AGU ADVANCING EARTH AND SPACE SCIENCE

Geophysical Research Letters

RESEARCH LETTER
10.1029/2022GL102072

Key Points:
- Climate-driven changes of hydrological regime can have a significant impact on bar morphology
- The formation of alternate bars in channelized rivers is promoted by a decrease of frequency of high flows
- Sensitivity of bar morphology to climatic stressors depends on how far the river width is from the key morphodynamic threshold value

Supporting Information:

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

Correspondence to:

M. Redolfi,
marco.redolfi@unitn.it

Citation:

Redolfi, M., Carlin, M., & Tubino, M. (2023). The Impact of climate change on river alternate bars. *Geophysical Research Letters*, *50*, e2022GL102072. https://doi.org/10.1029/2022GL102072

Received 17 NOV 2022
Accepted 30 DEC 2022

Author Contributions:

Conceptualization: M. Redolfi, M. Carlin, M. Tubino
Data curation: M. Redolfi, M. Carlin
Formal analysis: M. Redolfi, M. Carlin
Funding acquisition: M. Tubino
Investigation: M. Redolfi, M. Carlin, M. Tubino
Methodology: M. Redolfi, M. Carlin, M. Tubino
Resources: M. Carlin
Software: M. Redolfi, M. Carlin
Supervision: M. Tubino
Validation: M. Redolfi, M. Carlin
Visualization: M. Redolfi, M. Carlin
Writing – original draft: M. Redolfi, M. Carlin
Writing – review & editing: M. Redolfi, M. Tubino

The Impact of Climate Change on River Alternate Bars

M. Redolfi[1], M. Carlin[1], and M. Tubino[1]

[1]Department of Civil, Environmental and Mechanical Engineering, University of Trento, Trento, Italy

Abstract Climate change is expected to alter the distribution of flow discharge in rivers worldwide. We study the impact of climate-driven flow changes on the shape of riverbed, and specifically on alternate bars, large deposits of gravel/sand that often form in rivers. We consider the illustrative example of the Alpine Rhine River, showing two nearby reaches with similar hydro-morphological characteristics, but different channel width. Hydrological projections are obtained from literature, while the evolution of alternate bars is predicted through a novel, semi-analytical model. Results show a remarkably different behavior of the two reaches: the upstream one, being wide enough for a full development of alternate bars, is resistant to flow alterations; the downstream reach, whose width is close to threshold conditions, is highly susceptible to future changes, showing a strong tendency to increase bar prominence. These findings reflect a general tendency of near-threshold geomorphic systems to be vulnerable to anthropic stressors.

Plain Language Summary The worldwide alteration of the river flow induced by climate change is likely to significantly impact the bed morphology of embanked rivers, which is often characterized by the presence of alternate bars, namely repetitive sequences of large sediment deposits and scour zones. Bar formation is both a major issue for river management (due to local erosion at instream structures and increase of flood risk), and an important resource for sustaining biodiversity, because bar morphology templates rich habitats for river fauna and vegetation. We analyze the effect of climate change on river bars by considering existing state-of-the-art projections of future flow discharge, and by implementing a mathematical model suitable to perform long-term simulations, while keeping the essential ingredients to reproduce bar dynamics. Model results reveal a very different adaptation of the riverbed to climate change: relatively wide reaches are expected to maintain the current alternate bar characteristics, while reaches whose width is close to a critical threshold value are likely to experience a remarkable alteration in the next decades, which provides a noteworthy example of how near-threshold geomorphic systems may be highly sensitive to climate change.

1. Introduction

Climate change is expected to significantly alter the hydrological regime of rivers worldwide (Pörtner et al., 2022), by changing the spatial and temporal distribution of precipitations, reducing the snow and ice cover and increasing the evaporation rate. A direct consequence of such alteration is the possible increase in the magnitude and probability of dry periods and extremely high flow events, resulting in increased flood risk, loss of biodiversity and economical costs (e.g., Alfieri et al., 2015; Arnell & Gosling, 2016; Hirabayashi et al., 2013; Winsemius et al., 2016). Changes of flow regime can also impact the sedimentation processes and the resulting morphological structure of river corridors, which controls the overall functioning of riverine ecosystems (Kemp et al., 1999; Maddock, 1999).

The possible impact of the changing climate on the morphodynamical trajectories of alluvial rivers is still largely unexplored. The few contributions produced so far mainly focus on the variation of reach averaged parameters (riverbed slope, channel width) within a one-dimensional framework (Gomez et al., 2009; Hiemstra et al., 2020). However, morphological changes that are likely to produce a major impact on river functions often involve more complex, three-dimensional adjustments of river geometry at the reach scale, which can eventually lead to complete shifts of river style, for example from complex multi-thread braided pattern to a single-thread meandering course (Rinaldi et al., 2005; Stecca et al., 2019). In this perspective, despite some pioneering works (Guerrero et al., 2013; van Oorschot et al., 2018), there is a lack of information about the geomorphic river response to climatic-driven alterations of flow regime (Lotsari et al., 2015).

Morphological changes at the reach scale are mainly driven by alternate bars, namely large, three-dimensional bedforms consisting in a sequence of sediment deposits and scour holes (Church & Rice, 2009).

Downstream-migrating alternate bars often form in straightened river reaches as a result of an autogenic instability mechanism (Colombini et al., 1987; Parker, 1976; Redolfi, 2021), frequently resulting in bed elevation changes of the order of several meters. Therefore, they significantly impact river's navigation, produce intense erosion along banks and instream structures, and locally increase the flooding risk (Claude et al., 2014). However, they also provide important ecosystem functions, because their morphological diversity structures the physical habitat template for a number of aquatic and riparian species (Petts et al., 2000; Tockner et al., 2006), besides creating a valuable environment for recreational activities (Basak et al., 2021).

In this paper we take the Alpine stretch of the Rhine River as a case study to investigate the expected impact of climate change on the morphodynamical response of river bars. Specifically, we consider two consecutive channelized reaches with similar slope, bed material and hydrological regime, but with different channel width. The alteration of flow regime is estimated via existing hydrological projections from the Hydro-CH2018 project (Muelchi et al., 2021), while the associated variations of bar response are modeled by means of a custom-made semi-analytical morphodynamic model.

2. Methods

2.1. Study Site

Our study site is located in the so-called Alpine Rhine, the segment of the Rhine River flowing from the Swiss Alps to the Lake of Constance, whose subbasin covers an area of 6,123 km^2 among Liechtenstein, Austria and Switzerland. The flow regime is pluvio-nival, with significant snowmelt in spring and summer, and larger floods mainly occurring in autumn. The river segment was fully channelized in the last two centuries, by straightening the river course and reducing the width of the fluvial corridor, which unavoidably led to a drastic simplification of the original complex multi-thread morphology (Adami et al., 2016).

We specifically focus on two nearby reaches located upstream and downstream the confluence of the Ill River near Eichenwies (see Figure S2 in Supporting Information S1). The analysis of expected bar trajectories in the latter reach seems particularly relevant when considering the ongoing international project "Rhesi–Rhein, Erholung und Sicherhei" (Mähr et al., 2021), which aims at restoring a near-natural dynamics in the 26 km long stretch downstream the confluence of the Ill tributary by an extensive channel widening intervention, designed to increase the discharge capacity from the current 3,100 m^3s^{-1} up to at least 4,300 m^3s^{-1}.

