Indications of Ongoing Noise-Tipping of a Bifurcating River System

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DOI
10.1029/2024GL111846

Publication date
2024

Document Version
Final published version

Published in
Geophysical Research Letters

AGU ADVANCING EARTH AND SPACE SCIENCES

Geophysical Research Letters

RESEARCH LETTER
10.1029/2024GL111846

Key Points:

- Field observations suggest noise-tipping of a river bifurcation system
- Sediment deposition in one bifurcate resulting from a peak flow sequence in the 1990s caused a lasting change in flow partitioning
- Modeling suggests that peak flows can push a bifurcation system out of an attractor's stability domain, triggering noise-tipping

Supporting Information:

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

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Citation:
Blom, A., Ylla Arbós, C., Chowdhury, M. K., Doelman, A., Rietkerk, M., & Schielen, R. M. J. (2024). Indications of ongoing noise-tipping of a bifurcating river system. *Geophysical Research Letters*, *51*, e2024GL111846. https://doi.org/10.1029/2024GL111846

Received 6 AUG 2024
Accepted 6 NOV 2024

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Indications of Ongoing Noise-Tipping of a Bifurcating River System

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Abstract Tipping occurs when a critical point is reached, beyond which a perturbation leads to persistent system change. Here, we present observational indications demonstrating presently ongoing noise-tipping of a real-world system. Noise in a river system is associated with the changing flow rate. In particular, we consider the upper Rhine River delta, where flow and sediment fluxes are partitioned over the two downstream branches (bifurcates) of an important river bifurcation. Field observations show that a sequence of peak flows in the 1990s resulted in sudden sediment deposition in one bifurcate, triggering a persistent and ongoing change in the flow partitioning. This has caused the system to move toward an alternative equilibrium state or attractor. An idealized model confirms that a river bifurcation system under such conditions is prone to tipping, and provides insight on the onset of tipping.

Plain Language Summary Tipping occurs when reaching a critical point beyond which a perturbation leads to a significant and often unstoppable change. Real-life observations of such system tipping, however, are rare. Here we provide first-time indications of ongoing tipping of a real-world system, namely a major river system. These indications are based on field observations that indicate that a sequence of peak flows in the 1990s resulted in sudden sediment deposition in one bifurcate, redirecting the flow over the downstream branches, as well as modeling. These signs of tipping asks for increased attention from water management authorities, as flood safety and shipping are of large importance.

1. Introduction

Tipping occurs when a perturbation abruptly alters the system state, after which it gradually approaches another stable equilibrium state or attractor. In other words, tipping is when a system is pushed, or moves, out of the equilibrium state's domain of attraction (i.e., the set of states from where the dynamical system moves to a stable equilibrium) into the domain of attraction of another equilibrium (see Box 1).

BOX 1. Mathematics of Tipping

A system crosses a tipping point when the system state leaves the domain of attraction of the original equilibrium state, and evolves toward an alternative attractor (Rietkerk et al., 2021). Systems that are near such a critical point may be triggered to tip and undergo a qualitative and often irreversible change. There are various causes of tipping (Ashwin et al., 2012, 2017). Under slowly varying controls, for instance induced by climate change, the original attractor may become unstable or disappear (typically in a saddle node bifurcation). As a consequence, its domain of attraction vanishes and the system tips. This is called bifurcation-induced tipping (B-tipping). Noise-induced tipping (N-tipping) is when fluctuation of the controls pushes the system out of the domain of attraction of the original attractor. Rate-induced tipping (R-tipping) occurs when the controls change so rapidly that the system state can no longer follow the also changing domain of attraction of the equilibrium.

10.1029/2024GL111846

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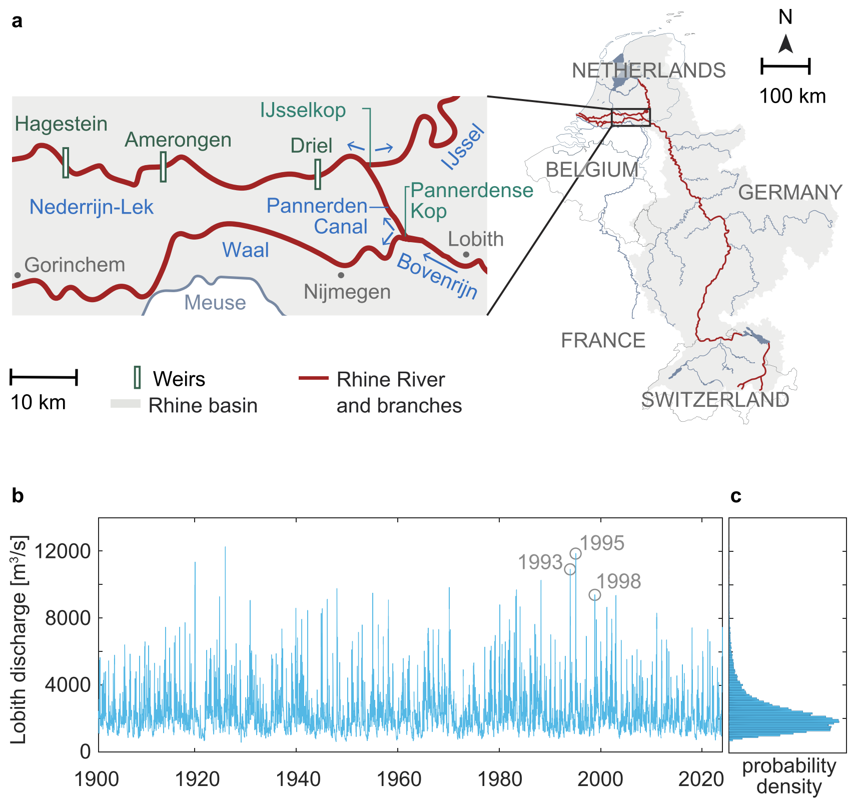

Figure 1. The system and its noisy forcing. (a) Rhine River basin with inset showing our domain of interest with river bifurcation Pannerdense Kop. (b) 123-year hydrograph at the German-Dutch border (Lobith) illustrating that the flow forcing has a noisy character. (c) Probability density function for the Lobith discharge.

