Water Resources Research

RESEARCH ARTICLE
10.1029/2022WR033714

Key Points:

- Deltaic floodplain connecting channels can modulate asymmetric water partitioning at upstream river bifurcations
- Flow exchange via connecting channels increases the hydrological connectivity of deltaic river networks
- Human disruption of the connecting channel in deltaic floodplains can significantly reduce its modulating function

Supporting Information:

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

Correspondence to:

D. Shao,
ddshao@bnu.edu.cn

Citation:

Gao, W., Wang, Z. B., Kleinhans, M. G., Miao, C., Cui, B., & Shao, D. (2023). Floodplain connecting channels as critical paths for hydrological connectivity of deltaic river networks. *Water Resources Research*, *59*, e2022WR033714. https://doi.org/10.1029/2022WR033714

Received 26 SEP 2022
Accepted 3 APR 2023

Floodplain Connecting Channels as Critical Paths for Hydrological Connectivity of Deltaic River Networks

Weilun Gao[1], Zheng Bing Wang[2,3], Maarten G. Kleinhans[4], Chiyuan Miao[5], Baoshan Cui[2], and Dongdong Shao[2]

[1]Guangdong Provincial Key Laboratory of Water Quality Improvement and Ecological Restoration for Watersheds, School of Ecology, Environment and Resources, Guangdong University of Technology, Guangzhou, China, [2]State Key Laboratory of Water Environment Simulation and School of Environment, Beijing Normal University, Beijing, China, [3]Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, The Netherlands, [4]Department of Physical Geography, Utrecht University, Utrecht, The Netherlands, [5]State Key Laboratory of Earth Surface Processes and Resource Ecology, Faculty of Geographical Science, Beijing Normal University, Beijing, China

Abstract A river bifurcation is critical for distributing water, sediment and nutrients to the downstream branches of deltaic river networks. However, the downstream branches of a bifurcation can be linked by a connecting channel cutting through deltaic floodplains. The floodplain connecting channel as a downstream control can affect water partitioning at the river bifurcation and hence the hydrological connectivity of the river network. However, its effects are still largely elusive. In this study, we explored how a connecting channel linking downstream branches affects water partitioning at the upstream bifurcation and water distribution along the two branches. The investigation was conducted through idealized numerical simulations using Delft3D, followed by analysis of the cascading effects on the hydrological connectivity of river networks using graph theory. The results show that connecting channels can mitigate asymmetric water partitioning at the upstream bifurcation. However, this happens at the expense of inducing more uneven flow at the downstream outlets. The flow adjustment is due to the altered spatial water surface slope in the two branches associated with the flow exchange from one channel to the other via the connecting channel. Further analysis of hydrological connectivity shows that connecting channels can generally reduce the vulnerability of the channel network to hydrological alterations, especially changing inflow, by enhancing flow exchange between the two branches. Our results suggest that connecting channels are critical paths for hydrological connectivity, which have important implications for the management of deltaic river networks and their floodplains.

Plain Language Summary River deltas commonly have multiple channels that form complex networks. Channel networks play important roles in distributing water, nutrients, etc., to deltaic wetlands and coastal habitats and are thus critical for navigation, flood safety, and ecological protection. In a channel network, the upstream discharge is commonly split unevenly into two downstream branches at a river node called a bifurcation. The downstream branches are commonly linked by relatively small connecting channels, forming a channel network of two forked channels linked by shortcut channels. The effects of these shortcut channels on water partitioning at a bifurcation are unclear. We modeled this channel network using a specialized computer program and found that the uneven water partitioning at the bifurcation is significantly reduced due to the connecting channel. The reduced unevenness of water partitioning is due to the balance of the water surface slope in the two downstream branches via the connecting channel acting as a "connected vessel." The connecting channel also enhances the river discharge exchanges in the network to reduce its vulnerability to upstream flow variations. With increasing human interventions on these connecting channels, our results demonstrate their value and the importance of safeguarding them for flood safety and other ecosystem services.

1. Introduction

River deltas, where river channels sculpt their morphology alongside waves and tides, etc., and form deltaic river networks, are of great economic and ecological importance (Edmonds et al., 2020; Gao et al., 2018; Giosan et al., 2014; Jerolmack, 2009; Konkol et al., 2022; Nienhuis et al., 2020; Tejedor et al., 2017). The complicated and splendid topological structure of deltaic river networks functions as natural conduits for the distribution of water, sediment, salinity and organisms along deltaic floodplains and coasts (Tejedor et al., 2017). The evolution of the deltaic river network and its connectivity, determining the water distribution in the river network and its responses to local perturbations, is crucial for both society (navigation, flood defense, etc.) and ecosystems (freshwater and marine habitats) and has received increasing attention in recent years (Chen et al., 2022; Hiatt et al., 2022; Konkol et al., 2022; Salter et al., 2020; Tejedor et al., 2017). With growing human interventions in deltaic river channels, understanding the response of their hydrological connectivity can help improve the management and restoration of river deltas (Bain et al., 2019; Chen et al., 2022).

Hydrological connectivity is of critical importance for ecosystem functioning and has been widely explored in different subsystems in river deltas, such as river networks (Chen et al., 2022; Tejedor et al., 2015a, 2015b) and channel-island systems (Hiatt et al., 2018; Wright et al., 2018). Among them, the topological structure of large-scale deltaic river networks in relation to hydrological connectivity has been recently investigated (Chen et al., 2022; Hiatt et al., 2022; Tejedor et al., 2015b, 2017), in which water partitioning at bifurcations has been the focus thus far (Dong et al., 2020; Hariharan et al., 2022; Tejedor et al., 2015a). The changes in water partitioning at bifurcations result in altered water distribution in the downstream channels and hence modified hydrological connectivity of the entire river network (Chen et al., 2022). Therefore, understanding water partitioning at river bifurcations is crucial for the long-term evolution of deltaic river networks and the associated hydrological connectivity (Chen et al., 2022; Edmonds et al., 2021; Ragno et al., 2020; Salter et al., 2020; Tejedor et al., 2017; Wang et al., 1995).

Typically, water partitioning at a river bifurcation is explored at the channel scale (Edmonds et al., 2021; Kleinhans et al., 2013). A river bifurcation tends to be asymmetric due to its intrinsic instability, leading to an uneven partitioning of river discharge, sediment load and nutrients to the downstream branches (Kleinhans et al., 2013). Many studies have explored how water (and sediment) partitioning is affected by the morphological characteristics of river bifurcations, such as curvature (Kleinhans et al., 2008), external forcing, such as tides (Buschman et al., 2010; Ragno et al., 2020), and downstream controls, such as river mouth progradation and slope differences between the two downstream branches (Redolfi et al., 2019; Salter et al., 2018).

However, in deltaic river networks, many downstream branches can rejoin in a downstream confluence (termed a "bifurcation-confluence unit" (Ragno et al., 2021)) or be linked by connecting channels cutting through the floodplain (termed a "bifurcation-connecting channel unit" and see Figure 1 for some examples), creating an anastomosing river pattern (Makaske, 2001; Marra et al., 2014; Nanson & Knighton, 1996; Tejedor et al., 2015a). The bifurcation-connecting channel unit consists of two branches splitting at an upstream bifurcation and a connecting channel further splitting from one of the branches and joining the other branch (see Figure 1). These floodplain connecting channels, on the one hand, are important conduits linking rivers and floodplains and sustaining fluvial ecosystems (Abrial et al., 2019; Sumaiya et al., 2021; Trigg et al., 2012; Tull et al., 2022). On the other hand, the connecting channel between the two branches can also act as a downstream control affecting the hydrodynamics in the two branches, such as their slope difference. The dynamics of the slope difference between the two downstream branches can further result in the adjustment of water partitioning at the upstream river bifurcation (Redolfi et al., 2019) and hence the hydrological connectivity of the river network. However, this effect is largely elusive to date.

To explore the relevant effects, we conducted idealized numerical simulations using Delft3D with a schematized "bifurcation-connecting channel unit." A variety of scenarios with varying combinations of river discharge at the upstream channel, slope difference between the two downstream branches and geometry of the connecting channel, including depth and width, were adopted to explore the effects of the connecting channel on water partitioning at the upstream river bifurcation. Based on the simulation results, the cascading impacts on hydrological connectivity, as well as the implications for the stability of river bifurcation and deltaic restoration, are also discussed.

This study aims to investigate how downstream floodplain connecting channels can affect water partitioning at the upstream bifurcation and the hydrological connectivity of deltaic river networks. Therefore, the numerical simulations focused on the in-channel hydrodynamics to explore the relevant mechanisms as appropriate. Notably, river channels can also connect with floodplains through flood-induced overbank flow in natural deltas (Hiatt et al., 2018; Nardin & Edmonds, 2014). However, this rarely occurs in urbanized deltas with flood defense structures in place and is therefore not considered in this study.

Figure 1. Examples of connecting channels in river deltas, braided rivers and anastomosing rivers: (a) the Dongjiang Delta (a subdelta of the Pearl River Delta) and (b) the Hanjiang Delta, in Guangdong, China, (c) the Wax Lake Delta, USA, (d) braided channels of the Wilberforce River, New Zealand, and (e) anastomosing channels of the Yukon River, USA. (f) A schematic showing the interactions between rivers and their floodplain through the floodplain connecting channels. Satellite images are from Google Earth (https://earth.google.com/).

