW-SW relationships serve as a valuable proxy that provides novel insight into flooding mechanisms and water sources.

We expected to observe one of three primary GW-SW relationships at each floodplain location, with patterns explained by different hydrologic dynamics during flood event rising limbs. With surface water level oriented on the x-axis and groundwater level on the y-axis, GW-SW relationships would show either clockwise hysteresis (initial floodplain surface water response lags groundwater response), counterclockwise hysteresis (initial floodplain groundwater response lags surface water response), or no hysteresis (surface water and groundwater level responses are simultaneous) for each event. In addition to these three simple hysteresis patterns, more complex dynamics are also possible. For example, events may exhibit clockwise to counterclockwise (C-CC) figure-eight hysteresis when initial floodplain surface water response lags groundwater response and then later groundwater response lags surface water response.

Finally, to infer the flow direction through each floodplain channel over the course of a flood event, the hydraulic gradient was calculated between the most upstream and downstream surface water monitoring locations for the flow-through channels and between the locations nearest and furthest from the river for the backwater channels. Instances in which the surface water logger locations were hydrologically disconnected via surface flows, determined from dry STIC sensors located between the two water level monitoring locations, were not included in the analysis.

3. RESULTS

3.1 Wet-up timescales and inundation duration

The normalized wet-up timescale over all events and locations did not correlate with the expected controls of elevation, distance from the nearest river connection along the channel centerline, or distance from the valley wall ($r^2 < 0.1$ in all cases; Figure 4b–d). Wet-up timescales varied between events (Figure 4a). Events with larger changes in river water level (Figure 3b; Events 1, 3, 8, 9, and 10) tended to have low mean wet-up timescales (mean of 0.1 to 0.2 days) and small spread (standard deviation of 0.1 to 0.3 days). Exceptions include that Events 1 and 8 had larger mean wet-up timescales (0.6 to 0.8 days), and Event 8 also had a greater standard deviation (0.5 days). Notably, precipitation during both of these events occurred in two distinct pulses (Figure 3a). Wet-up timescales for events with small to moderate changes in river water level (Events 2, 4, 6, 7, 11) tended to have larger mean wet-up timescales (0.8 to 1.9 days) and greater standard deviations (0.6 to 0.8 days). Event 5, the event with the smallest change in river water level, had the largest mean wet-up timescale (2.7 days) and standard deviation (2.5 days) and is also the only event in which no gage precipitation was recorded.

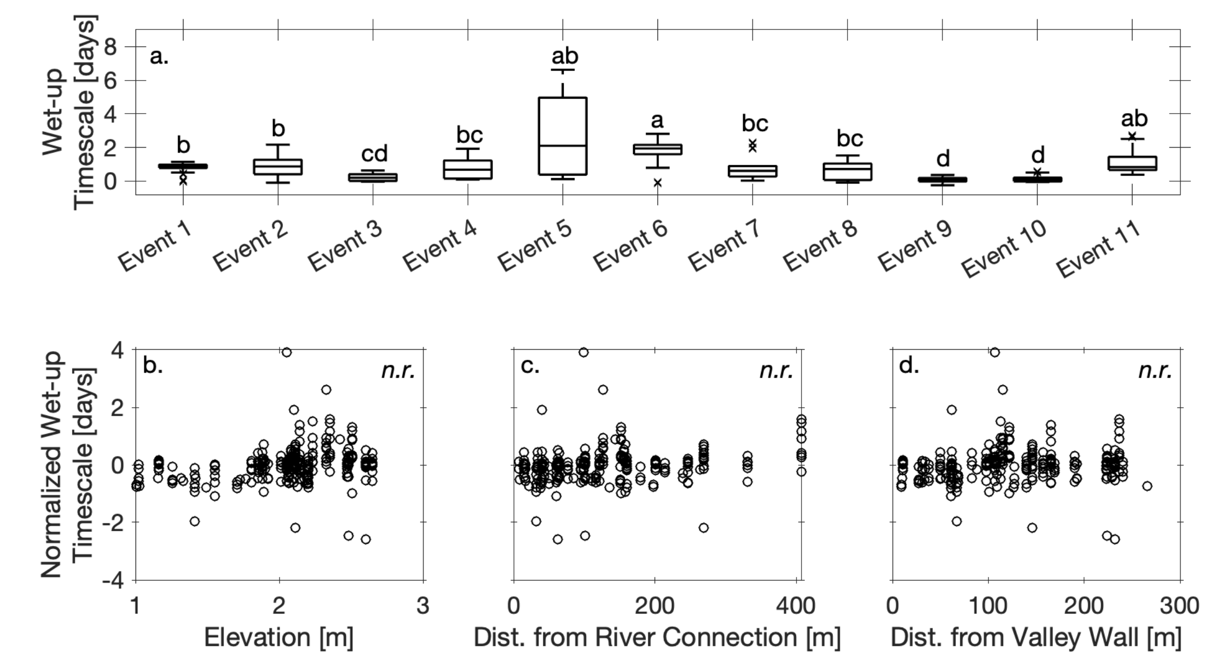


Figure 4. Boxplots representing wet-up timescale medians and interquartile ranges across the monitored locations for each event (a). Letters above boxplots indicate statistical differences in medians according to Kruskal-Wallis tests. Normalized wet-up timescales relative to

elevation (b), distance from nearest river connection along channel centerline (c), and distance from valley wall (d) for each location. '*n.r.*' indicates no relationship for linear regressions

