Large-Scale Channel Response to Erosion-Control Measures

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Key Points:

- Erosion-control measures reduce upstream incision and enhance downstream incision in an overall-incising river system
- The net amount and extent of enhanced downstream incision are larger than the reduced incision upstream
- For multiple erosion-control measures, the enhanced downstream incision increases with reduced spacing between measures

Supporting Information:

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

Correspondence to:

C. Ylla Arbós,
c.yllaarbos@tudelft.nl

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Author Contributions:

Conceptualization: C. Ylla Arbós
Data curation: C. Ylla Arbós, S. R. White, R. Patzwahl
Formal analysis: C. Ylla Arbós, A. Blom
Funding acquisition: A. Blom, R. M. J. Schielen
Investigation: C. Ylla Arbós
Methodology: C. Ylla Arbós, A. Blom
Project administration: A. Blom, R. M. J. Schielen
Resources: A. Blom
Supervision: A. Blom, R. M. J. Schielen
Validation: R. M. J. Schielen
Visualization: C. Ylla Arbós
Writing – original draft: C. Ylla Arbós
Writing – review & editing: A. Blom, S. R. White, R. Patzwahl, R. M. J. Schielen

Large-Scale Channel Response to Erosion-Control Measures

C. Ylla Arbós[1], A. Blom[1], S. R. White[2], R. Patzwahl[3], and R. M. J. Schielen[1,4]

[1]Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, The Netherlands, [2]Department of Civil and Environmental Engineering, University of California, Berkeley, CA, USA, [3]Department of Hydraulic Engineering in Inland Areas, Federal Waterways Engineering and Research Institute (BAW), Karlsruhe, Germany, [4]Ministry of Infrastructure and Water Management - DG Rijkswaterstaat, Utrecht, The Netherlands

Abstract Erosion-control measures in rivers aim to provide sufficient navigation width, reduce local erosion, or to protect neighboring communities from flooding. These measures are typically devised to solve a local problem. However, local channel modifications trigger a large-scale channel response in the form of migrating bed level and sediment sorting waves. Our objective is to investigate the large-scale channel response to such measures. We consider the lower Rhine River from Bonn (Germany) to Gorinchem (the Netherlands), where numerous erosion-control measures have been implemented since the 1980s. We analyze measured bed level data (1999–2020) around four erosion-control measures, comprising scour filling, bendway weirs, and two fixed beds. To get further insight on the physics behind the observed behavior, we set up an idealized one-dimensional numerical model. Finally, we study how the geometry and spacing of the measures affect channel response. We show that erosion-control measures reduce the sediment flux due to (a) lack of erosion over the measure and (b) sediment trapping upstream of the measure, resulting in downstream-migrating incision waves that travel tens of kilometers at decadal timescales. When the measures are in close proximity, their downstream effects may be amplified. We conclude that, despite fulfilling erosion-control goals at the local scale, erosion-control measures may worsen large-scale channel-bed incision.

1. Introduction

Rivers erode and aggrade in response to natural and anthropogenic change (Blom et al., 2016; De Vriend, 2015; Mackin, 1948). Such erosion and deposition may hinder navigation and increase flood risk (Buijse et al., 2002; Habersack et al., 2016; Hiemstra et al., 2022; Ylla Arbós et al., 2021a). For example, erosion pits may cause locally high flow velocities, which hampers navigation (Guan et al., 2014), and spatial variation in erosion rates may lead to locally reduced flow depths, which limits the amount of cargo that ships can transport, especially at low flows (Hiemstra et al., 2022; Ylla Arbós et al., 2021a). Excessive deposition may decrease the conveyance capacity of river channels and increase flood risk (e.g., Ahrendt et al., 2022), or reduce the navigable width at channel bends, as eroded sediment from the outer bend deposits in inner bends (Havinga, 2020).

Various measures have been implemented to control channel erosion around the world. Grade-control structures, ground sills or weirs made of different materials and setups are commonly installed to mitigate incision in high-gradient rivers. A non-exhaustive list includes examples in the United States (Simon & Darby, 2002), Japan (Yasuda, 2021), Taiwan (B.-S. Lin et al., 2008), Poland (Korpak et al., 2021), Austria (Habersack & Piégay, 2007; Stephan et al., 2018), Italy (Lenzi et al., 2003), Serbia (Kostadinov et al., 2018), and the Czech Republic (Galia et al., 2016). Other measures include bottom groynes (Alexy, 1995; Sanyal, 1991; Xu et al., 2023); the artificial supply of sediment to increase the sediment supply or fill erosion pits (Czapiga et al., 2022b; Frings et al., 2014; Gaeuman, 2012); and the installation of rip-rap layers or fixed beds (Havinga, 2020; Sloff et al., 2006) and bendway weirs (Abad et al., 2008; Havinga, 2020; Jia et al., 2009) to increase the navigable width.

Erosion-control measures are generally aimed at solving a problem locally (i.e., at scales of tens of meters to few kilometers). In the case of large-scale incision, multiple measures are carried out along the basin (e.g., Frings et al., 2014; Simon & Darby, 2002). Detailed feasibility studies and tests of different variants are conducted, often limited to numerical simulations and scale models, with the aim to find the solution that most effectively meets the specific erosion-control goal (e.g., Bormann & Julien, 1991; Jia et al., 2009; Sloff et al., 2006; Xu et al., 2023). However, the potential large-scale effects of such measures (i.e., considering scales of tens of kilometers or more) are often disregarded.