2. Methodology

2.1. Model Setup

In this study, we used idealized numerical simulations with schematized geometry and generic modeling parameters to investigate and quantify how a connecting channel affects the water partitioning of a bifurcation. The numerical simulations were conducted using the Delft3D model (Lesser et al., 2004), which is commonly adopted to explore water partitioning at river bifurcations through idealized numerical simulations (Buschman et al., 2010; Edmonds & Slingerland, 2008; Iwantoro et al., 2022). As shown in Figure 1, connecting channels cutting through floodplains are common in river deltas (Cox et al., 2021; Nanson & Knighton, 1996; Salter & Lamb, 2022; Swinkels et al., 2009), such as the Dongjiang Delta, which is a subdelta of the Pearl River Delta, as well as the Hanjiang Delta, in Guangdong, China, and the Wax Lake Delta in the USA. These river deltas can be populous or uninhabited. Similar floodplain connecting channels linking bifurcating channels are also widely found across braided and anastomosing rivers worldwide (e.g., Hiatt et al., 2020; Marra et al., 2014; Nanson &

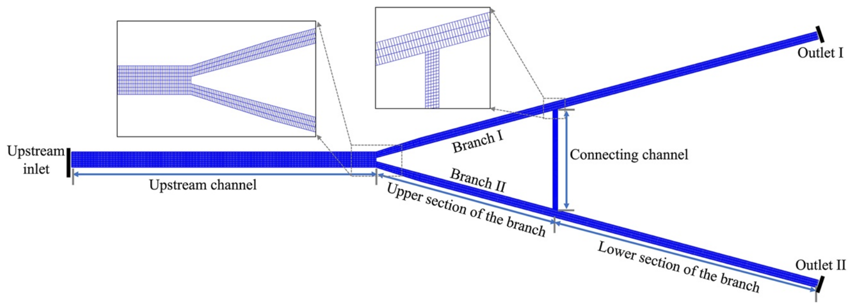

Figure 2. Computational domain of the schematized river bifurcation with an upstream river channel splitting into two downstream branches and the connecting channel connecting the two downstream branches. The two branches are separated into an upper section and a lower section upstream and downstream of the connections between the branches and the connecting channel.

Knighton, 1996; Nicholas et al., 2013) (Figure 1). Notably, some connecting channels emerge downstream of the river bifurcation and connect the two downstream branches, while others connect different waterways (Bain et al., 2019; Marra et al., 2014). In this study, we focus on the "bifurcation-connecting channel unit" (see examples in Figure 1) that has a connecting channel between the two bifurcating branches.

Table 1
Simulation Scenarios With Different Combinations of Boundary Conditions and Geometry of the Connecting Channel

RunID	River discharge Q_u (m^3/s)	Water level at two outlets: H_1 (m)	Water level at two outlets: H_2 (m)	Width of connecting channel B_t (m)	Bed level of connecting channel D_t (m)
R01	2,500	0	0	N. A.	N. A.
R02	2,500	0	−0.5	N. A.	N. A.
R03	2,500	0	−0.5	150	−4
R04	2,500	0	−0.5	90	−4
R05	2,500	0	−0.5	150	−2
R06	2,500	0	−0.5	90	−2
R07	2,000	0	0	N. A.	N. A.
R08	2,000	0	−0.5	N. A.	N. A.
R09	2,000	0	−0.5	150	−4
R10	2,000	0	−0.5	90	−4
R11	2,000	0	−0.5	150	−2
R12	2,000	0	−0.5	90	−2
R13	1,500	0	0	N. A.	N. A.
R14	1,500	0	−0.5	N. A.	N. A.
R15	1,500	0	−0.5	150	−4
R16	1,500	0	−0.5	90	−4
R17	1,500	0	−0.5	150	−2
R18	1,500	0	−0.5	90	−2
R19	1,000	0	0	N. A.	N. A.
R20	1,000	0	−0.5	N. A.	N. A.
R21	1,000	0	−0.5	150	−4
R22	1,000	0	−0.5	90	−4
R23	1,000	0	−0.5	150	−2
R24	1,000	0	−0.5	90	−2

Therefore, we schematized the computational domain as shown in Figure 2 without loss of generality. An upstream river channel splits into two symmetric downstream branches without curvature at the river bifurcation, following the generic settings of river bifurcations in previous studies (Buschman et al., 2010; Edmonds & Slingerland, 2008; Iwantoro et al., 2022). A straight connecting channel cutting through the floodplain further connects the two branches at two-fifths of their total length from the bifurcation to the outlet, separating the downstream branch into an upper section and a lower section (Figure 2).

The upstream river channel and downstream branches have constant widths of 500 and 250 m, respectively, with rectangular cross sections. A constant bed slope of 1×10^{-4} was adopted from the upstream channel to the downstream branches, resulting in bed elevations ranging from −2.5 m at the upstream boundary to −5 m at the two outlets. The width and bed level of the connecting channel range from 90 to 150 m and from −4 to −2 m, respectively. Notably, the widths of the branches at the bifurcation are 187.5 m due to the loss of two grid cells at the bifurcation (Figure 2), which are gradually widened to 250 m in a length of 50 grid cells.

Constant river discharge ranging from 1,000 to 2,500 m^3/s was imposed at the upstream boundary, while constant water levels were prescribed at the two downstream boundaries, neglecting tides. As such, we focus on the conditions when fluvial forcing is dominant. The water levels at the two outlets were set to 0 m for the baseline scenarios, which were further varied between the two outlets to create a slope difference between the two downstream branches and hence asymmetric water partitioning at the bifurcation (see Table 1). Notably, asymmetric water partitioning at the bifurcation can also be induced by adopting different lengths or bed slopes of the two downstream branches. However, the connecting channel is also able to reduce the asymmetry of water partitioning in such cases (see Figures S1 and S2 in Supporting Information S1). Nonetheless, the water level difference at the two outlets is more convenient to implement in this study by changing the downstream boundary conditions. A constant Chezy coefficient of 65 m$^{1/2}$/s was adopted. All simulations were conducted with a fixed bed. The long-term morphodynamics of the river channels were not considered in the model, which is also subject to upstream sediment supply.

2.2. Scenario Design

Baseline scenarios with identical water levels of 0 m at the two outlets were run to show the symmetric water partitioning at the upstream bifurcation with or without the connecting channel. Then, we lowered the water level at Outlet II to −0.5 m, creating a slope difference in the water surface between two downstream branches and hence asymmetric water partitioning at the upstream bifurcation without the connecting channel. Afterward, we added a connecting channel linking the two downstream branches to investigate how the connection can modulate asymmetric water partitioning. The width and depth of the connecting channel were further varied to explore how the alteration of the connecting channel caused by human activities such as land reclamation, affects the water partitioning at the upstream bifurcation. The simulation scenarios are listed in Table 1. Notably, the results with different channel widths of the two branches and different water level differences prescribed at the downstream outlets are provided in Figures S3–S6 of Supporting Information S1, which do not change the conclusions of this study.

In this study, the combination of upstream river discharge (1,000–2,500 m^3/s), the width-to-depth ratio (115–150) and bed slope of 1×10^{-4} were mainly derived from relatively wide and shallow lowland rivers with considerable discharges (Caldwell et al., 2019; Iwantoro et al., 2021; Kleinhans & van den Berg, 2011; Syvitski & Saito, 2007), such as the lower reach of the Dongjiang River (forming a subdelta of the Pearl River Delta, China) (Liu et al., 2018). Furthermore, the river channel is in a backwater regime with backwater lengths ranging from 45 to 50 km corresponding to the prescribed water depth at the outlet and bed slope, and the maximum Froude number is 0.268 such that the downstream hydrodynamic variations can well affect the upstream flows.

For the model results analyses, asymmetry of water partitioning at the river bifurcation ΔQ_b is defined below following Bolla Pittaluga et al. (2015):

$$\Delta Q_b = \frac{|Q_{b2} - Q_{b1}|}{Q_u} \tag{1}$$

where Q_u is the upstream river discharge, Q_{b1} and Q_{b2} are river discharges supplied to downstream branches I and II, respectively, at the bifurcation. ΔQ_b ranges from 0 to 1, where $\Delta Q_b = 0$ represents symmetric partitioning and increasing ΔQ_b represents more asymmetric partitioning. Similarly, the river discharge difference between the two outlets ΔQ_o is defined as follows:

$$\Delta Q_o = \frac{|Q_{o2} - Q_{o1}|}{Q_u} \tag{2}$$

where Q_{o1} and Q_{o2} are river discharges at the two outlets. ΔQ_o ranges from 0 to 1, where $\Delta Q_o = 0$ represents the same river discharge at the two outlets and increasing ΔQ_o represents a greater difference in river discharges between the two outlets.

The difference in water surface slope between the upper sections of the two branches is defined as follows:

$$\Delta S_u = \frac{|S_{u2} - S_{u1}|}{S_0} \tag{3}$$

where S_0 is the water surface slope in the upstream river channel, S_{u1} and S_{u2} are the water surface slopes in the upper sections of downstream branches I and II, respectively. Similarly, the difference in water surface slope between the lower sections of the two branches is defined as follows:

$$\Delta S_l = \frac{|S_{l2} - S_{l1}|}{S_0} \tag{4}$$

where S_{l1} and S_{l2} are the water surface slopes in the lower sections of downstream branches I and II, respectively. The river discharge and water level data at the end of the simulation were adopted to calculate the water partitioning and water surface slope, when the hydrodynamics along the river channels have already reached equilibrium.

