How can floodplain lowering and sediment nourishments help mitigate channel bed incision?

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Delft University of Technology
January 2024

Abstract

Engineered rivers are frequently associated with channel bed incision, which hampers navigation, flood safety, and ecology. Larger moderate-to-high discharges due to climate change are expected to enhance channel bed incision. To mitigate channel bed incision, river managers consider the deployment of different measures. Yet intervention planning and design does not tend to account for neither the large-scale effects of such measures nor the potential effects of climate change. In this paper we focus on the lower Rhine River (Bonn, Germany - Gorinchem, the Netherlands, 300 km), as it is a heavily engineered river that incises in response to past channelization works in the 18th-20th centuries, which is expected to continue to incise by up to 1.5 m in the upcoming 50 years due to both past human intervention and future climate change. Considering a 50-year timescale, our goal is to assess (1) the potential of two types of engineering measures, namely sediment nourishments and floodplain lowering, to mitigate large-scale channel bed incision, (2) the potential large-scale side effects of such measures, in the form of additional incision, and (3) the influence of climate change on the efficacy of the measures. To this end, we use a schematized one-dimensional numerical model, as it captures the primary component of large-scale channel response. We subject the model to different scenarios of sediment nourishments (with independently varying grain size, spacing, and volume), and floodplain lowering (by different heights and at different locations). In all cases, we consider the effects of a changed hydrograph and sea level rise due to moderate and high-end climate change. We find that floodplain lowering is not able to significantly mitigate channel bed incision (reduced incision by 0-0.20 m). This is likely due to the large timescale of channel adaptation to floodplain lowering and to a decreased floodplain inundation over time associated with channel bed incision. On the other hand sediment nourishments of sufficient volume (order of 150’000-200’000 m^3/a) may be able to reduce incision by 0-1 m.

Contents

1. Introduction

River systems have been engineered for centuries to protect populations against flooding, to ensure reliable navigation, to provide freshwater and energy, as well as for recreation (*Best*, 2019; *Marsh*, 1864). The most common forms of river engineering consist of channelization, dam construction, water diversion, and sediment management measures. These measures modify the river planform, channel geometry, and/or river controls (i.e., water discharge, sea level, and sediment flux), and alter the equilibrium state of the river (*Blom et al.*, 2016; *De Vriend*, 2015; *Mackin*, 1948). Rivers respond to such changes by adjusting (1) the channel width, (2) the channel slope, and (3) the bed surface grain size distribution. In engineered rivers with a fixed planform, this response is limited to changes in channel bed slope and bed surface grain size distribution.

Besides human intervention, rivers are increasingly affected by climate change. By modifying the hydrograph through more floods and droughts (*Blöschl et al.*, 2019; *Milliman et al.*, 2008), and base level through sea level rise (*IPCC*, 2022; *Chen et al.*, 2017), climate change alters the river controls, thereby prompting further channel adjustment. In engineered rivers, climate-related channel adjustment adds to intervention-related channel adjustment. These adjustments affect tens to hundreds of kilometers and develop over decades to centuries (*De Vriend*, 2015).

Channel adjustment in engineered rivers is often associated with channel bed incision (e.g., *Lin et al.*, 2023; *Chowdhury et al.*, 2023; *Czapiga et al.*, 2022a; *Martín-Vide et al.*, 2020). This can be due to different reasons. Channelization measures, for instance, narrow the river channel. A narrower channel requires a smaller equilibrium channel slope to transport the sediment supplied from the upstream part of the basin, which is achieved through channel bed incision *Mackin* (1948); *Blom et al.* (2016, 2017). Dam construction, on the other hand, reduces the sediment flux to the downstream part of the basin, through sediment trapping upstream of dams. A smaller sediment flux requires a smaller equilibrium channel slope, which is achieved through a downstream-migrating incision wave *Galay* (1983). These adjustments may be enhanced by climate change, due to larger moderate to high discharges. The latter are associated with a smaller equilibrium channel slope, which is achieved through channel bed incision (e.g. *Ylla Arbós et al.*, 2023; *Sanyal et al.*, 2021).

Channel bed incision is especially problematic for navigation. In particular, the spatial variability of channel bed incision creates navigation bottlenecks at non- or less erodible reaches. This is because water level lowering follows incision-related bed level lowering, which results in locally reduced flow depths over stretches with relatively smaller erosion rates. The reduced flow depths limit the available draught for ships, and thus the amount of goods they can transport (e.g., *Goda et al.*, 2007; *Havinga*, 2020). In addition, channel bed incision reduces the stability of in-river structure foundations (*Habersack et al.*, 2013), exposes cables and pipelines crossing the river (*Hiemstra et al.*, 2020), and results in water level (and thus, ground water level) lowering. The latter also hampers freshwater extraction and enhances main channel-floodplain disconnection, putting pressure on riparian ecosystems.

To cope with the above issues, as well as with different flood and drought regimes due to climate change, a number of measures are implemented by river managers. They range from nation-wide programs aimed at increasing the conveyance capacity of the river for flood protection (e.g., the Room for the River program), to localized sediment nourishments (*Czapiga et al.*, 2022a; *Frings et al.*, 2014) and erosion control structures for erosion mitigation (e.g., *Simon and Darby*, 2002; *Habersack and Piégay*, 2007; *An et al.*, 2019), or the installation of fixed beds to increase the navigable width (*Havinga*, 2020).