Like other river interventions (e.g., channelization, dam construction, channel diversions), erosion-control measures change channel characteristics, such as hydraulic geometry, grain size, roughness, or sediment supply. Channels respond to such changes through upstream- and downstream-migrating aggradation and incision waves (An et al., 2019; Chowdhury et al., 2023; De Vriend, 2015; Y. Lin et al., 2023; Martín-Vide et al., 2020; Madej & Ozaki, 1996). Depending on the magnitude and spatial extent of the change, channel response may develop over centuries and extend over hundreds of kilometers (e.g., Simon & Rinaldi, 2006; Surian & Rinaldi, 2003; Yang et al., 2018; Ylla Arbós et al., 2021a). Consequently, the side effects of interventions may negatively affect areas elsewhere in the basin. Examples range from sediment starvation in deltas due to upstream dams (e.g., Bussi et al., 2021; Hu et al., 2009; Rao et al., 2010; Syvitski et al., 2005), to local erosion pits of different depths downstream of erosion-control measures (Czapiga et al., 2022a; Korpak et al., 2021; Kostadinov et al., 2018; Lenzi et al., 2003).

Here we consider the lower Rhine River, the 300 km reach of the Rhine River between Bonn (Germany) and Gorinchem (the Netherlands), where numerous erosion-control measures have been undertaken since the 1980s (Figure 1). The lower Rhine River is the most important inland waterway in Europe, as it connects the continent with major shipping routes overseas via the port of Rotterdam (Christodoulou et al., 2020). The Rhine has been heavily engineered and intensely monitored to ensure reliable navigation and protect populations from floods (Frings et al., 2014; Quick et al., 2019; Ylla Arbós et al., 2021a). Past channelization measures in the lower Rhine River have led to meters of river bed incision over hundreds of kilometers over the past century (Frings et al., 2014; Quick et al., 2019; Ylla Arbós et al., 2021a). Current domain-wide incision rates range between 0 and 2 cm/a (Ylla Arbós et al., 2021a). To mitigate this incision and to maintain the navigation channel, various interventions have been carried out, ranging from sediment nourishments, to scour-filling measures, bendway weirs, longitudinal training walls, and fixed beds (Czapiga et al., 2022a, 2022b; Frings et al., 2014; Havinga, 2020; Quick et al., 2019; Ylla Arbós et al., 2021a).

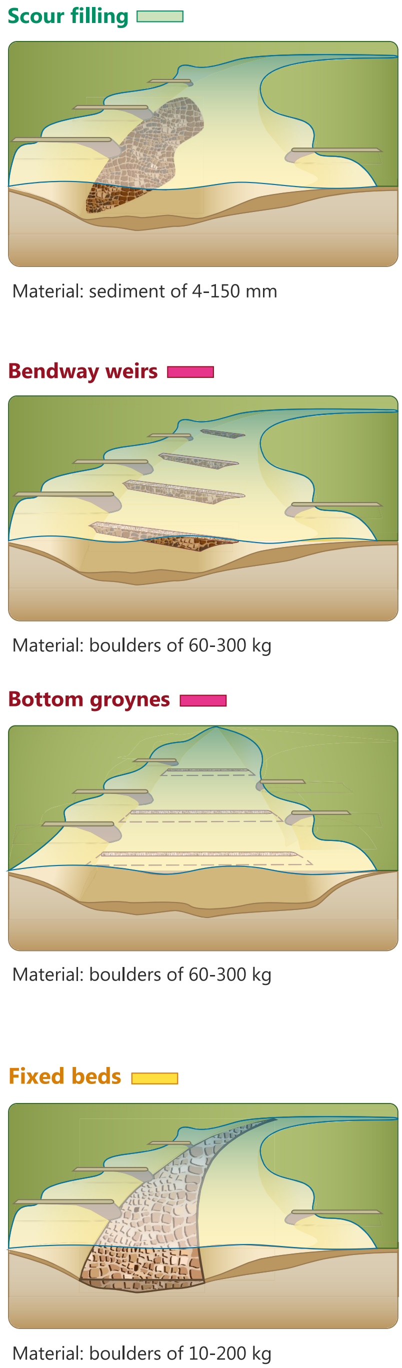
In this study, we focus on three types of erosion-control measures: scour filling, bendway weirs, and fixed beds (Figure 1). All these measures fix (a part of) the river bed, resulting in zones of locally reduced sediment mobility. Our objective is to assess the large-scale channel response to such measures in terms of bed level change. To this end, we first characterize the different types of measures (Section 2). We then analyze the local effects measured at four field sites, based on detailed bathymetric data over the period 1999–2020 (Section 3). Subsequently, we investigate the large-scale channel response to the measures by analyzing the propagation of bed level waves that appear after their construction (Section 4). To conceptualize the physics of the large-scale response, we set up an idealized one-dimensional numerical model that simulates channel response to an erosion-control measure (Section 5). Finally, we assess the effects of the length and spacing of erosion-control measures on channel response (Section 6).

2. Erosion-Control Measures in the Lower Rhine River

Despite having different configurations and goals, erosion-control measures share a number of characteristics. The most important ones are the reduction of sediment mobility (which limits or prevents incision at the measure itself), the increase of hydraulic roughness given the larger size of the material of the measures, and their protrusion onto the river bed as the surrounding bed incises. In this section we describe the three types of measures deployed in the lower Rhine River (Figure 1): (a) scour filling (Frings et al., 2014); (b) bendway weirs (Havinga, 2020); and (c) fixed beds (Havinga, 2020).