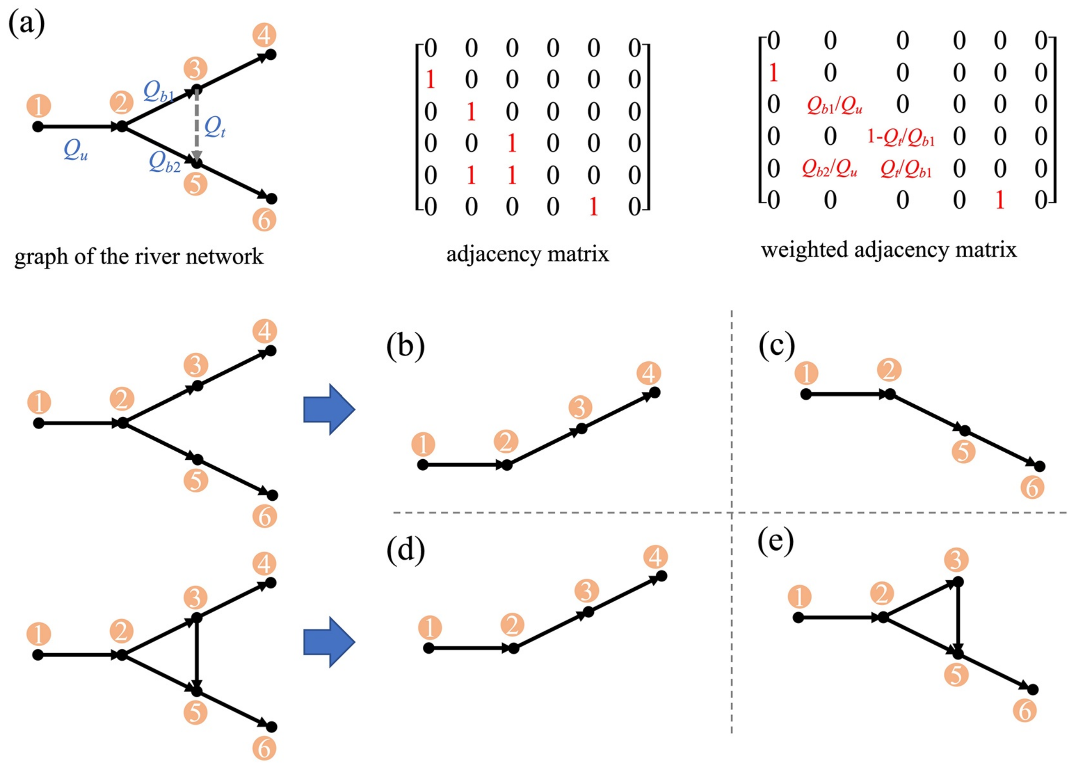

Figure 3. (a) Schematic graph of the river network and its adjacency matrix and weighted adjacency matrix. Panels (b and d) are contributing subnetwork 1 (CSN1), and (c and e) are contributing subnetwork 2 (CSN2) for scenarios without and with connecting channels, respectively. Black solid arrows represent the river segments with assumed flow directions, and filled orange circles indicate the numbering of river vertices.

2.3. Hydrological Connectivity Analysis

Based on our numerical simulations, we were able to calculate the water partitioning at the upstream bifurcation as well as that at the connection between the branches and the connecting channel. Using these water partitioning data, we can further establish the weighted adjacency matrix (Figure 3a) and analyze how the connecting channel can affect the hydrological connectivity based on graph theory (Tejedor et al., 2015a). When representing the river network using graph theory in this study, a vertex denotes a river node (i.e., the upstream apex, a bifurcation or confluence, or a river outlet at the coast), whereas a link indicates a river channel. The nonzero element (m, n) in the adjacency matrix represents a directed link from vertex n to vertex m, that is, a river channel with an upstream vertex n and downstream vertex m. The nonzero element (m, n) in the weighted adjacency matrix represents the fraction of river discharge drained from a parent (upstream) vertex n to its offspring (downstream) vertex m. m and n are the numbering of the vertices in Figure 3.

The outlet contributing subnetwork (CSN) of the "bifurcation-connecting channel" (Figure 2) was first identified in Figure 3. An outlet CSN includes a set of vertices and links that participate in draining river discharge from the upstream inlet to a specific downstream outlet, which is commonly adopted as a basic unit in analyzing the hydrological connectivity of deltaic river networks (Tejedor et al., 2015a). The CSNs corresponding to two outlets in this study are termed CSN1 and CSN2 hereinafter (Figure 3). The inclusion of the connecting channel results in a more complex CSN2 with more vertices and links.

While the changes in CSNs represent topological responses of the "bifurcation-connecting channel unit," global vulnerability (V) and leakage index (LI) were further adopted in this study to assess the dynamic responses of the river network upon its changing topological structure, following Tejedor et al. (2015a) and Tejedor et al. (2015b). Local vulnerability V_{mn}^{i} is first defined for the further calculation of global vulnerability, which describes how much the changes in discharge at a specific outlet can be affected by the local perturbation of discharge in an upstream river channel that drains a fraction of discharge to the specific outlet (Tejedor et al., 2015a). V_{mn}^{i} is

10.1029/2022WR033714

quantified by the ratio of the reduction in discharge at the outlet to the local reduction in discharge at an upstream river channel, that is, an α-reduction in discharge at a river channel can lead to an $\alpha\ V_{mn}^{i}$-reduction of discharge at the outlet (Tejedor et al., 2015a). Following Tejedor et al. (2015a), the local vulnerability of a specific channel can be calculated as follows:

$$V_{mn}^{i} = \frac{p_{mn}^{i}}{Q_{oi}/Q_{mn}} \tag{5}$$

where V_{mn}^{i} represents the local vulnerability of a specific channel *nm* in CSN*i*, p_{mn}^{i} is the fraction of discharge in river channel *nm* that finally drains to outlet *i*, Q_{mn} is the discharge in river channel *nm*, Q_{oi} is the discharge at outlet *i*, and *i* (=1 or 2) is the numbering of the two CSNs in this study. Global vulnerability (*V*) is subsequently calculated by averaging the local vulnerability of all channels in this CSN. A smaller global vulnerability indicates that a reduction in flux (river discharge, nutrient and wash load etc.) in any upstream channel tends to affect the flux at the outlet to a lesser extent, suggesting that the perturbation could be damped in the CSN (Tejedor et al., 2015a).

The leakage index (*LI*) is the fraction of the discharge leaving the CSN by bifurcating channels (Tejedor et al., 2015b), describing the flow exchange between the two CSNs in this study (Figure 3). Following Tejedor et al. (2015b), the leakage index (*LI*) can be calculated as follows:

$$LI^{i} = \frac{\sum_{n\in \mathrm{CNS}i} Q_{n} - \sum_{nm\in \mathrm{CNS}i} Q_{mn}}{\sum_{n\in \mathrm{CNS}i} Q_{n}} \tag{6}$$

where LI^{i} is the leakage index of CNS*i*, Q_n is the river discharge at vertex *n*, and Q_{mn} is the discharge of river channel *nm*. A larger *LI* for a CSN means that a greater fraction of river discharge in the shared river channels drains other CSNs (Tejedor et al., 2015b). Since we only have two CSNs in this study, a larger *LI* thus suggests stronger flow exchange between the two CSNs. Notably, both *V* and *LI* can be calculated using the weighted adjacency matrix (Figure 3a). More details on the relevant methodology can be found in Tejedor et al. (2015a) and Tejedor et al. (2015b).

3. Results

3.1. Water Partitioning at the Upstream River Bifurcation

As shown in Figure 4, the slope difference between the two downstream branches creates asymmetric water partitioning at the upstream bifurcation with ΔQ_b larger than 0. The asymmetry of water partitioning ΔQ_b decreases with increasing upstream river discharge Q_u (black line in Figure 4a). With the existence of the connecting channel linking the two downstream branches, the asymmetry of water partitioning ΔQ_b is significantly modulated (Figure 4). Specifically, the water partitioning becomes almost symmetric when the river discharge is relatively high ($Q_u = 2{,}500\ \mathrm{m^3/s}$), while water partitioning with relatively low river discharges remains asymmetric due to the initially larger asymmetry. When the upstream river discharge is relatively low, a shallower or (and) narrower connecting channel tends to affect the water partitioning to a lesser extent, resulting in an increasing ΔQ_b (Figure 4b). The results suggest that the connecting channel can reduce the asymmetry of water partitioning at the upstream bifurcation, yet with a potentially limited modulating capacity that further depends on its width and depth.

Figure 5a further shows the river discharge difference between the two outlets ΔQ_o for different scenarios with or without the connecting channel. Contrasting with the effects of the connecting channel on the upstream bifurcation, the existence of the connecting channel augments the river discharge difference between the two outlets, that is, ΔQ_o increases when a connecting channel connects the two branches (Figure 5). Furthermore, a wider and deeper connecting channel tends to further increase the difference (Figure 5b).