Discharge data recorded at intervals of 10 min are available from the Swiss station of Diepoldsau from 1984 to 2010. The two reaches have similar channel slope (0.13% and 0.10%, respectively) and nearly the same median grain size (25 mm), and are subject to a similar hydrological regime, despite the flow contribution from the tributary Ill River, which increases the two-years discharge from 1,075 to 1,231 m^3s^{-1}. However, the downstream reach is significantly narrower, showing a width reduction from 106 to 63 m.

The examined reaches are representative of two diverse morphological responses to channelization, the upstream one showing prominent, downstream-migrating alternate bars (Adami et al., 2016; Jaeggi, 1984), while the downstream one barely displaying low-relief bars. Based on the methodology recently proposed by Carlin et al. (2021) to predict the long-term response of bar topography to the hydrological regime, such different behavior can be explained in terms of the balance between the respective effectiveness of bar-forming and bar-suppressing flow events, which strongly depends on channel width.

2.2. Hydrological Effect of Climate Change

Hydrological scenarios are based on the projections made available by the project Hydro-CH2018, which provides data of the expected monthly discharge in the entire Swiss fluvial network for a reference period and for three future scenarios, depending on the representative concentration pathways of greenhouse gases RCP2.6, RCP4.5, RCP8.5 defined by IPCC (Moss et al., 2010; van Vuuren et al., 2011). These projections are based on the semi-distributed hydrological model PREVAH (Viviroli et al., 2009), which includes various sub-models to account for hydrologically relevant processes such as snowmelt, glacimelt, soil moisture, evapotranspiration, runoff, and baseflow generation (see Muelchi et al., 2021).

Monthly averaged runoff for the periods 2020–2049, 2045–2074, 2070–2099 are then compared to simulated values during the reference period (1981–2010) to compute monthly change factors for each representative

10.1029/2022GL102072

concentration pathway. To avoid unphysical discontinuities between different months, the change factors $c_f(t)$ are then calculated at the sub-daily scale through linear interpolation, obtaining the annual trends reported in Figure S1 in Supporting Information S1. In general, the model suggests a clear net increase of flowing discharge in winter and a reduction in summer. This is in line with the projections obtained by Middelkoop et al. (2001) and Brunner et al. (2019), who associated the above effects to the expected decrease in snow accumulation in Alpine catchments.

A classic multiplicative delta change method (Hay et al., 2000; Räty et al., 2014) is then applied to compute representative future flow series from historical records. Specifically, flow measurements from the reference period 1984–2010 are multiplied by the change factors to obtain projected hydrographs. Application of this method can be questionable for projecting extreme events statistics, as their variations can differ significantly from those of the monthly averaged values. However, this method seems appropriate for our specific purpose, considering that bar response mainly results from the cumulative work of moderate flow events, rather than from rare extreme floods (Carlin et al., 2021).

2.3. The Semi-Analytical Bar Evolution Model

Different modeling approaches are possible to simulate the adaptation of alternate bars to climate change scenarios. However, numerical morphodynamical models (e.g., Cordier et al., 2019; Nelson et al., 2015; Nicholas, 2010) remain computationally expensive, therefore unsuitable for modeling riverbed evolution on the scale of decades, especially when considering multiple scenarios. By comparison, existing analytical approaches are meant to model the bed response to individual flow events (Tubino, 1991) or to periodic flow variations (Carlin et al., 2020; Hall, 2004), rather than the long-term bar response to the complex hydrological regime. Therefore, in this work we adopt a novel model that is based on a semi-analytical implementation of the weakly nonlinear solution by Colombini et al. (1987) (hereinafter CST).

The CST model allows for computing the evolution in time of the bar amplitude through the following differential equation:

$$\frac{dA}{dt} = \gamma_1 A - \gamma_2 A^3, \tag{1}$$

where t is time and γ_1, γ_2 are coefficients that depend on flow discharge and channel characteristics. The amplitude A is technically defined as the difference between the maximum and the mean value of the first, double-sinusoidal Fourier component of bed topography (see Redolfi et al., 2020). A direct relationship between the amplitude A and the bar height (Figure S3 in Supporting Information S1) can be obtained from the CST model through the computation of the higher-order Fourier components that are needed to fully reconstruct the bed topography.

The original CST formulation was meant to model bar evolution and equilibrium bar characteristics for a given discharge value (steady flow conditions), in which case the γ coefficients are constant and Equation 1 can be analytically solved. The main implication is that bar development crucially depends on whether the flow discharge Q is larger or smaller than a critical value (Q_{cr}): in the former case the coefficient γ_1, which represents the linear growth rate, is negative and bar amplitude decays in time (bar-suppressing conditions); conversely when $Q < Q_{cr}$ the coefficient γ_1 is positive and the amplitude grows until it reaches an equilibrium value (bar-forming conditions). The ability of CST model to predict the formation of migrating bars and to provide an estimate of their equilibrium height has been tested based on comparison with a large number of flume experiments (Colombini et al., 1987; Redolfi, 2021).

In the present work we seek an extension of the model to unsteady flow conditions by simply allowing the γ coefficients to vary in time, depending on current discharge stage. From a computational point of view, Equation 1 is therefore integrated by discretizing the hydrograph at equally spaced time steps, and computing the amplitude evolution by a simple explicit Euler method. Based on experimental observations (Redolfi et al., 2020), our model also assumes that bars are morphologically inactive at flow stages that are not sufficient to completely submerge bar topography, when the CST assumption of fully wet domain is no longer valid.

3. Results

The time evolution of bar amplitude in the two study reaches predicted by the model for the reference period 1984–2010 is illustrated in Figure 1, which highlights the different behavior of the two consecutive reaches.