Across the 60 floodplain locations where the presence of surface water was monitored, inundation duration ranged from 30 to 93% of the monitored period (Figure 5) and had a median of 61%. Percent time inundated showed a weak correlation with elevation (r^2=0.40) but no relationship with distance from the nearest channel connection or distance from the valley wall ($r^2 < 0.1$ in all cases; Figure 6b–d). Feature type was not a strong control on percent time inundated (Figure 6a). Based on a post hoc analysis, two groupings were observed ($p < 0.01$; denoted as groups 'a' and 'b' in Figure 6a). The first group included Features B2 and F1, which had the largest mean inundation (66% and 68%). Feature B2 was also included in the second grouping which included B1, F2, D1, and D2 (56%, 55%, 56% and 53%, respectively).

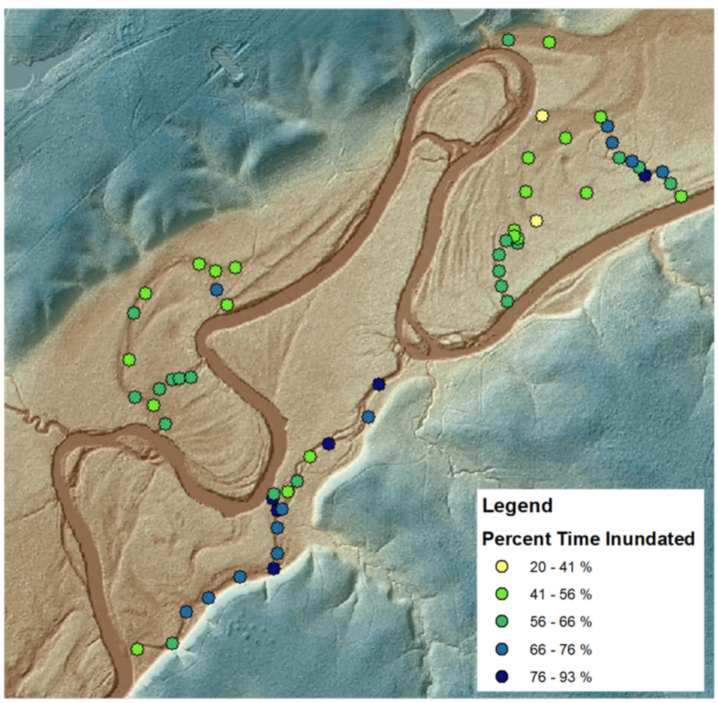


Figure 5. Percent time inundated at hydrogeomorphic feature locations.