Despite successfully achieving erosion mitigation, flood protection, or improved navigability goals at local scales, engineering measures have led to unintended side-effects (e.g., *Czapiga et al.*, 2022b; *Korpak et al.*, 2021; *Kostadinov et al.*, 2018; *Lenzi et al.*, 2003). These effects are in the form of erosional or depositional waves that migrate tens of kilometers downstream at decadal timescales. As such, they enhance channelization-related incision, rather than decrease it.

These experiences highlight the need to account for large-scale channel response to human intervention and climate change in future intervention planning. Yet such studies are not frequently carried out, most probably due to non-awareness of the relevance of large-scale and long-term dynamics.

Programs considering the mitigation of large-scale channel bed incision are starting to be introduced in river management, for example within the new policy program Integral River Management in the Netherlands (IRM). The latter aims to introduce a systems approach to river management, thereby enhancing resilience to (future) climate change impacts, while balancing ecosystem services related to navigability, fresh water availability, ecology, and flood protection. To this end, IRM considers mitigating large-scale channel bed incision, which requires insight on large-scale channel response to different engineering measures.

In this paper, we assess the potential of different adaptation measures to mitigate large-scale channel bed incision in engineered rivers affected by climate change, considering spatial scales of tens to hundreds of kilometers and a 50-year timescale. We focus on the lower Rhine River (Bonn, Germany - Gorinchem, the Netherlands), which was extensively channelized during the 18th-20th centuries for improved navigation and flood protection (*Ylla Arbós et al.*, 2021; *Quick et al.*, 2019, Figure 1). It flows through the most densely populated area in Europe, and is the busiest inland waterway in the continent.

Past channelization works in the lower Rhine River have caused up to 5 m of channel bed incision over the past century (*Ylla Arbós et al.*, 2021). While incision rates have decreased with time, the river continues to incise at up to 2 cm/a. Furthermore, channel bed incision will likely be enhanced by climate change in the upcoming decades (*Ylla Arbós et al.*, 2023). To adapt to this future adjustment several options are considered, including sediment nourishments, given their success in Germany (where nourishments since 1989 have largely mitigated channel bed incision, *Frings et al.*, 2014; *Quick et al.*, 2019), large-scale floodplain lowering, removal (or lowering) of fixed beds, or construction of longitudinal training walls (*Czapiga et al.*, 2022b).

While detailed feasibility studies for different adaptation measures are carried out, a more conceptual understanding of the large-scale channel response to such measures is lacking, especially regarding the influence of climate change. Given that climate change is expected to enhance the ongoing channelization-related incision *Ylla Arbós et al.* (2023), neglecting climate forcing in future intervention planning may result in ineffective or largely unsustainable measures.

Here we consider two types of adaptation measures for the Waal branch (Figure 1), as it is the branch where channel bed incision and its consequences are most prominent. Specifically, we consider sediment nourishments and floodplain lowering. The former aim to mitigate channel bed incision by increasing the sediment supply. Floodplain lowering aims to mitigate channel bed incision through a reduced flow depth in the main channel, which is associated with a spatial decrease of the sediment transport capacity. With a schematized one-dimensional numerical model of the lower Rhine River, we assess (1) the potential of these measures to mitigate large-scale channel bed incision, (2) the potential side-effects of such measures (in the form of additional incision), and (3) the influence of climate change on the efficacy of the measures.