Research on system tipping has mainly focused on ecosystems (Carrier-Belleau et al., 2022; Meng et al., 2020; Rietkerk et al., 2004, 2021; C. Wang et al., 2016), climate (Alley et al., 2003; Ashwin et al., 2012; Bakke et al., 2009; Klose et al., 2020; Lenton et al., 2008, 2019; Lohmann & Ditlevsen, 2021), finance (Gatfaoui & De Peretti, 2019), biology (He et al., 2012; Song et al., 2021), and water systems (Notebaert et al., 2018; Phillips, 2018). Tipping in river systems has been particularly associated with peak flow events, sea level rise, avulsions, and anthropogenic impact on the sediment supply (Notebaert et al., 2018; Phillips, 2018). Extremely enhanced sediment supply to a fluvial system due to a giant rockslide (Lavé et al., 2023), earthquake (Saikia, 2020), or dam break (Barrera Crespo et al., 2024) can also trigger approach to a new equilibrium state.

Despite the recent focus on tipping, there has been limited direct evidence of tipping in real-world systems. Evidence is generally restricted to ecosystems with limited extent and complexity such as shallow lakes (Scheffer et al., 2001). Tipping in larger and more complex Earth system components has been suggested (Lenton et al., 2008): it has been argued that the western Greenland ice sheet (Boers & Rypdal, 2021), the Amazon rain forest (Boulton et al., 2022), and the Atlantic meridional overturning circulation (Boers, 2021; Ditlevsen & Ditlevsen, 2023; Van Westen et al., 2024) are approaching a tipping point, indirectly inferred from early warning signals (Scheffer et al., 2009; Van Westen et al., 2024). However, no conclusive evidence exists to confirm tipping events in these systems, either past or present.

Here we focus on the bifurcation region in the upper delta of the Rhine River (Figure 1), where branches have been narrowed and channelized in the past and, resultingly, are no longer able to change their planform and width in response to changes of the controls (Chowdhury et al., 2023; Ylla Arbós et al., 2021, 2023). At a bifurcation, the river splits into two bifurcates that each transport a fraction of the upstream flow, and gravel and sand fluxes. Recent research by Chowdhury et al. (2023) has illustrated that two to three successive peak flow events have led to abrupt change in flow partitioning among the two bifurcates. Our research question is: "To what extent can we link the abrupt response to the successive peak flows to system tipping, specifically noise-induced tipping?" (see Box 1). In a river system, noise is associated with the forcings of flow rate, gravel flux, and sand flux, which all vary with time (Arkesteijn et al., 2019, 2021; Blom, Arkesteijn, et al., 2017), see Figure 1b. Our assessment is based on field observations and application of a idealized river bifurcation model.

2. River and Observations

The Rhine River originates in the Swiss Alps, flows through six countries, and discharges into the North Sea. After crossing the German-Dutch border, it bifurcates into two branches at the Pannerdense Kop bifurcation, which is our bifurcation of interest (Figure 1). The domain of interest has been characterized by channel bed incision, which is due to channelization measures conducted over the 18th to 20th centuries (Chowdhury et al., 2023; Ylla Arbós et al., 2021). Recent observations by Chowdhury et al. (2023) have illustrated that two to three successive peak flow events, in 1993, 1995 and possibly 1998, have led to abrupt sediment deposition and bed level increase (and hence flow depth decrease) at the upstream end of the Pannerden Canal bifurcate (Figure 2a). In other words, the gravel and sand supply exceeded the sediment transport capacity at that location.

The swift sequence of peak flows is succeeded by a notable reduction in the channel bed incision rate in both bifurcates. The peak flows appear to have resulted in the downstream displacement of relatively coarse sediment and its deposition over the upstream parts of the two bifurcates, which explains the significant temporal bed surface coarsening over the upstream parts of the bifurcates over this period (Figure 3). A coarser bed surface erodes more slowly than a finer one, as coarser sediment is less mobile and characterized by a larger equilibrium slope (Blom, Arkesteijn, et al., 2017; Blom et al., 2016). This explains the decrease in the channel bed incision rate in the bifurcates.

The abrupt change in bed level in response to the rapid succession of peak flows is accompanied by an abrupt change in the flow partitioning between the bifurcates. Since this sequence of peak flows, the Waal discharge has gradually increased at the expense of the Pannerden Canal discharge (Figure 2b). This continues to present day, and is associated with the Waal channel incision rate being larger than the one of the Pannerden Canal (Figure 2a).

Measured data illustrate that the bed surface sediment has coarsened with time (Figure 3). As the bed surface grain size distribution largely depends on the one of the sediment flux (Blom, Arkesteijn, et al., 2017; Blom et al., 2016), the latter has gradually coarsened with time, as well. This is associated with the downstream migration of the Rhine River's gravel-sand transition, which is a natural phenomenon and seems to have been accelerated by relatively coarse sediment nourishments in the German Rhine (Blom, Chavarrías, et al., 2017; Chowdhury et al., 2023; Ylla Arbós et al., 2021). The system incision and coarsening are expected to continue, as the system will respond to climate change over the next century (Ylla Arbós et al., 2023).