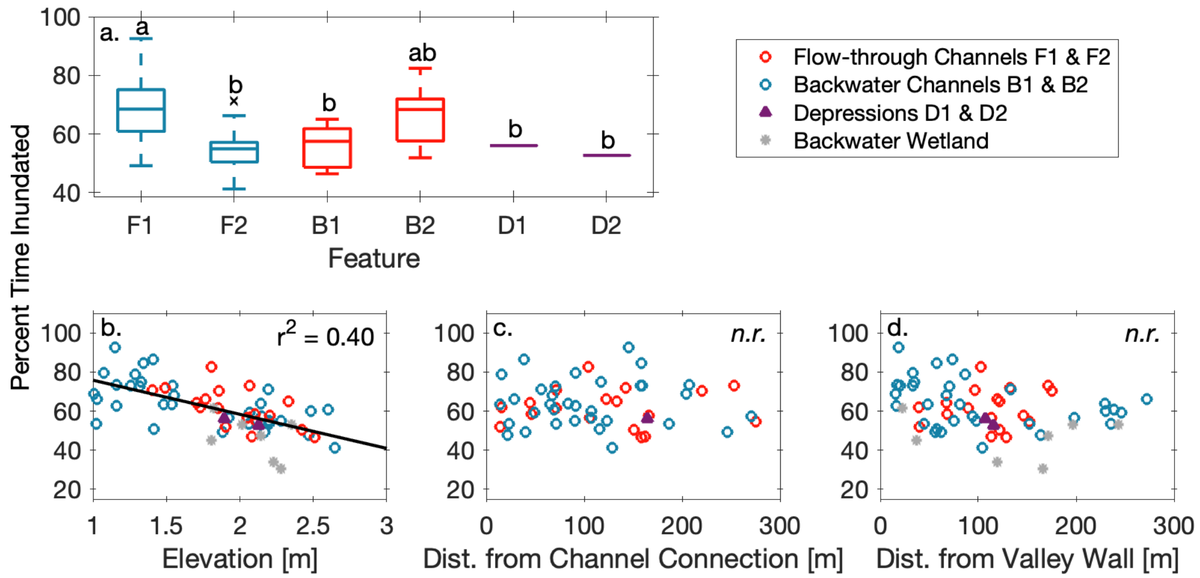


Figure 6. Boxplots representing percent time inundated medians and interquartile ranges across the monitored locations for each hydrogeomorphic feature (a). Letters above boxplots indicate statistical differences in medians according to Kruskal-Wallis tests. Note that while each channel feature has numerous inundation monitoring locations (n=8–22 sensors), each depression had one (n=1 sensor). Percent time inundated and linear regressions relative to elevation (b), distance from nearest river connection along channel centerline (c), and distance from valley wall (d) for each location. '*n.r.*' indicates no relationship for linear regressions

3.2 Groundwater-surface water level dynamics

Overall, GW-SW relationships across locations and events were dominated by counterclockwise hysteresis, indicating initial inundation by surface water and subsequent rising of the floodplain groundwater table (Figures 3b and 8; 61% across all events and monitored locations). Lower proportions of clockwise hysteresis (7%), C-CC hysteresis (18%), no hysteresis (13%), and no hydrologic response (2%) were also observed. GW-SW relationships varied by event characteristics and floodplain location (Figures 3b and 8). For example, the isolated depression D2 (Location i) showed primarily clockwise hysteresis while the near-channel depression D1 (Location h) displayed a mix of mainly counterclockwise and C-CC hysteresis. For floodplain channel locations, dominant GW-SW relationships tended to group by proximity to the river (i.e., near-river or mid-channel locations; see similar color distributions in pie charts in Figure 7 and similar horizontal color groupings in Figure 3b) rather than by channel type (i.e., backwater vs. flow-through channel). Near-river channel locations (Locations a, b, d, and f) displayed primarily a mix of clockwise hysteresis (59%) and no hysteresis (34%), whereas mid-channel locations (Locations c, e, g, j, k) displayed a mix of clockwise hysteresis (76%) and C-CC hysteresis (20%).

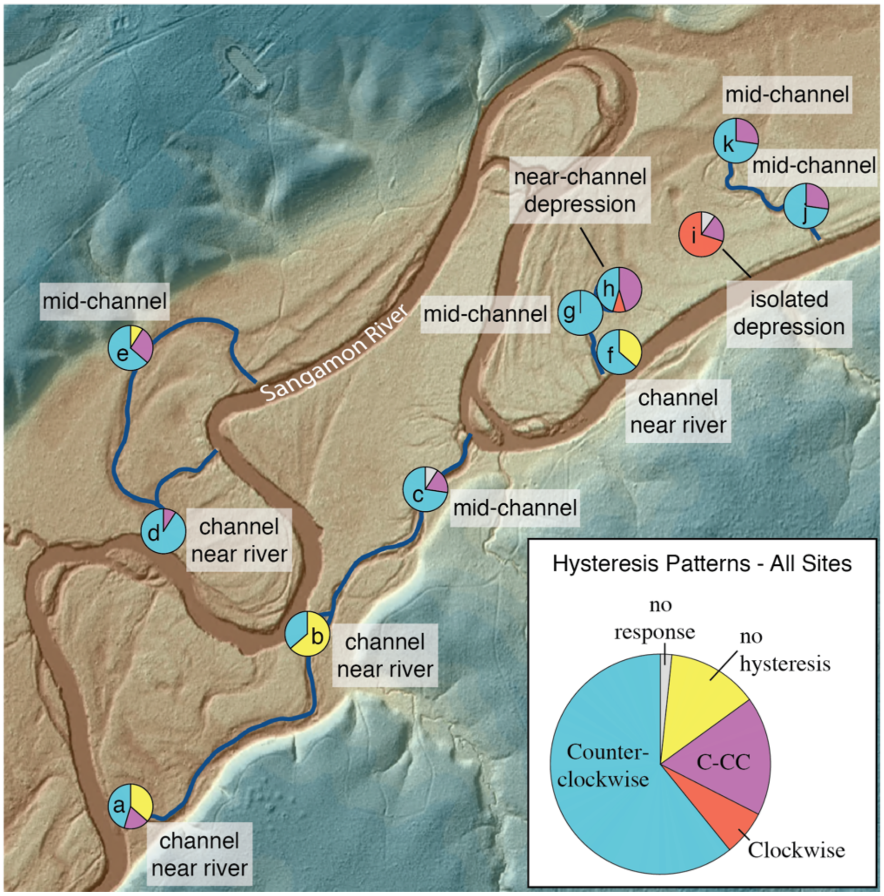


Figure 7. Pie charts display the proportion of each GW-SW hysteresis pattern observed at hydrogeomorphic feature locations. The inset displays proportions of GW-SW relationships across all locations. Letters representing locations correspond to Figure 3b. While counterclockwise hysteresis dominated floodplain channels, the isolated depression showed primarily clockwise hysteresis. Within floodplain channels, other GW-SW relationships observed tended to group by proximity to the river, with mid-channel locations exhibiting more clockwise-counterclockwise (C-CC) hysteresis and channel locations near the river more commonly exhibiting no hysteresis.