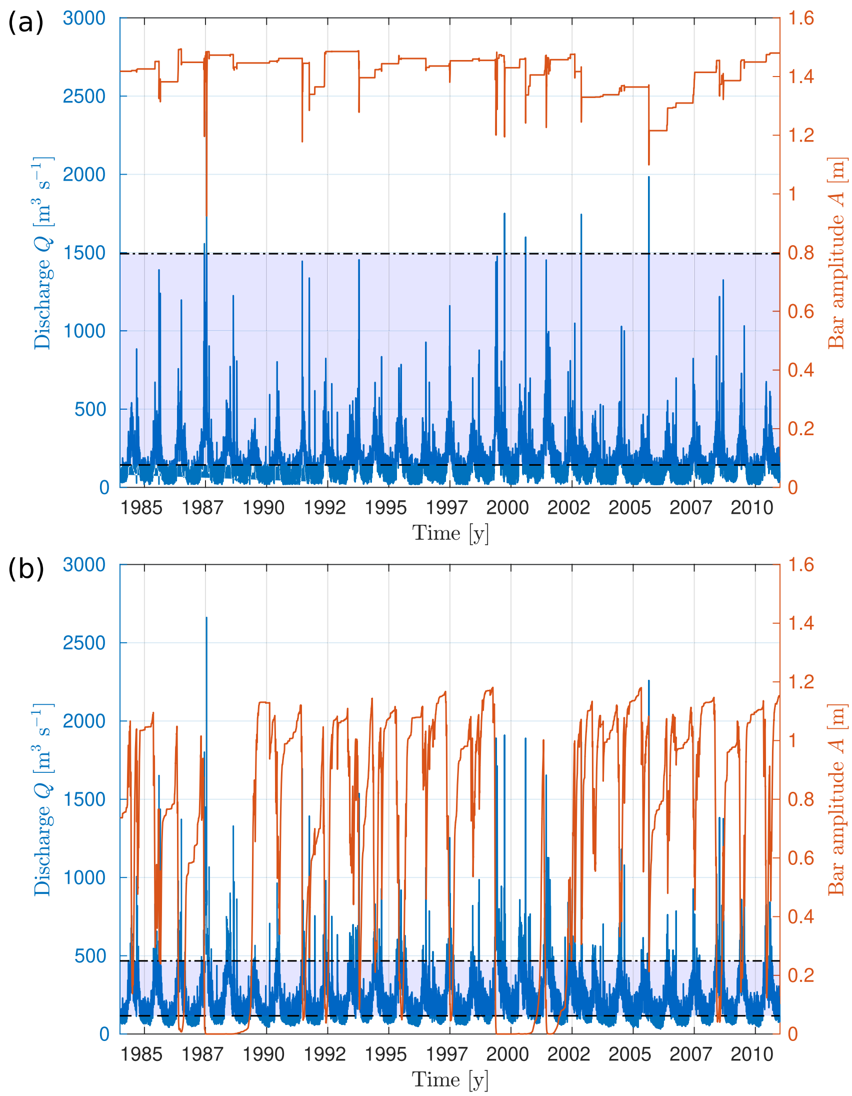

Figure 1. Simulated evolution of bar amplitude in the Alpine Rhine River for the reference period 1984–2010 (red line, right axis) and corresponding flow hydrograph (blue line, left axis): (a) upstream reach; (b) downstream reach. The shaded area represents bar-forming conditions, occurring when discharge lies between the condition of incipient sediment motion Q_i (dashed line) and the critical value for bar formation Q_{cr} (dash-dotted line); conversely, bar-suppressing conditions correspond to $Q > Q_{cr}$.

Specifically, for the upstream reach the model predicts well-developed alternate bars with a mean amplitude of 1.4 m, which slightly varies during flood events. Large flows tend to reduce bar height, which then recovers during the receding phase of the same flood, or during successive smaller floods. Conversely, the downstream reach manifests frequent shifts between a state of well developed bars and flat-bed conditions, which results in a reduced mean amplitude of 0.7 m. This is symptomatic of a near-critical situation, in which river's conditions frequently shift from bar-forming to bar-suppressing, mainly depending on water discharge. Critical discharge is indeed equal to $Q_{cr} = 467\,\mathrm{m}^3\mathrm{s}^{-1}$, a value which is easily exceeded during moderate floods.

The near-critical situation of the downstream reach can be assessed by evaluating the parameter P_{form} introduced by Carlin et al. (2021). The definition of this parameter is founded on the long-established idea (Andrews, 1980; Wolman & Miller, 1960) that the relevance of the different flow stages in determining the long-term river evolution depends on the product between their frequency of occurrence and their effectiveness to produce morphological alterations. For the specific case of alternate bars a suitable measure of the effectiveness is the bar growth rate $\gamma_1(Q)$, which is then multiplied by the flow probability density function to obtain a weighted frequency $f(Q)$.

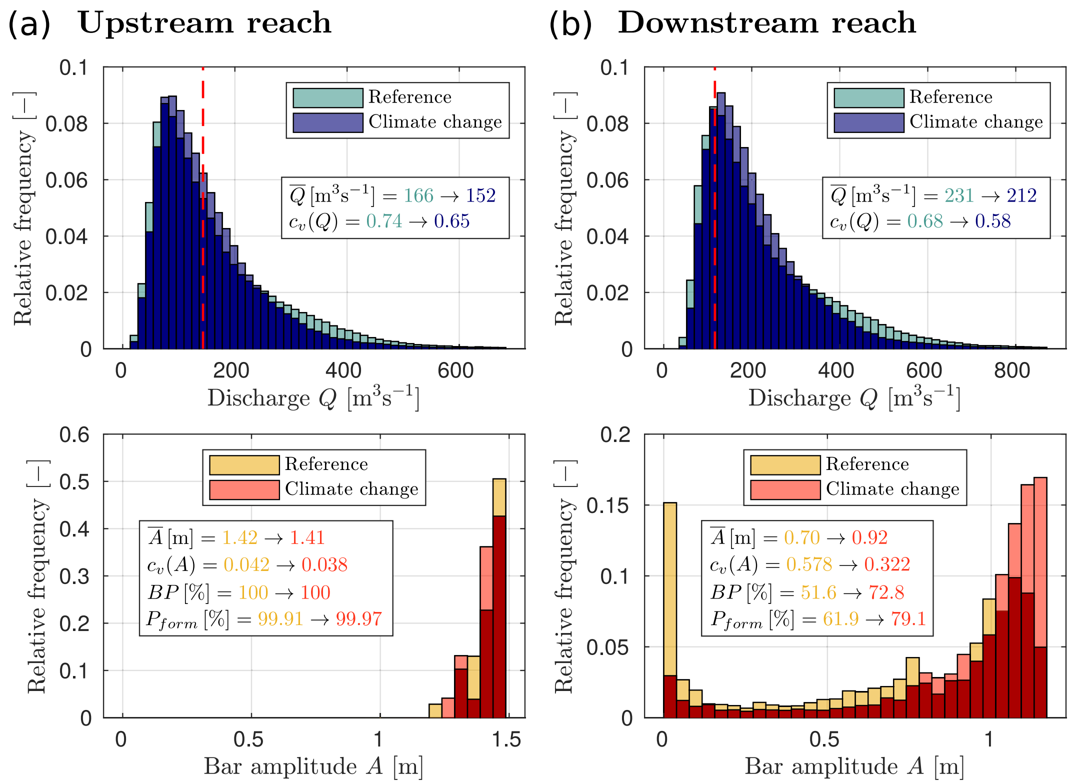

Figure 2. The distribution of flow discharge Q (upper panels) and bar amplitude A (lower panels) in the upstream (a) and the downstream (b) reaches: comparison between the reference period 1984–2010 and the climate change scenario (2045–2074, RCP4.5). The vertical dashed line indicates the incipient sediment motion discharge Q_i. $\overline{Q}$ and $\overline{A}$ denote the mean values, c_v is the coefficient of variation (i.e., the ratio between the standard deviation and the mean) and the "bar presence" metric (BP) is defined as the percentage of time when bar amplitude exceeds a minimum depth (here conventionally defined as the value that is exceeded 99% of time), while P_{form} is the relative frequency of bar-forming conditions (Equation 2).