Scour-filling measures aim to mitigate local scour. These measures have been carried out since the 1980s and are widespread in the Niederrhein (Frings et al., 2014; Figure 1). Specifically, coarse sediment with a diameter of 4–150 mm is dumped in scour holes to fill them, and then covered with a top layer of finer material, to avoid large spatial variations in roughness (Decker, 2014). This top layer is only slightly coarser than the surrounding bed surface sediment, which has a geometric mean grain size of 15–20 mm (Frings et al., 2014; Ylla Arbós et al., 2021a).

Fixed beds and bendway weirs have been used in the Waal since the 1980s. They are installed in the outer parts of river bends to increase the navigable width in relatively sharp bends (Havinga, 2020). Fixed beds (Figure 1) consist of a layer of boulders of 10–400 kg (rip-rap), which is placed on top of a finer filter layer. Bendway weirs are partial dams constructed on the river bed, made of boulders of 60–300 kg, placed on top of a filter layer. Bendway weirs aim to disrupt secondary currents and are oriented at an angle to the radius of the bend.



Installation	River km	Type	Purpose
1970	658.0-660.0	Scour filling	Erosion control
1998-1999	664.7-665.8	Scour filling	Erosion control
2001	666.5-668.2	Scour filling	Erosion control
1995-1996	670.0-672.4	Scour filling	Erosion control
1994-1996	714.0-716.1	Scour filling	Erosion control
1985-1987	721.8-725.1	Scour filling	Erosion control
1992-1993	732.0-733.4	Scour filling	Erosion control
1990-1991	741.1-742.8	Scour filling	Erosion control
1990-1991	743.2-745.6	Scour filling	Erosion control
2002-2003	752.0-753.0	Scour filling	Erosion control
1987-1990	764.4-766.7	Scour filling	Erosion control
1993-2002	778.9-781.5	Scour filling	Erosion control
1987-1992	784.9-788.0	Scour filling	Erosion control
1989-1990	789.2-790.8	Scour filling	Erosion control
1993-2010	820.0-824.9	Scour filling	Erosion control
1998-2003	832.0-837.7	Scour filling	Erosion control
1994-1996	841.7-843.7	Scour filling	Erosion control
1995-1998	847.3-849.0	Scour filling	Erosion control
2002-2007	850.5-857.2	Scour filling	Erosion control
2014	858.1-861.8	Scour filling	Erosion control
1994-1996	873.2-876.0	Bendway weirs	Increase navigable width
1985-1988	883.1-885.1	Fixed bed	Increase navigable width
1997-1999	925.0-928.1	Fixed bed	Increase navigable width

Figure 1. Erosion-control measures in the lower Rhine River, with details on their installation period, location, type, and main purpose. Numbers between parentheses on the map indicate streamwise river km, with origin at Konstanz (Bodensee).

Bendway weirs are not to be confused with bottom groynes (Figure 1). Despite having similar structural characteristics, bottom groynes aim to limit channel-bed incision (e.g., Alexy, 1995; Xu et al., 2023), by preventing the water level to drop below a certain threshold. Bottom groynes can be found, for instance, in the Elbe River, both at a river bend and in an incising straight reach downstream of a bedrock reach (Alexy, 1995).

There are two fixed beds in the lower Rhine River: one in the river bend at Nijmegen (river km 883.1–885.1, Figure 1) and one at the bend at Sint Andries (river km 925–928.1, Figure 1). The fixed bed at Nijmegen was installed in 1985–1988. It extends over two km along the gravel-sand transition zone of the lower Rhine River, where the geometric mean grain size of the channel bed ranges between 3 and 5 mm. The fixed bed was placed in the outer bend of the river and is 160–180 m wide. It consists of a 50–75 cm thick layer of 10–60 kg boulders lying on top of a 40 cm thick filter layer made of gravel sized 20–180 mm (Franssen, 1995).

The fixed bed at Sint Andries extends over three km, and is located at the sandy reach of the lower Rhine River (geometric mean grain size around 1 mm). In this area (the lower Rhine delta), the channel has aggraded (around 2 cm/a) over the past 20 years (Ylla Arbós et al., 2021a). The measure was constructed in the period 1997–1999, 10 years after the one at Nijmegen, which allowed for modification based on the experiences with the latter (Leeuwestein, 1996). To prevent instability of individual stones, a 80 cm thick layer of heavier boulders (40–200 kg) was installed on top of a 40 cm thick filter layer made of coarse gravel with size 40–100 mm (Leeuwestein, 1996). The fixed bed was placed in the outer bend of the river, and has a width of 140 m.

Bendway weirs were constructed in the river bend at Erlecom in 1994–1996 (river km 873.2–876, Figure 1). Despite pursuing the same goal as fixed beds (i.e., increasing the navigable width in relatively sharp bends), a different design was chosen under concerns that a fixed-bed type of measure would create undesirable backwater effects at the Pannerden bifurcation (Figure 1). The bendway weirs at Erlecom consist of 54 partial dams installed on the river bed, spaced by 50 m, at an angle of 67.5° relative to the thalweg (Van Amerongen, 1997). The weirs are between 1.80 and 2.80 m high.

Fixed beds and bendway weirs have the same working principle related to flow dynamics in bends. Specifically, bend curvature is associated with a centrifugal force that directs fluid toward the outer bend, leading to a superelevation of the water surface at the outer bend (Azpiroz-Zabala et al., 2017; Rozovskii, 1957). The resulting flow depth difference between the outer and inner bends leads to a transverse gradient in water pressure. The imbalance between these two forces (i.e., the centrifugal force directed to the outer bend, and the pressure gradient directed toward the inner bend) results in a transverse flow circulation characterized by the near-surface fluid flowing toward the outer bend, and the near-bed fluid flowing toward the inner bend (e.g., Azpiroz-Zabala et al., 2017; Thorne et al., 1985). This transverse flow pattern is superimposed to the streamwise flow, resulting in a helical flow pattern (Rozovskii, 1957; Thorne et al., 1985).