While counterclockwise hysteresis was observed across events, C-CC hysteresis occurred most commonly during events with low antecedent wetness conditions and high gross event precipitation that led to large changes in river stage (e.g., Events 1, 8, and 9). Patterns of no hysteresis most commonly occurred for events with more moderate changes in river stage (e.g., Events 2, 3, 4, 5, and 7). Two instances of no water level response were observed during Event 5, an event in which no gage precipitation was recorded. These occurred in the isolated depression and a mid-channel location. When hysteretic relationships were present during events with larger changes in river stage, GW-SW relationships became linear at higher water levels, typically after about 0.5 m–1 m of stage increase. This linear portion of GW-SW response corresponds to when groundwater wells, located at higher elevations than the hydrogeomorphic features, became flooded and groundwater and surface water responded in synchrony. Examples of observed GW-SW relationships for several events and locations are provided in Supplementary Information (Figure S2).

3.3 Floodplain channel surface flow

For the backwater floodplain channels, surface water hydraulic gradients were primarily from the river to the floodplain (positive values, Figure 8a), indicating flow directed from the river onto the floodplain. Negative hydraulic gradients, indicating flow directed from the floodplain to the river occasionally occurred for short periods of time during inundation onset and recession. In backwater channel B2, hydraulic gradients drop to near-zero, indicating little flow between the river and floodplain, around the time of peak river stage prior to increasing again during the falling limb. Hydraulic gradients along the flow-through floodplain channels were always in the downstream direction (positive values, Figure 8b). Similar to backwater channel B2, there is little hydraulic gradient driving water flow through the flow-through channel F2 at peak river stage.

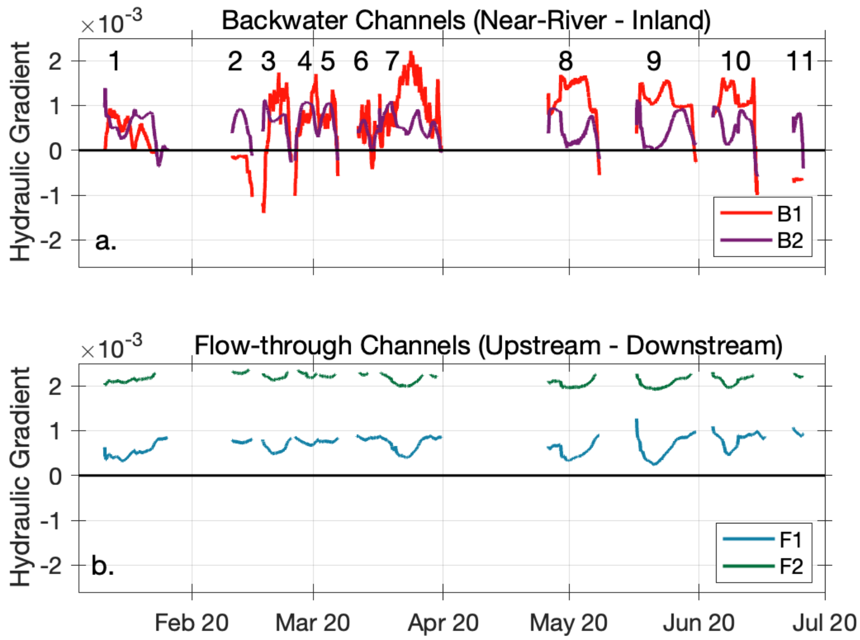


Figure 8. Floodplain channel surface water hydraulic gradients. For backwater channels (a), positive values indicate flow away from the river. For flow-through channels (b), positive values indicate flow in the downstream direction. Numbers designate the flood event number and correspond to Figure 3.

4. DISCUSSION

4.1 Spatial and temporal variability in hydrogeomorphic feature wet-up and inundation duration

Spatially and temporally complex patterns of hydrogeomorphic feature wet-up and inundation duration were present at the study site. We expected to find relationships between wet-up timescale and locational controls as indicators of dominant flooding mechanisms, where a relationship between wet-up timescale and elevation would have indicated initial floodwaters were likely due to groundwater rise. A relationship with distance from the nearest river connection along the channel centerline would have indicated floodplain network expansion away from the river and initially river-sourced floodwater, while a relationship with distance from the valley wall would have indicated that runoff from nearby slopes was a primary contribution to initial flooding. Instead, we found that within-event wet-up timescales are not correlated with any of the expected locational controls (Figure 4b–d). We hypothesize that within such low-gradient environments, variations in the floodplain surface at centimeter to meter scales (i.e., microtopography) influence where initial floodwaters pond within features, consistent with Diamond et al. (2021). The influence of such small-scale, localized topographic controls would not be revealed from regression analysis of wet-up timescale and elevation across the larger floodplain area. Further, interactions with antecedent wetness conditions and event characteristics result in inconsistency in wet-up patterns, obscuring relationships with expected controls. These results point towards the potential role of direct precipitation and saturation excess overland flow as flooding mechanisms in hydrogeomorphic features during wet-up. Initial inundation, or inundation that occurs prior to the onset of surface water connections between rivers and floodplains, is composed of either direct precipitation or a combination of direct precipitation and antecedent floodwater sources (Mertes, 1997). Notably, the magnitude of this inundation may be relatively small (i.e., our STIC sensors detect water at depths less than 3 cm on average). Nevertheless, this interpretation could explain why larger flood events, typically characterized by greater precipitation volumes, tended to have mean wet-up timescales near zero and small spread (Figure 4a).