Integrating over all bar-forming ($Q < Q_{cr}$, shaded area of Figure 1) and bar-suppressing ($Q > Q_{cr}$) stages gives the cumulative weighted frequencies f_{BF} and f_{BS}, which are finally combined to obtain the relative probability of bar-forming conditions:

$$P_{form} = \frac{f_{BF}}{f_{BF} + f_{BS}}. \tag{2}$$

Therefore, $P_{form} = 50\%$ represents a threshold condition in which bar-forming and bar-suppressing stages balance each other. This is almost the case of the downstream reach, for which a value $P_{form} = 62\%$ is found, indicating a near-threshold condition. By comparison, in the upstream reach the critical discharge ($Q_{cr} = 1{,}493\ \mathrm{m^3s^{-1}}$) is rarely exceeded, which makes bar-suppressing conditions very unlikely ($P_{form} = 99.9\%$).

To explore the possible future bar trajectories we first consider the intermediate scenario set by RCP4.5 and the medium-term period 2045–2074, and we compute the bar evolution in the two reaches using the projected flow series. Changes in the frequency distribution of flow discharge are illustrated in Figure 2 (upper panels), which reveals a similar effect on the upstream and the downstream reaches, both showing an increased frequency of intermediate discharge values, a reduced occurrence of moderately high flows, and a net decrease of the mean discharge of about 8%. Conversely, changes in the simulated bar amplitude distribution (lower panels) are markedly different in the two reaches: in the upstream one the distribution does not show any systematic variation, so that the mean amplitude remains essentially unchanged, while in the downstream reach the frequency of flat-bar states strongly reduces, and periods when bars are well developed ($A > 1$ m) become more frequent. As a result in the upstream reach all bar metrics remain basically unchanged, whereas in the downstream part significant alterations are expected. Specifically, for the downstream reach our analysis suggests a 35% increase of the mean bar amplitude (from 0.70 to 0.92 m) and a substantial reduction of its variability, as highlighted by the 45% decrease

10.1029/2022GL102072

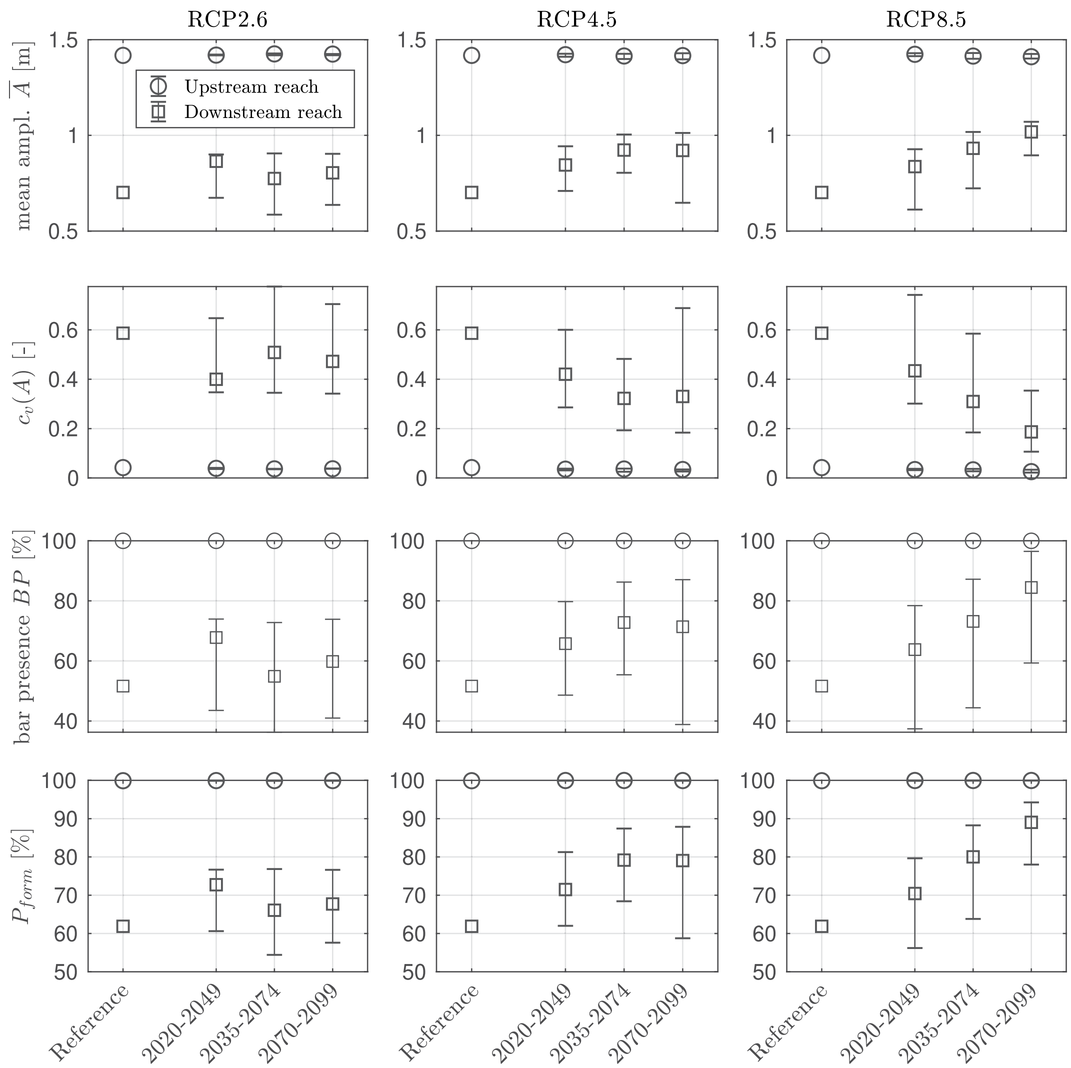

Figure 3. Expected future trends of mean bar amplitude, coefficient of variation, bar presence and relative frequency of bar-forming conditions, for different time periods and emission scenarios (RCPs). Circles and square markers refer to the upstream and the downstream reaches, respectively; error bars indicate the variation associated with extreme hydrological projections.

of the coefficient of variation. Moreover, the reduction of flat-bed states is revealed by the increase of the bar presence metric from 51.6% to 72.8%. Such higher propensity to form bars can be again explained in terms of the parameter P_{form}, which is expected to increase up to 79.1%.

A more complete overview of the expected bar trajectory depending on the emission scenario is illustrated in Figure 3, which confirms the general increase of mean bar amplitude, bar presence, and P_{form}, and the opposite trend of the coefficient of variation c_v. For the emission scenario RCP4.5 these changes progressively develop in time, though the metrics tend to reach a plateau toward the end of the century (period 2070–2099). By comparison, the pathway RCP2.6 leads to similar changes for the period 2020–2049, while a tendency to recover is expected for the second part of the century. Conversely, the scenario RCP8.5 leads to a strong, continuous morphological change, eventually leading to well developed bars (markedly increased bar amplitude, bar presence and P_{form}, strongly reduced c_v) for the period 2070–2099. Figure 3 also provides an estimate of the degree of uncertainty of bar response, computed by considering the extreme outcomes of the hydrological projections. This preliminary assessment highlights once again the differing response of the two reaches: while a significant degree of uncertainty appears in future bar trajectories for the downstream reach, especially when considering the most optimistic scenario RCP2.6, the future trend of the wider upstream reach seems much more predictable, being essentially unaffected by hydrological alterations.