The observations depicted in Figure 2 illustrate the ongoing tipping process at the Pannerdense Kop bifurcation.

3. Model and Simulations

There exists a number of models describing the stability of river bifurcations (see Box 2). These idealized models are valuable for understanding qualitative behavior such as equilibrium solutions and potential tipping, yet they are less suitable for precise quantitative predictions due to conceptual simplifications. These models show that there exists one solution to the equilibrium state of a one-channel system with non-erodible banks (Blom, Arkesteijn, et al., 2017; Blom et al., 2016; Howard, 1980), yet three to five solutions for a river bifurcation system (Bolla Pittaluga et al., 2003, 2015; Ragno, 2023; Ragno et al., 2023; Schielen & Blom, 2018).

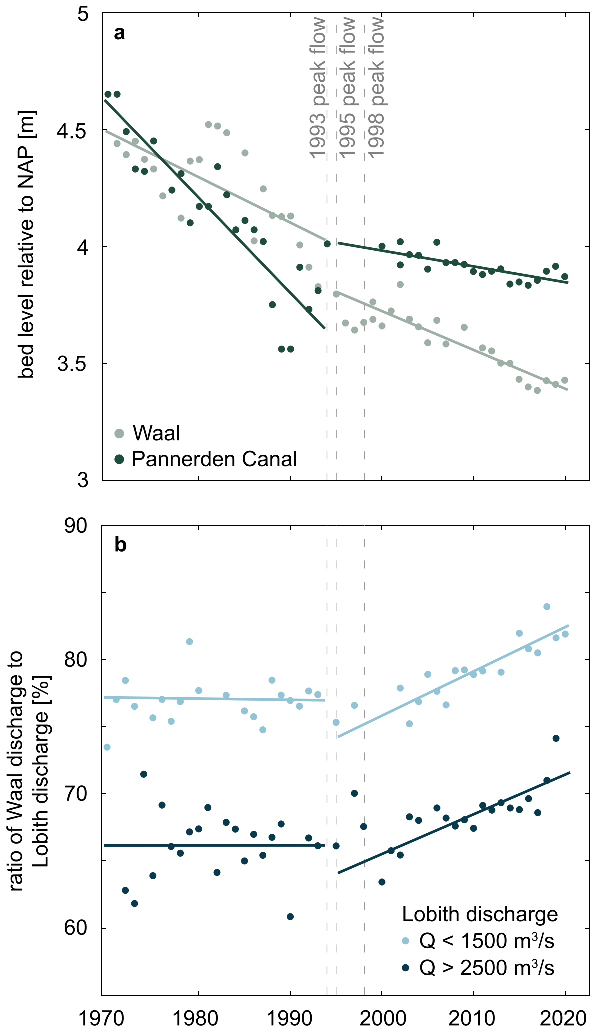

Figure 2. Observations of bed level and flow partitioning. (a) Bed level relative to Dutch reference level NAP at the upstream ends of the Waal and Pannerden Canal bifurcates (i.e., data have been averaged over a 3 km window right downstream of the bifurcation). (b) Ratio of Waal discharge to the upstream channel's water discharge (termed Lobith discharge). Subfigure (b) distinguishes two water discharge ranges: the lower range represents closed weir conditions for the three weirs in the Nederrijn-Lek branch (Figure 1a), which leads to backwater effects reaching up to the Pannnerdense Kop bifurcation and, resultingly, the Waal bifurcate taking a relative large share of the Lobith discharge at the expense of the Pannerden Canal. This weir-induced backwater effect is absent for the higher flow range as the weirs are lifted. Water discharge data are derived from Ott current meter until 1999 and since 2000 ADCP measurements (Chowdhury et al., 2023).

BOX 2. Bifurcation Stability Models

The Z. B. Wang et al. (1995) model was the first to address a river bifurcation as a stability problem, and to show that three equilibrium states exist (i.e., two active bifurcates or either one of the bifurcates active). Simplifying assumptions are: unisize sediment; each bifurcate adjusting uniformly; no effects of the lateral slope upstream of the bifurcation; and a nodal point relation partitioning the sediment flux over the bifurcates. Subsequently lateral bed slope effects were accounted for (Bolla Pittaluga et al., 2003, 2015; Ragno et al., 2023), as well as mixed-size sediment (Ragno et al., 2023; Schielen & Blom, 2018). All these models are highly idealized and exclude several physical mechanisms, such as the temporal variation of the flow rate, helical flow due to the offtake angle or Bulle effect (Bulle, 1926; Dutta et al., 2017), and flow separation in the offtake channel (Van der Mark & Mosselman, 2013). Stability analyses reveal that bifurcation systems are characterized by at least three or five equilibrium states. Under conditions with multiple stable equilibrium states, the initial conditions govern which stable equilibrium the system approaches (Paudel et al., 2022; Schielen & Blom, 2018).