This helical flow affects the direction of sediment transport. In rivers where sediment transport is bedload-dominated, the direction of sediment transport is mostly determined by the near-bed flow, and therefore predominantly directed from the outer bend to the inner bend (Sloff & Mosselman, 2012; Van der Mark & Mosselman, 2013). As a result, outer bends tend to be deeper than inner bends (Edwards & Smith, 2002). A shallow inner bend tends to reduce the available channel width for navigation (Havinga, 2020; Sloff et al., 2006).

Fixed beds and bendway weirs change the helical motion of the flow. By increasing and fixing the bed level at the outer bend, they direct a larger fraction of the flow toward the inner bend. As a result, the inner bend becomes deeper and the navigation channel widens (Havinga, 2020).

3. Local Channel Response to Erosion-Control Measures

Here we analyze the local channel response to four erosion-control measures belonging to the three categories described in Section 2, namely the scour-filling measure at Spijk (river km 858.1–861.8), the fixed beds at Nijmegen (river km 883-1-885.1) and Sint Andries (river km 925.1–928), and the bendway weirs at Erlecom (river km 873.2–876). We select these case studies given the availability of detailed bathymetric data in the area. These data consist of multibeam echo-soundings with a resolution of 1×1 m^2 over the period 1999–2020 (Figure 2).

The scour-filling measure at Spijk is 4 km long and has a variable width ranging from 30 to 100 m (Figure 2a). Its main purpose is erosion mitigation, though a secondary aim to increase navigable width has been reported. The measure is installed at the outer side of a mild bend, which is somewhat deeper than the inner bend (Figure 2a). The measure itself is not clearly visible on the bathymetric map (Figure 2a), which is likely due to (a) the use of a relatively similar material as the surrounding river bed, and (b) the fact that the measure does not protrude, which may be related to its recent installation (2014) and to the non-erosional character of the reach.

Figure 3a shows the temporal change in bed level at a cross-section located at river km 861.1, where the width of the scour-filling measure is maximal. The cross-sectional profiles show that the measure has so far been

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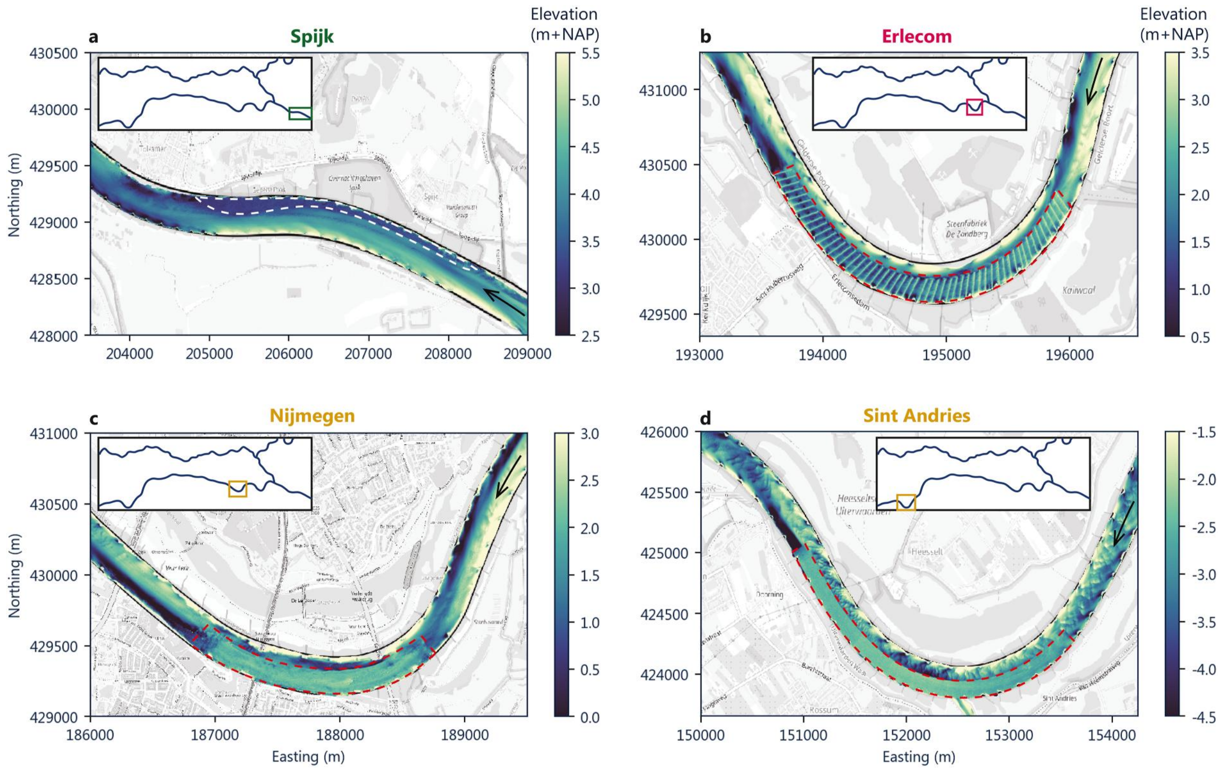

Figure 2. Two-dimensional bathymetric maps of the erosion-control measures at (a) Spijk (river km 858.1–861.8, scour filling), (b) Erlecom (river km 873.2–876, bendway weirs), (c) Nijmegen (river km 883-1-885.1, fixed bed), and (d) Sint Andries (river km 925.1–928, fixed bed). Dashed lines on each map show the extent of the measures. All the maps show data from 2020. Horizontal and vertical axes indicate, respectively, eastward and northward geographic Cartesian coordinates in the coordinate system Amersfoort/RD New (EPSG:28992). Elevation is relative to NAP (Amsterdam Ordnance Datum).

successful in achieving its primary and secondary goals. On the one hand, the scour hole has been filled, and bed level has remained stable since its construction in 2014. On the other hand, the inner bend has incised, increasing the navigable width. Figure 3e shows a series of longitudinal bed level profiles taken 85 m from the centerline of the river, over the scour-filling measure. The profiles show a sudden increase in bed level in 2014, when the scour hole was filled. The river bed has remained stable over the fixed bed since then. Downstream of the measure, a 1.5 m deep and 500 m long scour hole has developed, and seems to slightly migrate downstream with time.