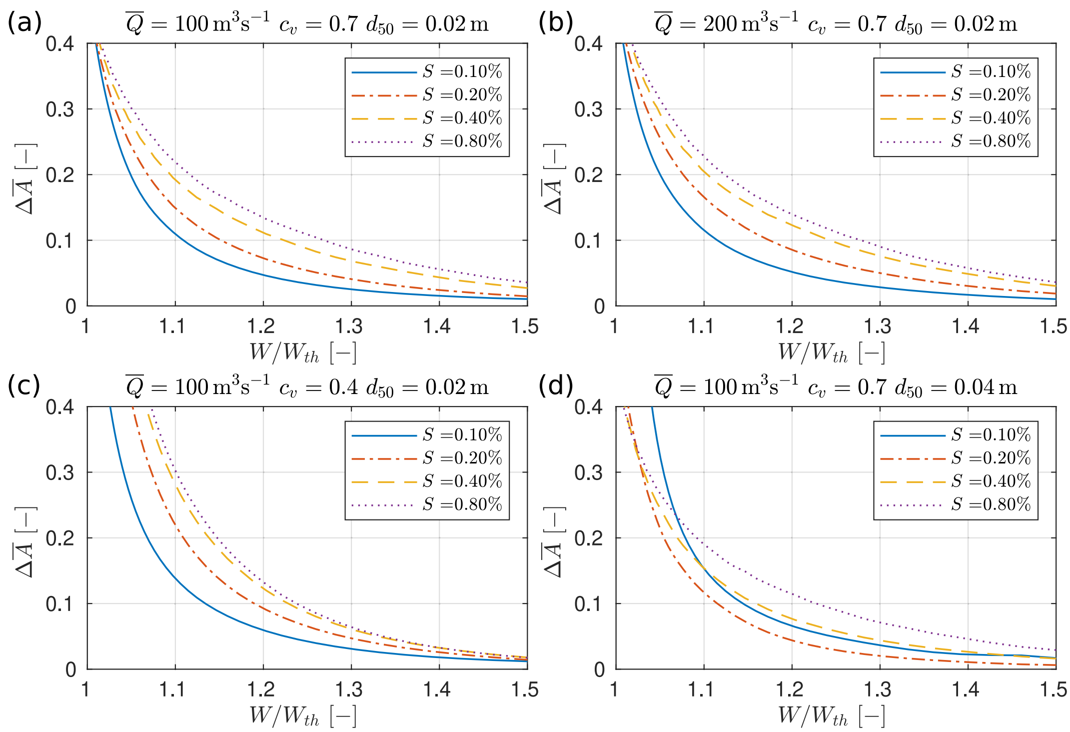

Figure 4. Sensitivity of mean bar amplitude to variations of water discharge as a function of the distance from threshold conditions, represented by the ratio W/W_{th}, and for different values of channel slope S. Panel (a): basic conditions; panels (b, c, and d): variation of mean discharge $\overline{Q}$, coefficient of variation c_v and grain size d_{50}.

3.1. Bar Sensitivity and River Characteristics

The relevance of the above results in a broader context can be explored by considering cases with different channel slope, width, grain size, subject to a synthetic flow series that contains the essential information about mean flow and its variability. Specifically, we consider a Compound Poisson Process (CPP) (e.g., Bertagni et al., 2018; Weiss, 1977), according to which the streamflow is modeled as a sequence of exponentially distributed random jumps, followed by an exponential flow decay. Such stochastic process is fully characterized by three independent parameters, namely the mean discharge $\overline{Q}$, the coefficient of variation of the flow series c_v and the characteristic time of flow decay τ, as detailed in Text S2 in Supporting Information S1.

For each combination of parameters, we consider a reference and a modified scenario, the latter constituted by the simplest possible hydrological alteration given by a constant change factor ($Q_{cc} = 0.9\ Q_{ref}$). Modeling long-term bar evolution in the two scenarios allows for computing bar sensitivity, which is measured through the parameter:

$$\Delta\overline{A} = \frac{\overline{A}_{cc}}{\overline{A}_{ref}} - 1, \tag{3}$$

where $\overline{A}_{ref}$ and $\overline{A}_{cc}$ indicate the mean bar amplitude in the reference and the modified scenario, respectively.

This enables for analyzing how bar sensitivity depends on the distance between the channel width W and the threshold value W_{th}, which is defined as minimum width for which alternate bars are expected to form, corresponding to the condition $P_{form} = 50\%$. Such threshold width can be uniquely defined as a function of flow probability density function, channel slope and grain size (Carlin et al., 2021), as illustrated in Figure S5 in Supporting Information S1. Analysis of bar sensitivity reveals the primary role played by the threshold width in controlling the bar response. Specifically, results illustrated in Figure 4 show that for any combination of river parameters the bar sensitivity ΔA increases when channel width approaches W_{th}, with the other parameters playing a secondary role.

10.1029/2022GL102072

4. Discussion

Taking advantage of state-of-the art hydrological projections, we propose a semi-analytical morphodynamic model for investigating the possible effects of climate change on development of large alternating bars in channelized rivers. Results reveal a markedly different response of alternate bars to similar climate forcings, depending on the distance between the average hydro-morphological conditions and the critical discharge Q_{cr} that discriminates favorable conditions for bar formation ($Q < Q_{cr}$) from those in which bars tend to be suppressed ($Q > Q_{cr}$).

The sharp dependence of the critical discharge on channel width (Carlin et al., 2021), which results from the fact that the suppressing effect of gravitational pull on bedload transport is much more effective in relatively narrow channels (Redolfi, 2021), implies that the response of alternate bars to climate change strongly depends on the width of the channelization. In relatively wide reaches, where the critical discharge is so high that it is rarely exceeded, bars are currently well-developed and are expected to easily absorb climatic alterations. Conversely, in reaches that are close to the geomorphic threshold set by the channel width W_{th}, bar-forming and bar-suppressing flow events are nearly balanced, so that relatively small hydrological changes are sufficient to produce long-term alterations of bar dynamics.

The semi-analytical model we propose, based on existing weakly nonlinear solutions of shallow water and sediment continuity equations, contains all the key ingredients needed to capture the overall evolution of river alternate bars in channelized reaches, including the sharp variations of bar properties in near-critical conditions and the dependence of bar growth rate on flow discharge (Carlin et al., 2021). If compared with alternative numerical approaches, based on fully nonlinear solutions (e.g., Crosato et al., 2012; Defina, 2003; Qian et al., 2017), our model provides a parsimonious, computationally efficient strategy to explore reach-scale bar trajectories driven by long-term hydrological changes.

