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ABSTRACT: Floods can cause punctuated changes to river channel morphology over short time scales. This work investigates whether spatial variation in river floodplain width drives enhanced morphodynamic change during floods. We examine the relationship between longitudinal variation in floodplain width and bed elevation change within and between flood events using high-resolution, biweekly bathymetry measurements from the Waal River, the Netherlands, over the last 20 years across a 10km study reach. We find that bed erosion during floods tends to occur just downstream of floodplain constrictions while deposition during floods tends to co-occur with spatial floodplain widening. Low flows show inverse bed elevation changes at the same locations resulting in a cyclic, along-channel variation in low- vs. high-flow bed elevation variation. This study suggests that spatial changes in planform channel geometry can help predict relative intra- and inter-flood morphodynamic changes.

1 BACKGROUND

1.1 *River morphodynamics and floods*

River channel morphodynamics are sensitive to floods; peak flow events can cause abrupt changes to channel geometry which can persist beyond the event and affect future flow conditions.

Persistent morphodynamic changes can also affect future flood hazards. Main channel deposition and narrowing can reduce flow conveyance and increase flood frequency with no change in peak flow conditions (Stover & Montgomery, 2001), whereas in-channel scour during flood flows can increase the conveyance capacity for subsequent floods (Guan et al., 2016). Recent work shows morphodynamic changes can contribute to flood hazard nonstationarity (Slater et al., 2015) and impresses the necessity of including geomorphic changes in frameworks for flood prediction (Sofia & Nikolopoulos, 2020). Thus, understanding morphodynamic change during floods is also important for predicting future flood hazards.

Predicting intra-flood morphodynamic response for a given discharge is often difficult due to temporal and spatial variation in patterns of erosion and deposition. A long period of low flows can stabilize the bed, increasing the threshold for incipient motion during subsequent high discharge events (Masteller et al. 2019). In regions where sediment production may periodically vary with climate (e.g. Anderson & Konrad, 2017), channel response may not consistently vary with discharge.

Previous work suggests that spatial changes in local river geometry can dictate river channel bed elevation change during floods (Van Denderen, 2014). Streamwise variations in lateral channel confinement have been shown to drive reach-scale gradients in stream power and channel response during floods (Sholtes et al., 2018). In this study, we analyze bed elevation changes in the Waal River, the Netherlands, in relation to spatial gradients in floodplain width. This work aims to assess whether spatial variation in channel planform geometry can explain bed elevation response to floods and inter-flood recovery. Since planform channel characteristics can be measured relatively easily from satellite imagery in areas that lack bathymetry and sediment-transport measurements, this work is relevant for predicting regions prone to morphodynamic adjustments during floods using simple measurements of spatial changes in floodplain geometry.

1.2 *Floodplain hypotheses*

River bed adjustments can be characterized into two categories based upon the time-scale of response: a quasi-static component (adjustment to controls operating on slow time-scales) and a dynamic component (adjustment to controls varying over short time scales, e.g. those associated with a hydrograph) (Arkesteijn et al. 2019). This work addresses the dynamic component by analyzing relatively short-term changes in the channel bed due to temporally variable discharge in a river with spatially varying floodplain width.

Along-channel variation in floodplain width generates gradients in flow velocity and sediment transport capacity during flood events which are not present during low-flow conditions in a main channel with constant width (Fig 1). During flood events, spatial floodplain widening allows flows to expand laterally (Fig 1a), which results in a streamwise decrease in flow velocity. This flow deceleration reduces the sediment transport capacity throughout this section. We thus expect that where the floodplain spatially widens, sediment is deposited during peak flows (hypothesis 1a). Where the floodplain spatially narrows, flow width is re-confined towards the main channel. This causes an acceleration of the flow and an increased sediment transport capacity along-channel. We thus expect that where the floodplain spatially narrows, the bed is eroded during peak flows (hypothesis 1b).