We adopt the Schielen and Blom (2018) model of a gravel-sand bifurcation system to assess whether sudden sediment deposition or associated abrupt decrease in flow depth in one bifurcate can lead to system tipping. The Supporting Information S1 provides more detailed information on the model and model parameters. We compute the model equilibrium solutions, and determine whether they are stable (nodes) or unstable (saddles). The phase plots in Figure 4 consider cases with five equilibrium states, three of them being stable and two of them being unstable. Each stable equilibrium has a domain of attraction, which is the collection of states from where trajectories converge to the specific equilibrium. The two red areas in Figure 4 each indicate an attraction domain of an equilibrium governed by a different active branch each, and the blue area is the domain of attraction of an equilibrium with two active branches.

Figure 4 addresses a situation where the system state initially is not far from, and gradually approaches, a stable equilibrium of two active bifurcates. We examine the case of abrupt change described in the previous section. Following the observations, we assess a situation where the peak flow succession leads to an abrupt increase in bed level and associated decrease in flow depth in bifurcate 2. The phase plot in Figure 4a represents a case where the domain of attraction is sufficiently large for the flow depth decrease in bifurcate 2 not to push the system to another domain of attraction. Thus, for a sufficiently large domain of attraction, the abrupt decrease in flow depth in bifurcate 2 leads to a somewhat adjusted path toward the stable equilibrium state but does not lead to tipping.

We argue that the temporal coarsening of the bed surface sediment (Figure 3) and sediment flux reduce the domain of attraction with time. This can be explained as follows. The partitioning of wash load (particle sizes generally considered smaller than 63 μm) over bifurcates typically correlates with the partitioning of the water discharge, while the partitioning of coarser sediment is more strongly related to the relative width of the bifurcates

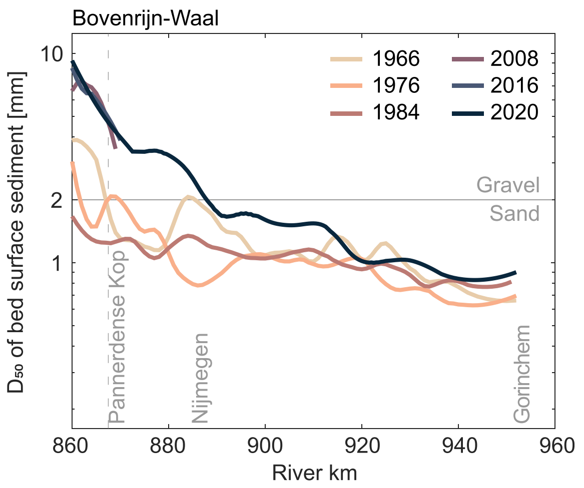

Figure 3. Observations of median bed surface grain size over Bovenrijn-Waal branches.

(Schielen & Blom, 2018). This is because wash load is more uniformly distributed over the cross-sectional area, while the transport of coarser sediment occurs close to the bed. This implies that the coarser the size fraction, the smaller the dependence on the discharge partitioning and the larger the dependence on the ratio of the width of the bifurcates. In the Schielen and Blom (2018) model, such a reduced dependence on the flow partitioning is expressed by a smaller value of the gravel-related nodal point coefficient, k_g. This yields a smaller domain of attraction of the stable equilibrium state. We refer to the Supporting Information S1 for further details on the nodal point relations and associated nodal point coefficients.

Figure 4b illustrates a phase plot for a case with similar stability properties as Figure 4a but a smaller domain of attraction of the equilibrium state (resulting from a reduced value of the gravel-related nodal point coefficient, k_g). Here the abrupt decrease in flow depth in bifurcate 2 does push the system state into another domain of attraction. Thus, a small domain of attraction allows the abrupt decrease in flow depth in bifurcate 2 to cause tipping (Figure 4b).

The temporal decrease of the domain of attraction due to recent system coarsening would explain why the 1993, 1995 and 1998 peak flow succession led to abrupt system response and subsequent gradual approach to a new equilibrium state, while there is no sign that previous sequences of peak flows (for instance, in 1924 and 1926) led to a similar response. Apparently, at that time the sediment flux was still sufficiently fine and the domain of attraction sufficiently large to prevent tipping from happening.