This work constitutes a precise example of application of the concept of river sensitivity, expressed as the likelihood that a given change in the key controls will produce a sensible, recognizable and persistent response (Brunsden & Thornes, 1979; Fryirs, 2017). In this perspective, our preliminary uncertainty analysis also suggests that highly sensitive cases are not only characterized by more intense morphological changes, but also by a stronger dependence on the unavoidable uncertainties in the modeling chain. The high sensitivity of river bars dynamics when channel width is close to W_{th} represents a noteworthy example of a more general characteristic of near-threshold geomorphic systems to be fragile and susceptible to external disturbances, potentially manifesting rapid shifts and transitions, in contrast to systems that being far from thresholds are likely to maintain their physical attributes in the long term (Phillips, 2006, 2009; Schumm, 1973). Notably, the role of the threshold in controlling the average, long-term bed response is rather sharp, despite the fact that critical conditions are frequently crossed due to flow variability. This is because bar evolution depends on the cumulative effect of flow events, so that an even marginal dominance of bar-forming or bar-suppressing conditions can result in markedly different long-term trajectories. In real conditions, different factors (e.g., channel curvature, width and bed-texture variations) can contribute to a more gradual bar response. However, the distance from threshold conditions is still expected to play a primary role, as it ultimately represents the key parameter that controls the long-term riverbed stability.

4.1. Relevance for River Widening Interventions

There is nowadays an increasing tendency to promote ecosystem-based river restoration practices, aimed at restoring river functionality and mitigating the effects of climate change by enhancing instream habitat diversity (Rohde et al., 2005; Wohl et al., 2015). This is often achieved by giving more space to the river, by dismantling artificial embankments or by increasing their distance. In this perspective, an assessment of the river response in a context of changing climate is essential for a successful and cost-effective implementation of this kind of intervention (Belletti et al., 2015). Our model can be regarded as an exploratory tool for assessing the possible geomorphic trajectories of rivers depending on hydro-morphological conditions and on the degree of channel widening, providing a support for the design of more detailed and sophisticated numerical or physical models (e.g., Duró et al., 2016; Rachelly et al., 2021). For example, our results for the Alpine Rhine River suggest that the above-mentioned river widening project "Rhesi" is likely to decrease the sensitivity of the river morphology to climate-driven alterations of the flow regime.

4.2. Limitations and Future Perspectives

Despite being derived for the specific case of alternate bars, our approach can be easily extended to model the dynamics of central or multiple-row bars, by considering higher-order modes in the Fourier representation of the bed topography (e.g., Tubino et al., 1999). Nonetheless, more investigation would be needed to confidently apply this approach, considering possible uncertainties in: (a) assessing the dominant bar mode (Crosato & Mosselman, 2009, 2020) under conditions of unsteady flow, when transitions among different regimes are possible (e.g., Rodrigues et al., 2015); (b) modeling the amplitude evolution of central and multiple-row bars. In this perspective, specifically designed numerical simulations would allow for directly addressing these points in future studies.

It is worth highlighting that the morphodynamic evolution scenario described in this work may change when the river is not channelized but laterally unconfined, which often generates complex multi-thread patterns (Ashmore, 2013; Garcia et al., 2015). In these cases, the river morphology is expected to be less sensitive to discharge variations, since part of them can be absorbed by a lateral flow expansion during floods (Egozi & Ashmore, 2009; Redolfi et al., 2016). Nevertheless, climate-driven flow changes may still significantly impact the geomorphic response of these river systems, as suggested by Guerrero et al. (2013). Therefore, further research is needed to assess future trajectories, especially considering the interaction between hydro-morphological processes and vegetation (e.g., Calvani et al., 2022).

Finally, our model neglects the effect of the alteration of the sediment supply, relying on the fact that readjusting river slope and bed composition involves moving large amounts of sediment over long distances and typically requires long geomorphic time. To fill this gap, the present approach could be hierarchically nested on large scale one-dimensional models (e.g., Gomez et al., 2009), as needed to estimate climatic-driven variations of slope and bed texture.

5. Conclusions

The development of a novel, semi-analytical model for the long-term evolution of river alternate bars provides a tool for assessing the morphological response of channelized rivers to projected hydrological alterations due to climate change. Application to two nearby reaches of the Alpine Rhine River with similar hydrological and sedimentological characteristics, but distinct channel width, reveals a markedly different response, with the wider reach appearing resistant to flow alterations, and the narrower one showing a significant increase of bar height magnitude and variability. Analysis of bar sensitivity in a wide range of parameters reveals that this contrasting behavior depends on the distance from the key threshold represented by the minimum width that allows the formation of bars. From a river management perspective, this implies that river channels that are sufficiently wide are almost unaffected by climatic alterations, being capable of preserving their physical characteristics in the long term. Finally, our results can be regarded as a noteworthy example of a more general property of near-threshold geomorphic systems to be highly sensitive to external disturbances.

Data Availability Statement

MATLAB simulation code and input data are made publicly available at https://doi.org/10.5281/zenodo.7422372.

Acknowledgments
We thank Maarten G. Kleinhans and an anonymous referee for the constructive comments.

References

Adami, L., Bertoldi, W., & Zolezzi, G. (2016). Multidecadal dynamics of alternate bars in the Alpine Rhine River. *Water Resources Research*, *52*(11), 8938–8955. https://doi.org/10.1002/2015WR018228

Alfieri, L., Burek, P., Feyen, L., & Forzieri, G. (2015). Global warming increases the frequency of river floods in Europe. *Hydrology and Earth System Sciences*, *19*(5), 2247–2260. https://doi.org/10.5194/hess-19-2247-2015

Andrews, E. D. (1980). Effective and bankfull discharges of streams in the Yampa River basin, Colorado and Wyoming. *Journal of Hydrology*, *46*(3–4), 311–330. https://doi.org/10.1016/0022-1694(80)90084-0

Arnell, N. W., & Gosling, S. N. (2016). The impacts of climate change on river flood risk at the global scale. *Climatic Change*, *134*(3), 387–401. https://doi.org/10.1007/s10584-014-1084-5

Ashmore, P. (2013). Morphology and dynamics of braided rivers. *Treatise on geomorphology*, (Vol. 9, pp. 289–312). Elsevier. https://doi.org/10.1016/B978-0-12-374739-6.00242-6

Basak, S. M., Hossain, M. S., Tusznio, J., & Grodzińska-Jurczak, M. (2021). Social benefits of river restoration from ecosystem services perspective: A systematic review. *Environmental Science & Policy*, *124*, 90–100. https://doi.org/10.1016/j.envsci.2021.06.005

Belletti, B., Rinaldi, M., Buijse, A. D., Gurnell, A. M., & Mosselman, E. (2015). A review of assessment methods for river hydromorphology. *Environmental Earth Sciences*, *73*(5), 2079–2100. https://doi.org/10.1007/s12665-014-3558-1

Bertagni, M. B., Perona, P., & Camporeale, C. (2018). Parametric transitions between bare and vegetated states in water-driven patterns. *Proceedings of the National Academy of Sciences*, *115*(32), 8125–8130. https://doi.org/10.1073/pnas.1721765115

Brunner, M. I., Farinotti, D., Zekollari, H., Huss, M., & Zappa, M. (2019). Future shifts in extreme flow regimes in Alpine regions. *Hydrology and Earth System Sciences*, *23*(11), 4471–4489. https://doi.org/10.5194/hess-23-4471-2019

Brunsden, D., & Thornes, J. B. (1979). Landscape sensitivity and change. *Geographers*, *4*, 463–484. https://doi.org/10.2307/622210

Calvani, G., Carbonari, C., & Solari, L. (2022). Threshold conditions for the shift between vegetated and barebed rivers. *Geophysical Research Letters*, *49*(1), https://doi.org/10.1029/2021GL096393

Carlin, M., Redolfi, M., & Tubino, M. (2020). Effect of flow unsteadiness on the long-term evolution of alternate bars. In *River flow 2020* (pp. 539–547). CRC Press.