Similar to wet-up timescale, we expected to observe relationships between percent time inundated and locational controls, including elevation, distance from the river connection, distance from the valley wall. Analyses of percent time inundated mainly reflect dry-down timing because differences in dry-down timing between locations were generally larger than differences in wet-up timing. Therefore, a relationship between percent time inundated and elevation would indicate that the falling groundwater table was a primary control on dry-down timing such that low spots stayed wet longer, and a relationship with distance from the nearest river connection along the channel centerline would indicate floodwater drainage to the river was a primary control on dry-down timing. While we did not find a relationship with distance from the nearest river connection, percent time inundated has a relationship with elevation (r^2=0.40; Figure 6b). This relationship suggests that the groundwater table is coincident with floodplain surface water elevations during late recession periods and that water table relaxation is a primary control on dry-down patterns. However, the relationship with elevation is weak. This may be due to spatial variation in water table depth across the study site (groundwater depths varied as much as 1.3 m between floodplain locations), the presence of discontinuous or perched water tables, or structural heterogeneity within the floodplain aquifer (e.g., King & Keim, 2019). Further, factors such as local topography (e.g., Edwards et al., 2016), the presence of vegetation (e.g., Prior, Aquilina, Czuba, Pingel, & Hession, 2021), and seasonal variations in evapotranspiration (e.g., Lee et al., 2020) may explain the spread of inundation duration with the factors analyzed.

While the ephemeral and intermittent nature of low-gradient floodplain channels resembles the more commonly studied headwater ephemeral and intermittent streams (Costigan et al., 2017; Fovet et al., 2021), the spatially variable wet-up and dry-down dynamics of the monitored low-gradient floodplain channel network differ from those of steep, headwater stream networks. Headwater mountain streams predominantly expand longitudinally in the upstream direction and contract longitudinally in the downstream direction in response to changes in stream discharge interacting with valley controls (e.g., Ward, Schmadel, & Wondzell, 2018; Zimmer & McGlynn, 2017, 2018), although non-contiguous sections of dry or wet streambed often persist in some locations. Both intermittent and ephemeral headwater streams and floodplains are effective bioreactors that regulate downstream water quality (Gómez-Gener et al., 2021; Gordon et al., 2020; Lane et al., 2022; Roley et al., 2012). However, it is unknown how these differing patterns of wet-up and dry-down influence factors controlling solute transport and biogeochemical processing, including the asynchronous integration of water and solute fluxes as isolated fragments reconnect and the structure and function of microbial communities responding to dynamic environmental conditions (Brooks, Covino, & Hall, 2022).

Although initial wet-up and dry-down comprise only a fraction of the total time of inundation, these periods could be particularly important for the biogeochemical processing within hydrogeomorphic features. Alternating wet-dry periods have been shown to increase denitrification due to paired nitrification-denitrification resulting from cycles of oxic-anoxic conditions and the pulsed release of nutrients during soil re-wetting (e.g., Baldwin & Mitchell, 2000). Our data show high variability in both the frequency and duration of inundation across hydrogeomorphic feature locations. Such variability should lead to hot spots and hot moments of peak biogeochemical activity (McClain et al., 2003; Vidon et al., 2010) within hydrogeomorphic features and influence the overall biogeochemical functioning in these systems. For example, while wet-dry cycles lead to increased nitrogen cycling, complete drying may lead to death of bacteria and decrease in microbial activity (Amalfitano et al., 2008; Baldwin & Mitchell, 2000). Saturated sediments of the hyporheic zone of intermittent streams have been shown to act as a refuge for microbes during drought (Febria, Beddoes, Fulthorpe, & Williams, 2012; Harjung, Perujo, Butturini, Romaní, & Sabater, 2019; Lewandowski et al., 2019), supporting enhanced nutrient turnover rates upon rewetting. Likewise, discontinuous patches of floodwater that remain for much of the year may similarly provide refuge for microbes and extend optimal conditions for anaerobic processing. Thus, knowledge of the spatial and temporal heterogeneity of floodplain inundation and subsequent integration of water and solute fluxes during flooding is critical to understanding the hydrologic and biogeochemical function of hydrogeomorphic features.