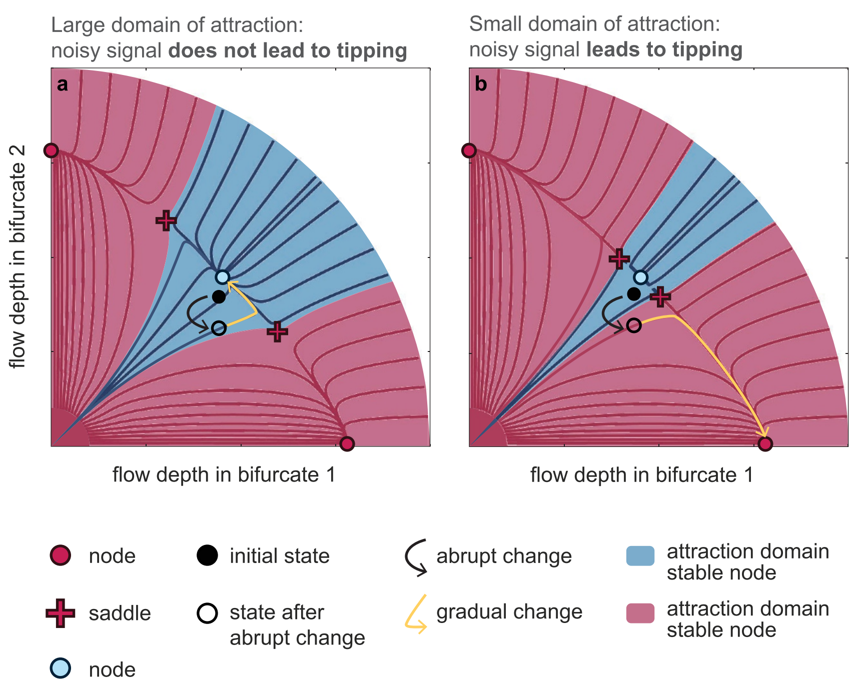

Figure 4. Phase plots illustrating possible development of a river bifurcation. (a) A relatively large domain of attraction of a stable equilibrium state with two open bifurcates. (b) A relatively small domain of attraction of a stable equilibrium state with two open bifurcates. Phase plots are predicted using the Schielen and Blom (2018) model. The nodal point coefficient for sand, k_s, is 1, while the nodal point coefficient for gravel, k_g, equals 3.5 (subfigure a) and 2.4 (subfigure b). We refer to the Supporting Information S1 for further details on the nodal point relations and other model parameters. Black arrows indicate "abrupt change", and yellow arrows indicate "gradual change." Note that here the phase plots are symmetric as we consider bifurcates with mostly equal properties, but typically phase plots would not be symmetric.

4. Conclusions

Over the past decades the bed surface sediment in a channelized bifurcation system has gradually coarsened. This seems to have slowly decreased the domain of attraction of the original stable equilibrium or attractor to the extent that tipping became possible. This enabled a peak flow sequence to initiate tipping, and the system has gradually evolved toward a different attractor since. The latter gradual change is reflected by one bifurcate (the Waal bifurcate) receiving an ever increasing share of the water discharge of the upstream branch, which is accompanied by it incising at a higher rate than the other bifurcate.

The reduced domain of attraction seems to have increased the probability for the system to be pushed out of the domain of attraction through the noisy controls for flow and sediment fluxes. Noise-induced tipping (N-tipping) is thus the probable tipping type.

An idealized model illustrates that there are a few stability regions in the parameter space, and that a reduced domain of attraction of the original attractor can allow a peak flow sequence to perturb the river system into a different attractor's stability region.

Tipping is a bidirectional process: the process may be reversed by system control change or interventions. This requires insight on the consequences of control changes or interventions that may (a) manipulate the system trajectory or (b) enlarge the domain of attraction of the stable equilibrium that the system originally approached.

The current analysis assumes a fixed channel network. River bifurcations are typically part of a river delta, and many deltas worldwide consist of a fixed channel network as a result of past and modern channelization works. Examples are the Mississippi River, Yangtze River, Pearl River, Yellow River, Po River, and Nile River, which are increasingly governed by fixed channels.

Recent research has illustrated that complex systems can evade tipping if they are governed by sufficient degrees of freedom regarding their response to control change (Rietkerk et al., 2021). The degrees of freedom of channel response of the considered system were reduced over the past few centuries, as river planform and channel width have been fixed. As a result, system response is limited to adjusting the main channel slope and the bed surface grain size distribution. Consequently, the extensive channelization measures of the past may have enabled the present tipping process of the Rhine River bifurcation.

One bifurcate attracting a gradually increasing share of the water discharge at the expense of the other bifurcate affects flood risk and shipping, and, as such, is relevant to water management authorities. This is because the Dutch flood protection system (i.e., a network of levees) is designed according to a specific flow partitioning at bifurcations. Also shipping is affected by a changing flow partitioning, as a decreasing share of the water discharge in a bifurcate reduces vessel draught, which has economic consequences.

Appendix A: Field Observations

Our analysis is based on field observations (Appendix A) and application of a idealized river bifurcation model (Appendix B).

We refer to Chowdhury et al. (2023) and Ylla Arbós et al. (2021) for information on measurement techniques, data collection, and data treatment regarding bed level and surface texture. There have been several temporal changes in measurement techniques (e.g., single-beam to multibeam echo sounders for bed level). In addition, as the Rhine River spans across borders, techniques also vary spatially. Such temporal and spatial changes in measurement techniques increase the uncertainties in the measured data.

Field observations comprise the following: (a) a 123-year hydrograph at the German-Dutch border; (b) flow partitioning based on water discharge in the branches; (c) channel bed level; and (d) median bed surface grain size.

Ad 1. The 123-year hydrograph at the German-Dutch border (Lobith) consists of water discharge data between 1 January 1901 and 31 December 2023. Water discharge (Figure 1) is derived from a stage-discharge relationship, which has been calibrated using ADCP measurements (Toonen, 2015). The stage-discharge relationship is regularly updated to account for local temporal change in bed level and hysteresis effects.

Ad 2. The flow partitioning between the two bifurcates (Figure 2b) is not based on stage-discharge relationships (data at gauging stations). This is because the associated uncertainty is large, and the Waal gauging station is not representative of the Waal branch due to its slightly upstream position. Instead, water discharge data are derived from Ott current meter until 1999 and ADCP measurements since 2000 (Chowdhury et al., 2023). Considered cross-sections were approximately 1 km downstream of the Pannerden bifurcation for the Waal and Pannerden Canal. Ott current meter data are associated with a larger inaccuracy (smaller than 20%) than ADCP data (smaller than 10%). ADCP transects were traversed repeatedly at least 10 times, within at least 5% agreement to the mean discharge value. Resulting values are averaged over a hydrologic year (as an example, the 1990 data point reflects the period between 1 October 1989 and 30 September 1990).

Ad 3. Bed level data were averaged over the cross-sectional profile between the groyne tips, and is relative to the Dutch reference level for mean sea level (NAP). Details on data processing are described by Ylla Arbós et al. (2021). Figure 2a shows data that are representative of the upstream ends of the Waal and Pannerden Canal bifurcates: the data have been averaged over a 3 km window right downstream of the bifurcation, and the moving average window does not extend across the bifurcation.