Carlin, M., Redolfi, M., & Tubino, M. (2021). The long-term response of alternate bars to the hydrological regime. *Water Resources Research*, *57*(7). https://doi.org/10.1029/2020WR029314

Church, M., & Rice, S. P. (2009). Form and growth of bars in a wandering gravel-bed river. *Earth Surface Processes and Landforms*, *34*(10), 1422–1432. https://doi.org/10.1002/esp.1831

Claude, N., Rodrigues, S., Bustillo, V., Bréhéret, J.-G., Tassi, P., & Jugé, P. (2014). Interactions between flow structure and morphodynamic of bars in a channel expansion/contraction, Loire River, France. *Water Resources Research*, *50*(4), 2850–2873. https://doi.org/10.1002/2013WR015182

Colombini, M., Seminara, G., & Tubino, M. (1987). Finite-amplitude alternate bars. *Journal of Fluid Mechanics*, *181*(1), 213–232. https://doi.org/10.1017/S0022112087002064

Cordier, F., Tassi, P., Claude, N., Crosato, A., Rodrigues, S., & Bang, D. P. V. (2019). Numerical study of alternate bars in alluvial channels with nonuniform sediment. *Water Resources Research*, *55*(4), 2976–3003. https://doi.org/10.1029/2017WR022420

Crosato, A., Desta, F. B., Cornelisse, J., Schuurman, F., & Uijttewaal, W. S. J. (2012). Experimental and numerical findings on the long-term evolution of migrating alternate bars in alluvial channels. *Water Resources Research*, *48*(6). https://doi.org/10.1029/2011WR011320

Crosato, A., & Mosselman, E. (2009). Simple physics-based predictor for the number of river bars and the transition between meandering and braiding. *Water Resources Research*, *45*(3), 1–14. https://doi.org/10.1029/2008WR007242

Crosato, A., & Mosselman, E. (2020). An integrated review of river bars for engineering, management and transdisciplinary research. *Water*, *12*(2), 596. https://doi.org/10.3390/w12020596

Defina, A. (2003). Numerical experiments on bar growth. *Water Resources Research*, *39*(4), 1–12. https://doi.org/10.1029/2002WR001455

Duró, G., Crosato, A., & Tassi, P. (2016). Numerical study on river bar response to spatial variations of channel width. *Advances in Water Resources*, *93*, 21–38. https://doi.org/10.1016/j.advwatres.2015.10.003

Egozi, R., & Ashmore, P. (2009). Experimental analysis of braided channel pattern response to increased discharge. *Journal of Geophysical Research*, *114*(F2), 1–15. https://doi.org/10.1029/2008JF001099

Fryirs, K. A. (2017). River sensitivity: A lost foundation concept in fluvial geomorphology. *Earth Surface Processes and Landforms*, *42*(1), 55–70. https://doi.org/10.1002/esp.3940

Garcia, L. G. A., Bertoldi, W., Henshaw, A. J., & Gurnell, A. M. (2015). The effect of lateral confinement on gravel bed river morphology. *Water Resources Research*, *51*(9), 7145–7158. https://doi.org/10.1002/2015WR017081

Gomez, B., Cui, Y., Kettner, A. J., Peacock, D. H., & Syvitski, J. P. (2009). Simulating changes to the sediment transport regime of the Waipaoa River, New Zealand, driven by climate change in the twenty-first century. *Global and Planetary Change*, *67*(3–4), 153–166. https://doi.org/10.1016/j.gloplacha.2009.02.002

Guerrero, M., Nones, M., Saurral, R., Montroull, N., & Szupiany, R. N. (2013). Parana River morphodynamics in the context of climate change. *International Journal of River Basin Management*, *11*(4), 423–437. https://doi.org/10.1080/15715124.2013.826234

Hall, P. (2004). Alternating bar instabilities in unsteady channel flows over erodible beds. *Journal of Fluid Mechanics*, *499*, 49–73. https://doi.org/10.1017/S0022112003006219

Hay, L. E., Wilby, R., & Leavesley, G. H. (2000). A comparison of delta change and downscaled GCM scenarios. *Journal of the American Water Resources Association*, *36*(2), 387–397. https://doi.org/10.1111/j.1752-1688.2000.tb04276.x

Hiemstra, K. S., van Vuren, S., Vinke, F. S., Jorissen, R. E., & Kok, M. (2020). Assessment of the functional performance of lowland river systems subjected to climate change and large-scale morphological trends. *International Journal of River Basin Management*, *20*, 1–22. https://doi.org/10.1080/15715124.2020.1790580

Hirabayashi, Y., Mahendran, R., Koirala, S., Konoshima, L., Yamazaki, D., Watanabe, S., et al. (2013). Global flood risk under climate change. *Nature Climate Change*, *3*(9), 816–821. https://doi.org/10.1038/nclimate1911

Jaeggi, M. N. R. (1984). Formation and effects of alternate bars. *Journal of Hydraulic Engineering*, *110*(2), 142–156. https://doi.org/10.1061/(ASCE)0733-9429(1984)110:2(142)

Kemp, J. L., Harper, D. M., & Crosa, G. A. (1999). Use of 'functional habitats' to link ecology with morphology and hydrology in river rehabilitation. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *9*(1), 159–178. https://doi.org/10.1002/(SICI)1099-0755(199901/02)9:1⟨159::AID-AQC319⟩3.0.CO;2-M

Lotsari, E., Thorndycraft, V., & Alho, P. (2015). Prospects and challenges of simulating river channel response to future climate change. *Progress in Physical Geography*, *39*(4), 483–513. https://doi.org/10.1177/0309133315578944

Maddock, I. (1999). The importance of physical habitat assessment for evaluating river health. *Freshwater Biology*, *41*(2), 373–391. https://doi.org/10.1046/j.1365-2427.1999.00437.x

Mähr, M., Valenti, B., & Schatzmann, M. (2021). Hochwasserschutz Alpenrhein Internationale Strecke (pp. 313–320).