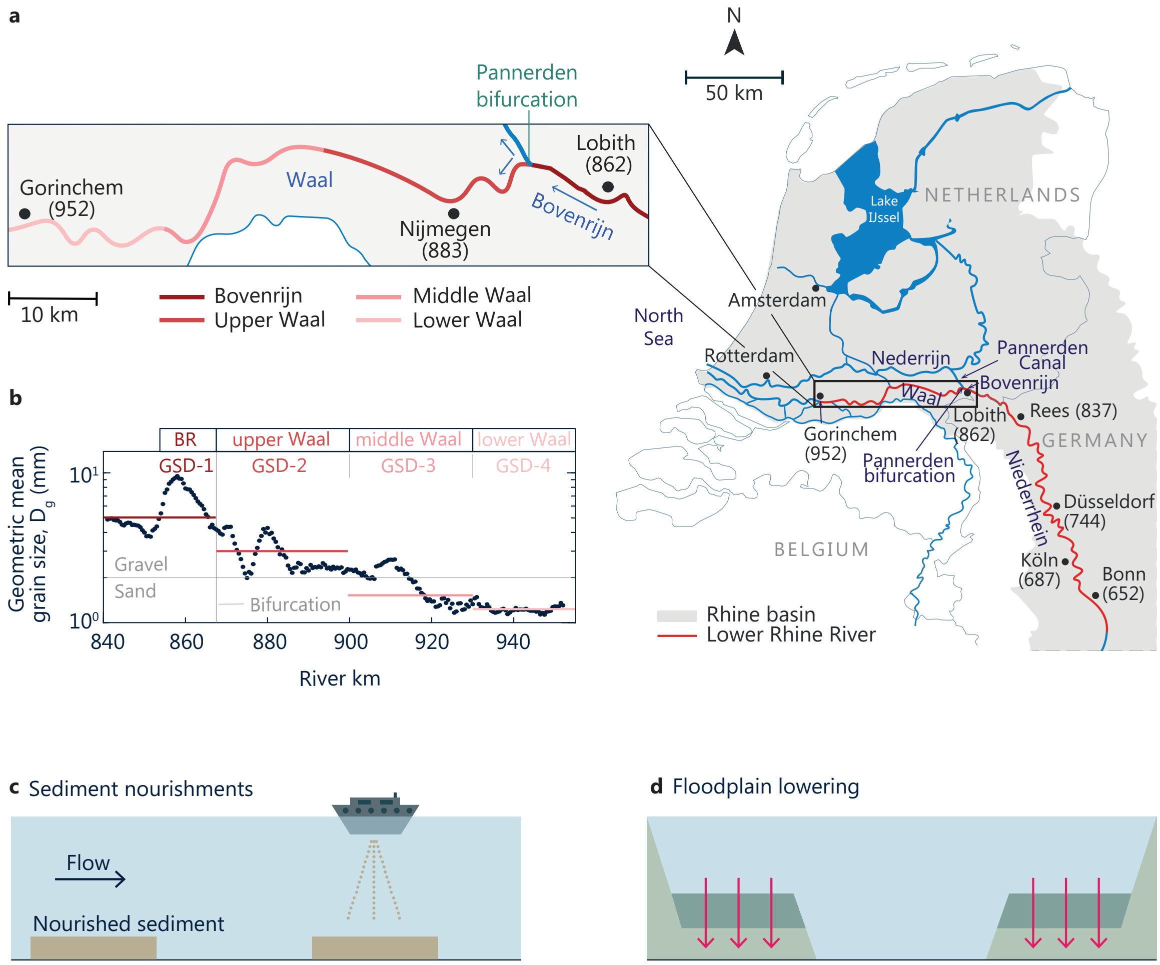

Figure 1: Domain of interest and considered adaptation measures. (a) The lower Rhine River between Bonn (Germany) and Gorinchem (The Netherlands), with inset on the Waal river. Numbers between parentheses indicate river km, with origin at Konstanz (Bodensee, not pictured). (b) geometric mean bed surface grain size, where horizontal lines indicate the reach-averaged values used in model runs, hereafter referred to as GSD-1, GSD-2, GSD-3, and GSD-4; (c) schematic of sediment nourishments; (d) schematic of floodplain lowering.

2. The model

Given our focus on large-scale channel response (tens to hundreds of kilometers) and multidecadal timescales, we use the highly schematized one-dimensional numerical model set up and calibrated by *Ylla Arbós et al.* (2023). We adopt a one-dimensional approach (with single cells covering the entire cross-section) rather than a two-dimensional one (with multiple cells over the cross-section, allowing for variation of bed level within the cross-section), as one-dimensional models are able to capture the primary component of channel response to widening and sediment nourishments.

The model is suitable for mixed-size sediment, and uses the steady solution of the *De Saint-Venant* (1871) shallow water equations for flow, mass conservation of bed sediment (*Exner*, 1925, 1931) for bed level change, and conservation of each grain size class for a surface layer (*Hirano*, 1971) for changes in the bed surface grain size distribution. As a closure relation, we use a sediment transport relation that includes a threshold of motion and accounts for hiding effects, respectively based on *Meyer-Peter and Müller* (1948) and *Egiazaroff* (1965).

The model includes five grain size classes ranging from fine sand to coarse gravel, with characteristic diameters in the order of, respectively, 0.5, 1.25, 5, 15, and 40 mm. The bed surface is coarser than the substrate. Specifically, the amount of the largest fraction is reduced by about 30%, while the amount of the sand fractions is increased by about 30% (*Ylla Arbós et al.*, 2023; *Frings et al.*, 2014). The model accounts for a compound cross-section, but does not deal with floodplain deposition or erosion. An extensive description of the model assumptions and initial conditions is provided in *Ylla Arbós et al.* (2023).

We consider a reference case representative of the current non-graded conditions of the river (period 1990-2020). The upstream water discharge consists of a 20-year cyclic hydrograph based on historical data (1967-1986), whose statistics best match those of the long-term series (1951-2006). The upstream sediment flux is based on *Frings et al.* (2014) estimates. The downstream boundary condition includes sea level rise at rates representing the centerline of the *KNMI* (2015) projections.

Climate change is accounted for through two scenario combinations: (1) moderate climate change (water discharge following the *KNMI* (2015) GL scenario, and sea level rise following the lower end of the RCP 4.5 scenario *IPCC* (2013)), and (2) high-end climate change (water discharge following the *KNMI* (2015) WH scenario, and sea level rise following the upper end of the *IPCC* (2013) RCP8.5 scenario). The transformation of climate scenarios to model boundary conditions is done following *Ylla Arbós et al.* (2023).

Sediment nourishment measures are schematized as an abrupt rise in bed elevation, which is repeated every five years. Each nourishment consists of 370'000 m^3 of sediment equivalent to about 70'000 m^3/a, or a 0.5 m rise in bed elevation over 3 km, covering the full river width. This volume of sediment is comparable to the volume nourished in pilot nourishment campaigns in the Waal (*Rijkswaterstaat*, 2023). Sediment is only nourished in the upper and middle Waal, as the Bovenrijn and lower Waal do not suffer from pronounced incision or are aggradational. To assess the effects of nourishment spreading, we consider four different nourishment schemes: (1) point-type nourishments, where all of the volume is dumped over a single 3 km long reach (river km 877-881); (2) 10-km-spaced nourishments, where the total nourished volume is spread over 3 km reaches spaced by 10 km, starting at river km 877-880; (3) 20-km-spaced nourishments, where the total nourished volume is spread over 3 km reaches spaced by 20 km, starting at river km 877-880 in the Bovenrijn, and at river km 894-897 in the Waal; and (4) full-spread nourishments, where the total volume is evenly distributed over the Bovenrijn, upper and middle Waal. To assess the effects of grain size of the nourished sediment we test, for each scheme, four different sediment mixtures based on the mean bed surface grain size distribution of, respectively, the Bovenrijn (GSD-1), upper Waal (GSD-2), middle Waal (GSD-3), and lower Waal (GSD-4) (Figure 1b). The geometric mean bed surface grain size (D_g) of these reaches is, respectively, 6, 3, 1.5 and 1.1 mm. The sediment mixture used for nourishments varies across scenarios, but is spatially constant for each nourishment scheme. To investigate the nourishment volumes required to halt channel bed incision, we consider nourished quantities of 150'000 and 200'000 m^3/a) for selected scenarios. We select these additional volumes of nourished sediment for comparability with previous studies (*Liptiay*, 2023).