Ad 4. Data on surface median grain size over the Bovenrijn-Waal branches (Figure 3) stem from grain size sampling campaigns that have varied in space and time (Ylla Arbós et al., 2021). Three samples (spaced 65 m) were taken per cross section, and we consider cross-section averaged values of bed surface grain size. The data have been smoothed using the Loess method. For smoothing, we used a span equal to 20% of the data points, except for the limited-extent 2008 and 2016 data series where the span was equal to 90%.

Appendix B: Mathematical Modeling

We adopt the Schielen and Blom (2018) model of a gravel-sand bifurcation system to assess whether sudden sediment deposition or associated abrupt decrease in flow depth in one bifurcate can lead to system tipping. It consists of conservation equations for mass (flow, gravel and sand) and momentum (flow), and nodal point relations that prescribe the partitioning of the gravel and sand fluxes over the bifurcates. The model predicts the temporal adjustment of branch-averaged bed level and surface gravel and sand content in the two bifurcates under constant water discharge, sediment supply, base level, and channel width. The Supporting Information S1 provides more detailed information on the model and model parameters.

Data Availability Statement

Data on bed level and bed surface grain size for Bovenrijn and Waal branches (1926–2018) are available from the 4TU.ResearchData repository (Ylla Arbós, 2021). Bed level and bed surface grain size along the Pannerden Canal branch, and the water discharge data for the Rhine branches are available at the 4TU.ResearchData repository (Chowdhury et al., 2022). The code to reproduce Figure 4 is hosted at the 4TU.ResearchData repository (Schielen et al., 2024).

Acknowledgments

AB and RS contributed equally and share first authorship. The authors thank Rijkswaterstaat for providing the field data, Kieran Dunne for proofreading the manuscript, and Eric Barefoot and an anonymous reviewer for helpful feedback. The research of A.D. and M. R. is supported by the ERC-Synergy project RESILIENCE (101071417) and NWO project "Resilience in complex systems through adaptive pattern formation" (OCENW.M20.169). Contributions by K.C. and C.Y.A. are part of the research program Rivers2Morrow, which is financed by the Dutch Ministry of Infrastructure and Water Management.

References

Alley, R. B., Marotzke, J., Nordhaus, W. D., Overpeck, J. T., Peteet, D. M., Pielke, R. A., et al. (2003). Abrupt climate change. *Science*, *299*(5615), 2005–2010. https://doi.org/10.1126/science.1081056

Arkesteijn, L., Blom, A., Czapiga, M. J., Chavarrías, V., & Labeur, R. J. (2019). The quasi-equilibrium longitudinal profile in backwater reaches of the engineered alluvial river: A space-marching method. *Journal of Geophysical Research: Earth Surface*, *124*(11), 2542–2560. https://doi.org/10.1029/2019JF005195

Arkesteijn, L., Blom, A., & Labeur, R. J. (2021). A rapid method for modeling transient river response under stochastic controls with applications to sea level rise and sediment nourishment. *Journal of Geophysical Research: Earth Surface*, *126*(12). https://doi.org/10.1029/2021JF006177

Ashwin, P., Perryman, C., & Wieczorek, S. (2017). Parameter shifts for nonautonomous systems in low dimension: Bifurcation- and rate-induced tipping. *Nonlinearity*, *30*(6), 2185–2210. https://doi.org/10.1088/1361-6544/aa675b

Ashwin, P., Wieczorek, S., Vitolo, R., & Cox, P. (2012). Tipping points in open systems: Bifurcation, noise-induced and rate-dependent examples in the climate system. *Philosophical Transactions of the Royal Society A*, *370*(1962), 1166–1184. https://doi.org/10.1098/rsta.2011.0306

Bakke, J., Lie, Ø., Heegaard, E., Dokken, T., Haug, G. H., Birks, H. H., et al. (2009). Rapid oceanic and atmospheric changes during the Younger Dryas cold period. *Nature Geoscience*, *2*(3), 202–205. https://doi.org/10.1038/ngeo439

Barrera Crespo, P. D., Espinoza Girón, P., Bedoya, R., Gibson, S., East, A. E., Langendoen, E. J., & Boyd, P. (2024). Major fluvial erosion and a 500-Mt sediment pulse triggered by lava-dam failure, Río Coca, Ecuador. *Earth Surface Processes and Landforms*, *49*(3), 1058–1080. https://doi.org/10.1002/esp.5751

Blom, A., Arkesteijn, L., Chavarrías, V., & Viparelli, E. (2017a). The equilibrium alluvial river under variable flow, and its channel-forming discharge. *Journal of Geophysical Research: Earth Surface*, *122*(10), 1924–1948. https://doi.org/10.1002/2017JF004213

Blom, A., Chavarrías, V., Ferguson, R. I., & Viparelli, E. (2017b). Advance, retreat, and halt of abrupt gravel-sand transitions in alluvial rivers. *Geophysical Research Letters*, *44*(19), 1–10. https://doi.org/10.1002/2017GL074231

Blom, A., Viparelli, E., & Chavarrías, V. (2016). The graded alluvial river: Profile concavity and downstream fining. *Geophysical Research Letters*, *43*(12), 1–9. https://doi.org/10.1002/2016GL068898