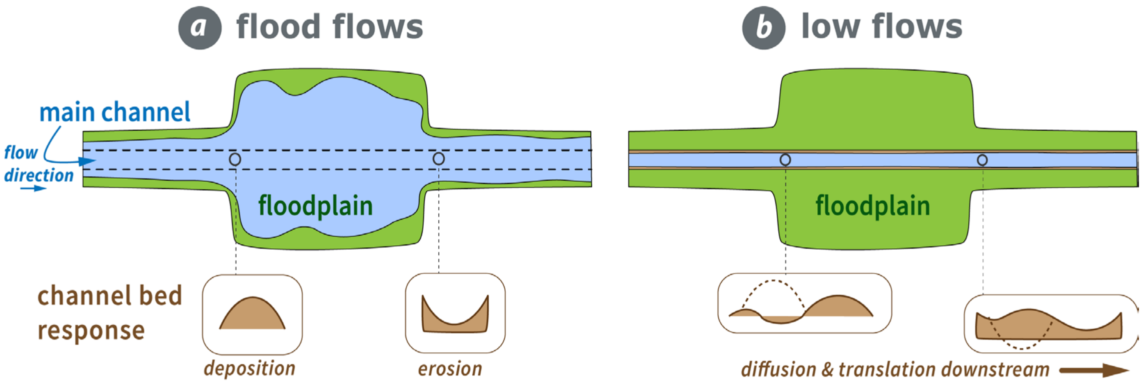

Figure 1. Hypothesized channel response due to longitudinal changes in floodplain width during (a) flood flows and (b) low flows.

During relatively low flow conditions (Fig 1b) where the flow is limited to the main channel with a constant width but is still high enough to transport sediment and rework the channel bed, the flow is no longer affected by spatial gradients in lateral confinement. Instead, the river responds to the morphodynamic changes that took place during previous floods. The flow velocity gradients resulting from the deposition mound and erosion pit created during the last flood cause the mound and pit to translate and disperse primarily downstream with mild spreading upstream. Thus, under low flows we expect a dispersive and diffusive effect of the intra-flood morphodynamic disturbances (hypothesis 2).

If the high and low flow hypotheses are valid (Fig 1), the bed elevation response in regions with gradients in floodplain width should show cyclic behavior between flood- and low-flows, the sign of which depends on whether the river widens or narrows in the downstream direction (hypothesis 3).

2 METHODS

2.1 *Data & Study Site*

To analyze bed elevation changes during high and low flow events, we use high-resolution bathymetry measurements from the Waal River in the Netherlands collected at bi-weekly intervals over the last 20 years (Fig 2, Van Denderen et al. (2022a): Supplemental Data). The Waal River is the southern branch of the Rhine River, flowing west from the Dutch-German border and discharging in the Atlantic Ocean. It is a heavily engineered channel with historic interventions that include manual channel narrowing, groyne construction, dam installation, and side-channel construction (Ylla Arbós, 2021). The mean annual maximum in daily discharge at Lobith is 6,650 m^3/s, and the mean discharge during the summer months (July-September) is 1,880 m^3/s according to mean daily streamflow data from the last century. To test the hypotheses proposed in Section 1.2, we select a study section with fewer floodplain interventions where there are variations in floodplain width in combination with relatively constant width main channel (Fig 2b). This section has an average width of 250m and average bankfull depth of 9m.

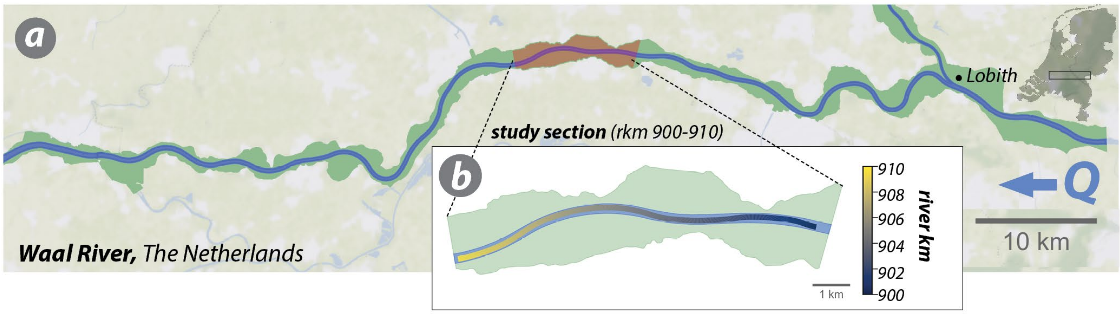

Figure 2. Site map of (a) the entire Waal River in the Netherlands and (b) the section focused on in this study (river km 900-910). Floodplains are plotted in green and the main channel is plotted in blue (channel and floodplain data from: Hoefsloot & Volleberg (2013)). The colored overlay in the main channel shows river km, defined along the main channel axis from an origin of Lake Constance (Bodensee).