Floodplain lowering measures are schematized by modifying the model cross sections such that all the points corresponding to the floodplains are lowered by 0.5, 1, and 1.5 m. We consider four different spatial distributions of floodplain lowering. Specifically, the floodplains are lowered over (1) the Bovenrijn, (2) the upper Waal, (3) the middle Waal, and (4) the reach comprising the Bovenrijn, upper and middle Waal.

In the field, summer levees reduce the occurrence of floodplain flow for, for instance, agricultural reasons. The model does not account for these summer levees, for simplicity reasons and because their effects are mostly relevant in cases with abrupt width changes (e.g., *Van Vuren et al.*, 2015), which do not occur in our model.

All scenarios for the two types of adaptation measures are tested for the reference-case boundary conditions (i.e., without accounting for climate change), and for the moderate and high-end climate change scenarios.

3. Sediment nourishment measures

In this section we address the effects of sediment nourishments on large-scale channel bed incision. We first focus on the effects of different nourishment schemes and grain size of the nourished sediment neglecting the effects of climate change. We then assess the effects of climate change for selected nourishment configurations.

Figure 2a shows the 50-year bed level change relative to the initial state in 2000 for different nourishment schemes, and a fine gravel nourishment mixture (GSD-2, D_g = 3 mm). Relative to the 0-1.5 m of incision expected without nourishment measures, all the nourishment schemes reduce incision by 20 cm to over 1 m locally. However, for this gravel-based sediment addition, only full-spread nourishments appear to be effective. This is because the nourished sediment is not mobile enough to be effectively transported downstream. The point nourishments, or nourishments spaced by 10 and 20 km, lead to bed level humps can be problematic for navigation.

For finer nourishment mixtures (e.g., GSD-4, D_g = 1.1 mm , Figure 2b), nourishment efficacy is independent of the nourishment scheme. This is due to the increased mobility of finer sediment, which, as such, does not form humps at the nourishment locations.

To assess the effects of nourishment grain size, and given the fact that coarse sediment nourishments are inefficient when not sufficiently spread, we consider full-spread nourishments (i.e., spread over the Bovenrijn, upper, and middle Waal, Figure 1) for four different nourishment mixtures (Figure 2c). We observe that, for spread nourishments, coarser nourishment mixtures are more effective at mitigating channel bed incision, especially in the upper Waal. While the finest mixture (D_g = 1.1 mm) reduces erosion by up to 20 cm, the coarsest mixture (D_g = 6 mm) reduces it by up to 0.75 m. This is due to the smaller mobility of gravel relative to sand, and to the larger equilibrium channel slope associated with a coarser bed surface, leading to less channel bed incision. These results are in agreement with previous findings on idealized test cases (*Czapiga et al.*, 2022a).

Climate change makes sediment nourishments less effective, regardless of the nourishment scheme (Figure 2d). This is because climate change leads to increased moderate-to-high discharges, and thus enhances channel bed incision by up to 0.35 m by 2050.

Including the effects of climate change, channel bed incision is expected to reach up to 1.5 m in the upper Waal (Figure 2d), even with nourishment measures. Sediment nourishments are, nonetheless, able to mitigate the additional incision caused by climate change by up to 60 cm (Figure 2d).

We also assess whether larger volumes of sediment would be sufficient to halt channel bed incision. Despite the large amounts of sediment required, we consider full-spread nourishments of 150’000 and 200’000 m^3/a, with a gravel sediment mixture (GSD-2, D_g = 3 mm, Figure 2e). With these larger quantities of sediment channel bed incision seems to be largely mitigated. Such nourishments also create excessive aggradation in the middle and lower Waal.

