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Mitigation of Channel Bed Erosion through Floodplain Lowering and Nourishments

Claudia Ylla Arbos[a], Ralph M.J. Schielen[a,b], Saskia van Vuren[b], Yvo Snoek[b], Astrid Blom[a*]
[a]*Faculty of Civil Engineering and Geosciences, Delft University of Technology, the Netherlands*
[b]*DG Rijkswaterstaat, Ministry of Infrastructure and Water Management, Utrecht, The Netherlands*

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Introduction

Channel adjustment in engineered rivers is often associated with channel bed incision (e.g., Chowdhury et al., 2023, Czapiga et al., 2022a, 2022b, Ylla Arbós et al., 2021). Channel bed incision reduces the stability of in-river structures, exposes river-crossing cables and pipelines, and the spatial variability of channel bed incision due to less erodible reaches creates shipping bottlenecks.

Various measures have been implemented to cope with these issues. They range from sediment nourishments to erosion control structures (e.g., Habersack and Piégay, 2007).

Our objective is to assess the potential of floodplain lowering and sediment nourishments in mitigating large-scale channel bed incision in engineered rivers affected by climate change, considering a spatial scale of hundreds of kilometres. Our domain of interest is the Rhine River between Bonn, Germany, to Gorinchem, Netherlands. This reach has been extensively channelized during the 18th-20th centuries for improved navigation and flood protection (e.g., Ylla Arbós et al., 2021).

Methods

We apply the schematized one-dimensional numerical model set up and calibrated by Ylla Arbós et al. (2023). The model uses the steady solution to the shallow water equations for describing the flow and the active layer model describing the conservation of grain size classes in a surface layer. We use a sediment transport relation that includes a threshold of motion and accounts for hiding effects. The model includes five grain size classes, which range from fine sand to coarse gravel, and have characteristic grain sizes of 0.5 to 40 mm.

The model initial state represents the current (non-graded) river conditions and is built on measured data of the period 1990-2020. Cross-sectional and bed surface grain size data are smoothed strongly such that the model focusses on large-scale trends and is incapable of replicating local effects.

Boundary conditions include a repeated 20-year hydrograph based on historical data (1967-1986 whose statistics best match those of the long-term series 1951-2006), sediment fluxes for the 5 five grain size classes (based on Frings et al., 2014), and a downstream boundary condition that accounts for a sea level rise at rates representing the centreline of the KNMI (2015) projections. Climate change is accounted for in the boundary conditions through two scenario combinations:

(1) moderate climate change
    water discharge following GL scenario (KNMI, 2015) and sea level following lower end of RCP 4.5 scenario (IPCC, 2013)

(2) high-end climate change
    water discharge following WH scenario (KNMI, 2015) and sea level following upper end of RCP 8.5 scenario (IPCC, 2013)

The conversion of climate scenarios to model boundary conditions follows Ylla Arbós et al. (2023).

Sediment nourishment measures are schematized as an abrupt rise in bed level, which is repeated every five years. Each nourishment consists of 370,000 m^3 of sediment equivalent to about 70,000 m^3/a, covering the full channel width. Sediment is only nourished in the upper and middle Waal, as the other river reaches do not suffer from pronounced incision. We consider four nourishment schemes (point-source nourishments, where the total volume is dumped over a single 3 km long reach, 10-km- and 20-km-spaced nourishments, and fully-spread nourishments, where the total volume is evenly distributed.

We consider nourishment volumes of 70,000, 150,000 and 200,000 m^3/a to investigate the effect of the nourishment volume.

Floodplain lowering is schematized by modifying the model cross sections such that all points corresponding to the floodplains are lowered by 0.5, 1, and 1.5 m.

Results and Conclusions

Our runs indicate that sediment nourishments have more potential to reduce channel bed incision than floodplain lowering. In our runs, floodplain lowering over a long reach is not able to halt channel bed incision by 2050 (Fig. 1). In runs with spatially alternating floodplain lowering (with short reaches in between without lowered floodplains) erosion is reduced more effectively, yet leading to significant spatial variation in bed level.