2.2 *Bed elevation and discharge analysis*

To detangle the dynamic component of bed elevation response from long-term, profile-scale adjustments, we identify bed elevation variation on longitudinal scales of 300m – 4km using the wavelet analysis presented in Van Denderen et al. (2022a). These length scales are longer than the Waal River groyne spacing (~200m) to filter out bed changes that may occur locally as a result of groynes. Previous work suggests these length scales are also typically most affected by discharge variations (Van Denderen et al. 2022a & 2022b). Average river bed variation is computed for eight discharge categories to identify the typical morphodynamic response to different flow conditions. We characterize the degree of difference in bed elevation changes between high and low flows using a linear fit (Fig 3a & 3b). We calculate the total range of bed level change across all discharge conditions, $\Delta\eta$, from the slope of this fit ($\delta\eta/ \delta Q$) multiplied by the total discharge range (Q_7- Q_0) (Fig 3b).

2.3 *Floodplain geometry analysis*

We characterize spatial changes in floodplain width to understand whether this corresponds to strong differences between high- and low-flow bed elevation variations. To quantify floodplain width, we generate a centerline of the Waal main channel and measure floodplain width at transects perpendicular to this line at ~5m spacing along the study section (Fig 2b). The difference in bed level variation between high and low flows ($\Delta\eta$) is compared to streamwise changes in floodplain width to identify whether the degree of difference between high and low flow bed elevation changes are explained by spatial gradients in floodplain width.

3 RESULTS & DISCUSSION

Along the study reach we observe streamwise variation in the bed elevation changes at high and low flows (Fig 3d) that often co-occurs with changes in floodplain width (Fig 3c). In some locations such as river km 903.2 (Fig 3a), high flows tend to erode whereas low flows deposit. This results in a negative Δη (local minimum in Fig 3e) and occurs just after the floodplain narrows by 225m over 200m in the streamwise direction. This is the most rapid decrease in floodplain width (gradient of -1.1 m/m) across the five major sections of floodplain narrowing highlighted in Fig 3c. We also note three other locations where high flows tend to be erosional which also occur just after floodplain narrowing: river kms901.3, 905.8, & 908 (blue arrows in Fig 3e). This provides support for hypothesis 1b: that where there is spatial narrowing of the floodplain, we will see erosion during peak flows.