3.2. Hydrological Connectivity

Based on our numerical simulations, we were able to further quantify the effects of connecting channels on hydrological connectivity. Figures 6a and 6b show that the vulnerability of CSNs for symmetric and asymmetric scenarios without connecting channels have the same value of unity (note that several markers with $V = 1$ overlap

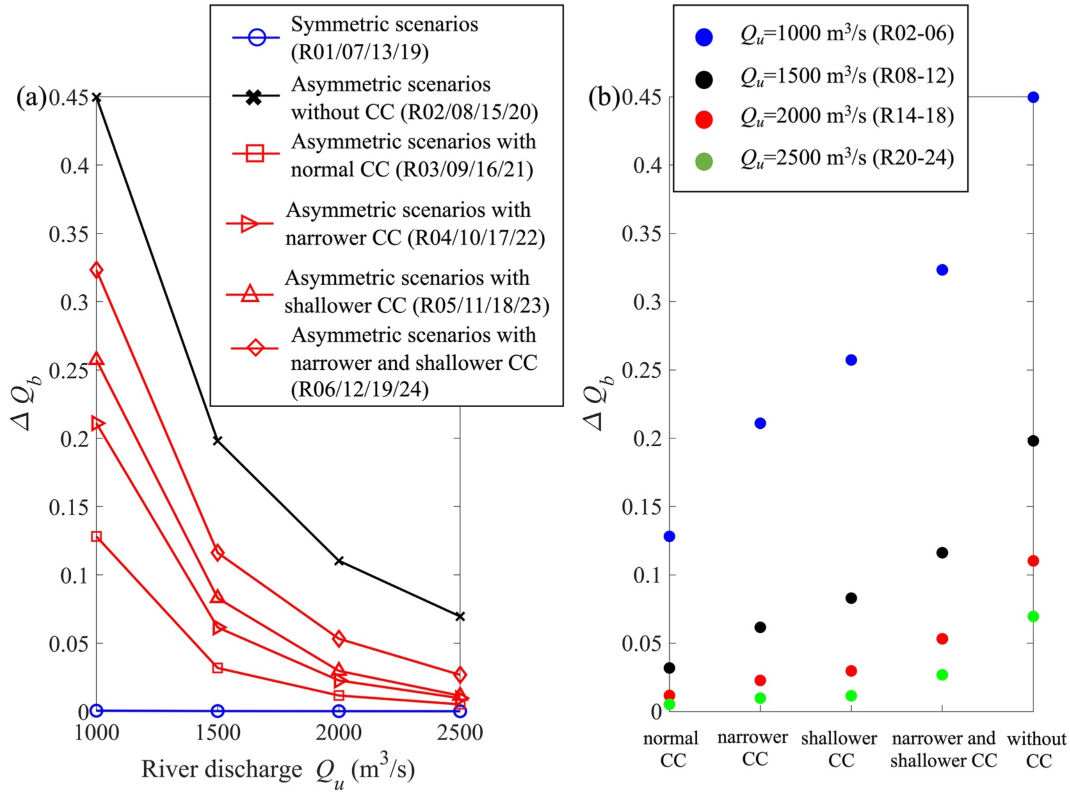

Figure 4. Asymmetry of water partitioning at the upstream bifurcation (ΔQ_b) against (a) upstream river discharge (Q_u) and (b) different scenarios of connecting channels. CC refers to connecting channel.

in Figures 6a and 6b), which means that a reduced fraction of the river discharge in any channel would lead to the same reduced fraction of the river discharge at the outlet. Nonetheless, the existence of the connecting channel that changes the topological structure of the CNSs, not surprisingly, also changes their vulnerability. Specifically, the existence of the connecting channel tends to reduce the vulnerability of CSN2 (Figure 6b), whilst it has no effect on CSN1. The decrease in vulnerability suggests that a reduced fraction of the discharge in any river channel of CSNs would lead to a less reduced fraction of the discharge at the outlet (Tejedor et al., 2015b).

Figures 6c and 6d show that the leakage index of the two CSNs both increase when the connecting channel exists in asymmetric scenarios, suggesting enhanced flow exchange between the two CSNs. Specifically, the existence of the connecting channel can modulate the asymmetric water partitioning at the bifurcation by driving river discharge from CSN2 to CSN1 and act as a conduit that drains river discharge from CSN1 back to CSN2. Increasing the *LI* also tends to reduce the vulnerability of CSN2 by the enhanced flow exchange in the subnetwork (Figure 7), as suggested in Tejedor et al. (2015b).

4. Discussion

4.1. Mechanism of Connecting Channel on Flow Adjustment

The existence of the connecting channel can mitigate asymmetric water partitioning at the upstream river bifurcation and result in a larger difference in river discharges between the two outlets (Figure 4). The opposite effects are presumably due to the varying water surface slope between the upper and lower sections of the two branches modulated by the connecting channel. Figure 8a shows the water level along the upstream channel and the two downstream branches. As different water levels were imposed at the two outlets, the water surface slopes downstream of the bifurcation must be different in the two branches when the connecting channel is absent, leading to a steeper water surface slope in branch II (red lines in Figure 8a). The difference in the water surface slope thus creates asymmetric water partitioning at the upstream river bifurcation (Figure 4a).

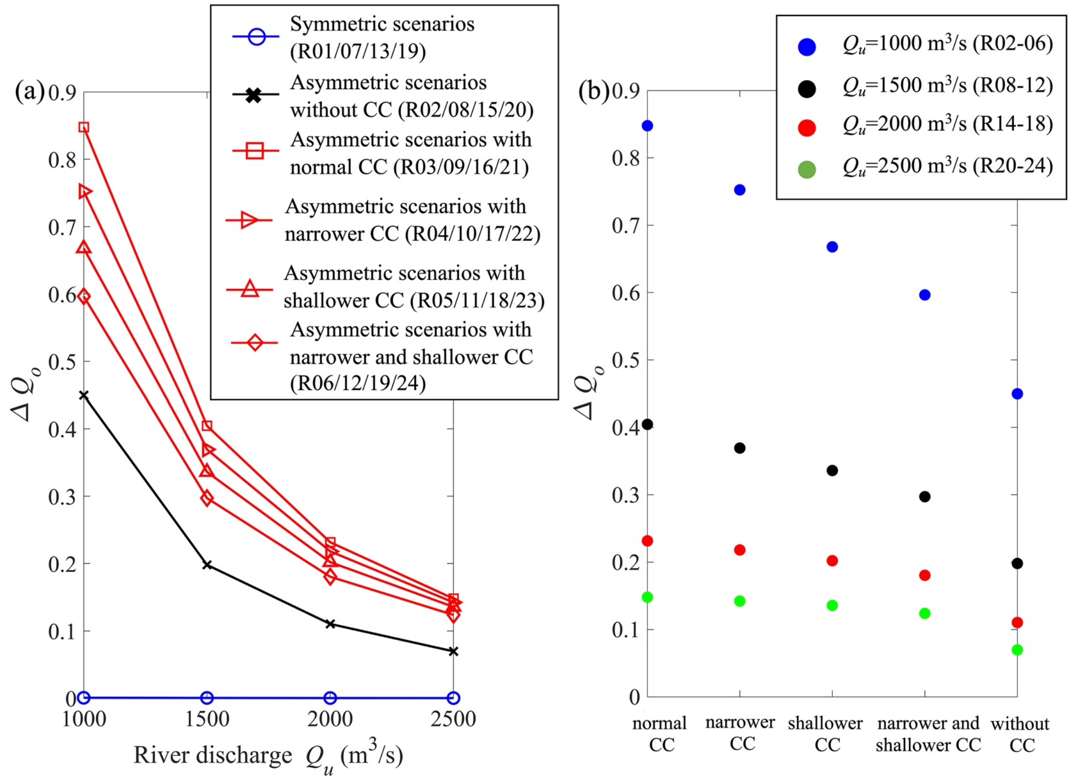

Figure 5. River discharge difference between the two outlets (ΔQ_o) against (a) upstream river discharge (Q_u) and (b) different scenarios of connecting channels. CC refers to connecting channel.

With the existence of the connecting channel between the two branches, the initial water level difference of the two branches (red line in Figure 8b) drives flow from branch I to branch II via the connecting channel, which in turn results in a converged water level in their upper sections (black lines in Figures 8a and 8b). As a result, the water surface slope increases and decreases in the upper sections of branches I and II, respectively (Figure 8c). Therefore, the differences in water level and water surface slope between the upper sections of the branches gradually diminish, leading to the modulation of asymmetric water partitioning at the upstream bifurcation (Figure 4a). Downstream of the connecting channel, the water level difference between the two branches increases at a higher rate as the water level approaches the different water levels imposed at the two outlets (Figure 8b). As a result, the difference in water surface slopes between the lower sections of the branches also increases (Figure 8d), leading to the increases of river discharge difference between the two outlets ΔQ_o (Figure 5a).

In this study, despite the generally increasing water surface slope in the river network with increasing river discharge, Figure 9 shows that the water surface slope difference between the upper sections of the two downstream branches (ΔS_u) decreases, which is consistent with the less asymmetric water partitioning at the upstream river bifurcation with increasing river discharge (Figure 4a). Consistent with the findings in Figures 4b and 5b, a wider and deeper connecting channel can reduce or increase the water surface slope difference between the upper and lower sections, respectively, of the two downstream branches (Figure 9).

The modulation of asymmetric water partitioning at the upstream bifurcation due to downstream controls can also be found in previous studies. In the "bifurcation-confluence unit" where the two downstream branches rejoin at a confluence, Ragno et al. (2021) suggested that the water level for the branch with higher discharge increased at the confluence and thus reduced its water surface slope. The decreasing water surface slope in the dominant branch in turn reduced its river discharge, mitigating the asymmetric water partitioning at the upstream bifurcation. The reduction in the water surface slope in the branch with higher discharge to modulate the asymmetric water partitioning at the upstream bifurcation is similar to our study. Notably, recent studies have also shown that tides with a certain range also tend to result in symmetric water partitioning at a single bifurcation without connecting channels (Iwantoro et al., 2022; Ragno et al., 2020).