For the bendway weirs at Erlecom, the two-dimensional bathymetry clearly shows the extent of the measure and the disposition of the weirs (Figure 2b). The measure extends over three km in an outer bend, and covers slightly more than half of the cross-section. Directly upstream of the weirs the bed is relatively shallow. Downstream, the outer bend is substantially deeper than the inner bend (Figure 2b).

Based on the temporal change of bed level at a cross-section approximately in the middle of the whole measure (river km 874.6, Figure 3b), we can affirm that the bendway weirs are successful in achieving their goal of increasing the navigable width through deepening the inner bend. In particular, the inner bend has systematically degraded at a rate of about 7 cm/a over the past 20 years, which is larger than the 20-year reach-averaged degradation rate of about 1.7 cm/a. The transverse profiles also show aggradation on the outer bend, indicating that sediment is deposited in-between weirs (Figure 3b). In the longitudinal direction, a profile measured 65 m from the centerline (Figure 3f) reveals a double 2 m deep erosion pit downstream of the bendway weirs that extends over 1 km. The pits migrate downstream with time.

Figure 2c shows the two-dimensional bathymetry around the fixed bed at Nijmegen. The fixed bed is at a higher elevation than the surrounding channel bed, indicating protrusion of the fixed bed. This protrusion is due to large-scale channel-bed incision, at an average rate of about 1.5 cm/a in Nijmegen over the past 20 years. Despite the intended non-erodability of the fixed bed, Figure 2c reveals lower bed levels at the upstream and downstream ends of the measure. This could be due to boulder displacement (especially at the downstream end, where boulders may