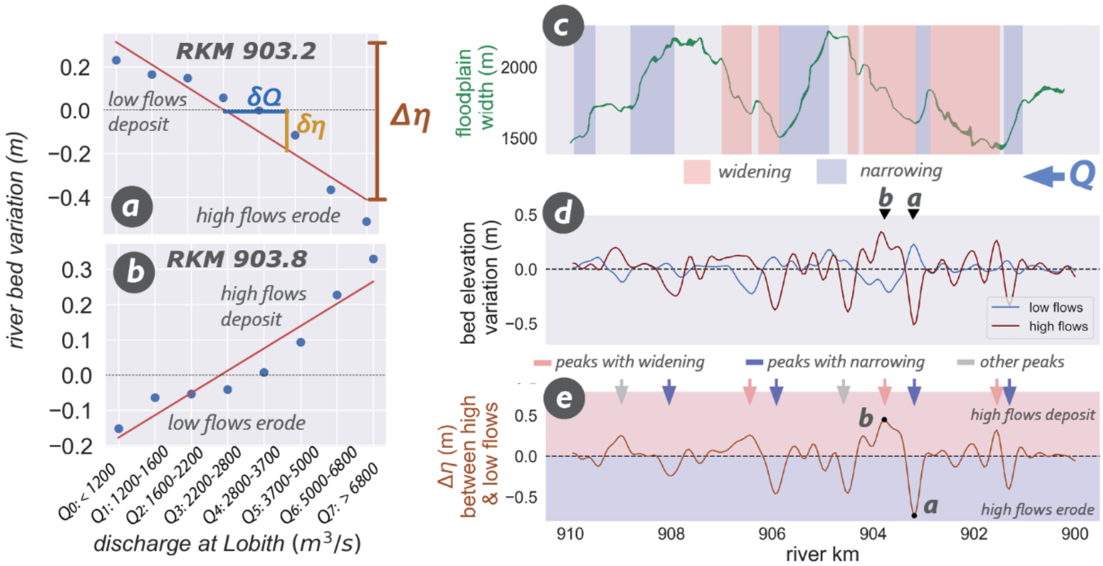

Figure 3: (a) and (b) show river bed variation for eight discharge categories for sections where high flows are erosional vs. depositional respectively. A linear fit is plotted on each; (a) shows the calculation of Δη from the slope of the fit, (δη/δQ), multiplied by the total discharge range, (Q_7- Q_0). (c) Along-channel floodplain width vs river km; sections of relatively continuous widening or narrowing of more than 200m are highlighted. (d) along-channel bed elevation variation for the highest and lowest discharge categories. (e) along-channel variation in Δη; positive values indicate that high flows typically deposit while low flows erode while negative values indicate that high flows typically erode while low flows deposit.

In other locations such as river km 903.8 (Fig 3b), high flows deposit and low flows erode. This results in a positive Δη and occurs just after a local minimum in floodplain (river km 903.1, Fig 3c) where the floodplain widens by 390 m over 1km (gradient of +0.4 m/m). We highlight two other locations where high flow deposition occurs with floodplain widening (river kms 901.5 & 906.4, red arrows in Fig 3e). This provides support for hypothesis 1a: that where there is spatial widening of the floodplain, we will see deposition during peak flows.

Notably, where high flows are most erosional (local peaks in the red line, Fig 3d) or most depositional (local minima in the red line, Fig 3d) there is a tendency for low-flow bed elevation change to 'mirror' these morphodynamic changes with the opposite effect (Fig 3d, blue line). This results in an amplification of the local maxima and minima in Δη (Fig 3e) and provides support for hypothesis 2: that under low flow conditions, we expect a dispersive and diffusive effect of the intra-flood morphodynamic disturbances. This is because during low flow conditions gradients in sediment transport capacity are not driven by floodplain width changes, but are instead a result of the morphodynamic changes that took place during the flood.

The streamwise variation in Δη representing fluctuations between regions of erosional and deposition high flows along the study reach (Fig 3e) additionally supports hypothesis 3: that bed elevation change will show cyclic behavior between flood- and low-flows, with a positive Δη if the floodplain spatially widens and a negative Δη if the floodplain spatially narrows. Floodplain narrowing appears to exert a slightly stronger effect than floodplain widening along the study section; there is a slight bias towards more abrupt minima in Δη (Fig 3e) with the range of Δη (-0.7 to +0.4m) extending towards slightly more negative values.

Not all peaks in Δη are explained by floodplain widening or narrowing. There are local minima and maxima at river kms 904.6 and 909.3 respectively that do not clearly correspond to floodplain width gradients (Fig 3e). Scrutiny of aerial imagery and Digital Terrain Models of this study section reveal other floodplain structures that can influence the spatial extent of flood flows before the distal floodplain boundaries, particularly in the western half of the study reach.

The greatest difference between peak- and low-flow bed elevation changes is strongest when the main channel nears the floodplain; minima in Δη noted in Fig 3e consistently co-occur with the smallest lateral distance between the channel and nearest floodplain boundary. This effect could either further constrain flow in the main channel or force floodplain flow to traverse the main channel towards the opposite side of the floodplain. Where floodplain flow is forced to cross the channel, discharge is added-to and subsequently expelled-from the main channel (Fig 4). This compound flow exchange can shift the position of maximum main channel velocities in comparison to solely main channel flow (Blom, 1997 & Ervine et al. 1993), which may amplify the difference in bed elevation change between low and high flows by increasing erosion and deposition at these locations during floods (Fig 4).