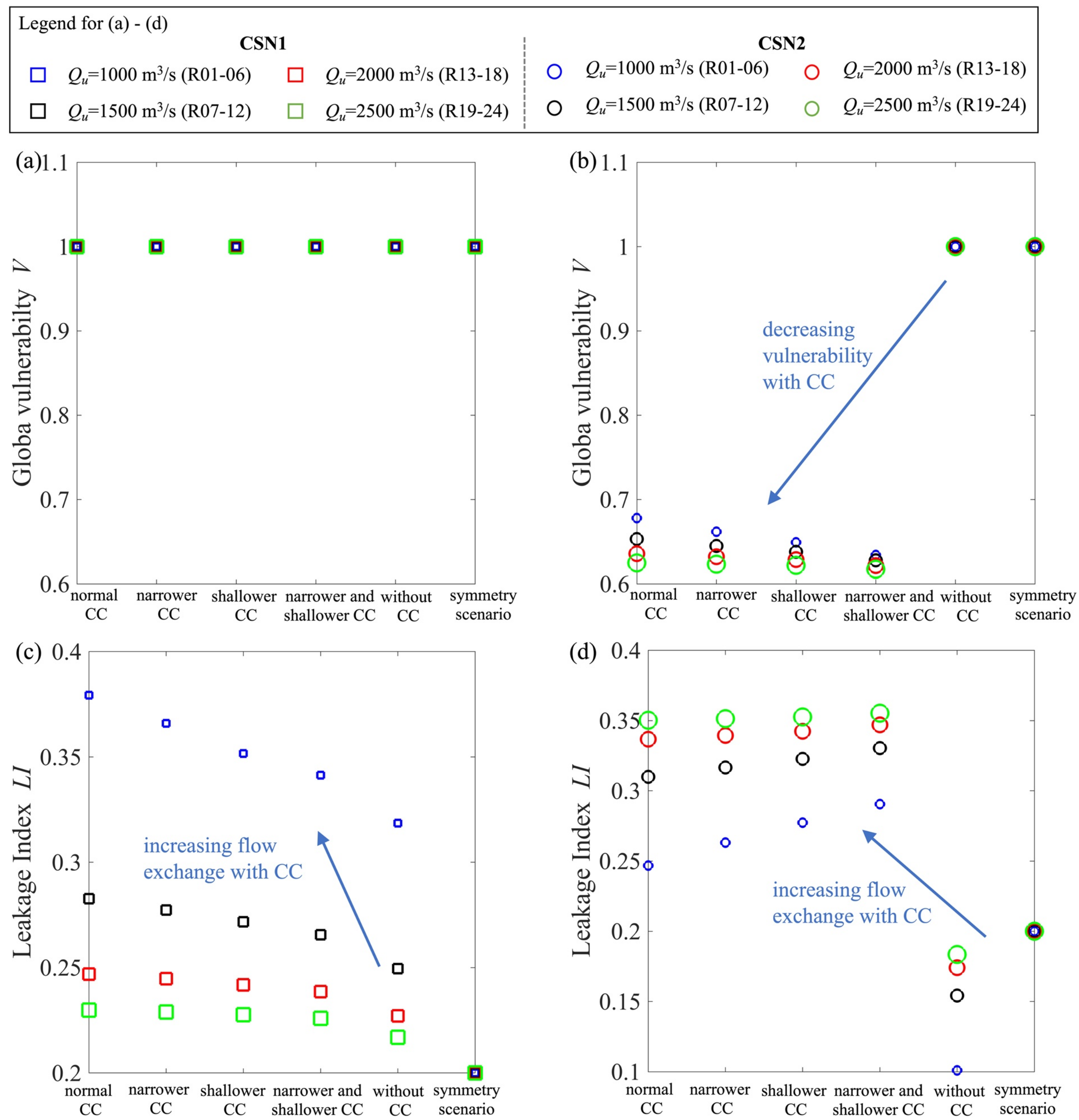

Figure 6. Panels (a and b) are global vulnerability (V), and (c and d) are leakage index (LI) of different contributing subnetworks (CSNs) for different simulation scenarios. Q_u is the upstream river discharge, and CSN and CC refer to the contributing subnetwork and the connecting channel, respectively.

The results of this study were verified in principle against natural cases. The Dongjiang River bifurcates into south and north branches at the apex (located at Shilong) (see Figure S9 in Supporting Information S1). The two branches interconnect each other by the further downstream channels, which could collectively act as proxies for connecting channels. The asymmetry of water partitioning at the delta apex decreases with increasing river discharge (Huang et al., 2022), which is consistent with our findings (Figure 4). Shaw et al. (2021) also showed that the dredging of new connecting channels for navigation in the channel network of the lower Atchafalaya River leads to a decreasing water surface slope in the dominant channel, which is consistent with our results (Figure 8). Interestingly, according to Konkol et al. (2022), deltaic channel networks are also similar to systems such as leaf vascular networks, where the numerous secondary connecting veins link main veins and thus create loops in the network to improve the resilience of the network to perturbations such as vein damage and variations in flow (Katifori et al., 2010).

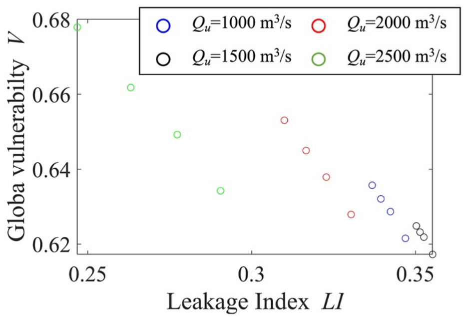

Figure 7. Global vulnerability (V) against leakage index (LI) of contributing subnetwork 2 for different simulation scenarios with connecting channels.

4.2. Importance for the Evolution and Restoration of Deltaic River Networks

The existence of the connecting channel can modulate asymmetric water partitioning at the upstream bifurcation (Figure 4), which could further affect the long-term morphodynamic equilibrium of the bifurcation per se (Edmonds et al., 2021; Kleinhans et al., 2013; Wang et al., 1995). Not surprisingly, the existence of the connecting channel tends to mitigate the difference in sediment supplies to the two branches (see Figure S7 in Supporting Information S1). However, the augmentation of the river discharge difference at the two outlets leads to increasing sediment export of the river network due to the nonlinearity between sediment transport and flow velocity (Ma et al., 2020), that is, increasing river discharge at one outlet leads to disproportionately increasing sediment export that outweighs the reduction in sediment export at the other outlet (see Figure S8 in Supporting Information S1). This suggests that given an identical total river discharge, its variable partitioning can lead to different sediment transport capacities in the river network. The increasing sediment export could generally lead to less sedimentation of river channels and thus enhanced flood safety. Furthermore, the results show that the asymmetry of water partitioning at the upstream bifurcation decreases with increasing upstream river discharge (Figure 4), which implies that the

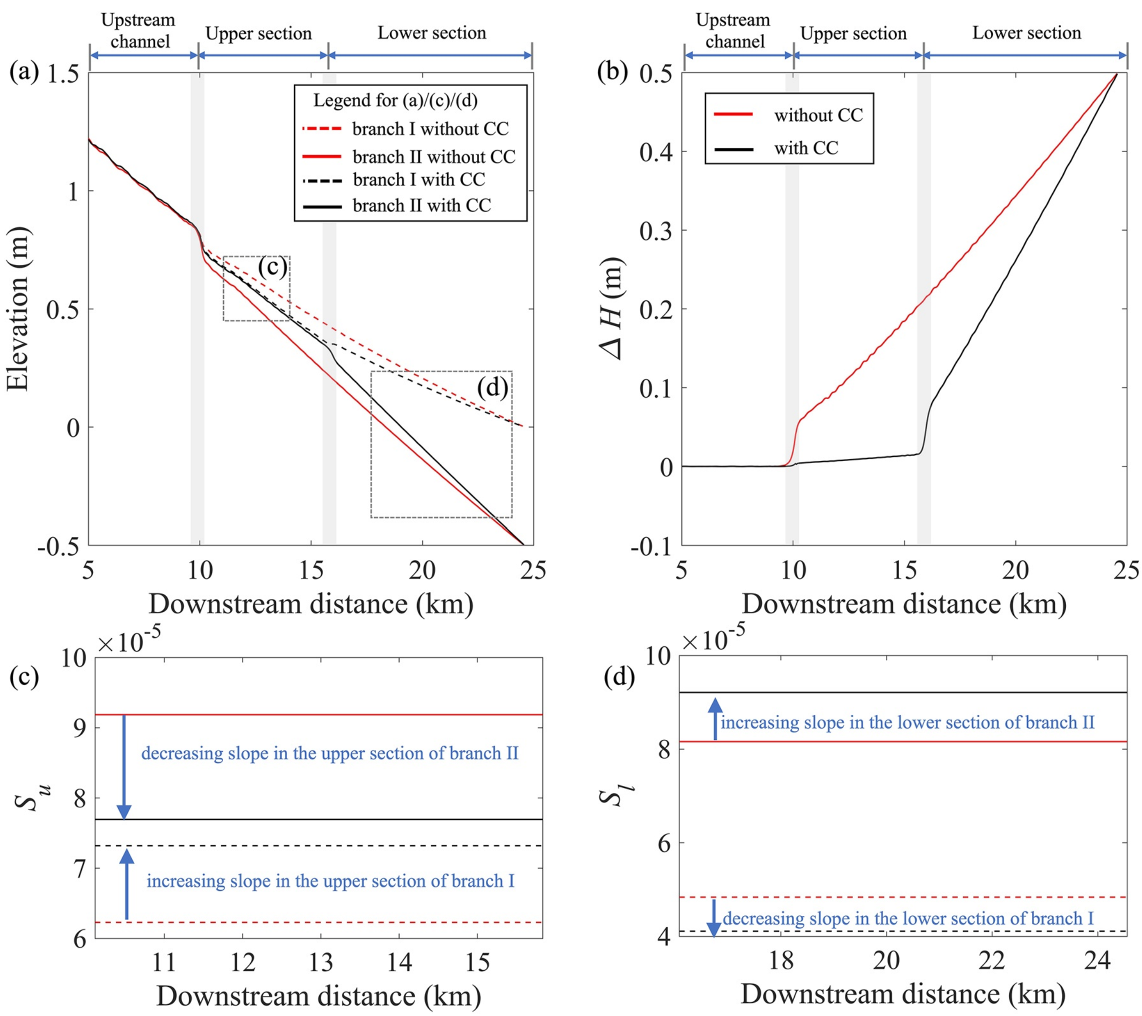

Figure 8. (a) Water level along the two downstream branches for representative scenarios with $Q_u = 2{,}500$ m³/s. (b) Water level difference (ΔH) along two branches. The gray shaded area marks the positions of the bifurcation and the connecting channel. CC in the legend refers to the connecting channel. Panels (c and d) are the average water surface slopes of the upper and lower sections of the two downstream branches.