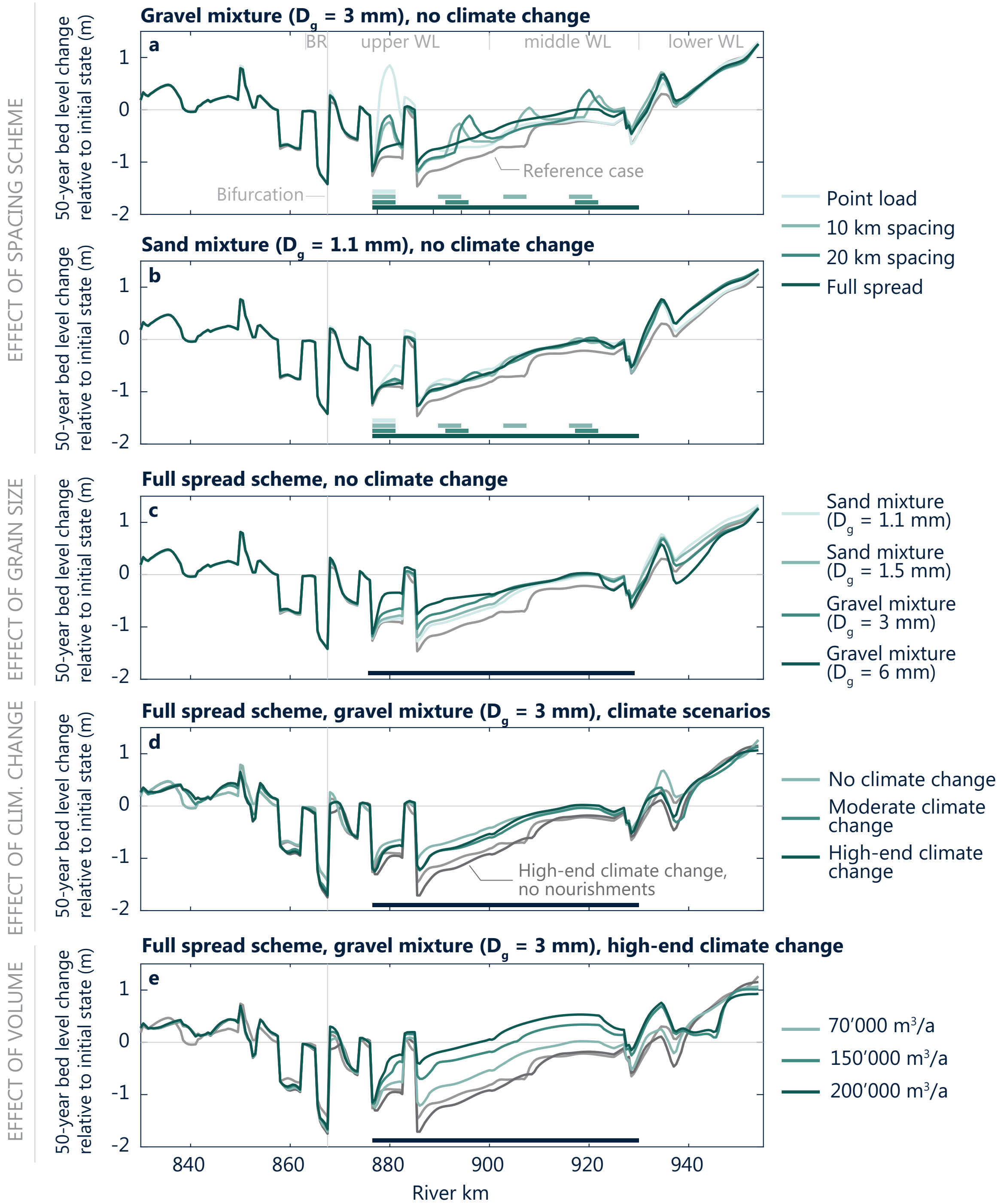

Figure 2: Potential of sediment nourishments to mitigate channel bed incision. 50-year bed level change relative to model initial state for (a) gravel nourishments (D_g = 3 mm) with different spacing schemes, neglecting climate change; (b) sand nourishments (D_g = 1.1 mm) with different spacing schemes, neglecting climate change; (c) full spread nourishments of different grain sizes, neglecting climate change; (d) full spread gravel nourishments (D_g = 3 mm) for different climate scenario combinations; and (e) full spread gravel nourishments of different volumes for the high-end climate change scenario. Lines at the bottom of the plots indicate the reaches where sediment has been nourished. Abbreviations BR and WL stand, respectively, for Bovenrijn and Waal.

4. Floodplain lowering measures

In this section we assess whether floodplain lowering measures are able to mitigate channel bed incision. We first consider floodplain lowering over the entire stretch between the Bovenrijn and the middle Waal, and then assess the influence of lowering at different locations.

Figure 3a shows the 50-year bed level relative to the initial state for 0.5, 1, and 1.5 lower floodplains between the Bovenrijn and the middle Waal. Irrespective of the lowered height, the effect of floodplain lowering seems negligible in terms of channel bed incision mitigation (up to 20 cm of locally reduced incision, relative to the 1.5 m of expected incision without adaptation measures).

The spatial extent or length of floodplain lowering plays a role in the potential to mitigate channel bed incision. First, the longer the extent of floodplain lowering, the larger the region with increased slope and increased bed level, and the more the reach upstream of the lowered floodplain will rise eventually (Figure 4f).

The spatial extent of floodplain lowering also plays a role in the time scale of erosion mitigation. This can be explained as follows. Floodplain lowering reduces the specific discharge over the lowered reach (Figure 4a). This leads to an M1 backwater over the lowered reach and an M2 backwater upstream of the lowered reach (Figure 4b). This results, in the short term, in aggradation over the lowered reach, and degradation upstream of the lowered reach (Figure 4e). The sudden spatial increase in the sediment transport rate at the downstream end of the lowered reach results in a scour pit, and the sudden spatial decrease in the sediment transport rate at the upstream end of the lowered reach creates a hump.

Over time, the hump and scour propagate downstream and tend to dominate the process of transient response (Figure 4f, t1 and t2). In the long term (Figure 4, t3), the lowered reach has increased its slope and bed level, as a reduced specific discharge is associated with a larger equilibrium channel slope. Downstream, the scour has dispersed and migrated out of the domain. Upstream, the bed level has aggraded as the base level for the upstream reach has increased due to the increased slope of the lowered reach, and maintains its initial slope.

The longer the lowered reach, the longer it takes for the channel to respond to the change. This also has to do with the trapping of sediment due to the backwater upstream of the lowered reach. As a result, the time scale of channel response to a lowered floodplain increases non-linearly with the extent or length of the lowered floodplain reach. This implies that for a longer reach of lower floodplains, erosion mitigation requires a much longer time. As a consequence, lowering floodplains in an alternate pattern (so over multiple short reaches) increases the average erosion mitigation efficacy, yet bed level in the main channel spatially varies significantly.