4.2 Flooding mechanisms are controlled by location, antecedent wetness, and event characteristics

Groundwater-surface water level relationships during flood events provide insight into how hydrogeomorphic feature inundation mechanisms vary by location, event characteristics, and antecedent wetness conditions (Figure 9). Surface water forcing was a strong driver of inundation dynamics, as indicated by a dominance of counterclockwise hysteresis across locations and events (Figure 7), particularly in backwater and flow-through channels. While it is difficult to distinguish between river-sourced or direct precipitation-sourced water using STIC and water-level data alone, we expect that for large events this pattern is primarily the result of a dominance of river-sourced floodwater contributions (i.e., flooding from the river to the floodplain via breaks in channel banks). This is because the hysteretic portion of the GW-SW relationship (i.e., prior to the linear portion of the GW-SW relationship indicating broader floodplain inundation above topographically low hydrogeomorphic features) commonly spans water level changes of as much as 0.5–1 m. Such an increase in surface water levels over a single event would require an unrealistically large volume of overland flow from the surrounding landscape. Therefore, we find it more plausible that the overall relationship during large events is primarily driven by river dynamics.

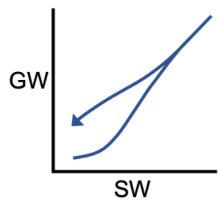
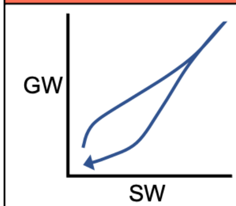
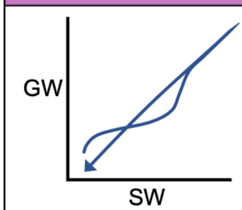
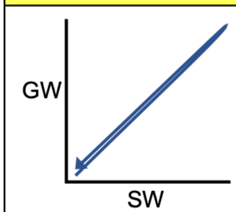
Observed Hysteresis	Description	Inferred Inundation Mechanism	Location, Antecedent Wetness, & Event Characteristics
counterclockwise (CC) 	Initial groundwater response lags floodplain surface water response (surface water forcing).	Initial floodwater contributions are likely primarily river-sourced or direct precipitation/overland flow.	Most common behavior observed across floodplain feature locations and events.
clockwise (C) 	Initial floodplain surface water response lags groundwater response (groundwater forcing).	Floodwater contributions are likely initially groundwater-sourced.	Common for isolated depression.
C-CC figure-eight 	Initial floodplain surface water response lags groundwater and then groundwater response lags surface water.	Early in event, groundwater levels rise rapidly due to recharge from high intensity precipitation, leading to initial groundwater-sourced floodwater contributions. Later transition to contributions that are primarily river-sourced or direct precipitation/overland flow.	Common in mid-channel locations and the near-channel depression during events with low antecedent wetness and high gross event precipitation.
no hysteresis 	Surface water and groundwater responses are simultaneous.	Indicates strong influence from nearby river channel and that floodwater contributions are primarily river-sourced.	Common for locations near the river.

Figure 9. Expected hysteresis between surface water (SW) and groundwater (GW) levels, description of the pattern, inferred mechanism that would explain each relationship, and common locations, antecedent wetness, and event characteristics associated with the relationship.

While counterclockwise hysteresis was the most commonly observed GW-SW relationship, other patterns were observed at the study site (Figure 7). Synchronous groundwater and surface water level response (i.e., no hysteresis) was common at near-river channel locations, indicating a strong influence from the nearby river channel and primarily river-sourced floodwaters. This pattern mainly occurred during events with high antecedent wetness (i.e., high antecedent inundation and river stage; Figure 3). Although soil moisture was not monitored during this study, we expect high soil moisture is important for this observed tight coupling of groundwater and surface water dynamics, consistent with studies of other systems (e.g., Cain et al., 2022; Jencso et al., 2009; McGlynn, McDonnell, Seibert, & Kendall, 2004).

We had expected that initial groundwater-sourced flooding, indicated by clockwise hysteresis, would dominate across events for the most hydrologically isolated location monitored in the study, the isolated depression, as well as the moderately isolated near-channel depression and mid-channel locations further from the river. While groundwater forcing was indeed most common for the isolated depression, this was not the case for the near-channel depression and mid-channel locations. Instead, these locations exhibited a mixture of surface water forcing (counterclockwise hysteresis) and initial groundwater forcing followed by subsequent surface water forcing (C-CC figure-eight hysteresis). The latter pattern was primarily observed during events with large changes in river stage (Figure 3), the result of low antecedent wetness conditions and high gross event precipitation. We infer that high intensity precipitation leads to rapid groundwater level rise, increasing the likelihood of groundwater-sourced floodwater contributions towards the beginning of the rising limb. Later during the rising limb, river stage rise exceeds groundwater table rise and these locations experience surface water forcing. As this pattern was most common during large events in which STIC data indicate accumulated precipitation as an important early source of floodwaters, we expect surface water level measurements were too high above the ground surface to capture these early, shallow dynamics.