Boers, N. (2021). Observation-based early-warning signals for a collapse of the Atlantic meridional overturning circulation. *Nature Climate Change*, *11*(8), 680–688. https://doi.org/10.1038/s41558-021-01097-4

Boers, N., & Rypdal, M. (2021). Critical slowing down suggests that the western Greenland Ice Sheet is close to a tipping point. *Proc. National Academy of Sciences U.S.A.*, *118*(21). https://doi.org/10.1073/pnas.2024192118

Bolla Pittaluga, M., Repetto, R., & Tubino, M. (2003). Channel bifurcation in braided rivers: Equilibrium configurations and stability. *Water Resources Research*, *39*(3), 1046. https://doi.org/10.1029/2001WR001112

Bolla Pittaluga, M., Tambroni, N., Canestrelli, A., Slingerland, R., Lanzoni, S., & Seminara, G. (2015). Where river and tide meet: The morphodynamic equilibrium of alluvial estuaries. *Journal of Geophysical Research: Earth Surface*, *120*(1), 75–94. https://doi.org/10.1002/2014JF003233

Boulton, C. A., Lenton, T. M., & Boers, N. (2022). Pronounced loss of Amazon rainforest resilience since the early 2000s. *Nature Climate Change*, *12*(3), 271–278. https://doi.org/10.1038/s41558-022-01287-8

Bulle, H. (1926). Untersuchungen über die Geschiebeableitung bei der Spaltung von Wasserläufen: Modellversuche aus dem Flussbaulaboratoriumder Technischen Hochschule zu Karlsruhe. *VDI Verlag Berlin*, *283*.

Carrier-Belleau, C., Pascal, L., Nozais, C., & Archambault, P. (2022). Tipping points and multiple drivers in changing aquatic ecosystems: A review of experimental studies. *Limnology & Oceanography*, *67*(S1), S312–S330. https://doi.org/10.1002/lno.11978

Chowdhury, M. K., Blom, A., Ylla Arbós, C., Verbeek, M. C., Schropp, M. H. I., & Schielen, R. M. J. (2022). Bed elevation, bed surface grain size (D_{50} and D_{50}), and water discharge—Waal, Pannerden Channel, Nederrijn, and IJssel, 1928–2020 [Dataset]. *4TU.ResearchData*. https://doi.org/10.4121/19650873

Chowdhury, M. K., Blom, A., Ylla Arbós, C., Verbeek, M. C., Schropp, M. H. I., & Schielen, R. M. J. (2023). Semicentennial response of a bifurcation region in an engineered river to peak flows and human interventions. *Water Resources Research*, *59*(4). https://doi.org/10.1029/2022WR032741

Ditlevsen, P., & Ditlevsen, S. (2023). Warning of a forthcoming collapse of the Atlantic meridional overturning circulation. *Nature Communications*, *14*(1), 1–12. https://doi.org/10.1038/s41467-023-39810-w

Dutta, S., Wang, D., Tassi, P., & Garcia, M. H. (2017). Three-dimensional numerical modeling of the Bulle effect: The nonlinear distribution of near-bed sediment at fluvial diversions. *Earth Surface Processes and Landforms*, *42*(14), 2322–2337. https://doi.org/10.1002/esp.4186

Gatfaoui, H., & De Peretti, P. (2019). Flickering in information spreading precedes critical transitions in financial markets. *Scientific Reports*, *9*(1), 1–11. https://doi.org/10.1038/s41598-019-42223-9

He, D., Liu, Z.-P., Honda, M., Kaneko, S., & Chen, L. (2012). Coexpression network analysis in chronic hepatitis B and C hepatic lesions reveals distinct patterns of disease progression to hepatocellular carcinoma. *Journal of Molecular Cell Biology*, *4*(3), 140–152. https://doi.org/10.1093/jmcb/mjs011

Howard, A. (1980). *Thresholds in geomorphology*. In D. Coates & J. Vitek (Eds.), (pp. 227–258). Allen and Unwin.

Klose, A. K., Karle, V., Winkelmann, R., & Donges, J. F. (2020). Emergence of cascading dynamics in interacting tipping elements of ecology and climate. *Royal Society Open Science*, *7*(6), 200599. https://doi.org/10.1098/rsos.200599

Lavé, J., Guérin, C., Valla, P. G., Guillou, V., Rigaudier, T., Benedetti, L., et al. (2023). Medieval demise of a Himalayan giant summit induced by mega-landslide. *Nature*, *619*(7968), 94–101. https://doi.org/10.1038/s41586-023-06040-5

Lenton, T. M., Held, H., Kriegler, E., Hall, J. W., Lucht, W., Rahmstorf, S., & Schellnhuber, H. J. (2008). Tipping elements in the Earth's climate system. *Proceeding National Academy of Sciences U.S.A*, *105*(6), 1786–1793. https://doi.org/10.1073/pnas.0705414105

Lenton, T. M., Rockstrom, J., Gaffney, O., Rahmstorf, S., Richardson, K., Steffen, W., & Schellnhuber, H. J. (2019). Climate tipping points—Too risky to bet Against. *Nature*, *575*(7784), 592–595. https://doi.org/10.1038/d41586-019-03595-0

Lohmann, J., & Ditlevsen, P. D. (2021). Risk of tipping the overturning circulation due to increasing rates of ice melt. *Proceeding National Academy of Sciences U.S.A.*, *118*(9). https://doi.org/10.1073/pnas.2017989118

Meng, Y., Lai, Y.-C., & Grebogi, C. (2020). Tipping point and noise-induced transients in ecological networks. *Journal of the Royal Society Interface*, *17*(171), 20200645. https://doi.org/10.1098/rsif.2020.0645