An additional reason for the limited influence of floodplain lowering on large-scale channel may be the fact that the inundation frequency decreases over time due to channel bed incision, as water level decrease follows bed level decrease. As a result, their contribution to erosion mitigation may decrease over time.

For the largest amount of floodplain lowering (1.5 m), we consider how the location of floodplain lowering affects erosion mitigation (Figure 5). The location of the measure does not seem to have a significant influence on the total amount of erosion mitigation, which remains at 0-0.20 m, relative to the 1.5 m of expected incision without floodplain lowering. Nonetheless, their effect is slightly more pronounced in the middle Waal, which is possibly due to a larger ratio of floodplain lowering height to flow depth, which enhances backwater effects and the associated aggradation (Figure 4b-e).

Figure 5 also shows the downstream propagation of the erosion pit downstream of the lowered reach, characteristic of the transient morphodynamic response (Figure 4f). This downstream migration of the erosion pit implies that large scale channel bed incision downstream of the lowered reach is enhanced over a period of decades.

When taking climate change into account, the effect of floodplain lowering measures remains negligible (Figure 3b). However, while floodplain lowering measures may be ineffective regarding mitigation of channel bed incision, they may contribute to decreased flood risk through lower water levels.

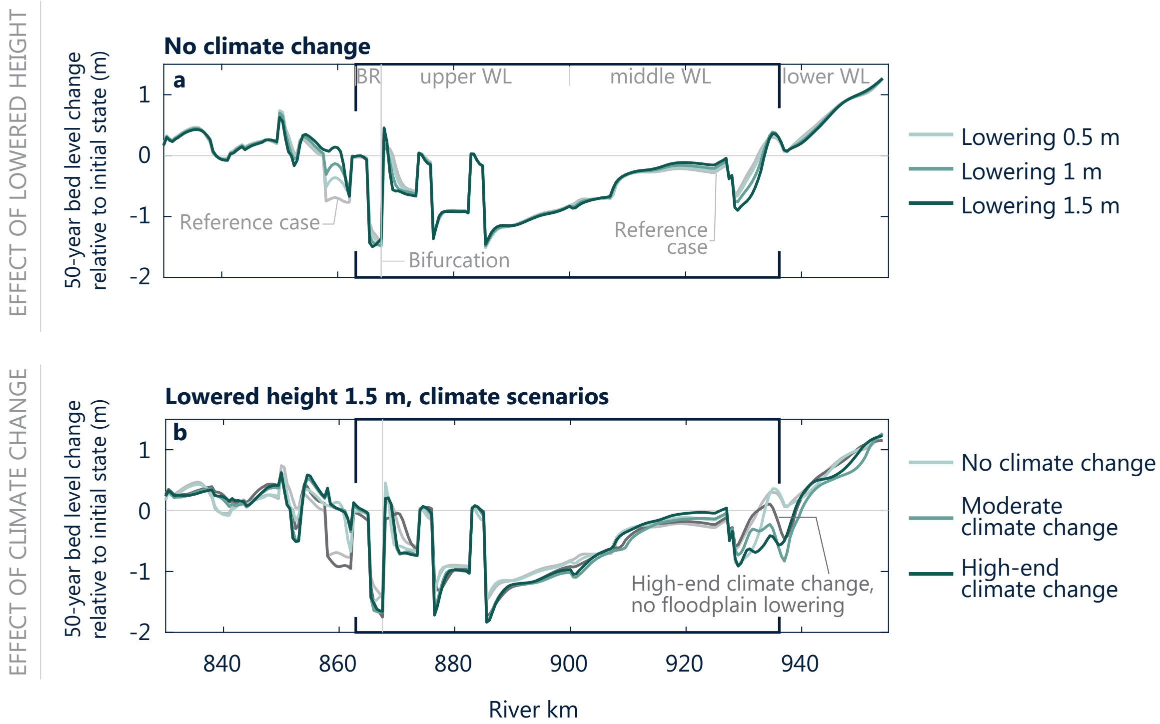

Figure 3: Potential of floodplain lowering measures to mitigate channel bed incision. 50-year bed level change relative to model initial state for (a) floodplain lowering by different heights in the Bovenrijn and Waal; and (b) floodplain lowering by 1.5 m in the Bovenrijn and Waal, for different climate scenarios. Abbreviations BR and WL stand, respectively, for Bovenrijn and Waal. The rectangle on the plots indicates the reach where floodplains have been lowered.