Our hysteresis analysis highlights that perirheic zones form at the hydrogeomorphic feature scale. These results differ from those of Berezowski et al. (2019) who found that the active perirheic zone primarily formed as a front along the river’s edge, and it expanded and contracted with the rising and falling limnb of the hydrograph. In contrast, we observed spatial and temporal variability in mixing of river-sourced floodwaters and antecedent waters (i.e., some combination of antecedent floodwaters, direct precipitation, and groundwater). The difference in observations may be due to the presence of floodplain channels that preferentially convey floodwaters to hydrogeomorphic features across the floodplain. Further, whereas previous studies of perirheic zone formation processes have tended to focus on large river-floodplain systems (Jones et al., 2014; Mertes, 1997), our study demonstrates the relevance of hydrogeomorphic feature-scale processes on perirheic zone formation within a moderate-sized river-floodplain system. As smaller rivers make up a greater extent of total river length (Leopold, Wolman, & Miller, 1964), understanding the dominant processes contributing to the occurrence of perirheic zone formation in their floodplains is critical for understanding the role of perirheic zones across the entire river-floodplain network (Scott et al., 2019).

The novel GW-SW hysteresis approach used in this study provides insight into inundation dynamics and perirheic mixing from hydrogeomorphic feature to floodplain scale. Future studies may benefit from further examining breakpoints in hysteretic relationships (i.e., deviations from the 1:1 line; Figures 9 and S2). Previous work highlights the importance of breakpoints in hydrologic relationships such as rainfall-runoff (Cain et al., 2022; McGuire & McDonnell, 2010) and stage-volume (Jones et al., 2018; McLaughlin, Diamond, Quintero, Heffernan, & Cohen, 2019) for identifying hydrologic connectivity thresholds. Breakpoints may similarly provide insight into storage and connectivity relationships across hydrogeomorphic features during flood onset and recession. For example, breakpoints may indicate when disparate patches of antecedent floodwaters connect, the development of losing or gaining conditions in floodplain hydrogeomorphic features (i.e., GW-SW connectivity), or when hydrogeomorphic features connect with the upper floodplain (i.e., full inundation). Further, while Figure 9 depicts idealized hysteresis archetypes based on common characteristics of observed data, hysteresis patterns exhibit variations in the presence and locations of breakpoints (Figure S2), presumably due to differences in precipitation patterns and other forcing conditions (e.g., antecedent water level). Such variations in hysteretic form across events and locations underscore the complexity of connectivity dynamics on floodplains.

4.3 Hydrogeomorphic feature functioning: sinks or sources?

Floodplain channel hydraulic gradients reveal complex surficial river-floodplain interactions over the course of flood events, as well as differences between the hydrologic functioning of backwater and flow-through floodplain channels. Backwater channels monitored in this study predominantly conveyed flow onto the floodplain. During high flow conditions, these channels drain into a non-channelized backwater wetland in the northeastern portion of the study site (Figure 1). While the wetland connects to the river during extreme floods, it is relatively isolated from the river under moderate flooding and is expected to be a primary site for groundwater recharge. Thus, during moderate flood levels, the backwater channels at our site primarily functioned as net sinks of river water to the floodplain, which was ultimately stored in backwater wetlands. Moreover, this water flux would be associated with both dissolved and suspended materials delivered from the river to the floodplain.

Although backwater channel hydraulic gradients were towards the floodplain for the majority of the rising limb, peak river stage, and falling limb, hydraulic gradients indicating flow from the floodplain to the river (i.e., “reverse flow”) were recorded for shorter periods during early wet-up and late dry-down (Figure 8a). Reverse flow during wet-up occurred for events with a high percent antecedent inundation (e.g., Events 3, 4, and 7), with the exception of Event 5 which had no gage precipitation recorded. Therefore, we expect that wet-up reverse flow occurs when overland flow during precipitation rapidly increases water levels of antecedently flooded channels, reconnecting flooded fragments with the river prior to river stage exceeding floodplain water levels. Reverse flow during dry-down presumably results from floodplain channel surface water levels lagging declines in river stage (Byrne, Stone, & Morrison, 2019; Tull et al., 2022). As noted above, floodplain channel surface water levels are expected to be tightly coupled with groundwater levels during dry-down. Groundwater contributions to hydrogeomorphic features maintain residually high surface water levels during the late falling limb compared to the river. Thus, water draining from floodplain channels to the river during recession would be a combination of high residence time floodwater and what was recently groundwater.

While periods of reverse flow in backwater channels are relatively short, they could be important times for floodplain sourcing of pollutants to rivers. Although flooding tends to increase nitrogen removal, long-residence time water and anaerobic conditions can lead to enhanced release of phosphorous from floodplains (Amarawansha, Kumaragamage, Flaten, Zvomuya, & Tenuta, 2016; Loeb, Lamers, & Roelofs, 2008). For example, Jones et al. (2014) found greater accumulation of soluble reactive phosphorous (SRP) and dissolved organic matter (DOM) in a relatively disconnected backwater wetland compared to a flow-through wetland. They surmise that during periods of high river-floodplain connectivity, much of the accumulated SRP and DOM is flushed downstream. Since much of the water that drains from the backwater channels at our study site is antecedent floodwater with long residence times, we expect that reverse flows similarly export accumulated solutes.