Sediment nourishments are more effective, yet halting of erosion requires the addition of order 200,000 m^3 of sediment annually (Fig. 2) and leads to an increase of the bed level in the downstream reach (that is already aggradational).

Considering climate change, our runs show that nourishment schemes with reasonable nourishment volumes (70,000 m^3/a) lead to more than 1 m of incision by 2050.

Effect of nourishments largely depends on parameters (grain size, spreading, nourished volume and frequency). Coarser nourishments are more effective at mitigating channel bed incision, although they require spatial spreading, which is associated with larger operational constraints. For finer nourishments the spatial spreading is less important, but they require a larger volume for equal efficacy.

Climate change enhances incision and not accounting for it in future intervention design may make measures ineffective.

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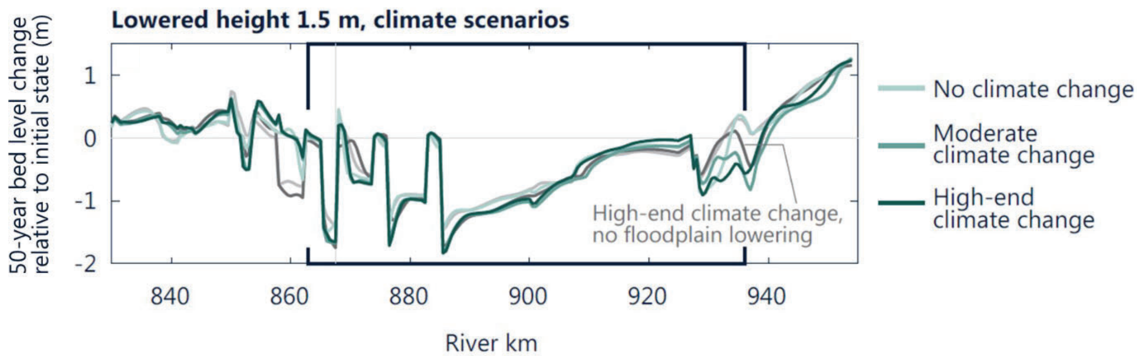

Figure 1: Predicted 2050 bed level profile for a reference case (gray) without floodplain lowering and high end climate change compared to three cases of 1.5 m floodplain lowering over Bovenrijn-Waal for three climate change scenarios (no, moderate and high).

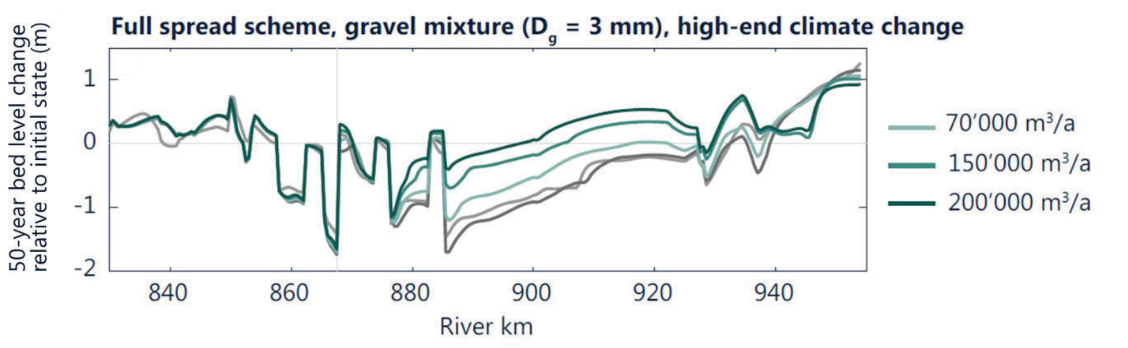

Figure 2: Predicted 2050 bed level profile for two reference cases without nourishments (light gray without climate change and dark gray for high end climate change) compared to three cases of fully spread nourishments (grain size distribution similar to the average one of the upper Waal) of different volume (70,000, 150,000 and 200,000 m^3/a) for the high end climate change.