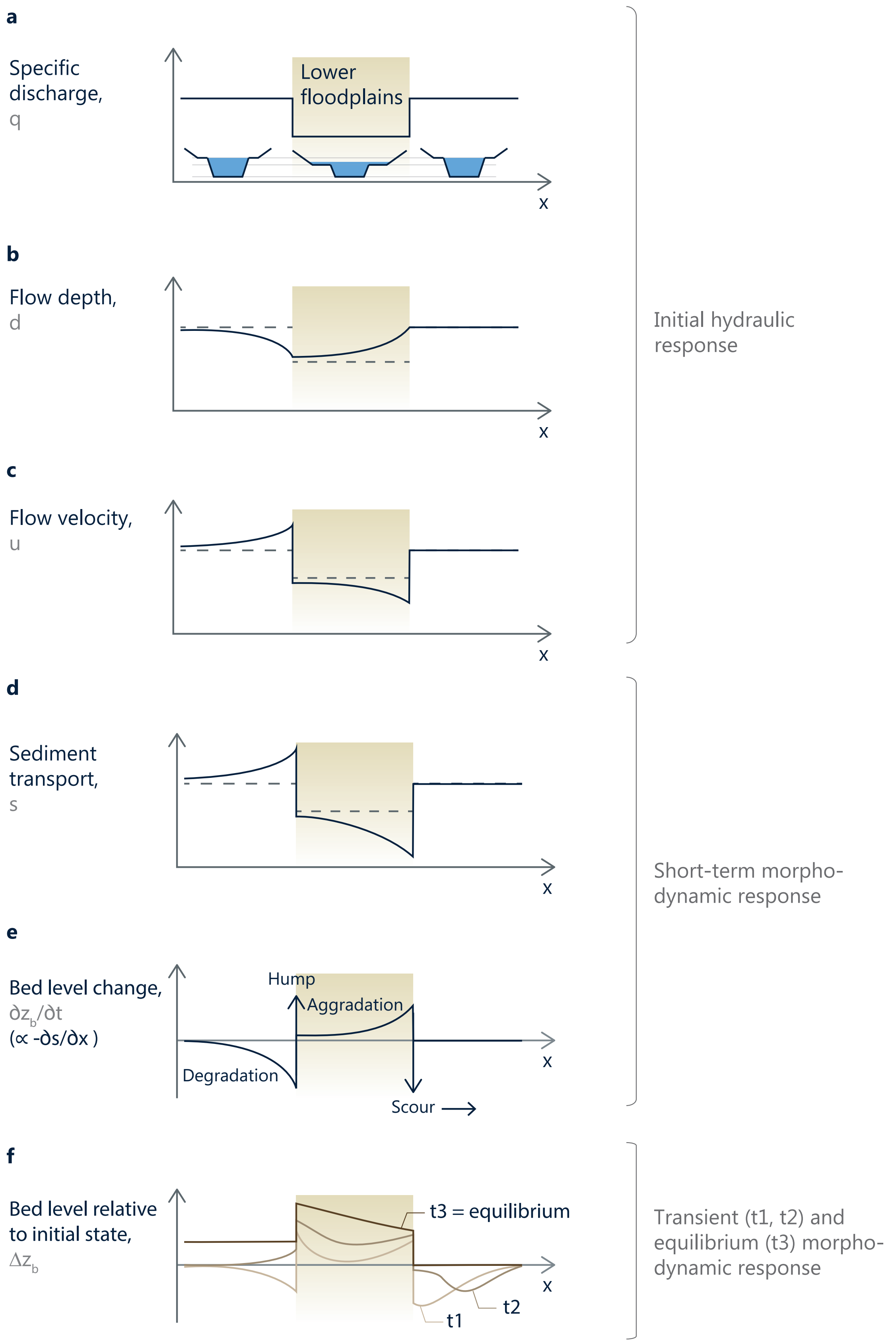

Figure 4: Conceptual channel response to floodplain lowering. Initial hydraulic response, in terms of (a) specific discharge, (b) flow depth, and (c) flow velocity; short-term morphodynamic response, in terms of (d) sediment transport, and (e) bed level change; and (f) transient and equilibrium morphodynamic response in terms of bed level relative to initial state. Label x on horizontal axes indicates streamwise coordinate.

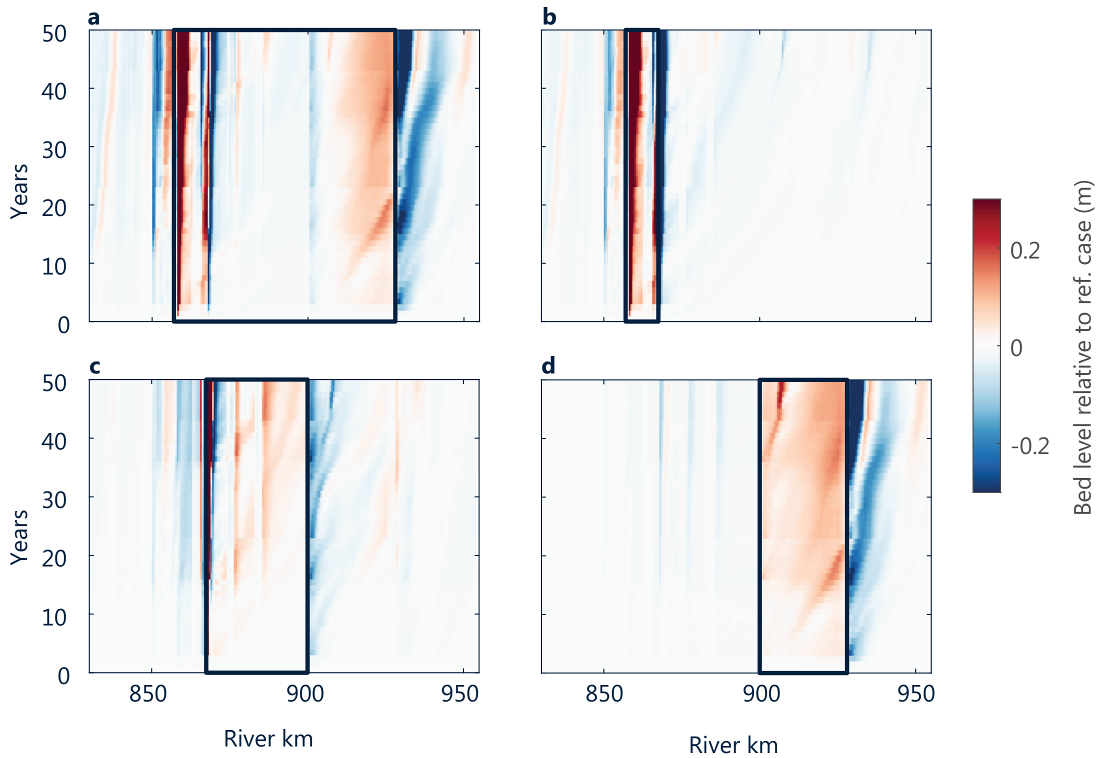

Figure 5: Space-time plots of bed level relative to the initial state over 50 years, for floodplain lowering measures by 1.5 in the (a) Bovenrijn and Waal; (b) Bovenrijn; (c) upper Waal; and (d) middle Waal. The rectangle on the plots highlights the reach where floodplains have been lowered.