In contrast to backwater channels that primarily function as sinks of river-derived water and solutes to the floodplain with short source periods, our data indicate that flow-through channels consistently convey flow from upstream to downstream, with water entering the channel at an upstream inlet and exiting at a downstream outlet throughout the flood event. However, like streams, flow-through channels can alter the quality of return flows by delaying downstream transport relative to the main river channel (Czuba et al., 2019), increasing the benthic surface area to water volume ratio (Ensign & Doyle, 2006) and enhancing floodplain surface-subsurface exchange (Krause, Bronstert, & Zehe, 2007). In addition to differences in the timing and directionality of river-floodplain exchange between floodplain channel types, mean residence times would be shorter for water entering flow-through channels compared to backwater channels. However, it is unclear how these differences in residence times influence biogeochemical functioning. For example, although greater residence times lead to increased nitrogen removal from a parcel of water, nitrogen removal could also be limited by transport onto the floodplain (Forshay & Stanley, 2005; Jones et al., 2014).

Overall, our data highlight that differentiation of whether a floodplain reach is a net source or a sink is confounded by high spatial and temporal variation in the directionality of connectivity and timescales influencing biogeochemical processing. As floodplain channels are the primary conduits for flow to and from the floodplain during moderate flooding, understanding of differences in feature-scale hydrologic functioning is needed to accurately develop water, nutrient, and sediment budgets in channelized floodplain systems.

5. CONCLUSIONS

This study of a lowland, meandering river-floodplain system demonstrates the complexity of inundation onset and recession patterns, flooding mechanisms, and river-floodplain exchange that can occur across hydrogeomorphic feature networks. Our observations elevate floodplain hydrogeomorphic features as distinct landscape units characterized by intermittent and ephemeral inundation dynamics which could play a disproportionate role in maintaining the integrity of downstream waters. We found that although there is a strong influence of overbank flooding on hydrologic response over the course of a flood, initial feature inundation is characterized by dynamic contributions from direct precipitation, groundwater, and antecedent floodwater that accumulate in non-contiguous sections designated by local topography. Eventually these isolated fragments connect and mix with river-derived water. The role of differentially-sourced water on initial flooding suggests that hydrogeomorphic features influence perirheic zone formation, and thus may be important sites for biogeochemical transformation on floodplains.

Inundation mechanisms varied as a function of location, antecedent wetness, and event characteristics. Whereas floodplain channel locations were dominated by surface water forcing overall (i.e., counterclockwise hysteresis), an isolated depression was exclusively characterized by initial groundwater forcing (i.e., clockwise hysteresis). During large events with low antecedent wetness conditions, floodplain channel locations further from the river and a near-channel depression showed an early period of groundwater forcing followed by a dominance of surface water forcing as flooding progressed (i.e., clockwise-counterclockwise figure-eight hysteresis). Finally, floodplain channels were characterized by spatial and temporal variation in flow direction. Whereas flow-through channels at the site conveyed flow upstream to downstream, backwater channels primarily functioned as sinks of river-derived water and associated materials to the floodplain with short source periods. Given that floodplain channels are the primary pathways for water to and from the floodplain during early and late flooding, these feature-scale processes must be taken into account to predict when and where floodplains are sources or sinks of water and dissolved and suspended materials.

Overall, our data demonstrate that hydrogeomorphic feature networks enhance river-floodplain connectivity at moderate flood stages, controlling hydrologic dynamics and water-sourcing across flood events. While our study focuses on empirical observations of hydrological processes in a relatively undisturbed forest, the study site is located in an otherwise highly agricultural landscape where riverine flows are characterized by elevated nutrients loads from fertilization (Brown & Peterson, 1983). Targeted restoration of floodplains along waterways with higher nutrient concentrations—like the one studied here—has been proposed as a cost-effective investment for nutrient removal (Gordon et al., 2020). Further, river-floodplain connectivity is increasingly the focus of river corridor management strategies, including the removal of excess nutrients as well as attenuation of flood peaks (Buijse et al., 2002; Freitag, Bolton, Westerlund, & Clark, 2012), and a basis for regulations aimed at protecting watersheds (USDOD & USEPA, 2015, 2020). Thus, the distribution of floodplain hydrogeomorphic features, dynamics of their inundation and connectivity, and associated biogeochemical functions are important considerations in the management of rivers in the Midwestern U.S. and similar landscapes. While inundation patterns and mechanisms will vary by site-specific characteristics (e.g., hydraulic conductivity, spatial heterogeneity of hydrogeomorphic features, vegetation), we expect the broader implications of our results are applicable across topographically complex floodplains.

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DATA AVAILABILITY

The data used in this publication are accessible via HydroShare at https://www.hydroshare.org/resource/0239c740abd14271ab843e068e6d452f/.

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