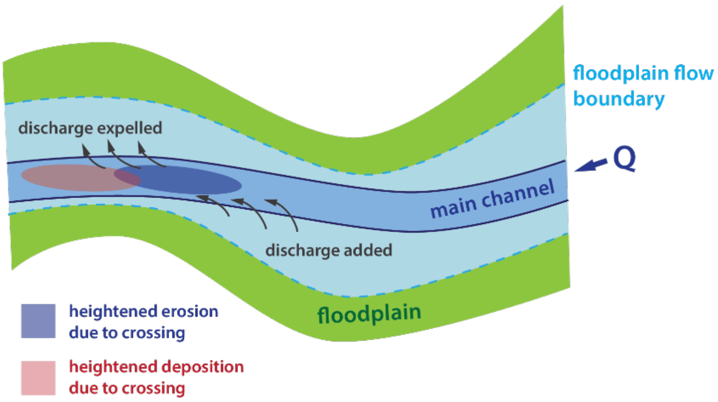

Figure 4: Hypothesized effect of floodplain discharge crossing the main channel during peak flows with compound main channel and floodplain flow. The erosional effect during peak flows is heightened where discharge is added from the floodplain to the main channel. The depositional effect during peak flows is heightened just downstream, where flow is expelled from the main channel back onto the floodplain.

For a simple, straight channel (e.g. Fig 1), we may expect Δη to scale with gradients in floodplain width (ΔW), where greater floodplain constrictions and expansions result in more pronounced differences in bed elevation changes between high and low flows. Fig 5 shows Δη plotted against ΔW for two sections along the channel (river km 901 – 902 & 902.5 – 904) where the floodplain narrows and subsequently widens (Fig 3c). While the data in Fig 5b & 5c often overlap, or parallel the 1:1 relationship between Δη and ΔW, the trend is not consistent along the channel; we identify three different trends in Δη vs ΔW for the two sections (Fig 5b & 5c), some of which adhere to the scaling relationship between width gradient and bed elevation variation within and between peak flows and some of which deviate from the expected behavior.

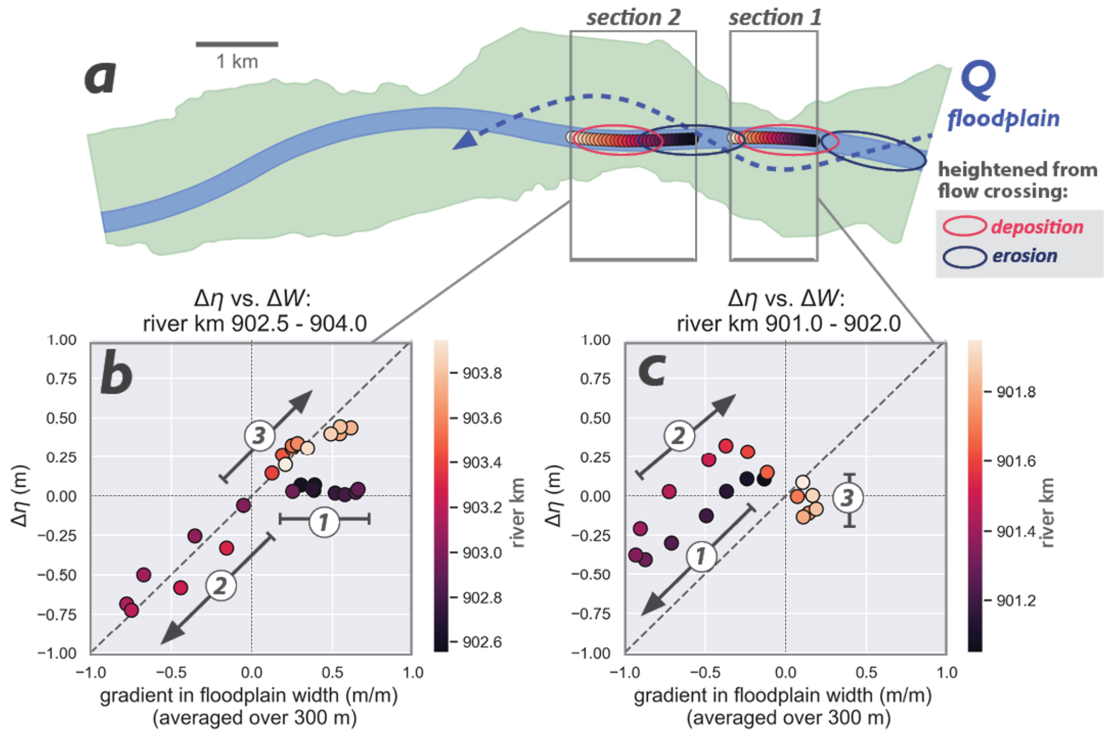

Figure 5. The relationship between Δη (variation between peak and low flows) and ΔW (gradient in floodplain width) for two example sections. (a) shows the location of these sections along the study reach. The location of the floodplain centerline is delineated to highlight regions of potential floodplain flow crossing and resultant depositional/erosional patches corresponding to the schematic in Figure 4. (b) and (c) show Δη vs. ΔW for section 2 (river km 902.5-904) and section 1 (river km 901-902) respectively. Data points are plotted every 50m and colored by river km. The grey dashed line shows the 1:1 relationship as a prospective scaling behavior under the straight-channel conditions shown in Fig 1. Numbers 1, 2, & 3 on each plot denote different bulk trends within each section where differences are explained in relation to expected regions of floodplain flow crossing due to channel and floodplain meandering.