10.1029/2022WR033714

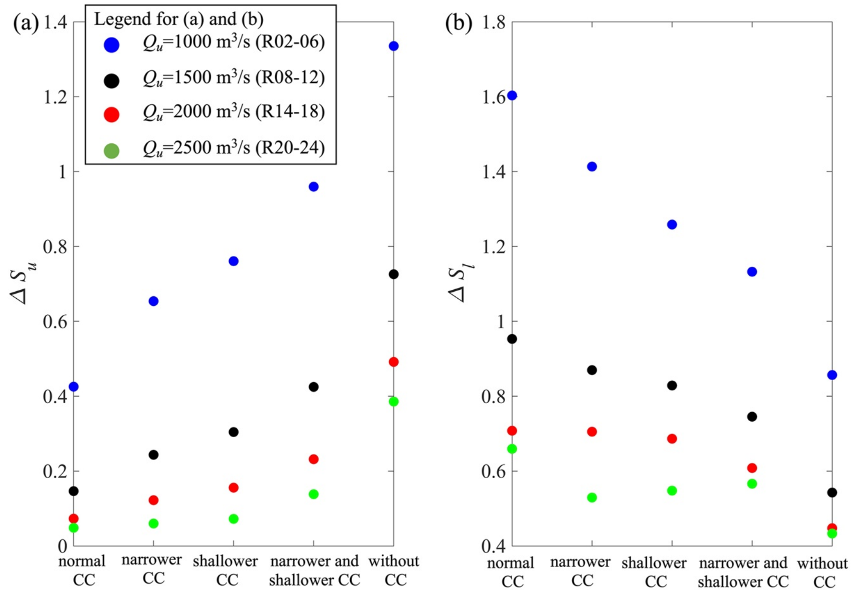

Figure 9. Water surface slope difference between the (a) upper (ΔS_u) and (b) lower (ΔS_l) sections of the two downstream branches for different scenarios of connecting channels. Q_u is the upstream river discharge, and CC refers to the connecting channel.

geomorphologically relevant flows that maintain the connecting channels tend to be smaller, which might help explain why these connecting channels often appear much smaller than the main distributary channels in real deltas. However, the long-term morphological evolution of river channels can in turn affect the water partitioning and sediment transport (Bolla Pittaluga et al., 2015; Edmonds & Slingerland, 2008; Wang et al., 1995). These complexities are beyond the scope of this study and are recommended in future studies.

Although the river discharge difference between the two outlets tends to be greater with the existence of the connecting channel, the vulnerability of the river network is reduced due to the enhanced flow exchange between different river channels (Figures 6 and 7). Therefore, we proposed a conceptual model to illustrate the importance of connecting channels in a large-scale river network as shown in Figure 10. In large-scale river networks, the two main bifurcating branches can interconnect each other via many further downstream connecting channels. These connecting channels in deltaic river networks act collectively as "connected vessels" between two bifurcating river channels, enhancing flow exchange, modulating upstream water partitioning and reducing vulnerability in the river network. Furthermore, these connecting channels create more channel volume to store large floods and help adjust the water level difference between two branches (reduce water level in the dominant branch and increase water level in the other branch, see Figure 8). The decreasing higher water level in the dominant branch could also increase flood safety in river deltas since the risk of flooding largely depends on the extreme water level (Ma et al., 2022; Merz et al., 2021).

4.3. Implications for Floodplain Management

Connecting channels can be relatively small in scale, which are thus easily subject to increasing human interventions in floodplains (e.g., Bain et al., 2019; Cox et al., 2021; Irwin, 1968; Mazzoleni et al., 2021), such as reclamation and construction of flow-regulation devices in densely populated floodplains (Figure 10; see also Figure 1b), resulting in shallower or narrower connecting channels and even the blockage of the connection altogether (e.g., Irwin, 1968; Swanson et al., 2017). A shallower and/or narrower connecting channel plays a lesser role in modulating the asymmetry of water partitioning and reducing the vulnerability (Figures 4b and 6). Additionally, these connecting channels are also of important ecological value for providing aquatic habitats (Abrial et al., 2019). As such, human intervention in connecting channels and its consequences need to be properly monitored and assessed.

Previous studies have suggested that water partitioning at river bifurcations can be increasingly more asymmetric as a result of unevenly deepening river channels due to excessive sand mining (e.g., Chen et al., 2022; Huang

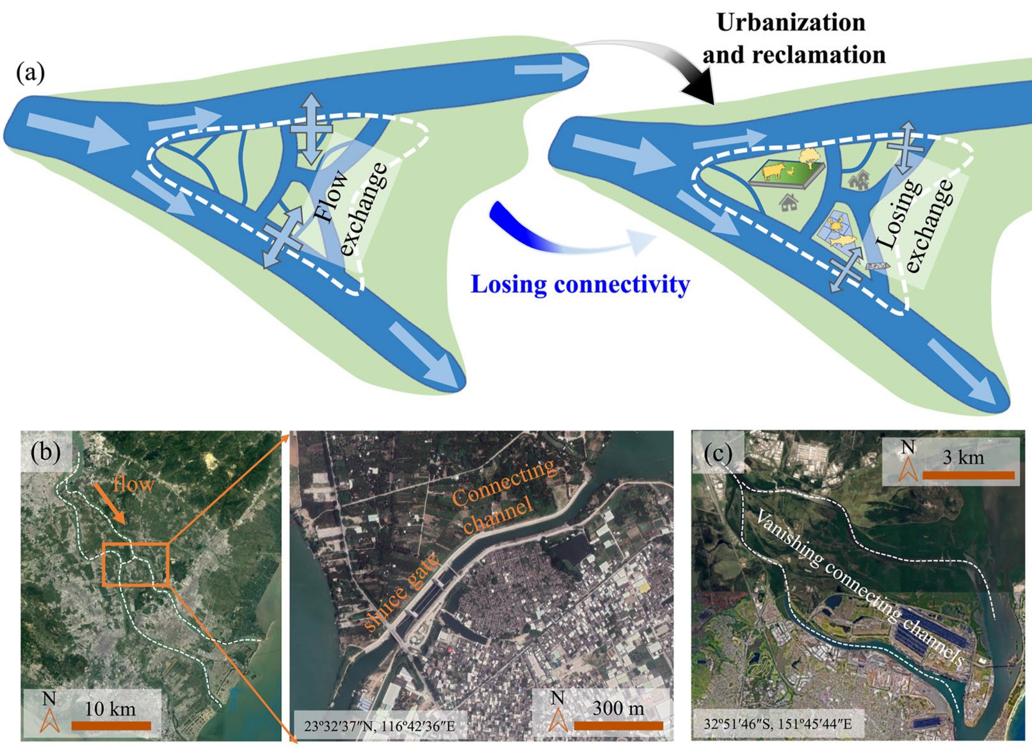

Figure 10. (a) Conceptual model illustrating the flow exchange between branches via connecting channels in a larger river network and their responses to human interventions on the floodplain. (b) Sluice gate on a connecting channel cutting through a populous floodplain in the Hanjiang Delta, Guangdong, China. (c) Vanishing connecting channels due to land reclamation in the islands of the Hunter River Estuary, Newcastle Australia (see Irwin (1968) and Swanson et al. (2017)). Satellite images are from Google Earth (https://earth.google.com/).

et al., 2022). Presumably, the reclamation of the floodplain due to urbanization in the delta could potentially result in narrowing connecting channels or loss of connecting channels between the branches (Figure 10). On the one hand, the shrinkage of connecting channels could affect the flow and sediment exchanges between rivers and their floodplains (Sumaiya et al., 2021; Tull et al., 2022). On the other hand, this could also lead to a decreasing modulating capacity of water partitioning at the upstream bifurcation and hence the hydrological connectivity of the river network. We thus suggest the protection and restoration of floodplain connecting channels, as they can act as an effective conduit and critical path for the hydrological connectivity of deltaic river networks.

4.4. Limitations of This Study

In this study, we examined the effects of connecting channels as a downstream control on modulating water partitioning at upstream bifurcations. The results suggest that the connecting channel can modulate asymmetric water partitioning at upstream bifurcations by balancing the water level at the two junctions and thus reducing the water surface slope difference between the upper sections of the two branches. Notably, the modulation of the water surface slope is dependent on the length and original water levels at the two junctions. As such, the locations of the connecting channels relative to the bifurcation could affect their modulating function and need to be accounted for in making relevant assessments (see Figures S10 and S11 in Supporting Information S1). Furthermore, the long-term evolution of bed elevation and the adjustment of channel width could also be considered, as morphological changes can also feedback on the bed elevation of the branches and water partitioning of the upstream bifurcation (Kleinhans et al., 2013; Shaw et al., 2021). Such an effect is worth further pursuit in future studies, with one-dimensional models recommended to fully explore a wider parameter space.