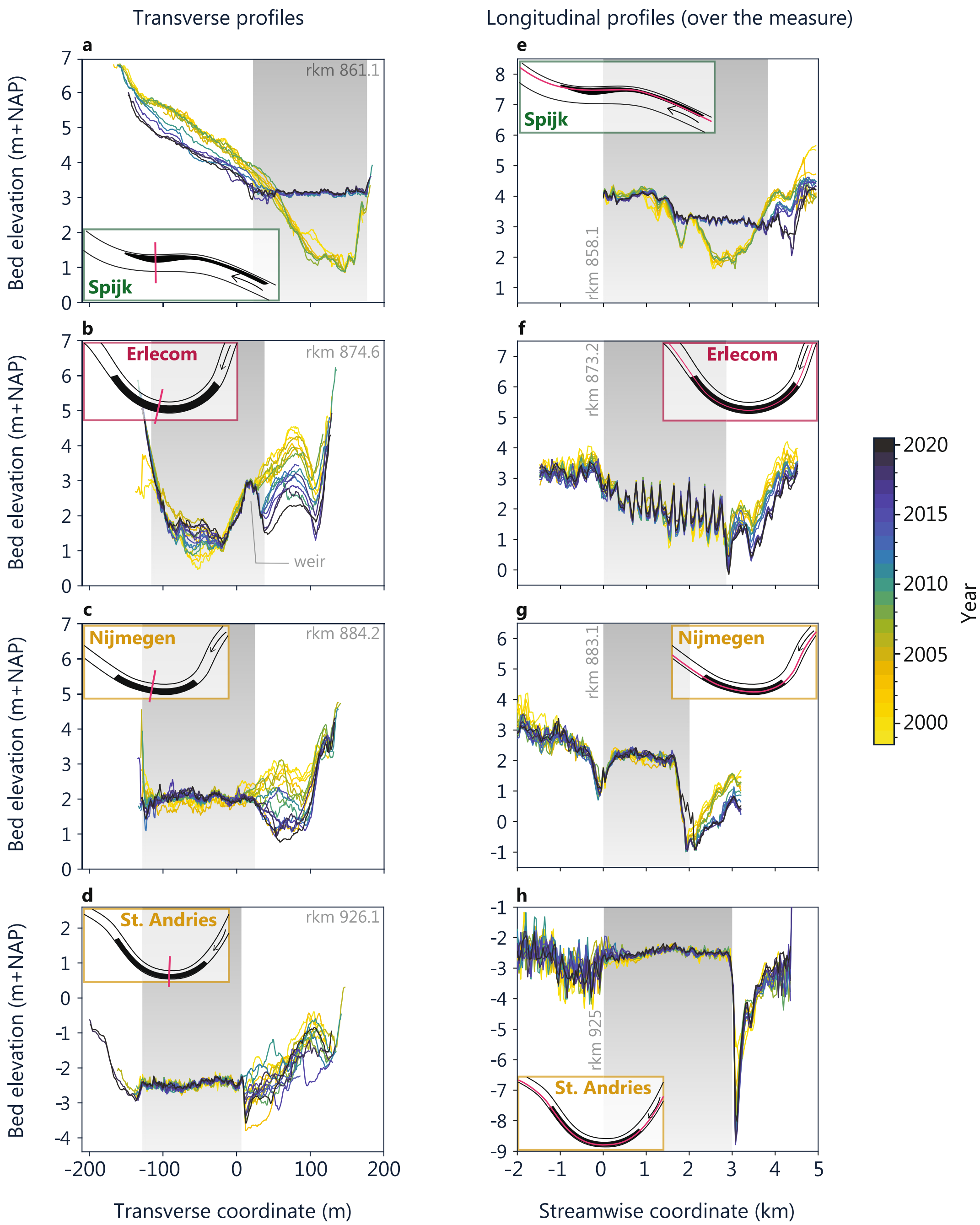

Figure 3. Bed level around the erosion-control measures over the period 1999–2020: respectively, transverse and longitudinal profiles at Spijk (a, e), Erlecom (b, f), Nijmegen (c, g), and Sint Andries (d, h). The 0 coordinate in the transverse and longitudinal profiles refers to, respectively, the centerline of the river and to the upstream end of the fixed bed. Negative transverse coordinates correspond to the left (south) bank. Longitudinal profiles are measured at 85 m from the centerline for Spijk, and 65 m from the centerline for the remaining measures. The river km on the transverse and longitudinal profiles corresponds to, respectively, the measured cross-section and to the upstream end of the fixed bed. Shaded gray areas highlight the extent of the fixed bed. All the transverse profile plots have the same aspect ratio but different absolute bed levels. The same holds for the longitudinal profiles.

fall into the erosion pit) or due to mechanical removal of the most protruding boulders in 2020 (Rijkswaterstaat, 2020). Franssen (1995) reports instabilities at the lateral edges of the fixed bed, which are potentially due to locally smaller thickness of the top layer and heavy loading from ship manoeuvres.

The surface of the fixed bed does not appear to be smooth, which may indicate some alluvial cover on the structure (Figure 2c). Cross-sectional profiles measured halfway along the fixed bed (river km 884.2, Figure 3c) seem to confirm this alluviation. These profiles also show significant bed erosion in the inner bend over time. Bed incision rates at the inner bend were about about 5 cm/a until 2010, and 3.5 cm/a since then. These rates are larger than the 20-year 5 km reach-averaged degradation rate of 1.5 cm/a and indicate success in achieving the intended goal of increasing the navigable width.

Figure 2c shows a long erosion pit downstream of the fixed bed at Nijmegen. Figure 3g shows that the pit is about 3 m deep, and has migrated downstream with time. The protrusion of the fixed bed from the surrounding channel bed (Figure 3g) has caused numerous problems to navigation (Havinga, 2020). In addition, Figure 3g shows some slight aggradation over the fixed bed during the early 2000s, which may be associated with a temporary aggradation wave.

The fixed bed at Sint Andries shows a smoother surface than the one at Nijmegen (compare fixed-bed surfaces shown in Figures 2d and 2c). Near the Sint Andries fixed bed, we observe relatively large bedforms (about 20–80 m long and 1 m high). This may be due to the sandy nature of the river bed at Sint Andries. The inner bend appears deeper than the outer bend, especially halfway along the fixed bed (Figure 3d). We also observe a deep pit downstream of the fixed bed (Figure 3h).

The transverse profiles (Figure 3d) show a stable and smooth surface of the fixed bed in the outer bend, which is shallower than the inner bend. Gradual bed erosion in the inner bend is less obvious than in other measures, which may be due to the presence of migrating bedforms. This bedform-induced noise is also observed in Figure 3h, upstream from the fixed bed.

At the upstream end of the fixed bed, some alluvial cover is visible, indicating that some sediment may be transported onto the upstream end of the fixed bed, and then directed toward the inner bend due to the helical flow. A deep erosion pit (over 6 m deep) is present downstream of the fixed bed (Figure 3h). The pit is shorter, advances more slowly in the downstream direction, and shows a faster incision rate than the pit downstream of the fixed bed at Nijmegen (Figure 3g). A reason for these differences seems to be the finer bed surface sediment at Sint Andries (Ylla Arbós et al., 2021a).

The continued incision of the pit can likely be attributed to two-dimensional effects (i.e., the flow in the inner bend being increasingly attracted toward the erosion pit, deepening it with time). This may be analogous to the two-dimensional effects observed downstream of the storm surge barrier in the Eastern Scheldt estuary in the Netherlands (Broekema et al., 2018).

4. Large-Scale Channel Bed Incision Downstream of Erosion-Control Measures: Insights From Measured Data

In Section 3 we have shown that the different erosion-control measures have succeeded in achieving their intended goals (i.e., erosion mitigation or widening of the navigation channel). Yet we have also observed some unintended side effects, namely erosion pits of variable depths and lengths downstream of the measures. These pits seem to migrate downstream in the form of an incision wave. In this section we focus on the large-scale dynamics of these waves.

Even though many of the erosion-control measures are installed on river bends and their dynamics are influenced by two-dimensional flow features, a one-dimensional analysis captures the primary component of the longitudinal channel response to erosion-control measures. Specifically, we focus on the (conceptual) large-scale stream-wise propagation of incision waves associated with erosion-control measures, the computation of which is expensive in two dimensions. To this end we analyze a space-time plot of 5-year aggradation rates, based on the cross-sectionally averaged measured bed level over the period 1982 until 2020 (Figure 4a). Data prior to 1999 are obtained with single beam echo-soundings (see Ylla Arbós et al. (2021a) for further details on data collection and pre-processing).