Notebaert, B., Broothaerts, N., & Verstraeten, G. (2018). Evidence of anthropogenic tipping points in fluvial dynamics in Europe. *Global and Planetary Change*, *164*, 27–38. https://doi.org/10.1016/j.gloplacha.2018.02.008

Paudel, S., Singh, U., Crosato, A., & Franca, M. J. (2022). Effects of initial and boundary conditions on gravel-bed river morphology. *Advances in Water Resources*, *166*, 104256. https://doi.org/10.1016/j.advwatres.2022.104256

Phillips, J. D. (2018). Tipping points in Texas Rivers. *Earth Surface Processes and Landforms*, *43*(9), 1768–1781. https://doi.org/10.1002/esp.4352

Ragno, N. (2023). Viewing second-order phase transitions as a metaphor for river bifurcations. *Journal of Fluid Mechanics*, *974*, A53. https://doi.org/10.1017/jfm.2023.831

Ragno, N., Redolfi, M., Tambroni, N., & Tubino, M. (2023). Modeling steady grain sorting in river Bifurcations. *Journal of Geophysical Research: Earth Surface*, *128*(9). https://doi.org/10.1029/2023JF007230

Rietkerk, M., Bastiaansen, R., Banerjee, S., van de Koppel, J., Baudena, M., & Doelman, A. (2021). Evasion of tipping in complex systems through spatial pattern formation. *Science*, *374*, 6564. https://doi.org/10.1126/science.abj0359

Rietkerk, M., Dekker, S. C., De Ruiter, P. C., & van de Koppel, J. (2004). Self-organized patchiness and catastrophic shifts in ecosystems. *Science*, *305*(5692), 1926–1929. https://doi.org/10.1126/science.1101867

Saikia, A. (2020). Earthquakes and the environmental transformation of a floodplain landscape: The Brahmaputra valley and the earthquakes of 1897 and 1950. *Environment and History*, *26*(1), 51–77. https://doi.org/10.3197/096734019X15755402985550

Scheffer, M., Bascompte, J., Brock, W. A., Brovkin, V., Carpenter, S. R., Dakos, V., et al. (2009). Early-warning signals for critical transitions. *Nature*, *461*(7260), 53–59. https://doi.org/10.1038/nature08227

Scheffer, M., Carpenter, S., Foley, J. A., Folke, C., & Walker, B. (2001). Catastrophic shifts in ecosystems. *Nature*, *413*(6856), 591–596. https://doi.org/10.1038/35098000

Schielen, R. M. J., & Blom, A. (2018). A reduced complexity model of a gravel-sand river bifurcation: Equilibrium states and their stability. *Advances in Water Resources*, *121*, 9–21. https://doi.org/10.1016/j.advwatres.2018.07.010

Schielen, R. M. J., Blom, A., Chowdhury, M. K., Ylla Arbós, C., Doelman, A., & Rietkerk, M. (2024). MATLAB files for reproducing the phase plane figures in the GRL-paper "Evidence of ongoing noise-tipping of a bifurcating river system" Version 2 [Software]. *4TU.ResearchData*. https://doi.org/10.4121/2a9664e4-02eb-41fe-9016-fbb63a2b4bea.v2

Song, Y., Xu, W., & Jiao, Y. (2021). Bifurcation-and noise-induced tipping in two-parametric gene transcriptional regulatory system. *The European Physical Journal Plus*, *137*(1), 68. https://doi.org/10.1140/epjp/s13360-021-02300-3

Toonen, W. H. J. (2015). Flood frequency analysis and discussion of non-stationarity of the Lower Rhine flooding regime (AD 1350–2011): Using discharge data, water level measurements, and historical records. *Journal of Hydrology*, *528*, 490–502. https://doi.org/10.1016/j.jhydrol.2015.06.014

Van der Mark, C. F., & Mosselman, E. (2013). Effects of helical flow in one-dimensional modelling of sediment distribution at river bifurcations. *Earth Surface Processes and Landforms*, *38*(5), 502–511. https://doi.org/10.1002/esp.3335

Van Westen, R. M., Kliphuis, M., & Dijkstra, H. A. (2024). Physics-based early warning signal shows that AMOC is on tipping course. *Science Advances*, *10*(6), eadk1189. https://doi.org/10.1126/sciadv.adk1189

Wang, C., Wang, Q., Meire, D., Ma, W., Wu, C., Meng, Z., et al. (2016). Biogeomorphic feedback between plant growth and flooding causes alternative stable states in an experimental floodplain. *Advances in Water Resources*, *93*, 223–235. https://doi.org/10.1016/j.advwatres.2015.07.003

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

Ylla Arbós, C. (2021). Bed elevation and bed surface grain size D_{50} Bovenrijn and Waal, 1926–2020 [Dataset]. *4TU.ResearchData*. https://doi.org/10.4121/13065359.V2

Ylla Arbós, C., Blom, A., Sloff, C. J., & Schielen, R. M. J. (2023). Centennial channel response to climate change in an engineered river. *Geophysical Research Letters*, *50*(8). https://doi.org/10.1029/2023GL103000

Ylla Arbós, C., Blom, A., Viparelli, E., Reneerkens, M., Frings, R. M., & Schielen, R. M. J. (2021). River response to anthropogenic modification: Channel steepening and gravel front fading in an incising river. *Geophysical Research Letters*, *48*(4). https://doi.org/10.1029/2020GL091338