The numerical simulations were conducted in a simple yet representative channel network, that is, the "bifurcation-connecting channel" unit, which provides a first step toward understanding how the interaction between interconnected channels can affect the water distribution and hydrological connectivity of a river network. Nonetheless, in large-scale river networks where multiple channels can have more complex topological structures than the “bifurcation-connecting channel” unit, the hydrodynamic interactions between different channels can lead to emergent behaviors that are not captured in this study. The dynamics of large-scale river networks require further studies.

5. Conclusions

How connecting channels that connect the downstream branches affect water partitioning at the upstream bifurcation was investigated using idealized numerical simulations in Delft3D. The cascading impacts on the hydrological connectivity of a basic deltaic river network were further examined. The main conclusions are as follows:

1. A connecting channel can mitigate the asymmetry of water partitioning at the upstream bifurcation and yet augment the river discharge difference between the two downstream outlets.
2. The above contrasting effects are due to a spatially varying modulation on the difference in water surface slope between the upper and lower sections of the two branches thus divided by the connecting channel. Specifically, the difference in water surface slope decreases in the upper sections and increases in the lower sections.
3. A connecting channel enhances the flow exchange of the channel network to improve its hydrological connectivity and therefore reduces the vulnerability of the network to flow alteration.

This study is a first step toward understanding how floodplain connecting channels act as conduits to modulate asymmetric water partitioning at river bifurcations and examines their cascading impacts on the hydrological connectivity as well as the evolution and restoration of deltaic river networks. The findings of this study suggest the importance of preserving natural connecting channels or creating proper artificial channels in floodplains for the protection and restoration of deltaic river networks. As a follow-up of the current study, adoption of more complex geometry of the river channels and location of the connecting channel, as well as incorporation of external forcing, such as tides (Buschman et al., 2010; Iwantoro et al., 2022; Ragno et al., 2020; Swinkels et al., 2009), can be explored in the future.

Data Availability Statement

The Delft3D model setup files for the hydrodynamic simulations of the river network are available at a repository on Zenodo (https://zenodo.org/record/7538334#.Y8PKFS-KFQI).

Acknowledgments

This work was supported by the Key Project of National Natural Science Foundation of China (Grant 52239005) and the Program for Guangdong Introducing Innovative and Entrepreneurial Teams (Grant 2019ZT08L213). D. Shao was supported by the National Key R&D Program of China (Grant 2019YFE0121500), and W. Gao acknowledged the support from the Young Scientists Fund of National Natural Science Foundation of China (Grant 52101297).

References

Abrial, E., Espinola, L. A., Amsler, M. L., Rabuffetti, A. P., Latosinski, F. G., Szupiany, R. N., et al. (2019). Fish structure in channel networks of a large anabranching floodplain: Effect of isolation/connection processes. *Water Resources Research*, *55*(12), 10993–11006. https://doi.org/10.1029/2019WR025063

Bain, R. L., Hale, R. P., & Goodbred, S. L. (2019). Flow reorganization in an anthropogenically modified tidal channel network: An example from the southwestern Ganges-Brahmaputra-Meghna Delta. *Journal of Geophysical Research-Earth Surface*, *124*(8), 2141–2159. https://doi.org/10.1029/2018JF004996

Bolla Pittaluga, M., Coco, G., & Kleinhans, M. G. (2015). A unified framework for stability of channel bifurcations in gravel and sand fluvial systems. *Geophysical Research Letters*, *42*(18), 7521–7536. https://doi.org/10.1002/2015GL065175

Buschman, F. A., Hoitink, A. J. F., van der Vegt, M., & Hoekstra, P. (2010). Subtidal flow division at a shallow tidal junction. *Water Resources Research*, *46*(12), W12515. https://doi.org/10.1029/2010WR009266

Caldwell, R. L., Edmonds, D. A., Baumgardner, S., Paola, C., Roy, S., & Nienhuis, J. H. (2019). A global delta dataset and the environmental variables that predict delta formation. *Earth Surface Dynamics*, *7*(3), 773–787. https://doi.org/10.5194/esurf-7-773-2019

Chen, X. Q., Yu, M. H., Liu, C. J., Wang, R. P., Zha, W., & Tian, H. Y. (2022). Topological and dynamic complexity of the Pearl River Delta and its responses to human intervention. *Journal of Hydrology*, *608*, 127619. https://doi.org/10.1016/j.jhydrol.2022.127619

Cox, J. R., Huismans, Y., Knaake, S. M., Leuven, J. R. F. W., Vellinga, N. E., van der Vegt, M., et al. (2021). Anthropogenic effects on the contemporary sediment budget of the lower Rhine-Meuse delta channel network. *Earth's Future*, *9*(7), e2020EF001869. https://doi.org/10.1029/2020EF001869

Dong, T. Y., Nittrouer, J. A., McElroy, B., Il'icheva, E., Pavlov, M., Ma, H. B., et al. (2020). Predicting water and sediment partitioning in a delta channel network under varying discharge conditions. *Water Resources Research*, *56*(11), e2020WR027199. https://doi.org/10.1029/2020WR027199

Edmonds, D. A., Caldwell, R. L., Brondizio, E. S., & Siani, S. M. O. (2020). Coastal flooding will disproportionately impact people on river deltas. *Nature Communications*, *11*(1), 4741. https://doi.org/10.1038/s41467-020-18531-4

Edmonds, D. A., Chadwick, A. J., Lamb, M. P., Lorenzo-Trueba, J., Murray, A. B., Nardin, W., et al. (2021). *Morphodynamic modeling of river-dominated deltas: A review and future perspectives*, *Reference Module in Earth Systems and Environmental Sciences*. Elsevier.

Edmonds, D. A., & Slingerland, R. L. (2008). Stability of delta distributary networks and their bifurcations. *Water Resources Research*, *44*(9), W09426. https://doi.org/10.1029/2008WR006992

Gao, W., Shao, D., Wang, Z. B., Nardin, W., Yang, W., Sun, T., & Cui, B. (2018). Combined effects of unsteady river discharges and wave conditions on river mouth bar morphodynamics. *Geophysical Research Letters*, *45*(23), 12903–12911. https://doi.org/10.1029/2018GL080447

Giosan, L., Syvitski, J., Constantinescu, S., & Day, J. (2014). Protect the world's deltas. *Nature*, *516*(7529), 31–33. https://doi.org/10.1038/516031a

Hariharan, J., Piliouras, A., Schwenk, J., & Passalacqua, P. (2022). Width-based discharge partitioning in distributary networks: How right we are. *Geophysical Research Letters*, *49*(14), e2022GL097897. https://doi.org/10.1029/2022GL097897

Hiatt, M., Addink, E. A., & Kleinhans, M. G. (2022). Connectivity and directionality in estuarine channel networks. *Earth Surface Processes and Landforms*, *47*(3), 807–824. https://doi.org/10.1002/esp.5286

Hiatt, M., Castaneda-Moya, E., Twilley, R., Hodges, B. R., & Passalacqua, P. (2018). Channel-island connectivity affects water exposure time distributions in a coastal river delta. *Water Resources Research*, *54*(3), 2212–2232. https://doi.org/10.1002/2017WR021289

Hiatt, M., Sonke, W., Addink, E. A., van Dijk, W. M., van Kreveld, M., Ophelders, T., et al. (2020). Geometry and topology of estuary and braided river channel networks automatically extracted from topographic data. *Journal of Geophysical Research-Earth Surface*, *125*(1), e2019JF005206. https://doi.org/10.1029/2019JF005206

Huang, C., Wang, Y., Yang, Q., & Liu, F. (2022). Spatiotemporal variation of discharge and its influencing factors in Pearl River Delta network area. *Periodical of Ocean University of China*, *52*(5), 97–106. https://doi.org/10.16441/j.cnki.hdxb.20210241

Irwin, P. G. (1968). Reclamation of the Hunter River Islands. *Australian Geographer*, *10*(5), 413–415. https://doi.org/10.1080/00049186808702511

Iwantoro, A. P., van der Vegt, M., & Kleinhans, M. G. (2021). Effects of sediment grain size and channel slope on the stability of river bifurcations. *Earth Surface Processes and Landforms*, *46*(10), 2004–2018. https://doi.org/10.1002/esp.5141

Iwantoro, A. P., van der Vegt, M., & Kleinhans, M. G. (2022). Stability and asymmetry of tide-influenced river bifurcations. *Journal of Geophysical Research: Earth Surface*, *127*(6), e2021JF006282. https://doi.org/10.1029/2021JF006282

Jerolmack, D. J. (2009). Conceptual framework for assessing the response of delta channel networks to Holocene sea level rise. *Quaternary Science Reviews*, *28*(17), 1786–1800. https://doi.org/10.1016/j.quascirev.2009.02.015

Katifori, E., Szöllosi, G. J., & Magnasco, M. O. (2010). Damage and fluctuations induce loops in optimal transport networks. *Physical Review Letters*, *104*(4), 048704. https://doi.org/10.1103/PhysRevLett.104.048704

Kleinhans, M. G., Ferguson, R. I., Lane, S. N., & Hardy, R. J. (2013). Splitting rivers at their seams: Bifurcations and avulsion. *Earth Surface Processes and Landforms*, *38*(1), 47–61. https://doi.org/10.1002/esp.3268