As the Spijk scour-filling measure is too recent to recognize any large scale trends (given the multi-decadal timescales of channel response), we focus on the bendway weirs at Erlecom and the fixed beds in Nijmegen and Sint Andries. The 5-year aggradation rates (Figure 4a) reveal downstream-migrating incision waves after

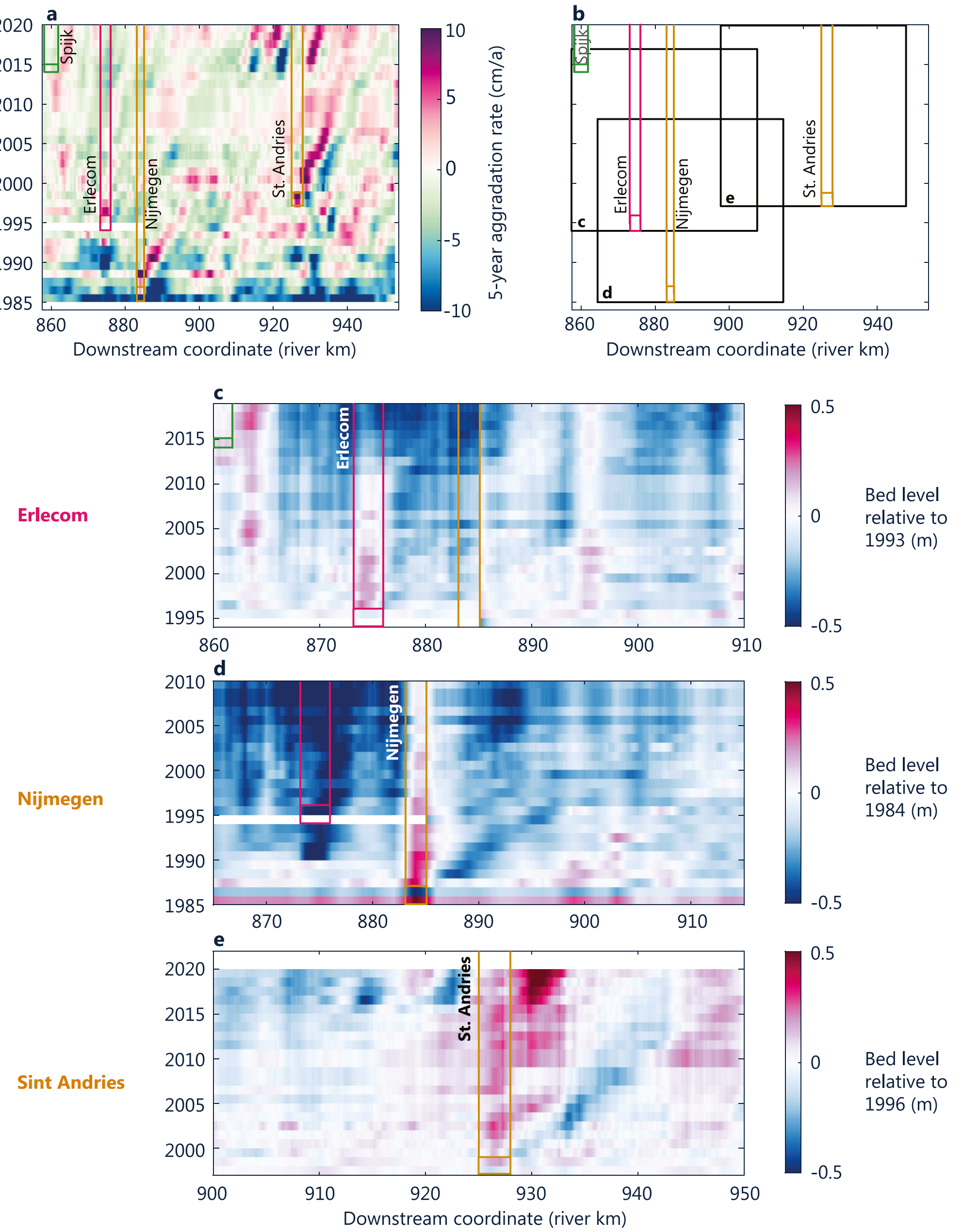

Figure 4. Aggradation rates in the study area and space-time plots of bed level change after project completion. (a) 5-year aggradation rates; (b) schematic of spatio-temporal domains depicted in panels (c–e); (c) bed level relative to 1994 at the vicinity of Erlecom; (d) bed level relative to 1985 at the vicinity of Nijmegen; (e) bed level relative to 1997 at the vicinity of Sint Andries. Vertical lines on all plots represent the location of the erosion-control measures, with the box at the bottom of the lines indicating the construction period. Bed levels are averaged over 2 km. Note that panels (c–e) have different baseline years, respectively set to the average of 3 years before construction of the measure.

construction of the different erosion-control measures, especially the fixed beds at Nijmegen and Sint Andries. Downstream of Erlecom, only a mild incision wave is visible.

The aggradation rates (Figure 4a) show that the above-mentioned incision waves are followed by an aggradation wave of the same celerity. These aggradation waves indicate deposition of sediment in the erosion pits, which implies that (part of the) response is a temporary effect. This is particularly visible for the fixed beds in Nijmegen and Sint Andries, and less so for Erlecom.

After establishing that bed level waves appear upon construction of the measures, we consider bed level change over space-time windows of 50 km by 25 years (Figure 4b). To focus on the response to the measure itself, we set the baseline year for each of these windows to the average of 3 years prior to the construction of each measure (e.g., for Erlecom, Figure 4c shows bed level relative to the average bed level over the period 1991–1993).