Floodplain flow crossing during peak flows may explain why the relationship between local bed elevation variation between high and low flows, Δη, and local gradient in floodplain width, ΔW, changes along-channel. Within the study section, the centerline of the floodplain meanders more than the main channel, crossing the main channel just upstream of section 1 and again near the start of section 2 (Fig 5a). Based on the hypothesis presented in Fig 4, floodplain flow traversing the main channel can cause regions of heightened erosion and deposition where water is added and subsequently expelled from the main channel. Considering these regions (Fig 5a) we explain the change in relationship between Δη vs. ΔW for sections 1 and 2 as follows:

In the upstream portion of section 1 (Fig 5c, trend 1), Δη becomes increasingly negative (erosional peak flows) as the floodplain narrows (-ΔW), however, this trend is shifted above the 1:1 line towards more positive Δη values which may be explained by the depositional effects of flow crossing at the same location (Fig 5a). As the floodplain gradient becomes less negative (trend 2), there are even tendencies towards deposition at peak flows despite a -ΔW. The floodplain then becomes relatively constant width (trend 3), with minimal to slightly negative changes in bed elevation, perhaps due to the floodplain centerline re-crossing the main channel near the end of section 1.

In section 2 (Fig 5b), despite floodplain widening in the upstream section there is relatively minimal bed elevation variation between high and low flows (trend 1). This may be explained by the erosional influence of floodplain flow crossing which co-occurs with the beginning of section 2 (Fig 5a). As the floodplain subsequently narrows (trend 2), there is a strong trend towards -Δη (erosional peak flows) which may be due to the overlapping effects of floodplain narrowing and flow crossing (Fig 5a). The floodplain then widens in the same location where the depositional effect of flow-crossing is expected (trend 3) causing $\Delta\eta$ to increase positively with $+\Delta W$.

While the relationships between $\Delta\eta$ and ΔW in Fig 5b & 5c suggest that both gradients in floodplain width and floodplain flow crossing are important in driving cyclic variation in low vs. high flow bed elevation change, compound channel and floodplain flow is a complex three-dimensional process; further comparison of main channel flow velocities during low flow vs. peak flow conditions are needed to confirm whether the locations of floodplain flow crossing indeed dictate the strength of the relationship between $\Delta\eta$ and ΔW. Since it is relatively rare to find straight natural channels within a variable-width floodplain (e.g. Fig 1), future morphodynamic modeling studies of idealized planform channel geometries will be useful for flushing out the relative role of floodplain width gradients vs. floodplain flow-crossing in driving bed elevation variation within and between peak flows.

4 CONCLUSIONS

In this study, we find cyclic behavior in bed elevation variation between high and low flows that depends on whether the floodplain width spatially increases or decreases. Flood flows tend to deposit where streamwise widening of the floodplain causes streamwise decreases in flow velocities, and flood flows tend to erode where streamwise narrowing of the floodplain causes streamwise increases in velocity. In the same locations, low flows typically show an inverse and dispersive effect, counteracting flood flow bed elevation changes. We quantify the maximum difference in bed elevation change between peak and low flows as $\Delta\eta$, which ranges from -0.7m where the floodplain narrows rapidly along the study reach to 0.4m where the floodplain widens along-channel. Peaks in $\Delta\eta$ appear to be sensitive to the location of the main channel with respect to the floodplain boundary; the strength of the relationship between $\Delta\eta$ and gradient in local gradient in floodplain width also depends on channel location, suggesting that compound flow during floods such as crossing of floodplain flow across the main channel may be important for driving local differences in bed elevation change between peak and low flows. Results from this study suggest that spatial gradients in planform channel geometry are an important factor in estimating intra- and inter-flood morphodynamic change.

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