Kleinhans, M. G., Jagers, H. R. A., Mosselman, E., & Sloff, C. J. (2008). Bifurcation dynamics and avulsion duration in meandering rivers by one-dimensional and three-dimensional models. *Water Resources Research*, *44*(8), W08454. https://doi.org/10.1029/2007WR005912

Kleinhans, M. G., & van den Berg, J. H. (2011). River channel and bar patterns explained and predicted by an empirical and a physics-based method. *Earth Surface Processes and Landforms*, *36*(6), 721–738. https://doi.org/10.1002/esp.2090

Konkol, A., Schwenk, J., Katifori, E., & Shaw, J. B. (2022). Interplay of river and tidal forcings promotes loops in coastal channel networks. *Geophysical Research Letters*, *49*(10), e2022GL098284. https://doi.org/10.1029/2022GL098284

Lesser, G. R., Roelvink, J. A., van Kester, J. A. T. M., & Stelling, G. S. (2004). Development and validation of a three-dimensional morphological model. *Coastal Engineering*, *51*(8–9), 883–915. https://doi.org/10.1016/j.coastaleng.2004.07.014

Liu, F., Hu, S., Guo, X., Luo, X., Cai, H., & Yang, Q. (2018). Recent changes in the sediment regime of the Pearl River (South China): Causes and implications for the Pearl River Delta. *Hydrological Processes*, *32*(12), 1771–1785. https://doi.org/10.1002/hyp.11513

Ma, H., Nittrouer, J. A., Wu, B., Lamb, M. P., Zhang, Y., Mohrig, D., et al. (2020). Universal relation with regime transition for sediment transport in fine-grained rivers. *Proceedings of the National Academy of Sciences*, *117*(1), 171–176. https://doi.org/10.1073/pnas.1911225116

Ma, H. B., Nittrouer, J. A., Fu, X. D., Parker, G., Zhang, Y. F., Wang, Y. J., et al. (2022). Amplification of downstream flood stage due to damming of fine-grained rivers. *Nature Communications*, *13*(1), 3054. https://doi.org/10.1038/s41467-022-30730-9

Makaske, B. (2001). Anastomosing rivers: A review of their classification, origin and sedimentary products. *Earth-Science Reviews*, *53*(3–4), 149–196. https://doi.org/10.1016/S0012-8252(00)00038-6

Marra, W. A., Kleinhans, M. G., & Addink, E. A. (2014). Network concepts to describe channel importance and change in multichannel systems: Test results for the Jamuna River, Bangladesh. *Earth Surface Processes and Landforms*, *39*(6), 766–778. https://doi.org/10.1002/esp.3482

Mazzoleni, M., Mard, J., Rusca, M., Odongo, V., Lindersson, S., & Di Baldassarre, G. (2021). Floodplains in the Anthropocene: A global analysis of the interplay between human population, built environment, and flood severity. *Water Resources Research*, *57*(2), e2020WR027744. https://doi.org/10.1029/2020wr027744

Merz, B., Blosch, G., Vorogushyn, S., Dottori, F., Aerts, J. C. J. H., Bates, P., et al. (2021). Causes, impacts and patterns of disastrous river floods. *Nature Reviews Earth & Environment*, *2*(9), 592–609. https://doi.org/10.1038/s43017-021-00195-3

Nanson, G. C., & Knighton, A. D. (1996). Anabranching rivers: Their cause, character and classification. *Earth Surface Processes and Landforms*, *21*(3), 217–239. https://doi.org/10.1002/(SICI)1096-9837(199603)21:3<217::AID-ESP611>3.0.CO;2-U

Nardin, W., & Edmonds, D. A. (2014). Optimum vegetation height and density for inorganic sedimentation in deltaic marshes. *Nature Geoscience*, *7*(10), 722–726. https://doi.org/10.1038/NGEO2233

Nicholas, A. P., Ashworth, P. J., Smith, G. H. S., & Sandbach, S. D. (2013). Numerical simulation of bar and island morphodynamics in anabranching megarivers. *Journal of Geophysical Research-Earth Surface*, *118*(4), 2019–2044. https://doi.org/10.1002/jgrf.20132

Nienhuis, J. H., Ashton, A. D., Edmonds, D. A., Hoitink, A. J. F., Kettner, A. J., Rowland, J. C., & Törnqvist, T. E. (2020). Global-scale human impact on delta morphology has led to net land area gain. *Nature*, *577*(7791), 514–518. https://doi.org/10.1038/s41586-019-1905-9

Ragno, N., Redolfi, M., & Tubino, M. (2021). Coupled morphodynamics of river bifurcations and confluences. *Water Resources Research*, *57*(1), e2020WR028515. https://doi.org/10.1029/2020WR028515

Ragno, N., Tambroni, N., & Bolla Pittaluga, M. (2020). Effect of small tidal fluctuations on the stability and equilibrium configurations of bifurcations. *Journal of Geophysical Research-Earth Surface*, *125*(8), e2020JF005584. https://doi.org/10.1029/2020JF005584

Redolfi, M., Zolezzi, G., & Tubino, M. (2019). Free and forced morphodynamics of river bifurcations. *Earth Surface Processes and Landforms*, *44*(4), 973–987. https://doi.org/10.1002/esp.4561

Salter, G., & Lamb, M. P. (2022). Autocyclic secondary channels stabilize deltaic islands undergoing relative sea level rise. *Geophysical Research Letters*, *49*(15), e2022GL098885. https://doi.org/10.1029/2022GL098885

Salter, G., Paola, C., & Voller, V. R. (2018). Control of delta avulsion by downstream sediment sinks. *Journal of Geophysical Research-Earth Surface*, *123*(1), 142–166. https://doi.org/10.1002/2017JF004350

Salter, G., Voller, V. R., & Paola, C. (2020). Chaos in a simple model of a delta network. *Proceedings of the National Academy of Sciences of the United States of America*, *117*(44), 27179–27187. https://doi.org/10.1073/pnas.2010416117

Shaw, J. B., Mason, K. G., Ma, H., & McCain, G. W. (2021). Influences on discharge partitioning on a large river delta: Case study of the Mississippi-Atchafalaya Diversion, 1926–1950. *Water Resources Research*, *57*(5), e2020WR028090. https://doi.org/10.1029/2020WR028090

Sumaiya, S., Czuba, J. A., Schubert, J. T., David, S. R., Johnston, G. H., & Edmonds, D. A. (2021). Sediment transport potential in a hydraulically connected river and floodplain-channel system. *Water Resources Research*, *57*(5), e2020WR028852. https://doi.org/10.1029/2020WR028852

Swanson, R. L., Potts, J. D., & Scanes, P. R. (2017). *Preliminary ecological assessment of the lower to mid Hunter River estuary*. Retrieved from Office of Environment and Heritage. Retrieved from www.environment.nsw.gov.au

Swinkels, C. M., Jeuken, C. M. C. J. L., Wang, Z. B., & Nicholls, R. J. (2009). Presence of connecting channels in the Western Scheldt Estuary. *Journal of Coastal Research*, *25*(3), 627–640. https://doi.org/10.2112/06-0719.1

Syvitski, J. P. M., & Saito, Y. (2007). Morphodynamics of deltas under the influence of humans. *Global and Planetary Change*, *57*(3–4), 261–282. https://doi.org/10.1016/j.gloplacha.2006.12.001

Tejedor, A., Longjas, A., Edmonds, D. A., Zaliapin, I., Georgiou, T. T., Rinaldo, A., & Foufoula-Georgiou, E. (2017). Entropy and optimality in river deltas. *Proceedings of the National Academy of Sciences of the United States of America*, *114*(44), 11651–11656. https://doi.org/10.1073/pnas.1708404114

Tejedor, A., Longjas, A., Zaliapin, I., & Foufoula-Georgiou, E. (2015a). Delta channel networks: 1. A graph-theoretic approach for studying connectivity and steady state transport on deltaic surfaces. *Water Resources Research*, *51*(6), 3998–4018. https://doi.org/10.1002/2014WR016577

Tejedor, A., Longjas, A., Zaliapin, I., & Foufoula-Georgiou, E. (2015b). Delta channel networks: 2. Metrics of topologic and dynamic complexity for delta comparison, physical inference, and vulnerability assessment. *Water Resources Research*, *51*(6), 4019–4045. https://doi.org/10.1002/2014WR016604

Trigg, M. A., Bates, P. D., Wilson, M. D., Schumann, G., & Baugh, C. (2012). Floodplain channel morphology and networks of the middle Amazon River. *Water Resources Research*, *48*(10), W10504. https://doi.org/10.1029/2012wr011888

Tull, N., Passalacqua, P., Hassenruck-Gudipati, H. J., Rahman, S., Wright, K., Hariharan, J., & Mohrig, D. (2022). Bidirectional river-floodplain connectivity during combined pluvial-fluvial events. *Water Resources Research*, *58*(3), e2021WR030492. https://doi.org/10.1029/2021WR030492

Wang, Z. B., De Vries, M., Fokkink, R. J., & Langerak, A. (1995). Stability of river bifurcations in 1D morphodynamic models. *Journal of Hydraulic Research*, *33*(6), 739–750. https://doi.org/10.1080/00221689509498549

Wright, K., Hiatt, M., & Passalacqua, P. (2018). Hydrological connectivity in vegetated river deltas: The importance of patchiness below a threshold. *Geophysical Research Letters*, *45*(19), 10416–10427. https://doi.org/10.1029/2018GL079183