Middelkoop, H., Daamen, K., Gellens, D., Grabs, W., Kwadijk, J. C., Lang, H., et al. (2001). Impact of climate change on hydrological regimes and water resources management in the Rhine basin. *Climatic Change*, *49*(1/2), 105–128. https://doi.org/10.1023/A:1010784727448

Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., Vuuren, D. P. V., et al. (2010). The next generation of scenarios for climate change research and assessment. *Nature*, *463*(7282), 747–756. https://doi.org/10.1038/nature08823

Muelchi, R., Rössler, O., Schwanbeck, J., Weingartner, R., & Martius, O. (2021). An ensemble of daily simulated runoff data (1981–2099) under climate change conditions for 93 catchments in Switzerland (Hydro-CH2018-Runoff ensemble). *Geoscience Data Journal*, *9*, 1–12. https://doi.org/10.1002/gdj3.117

Nelson, P. A., McDonald, R. R., Nelson, J. M., & Dietrich, W. E. (2015). Coevolution of bed surface patchiness and channel morphology: 2. Numerical experiments. *Journal of Geophysical Research F: Earth Surface*, *120*(9), 1708–1723. https://doi.org/10.1002/2014JF003429

Nicholas, A. P. (2010). Reduced-complexity modeling of free bar morphodynamics in alluvial channels. *Journal of Geophysical Research*, *115*(F4), 1–16. https://doi.org/10.1029/2010JF001774

Parker, G. (1976). On the cause and characteristic scales of meandering and braiding in rivers. *Journal of Fluid Mechanics*, *76*(3), 457. https://doi.org/10.1017/S0022112076000748

Petts, G. E., Gurnell, A. M., Gerrard, A. J., Hannah, D. M., Hansford, B., Morrissey, I., et al. (2000). Longitudinal variations in exposed riverine sediments: A context for the ecology of the Fiume Tagliamento, Italy. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *10*(4), 249–266. https://doi.org/10.1002/1099-0755(200007/08)10:4⟨249::AID-AQC410⟩3.0.CO;2-R

Phillips, J. D. (2006). Evolutionary geomorphology: Thresholds and nonlinearity in landform response to environmental change. *Hydrology and Earth System Sciences*, *10*(5), 731–742. https://doi.org/10.5194/hess-10-731-2006

Phillips, J. D. (2009). Changes, perturbations, and responses in geomorphic systems. *Progress in Physical Geography*, *33*(1), 17–30. https://doi.org/10.1177/0309133309103889

Pörtner, H. O., Roberts, D. C., Adams, H., Adler, C., Aldunce, P., Ali, E., et al. (2022). *Climate change 2022: Impacts, adaptation and vulnerability*. IPCC.

Qian, H., Cao, Z., Liu, H., & Pender, G. (2017). Numerical modelling of alternate bar formation, development and sediment sorting in straight channels. *Earth Surface Processes and Landforms*, *42*(4), 555–574. https://doi.org/10.1002/esp.3988

Rachelly, C., Mathers, K. L., Weber, C., Weitbrecht, V., Boes, R. M., & Vetsch, D. F. (2021). How does sediment supply influence refugia availability in river widenings? *Journal of Ecohydraulics*, *6*(2), 121–138. https://doi.org/10.1080/24705357.2020.1831415

Räty, O., Räisänen, J., & Ylhäisi, J. S. (2014). Evaluation of delta change and bias correction methods for future daily precipitation: Intermodel cross-validation using ENSEMBLES simulations. *Climate Dynamics*, *42*(9–10), 2287–2303. https://doi.org/10.1007/s00382-014-2130-8

Redolfi, M. (2021). Free alternate bars in rivers: Key physical mechanisms and simple formation criterion. *Water Resources Research*, *57*(12). https://doi.org/10.1029/2021wr030617

Redolfi, M., Tubino, M., Bertoldi, W., & Brasington, J. (2016). Analysis of reach-scale elevation distribution in braided rivers: Definition of a new morphologic indicator and estimation of mean quantities. *Water Resources Research*, *52*(8), 5951–5970. https://doi.org/10.1002/2015WR017918

Redolfi, M., Welber, M., Carlin, M., Tubino, M., & Bertoldi, W. (2020). Morphometric properties of alternate bars and water discharge: A laboratory investigation. *Earth Surface Dynamics*, *8*(3), 789–808. https://doi.org/10.5194/esurf-8-789-2020

Rinaldi, M., Wyzga, B., & Surian, N. (2005). Sediment mining in alluvial channels: Physical effects and management perspectives. *River Research and Applications*, *21*(7), 805–828. https://doi.org/10.1002/rra.884

Rodrigues, S., Mosselman, E., Claude, N., Wintenberger, C. L., & Juge, P. (2015). Alternate bars in a sandy gravel bed river: Generation, migration and interactions with superimposed dunes. *Earth Surface Processes and Landforms*, *40*(5), 610–628. https://doi.org/10.1002/esp.3657

Rohde, S., Schütz, M., Kienast, F., & Englmaier, P. (2005). River widening: An approach to restoring riparian habitats and plant species. *River Research and Applications*, *21*(10), 1075–1094. https://doi.org/10.1002/rra.870

Schumm, S. A. (1973). Geomorphic thresholds and complex response of drainage systems. *Fluvial geomorphology*, *6*, 69–85.

Stecca, G., Zolezzi, G., Hicks, D. M., & Surian, N. (2019). Reduced braiding of rivers in human-modified landscapes: Converging trajectories and diversity of causes. *Earth-Science Reviews*, *188*, 291–311. https://doi.org/10.1016/j.earscirev.2018.10.016

Tockner, K., Paetzold, A., Karaus, U. T. E., Claret, C., & Zettel, J. (2006). *Ecology of braided rivers* (Vol. 36, p. 339). Special Publication-International Association of Sedimentologists.

Tubino, M. (1991). Growth of alternate bars in unsteady flow. *Water Resources Research*, *27*(1), 37–52. https://doi.org/10.1029/90WR01699

Tubino, M., Repetto, R., & Zolezzi, G. (1999). Free bars in rivers. *Journal of Hydraulic Research*, *37*(6), 759–775. https://doi.org/10.1080/00221689909498510

van Oorschot, M., Kleinhans, M., Buijse, T., Geerling, G., & Middelkoop, H. (2018). Combined effects of climate change and dam construction on riverine ecosystems. *Ecological Engineering*, *120*, 329–344. https://doi.org/10.1016/j.ecoleng.2018.05.037

van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., et al. (2011). The representative concentration pathways: An overview. *Climatic Change*, *109*(1–2), 5–31. https://doi.org/10.1007/s10584-011-0148-z

Viviroli, D., Zappa, M., Gurtz, J., & Weingartner, R. (2009). An introduction to the hydrological modelling system PREVAH and its pre- and post-processing-tools. *Environmental Modelling & Software*, *24*(10), 1209–1222. https://doi.org/10.1016/j.envsoft.2009.04.001

Weiss, G. (1977). Shot noise models for the generation of synthetic streamflow data. *Water Resources Research*, *13*(1), 101–108. https://doi.org/10.1029/WR013i001p00101

Winsemius, H. C., Aerts, J. C., Beek, L. P. V., Bierkens, M. F., Bouwman, A., Jongman, B., et al. (2016). Global drivers of future river flood risk. *Nature Climate Change*, *6*(4), 381–385. https://doi.org/10.1038/nclimate2893

Wohl, E., Lane, S. N., & Wilcox, A. C. (2015). The science and practice of river restoration. *Water Resources Research*, *51*(8), 5974–5997. https://doi.org/10.1002/2014WR016874

Wolman, G. M., & Miller, J. P. (1960). Magnitude and frequency of forces in geomorphic processes. *The Journal of Geology*, *68*(1), 54–74. https://doi.org/10.1086/626637

References From the Supporting Information

Engelund, F., & Hansen, E. (1967). *A monograph on sediment transport in alluvial streams*. Technical University of Denmark Øster Voldgade.

Parker, G. (1978). Self-formed rivers with equilibrium banks and mobile bed. Part 2. The gravel river. *Journal of Fluid Mechanics*, *89*(1), 127–146. https://doi.org/10.1017/S0022112078002505