5. Discussion

Our analysis shows that sediment nourishments and floodplain lowering measures have a differential potential to mitigate large-scale channel bed incision. While sediment nourishments in sufficient volumes may reduce channel bed incision, floodplain lowering measures are not capable to do so. In addition, the latter may enhance incision downstream of the lowered reach.

Floodplain lowering seems to be inefficient in terms of erosion mitigation, reducing incision by up to 0-0.20 m by 2050. This limited magnitude of reduced incision is consistent with previous studies (*Barneveld et al.*, 2019; *Van Vuren*, 2005). The little efficacy of floodplain lowering regarding erosion mitigation may be due to (1) the long timescales of adaptation associated with floodplain lowering, and (2) a decreased floodplain inundation with time, due to channel bed incision. Nonetheless, floodplain lowering measures seem to increase channel-floodplain connectivity, and have a significant contribution to lowering water levels and thereby reducing flood risk.

The larger efficacy of sediment nourishments is due to their direct contribution to an increased sediment flux, and, depending on the sediment mixture, to a coarser sediment flux. Both the increased and coarsened flux are associated with a larger equilibrium channel slope, and therefore lead to less channel bed incision.

Halting channel bed incision through sediment nourishments requires hundreds of thousands of cubic meters of sediment per year (order of 150’000-200’000 m^3/a). These volumes are over three times larger than those used in the Niederrhein (*Frings et al.*, 2014), and need to be supplied over decades. It is, therefore, questionable whether such measures are economically and environmentally feasible and sustainable.

Besides economic constraints, the implementation of sediment nourishments is tied to operational constraints. For instance, coarse sediment nourishments are more effective at mitigating channel bed incision, but they require spatial spreading, which may disturb navigation over longer reaches and for longer periods. On the other hand, finer sediment mixtures can be nourished at fewer locations, which may reduce operational constraints, but they require larger amounts of sediment for equal efficacy.

We expect that the primary component of large-scale channel response to floodplain lowering and sediment nourishments is well captured with a one-dimensional model. Bifurcation dynamics may, however, be better represented in two-dimensional models. Nonetheless, two dimensional models require a larger amount of information and associated level of detail to provide useful results. As such, they are often associated with a large level of uncertainty of the input. Regarding the large-scale channel response to interventions at 50-year timescales, we do not expect a fundamentally different response between a one-dimensional and a two-dimensional model.

6. Conclusion

Assessment of channel response to adaptation measures aimed at mitigating large-scale channel bed incision shows that floodplain lowering is not able to halt channel bed incision at 50-year timescales, while sediment nourishments may be able to do so.

Floodplain lowering may reduce incision by 0-0.20 m over 50 years, relative to the 0-1.5 m expected with climate change. These magnitudes of erosion mitigation are consistent with previous studies (e.g., *Barneveld et al.*, 2019; *Van Vuren*, 2005). The longer the lowered reach, the larger the amount of erosion mitigation, but the longer the timescale of adaptation. Floodplain lowering in an alternating pattern over shorter reaches increases the average mitigation efficacy, but also leads to large spatial variability in bed level. Floodplain lowering is also associated with enhanced incision downstream of the lowered reach.

Sediment nourishments have a significantly larger potential than floodplain lowering to limit large-scale channel bed incision, with an erosion mitigation potential of 0.20-1 m at 50-year timescales. This requires additions of over 150’000-200’000 m^3/a cubic meters of sediment per year, which is about twice to three times the annual volumes nourished in the Niederrhein *Frings et al.* (2014). These magnitudes are consistent with previous studies *Liptiay* (2023).

Coarser nourishments are more effective at mitigating channel bed incision, although they require spatial spreading, which is associated with larger operational constraints. Finer nourishments are easier to implement, though require larger quantities for equal efficacy.

Climate change is associated with enhanced incision of up to 30 cm at 50-year timescales. Failure to account for its effects in future intervention planning and design may make measures ineffective or unsustainable. Given the uncertainty associated with climate change predictions, river management may benefit from flexible policy making that accounts for future uncertainty and considers adaptation alternatives as new information becomes available.

7. Recommendations

Based on this study, we make the following recommendations:

- Systematically carry out one-dimensional schematized analyses of large-scale channel response to interventions in future intervention planning and design.
- Consider the effects of climate change in future intervention planning and design. Update boundary conditions and model results as new climate scenarios become available.
- Gain additional insight on bifurcation dynamics to improve bifurcation treatment in one-dimensional models can be improved (e.g., Rivers2Morrow research by M.K. Chowdhury, TU Delft). Consider combined one- and two-dimensional approaches, especially at the bifurcation region.
- Assess the influence of the spatial density of floodplain lowering measures, which may prove more efficient in terms of erosion mitigation due to shorter adaptation timescales.
- Assess the comparability of different widening-type measures (e.g., floodplain lowering and multiple channel systems).

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