The downstream effects of the bendway weirs at Erlecom (Figure 4c) are mild. There is a sign of a mild wave that travels, approximately, from river km 876 in 1996 to river km 894 in 2006, that is, some 18 km in 10 years (celerity of 1.8 km/a), although this wave may also be related to the Pannerden bifurcation (river km 867.5), where large incision rates have been reported, possibly due to instability of the bifurcation (Chowdhury et al., 2023). Some slight aggradation can be observed at the location of the weirs, which seems to be due to trapping of sediment between the weirs. Mild aggradation is noticeable upstream of the measure after its construction.

Figure 4d shows a downstream-migrating incision wave downstream of the fixed bed at Nijmegen. Over a period of 10 years, the wave has migrated about 15 km in the downstream direction (approximately, from river km 885 in 1986 to river km 900 in 1996), which implies a celerity of 1.5 km/a. The migrating pit seems to be partially filled with time. We also see deposition on the fixed bed, especially in the first 5 years after its construction. Upstream of the fixed bed, incision over the period 1985–1995 appears to be milder than in the surrounding spatio-temporal domain. There is no data in 1994 between river km 857–885.

A downstream-migrating incision wave also appears downstream of the fixed bed at Sint Andries (Figure 4e). This wave has advanced, approximately, from river km 928 in 1999 to river km 940 in 2009, that is, about 12 km in 10 years, (celerity of 1.2 km/a) and has been followed by a deposition wave. The area around Sint Andries shows very mild incision rates and even some aggradation, already prior to the construction of the fixed bed. Figures 4a and 4e indicate aggradation on top of the fixed bed as well as upstream of it.

Cross-sectionally averaged aggradation around Sint Andries (Figure 4e) is likely related to its location in the lower Rhine Delta, rather than the fixed bed. As the river is decreasing its slope in response to past channelization, incision rates at its downstream end were already mild, and even aggradational, before fixed bed construction (see also Ylla Arbós et al., 2021a). Note that downstream of the fixed bed itself, the response remains incisive (Figure 3h).

Figure 4a shows a succession of incising and aggrading waves around Sint Andries after 2015. These waves are not related to the fixed bed, but rather a response to the construction of longitudinal training walls over river km 912–918 in the period 2014–2015 (Czapiga et al., 2022a).

5. Large-Scale Channel Response to Erosion-Control Measures: Insights From Numerical Simulations

Measured data on bed level around the erosion-control measures suggest that such measures are associated with a large-scale channel response. Specifically, we notice a downstream-migrating incision wave propagating from the downstream end of the measure, and a zone of slightly reduced incision upstream of the measure. Yet the measured data does not allow for identifying channel response to solely the erosion-control measures. This is because these data reflect channel response to the combination of numerous interventions, natural variability of the system, and climate change.

To better understand the physics of this large-scale response, we set up an idealized one-dimensional numerical model. Numerical simulations allow for comparison with a base case without erosion-control measures, which is more difficult in the field. In addition, an idealized model allows us to set and control channel characteristics, such that we can isolate the effects of an erosion-control measure.

We use the numerical research code Elv (Blom, Chavarrías, et al., 2017; Chavarrías et al., 2019), which is suitable for mixed-size sediment morphodynamics. Flow is computed by solving the backwater equation, changes in bed elevation are computed using the Exner (1920) equation, and changes in the bed surface grain size distribution are computed with the Hirano (1971) active layer model, regularized to avoid ill-posedness following Chavarrías et al. (2019). We model erosion-control measures as non-erodible reaches, in particular by using a sediment size that is sufficiently large to be immobile under all flow conditions. We use the approach of Chavarrías et al. (2022, specifically the ILSE model), as the Hirano (1971) model does not provide realistic results with immobile sediment under aggradational conditions.

We use a spatial step of 500 m. We consider an active layer of 1 m (e.g., Arkesteijn et al., 2021), and a constant non-dimensional friction coefficient c_f ($c_f \equiv \tau_b/\rho u^2$, with τ_b the bed shear stress, ρ the fluid density, and u the flow velocity) of 0.008 (e.g., Blom et al., 2016). As a closure relation we use the Meyer-Peter and Müller (1948) sediment transport relation, and we include hiding effects following Egiazaroff (1965). All model assumptions are detailed in Chavarrías et al. (2019).

We consider a 200 km long rectangular channel in equilibrium, which we subject to narrowing to half its width (from 500 to 250 m) to create domain-wide incision. We let the channel adjust to narrowing for a few decades, until the maximum incision rates are below 2 cm/a, which is comparable to conditions in the Rhine River (Quick et al., 2019; Ylla Arbós et al., 2021a). We then install a 4 km long erosion-control measure made of immobile sediment with a grain size of 85 mm. The model initial state corresponds to the moment when the measure is installed. We run the model for 50 years. The length of the modeled erosion-control measure is of the same order as the measures in the lower Rhine River. Note that by using a one-dimensional model, the erosion-control measure is assumed to occupy the full width of the channel.

We consider four cases in order to understand the effects of grain size and variable flow: (a) constant discharge-unisize sediment; (b) constant discharge-mixed-size sediment; (c) variable discharge-unisize sediment; and (d) variable discharge-mixed-size sediment. The constant discharge cases have a formative discharge of 3,000 m^3/s, which corresponds to the dominant discharge of the hydrograph used in the variable discharge-unisize sediment case. By dominant discharge we refer to the constant discharge that, for a given sediment supply rate, leads to the same equilibrium channel slope as the natural hydrograph (Blom, Arkesteijn, et al., 2017). For simplicity, we use the same discharge in the constant discharge-mixed-size sediment case, as the definition of the dominant discharge for a mixed-size sediment case is less straightforward (Blom, Arkesteijn, et al., 2017). In the variable discharge cases, we use a 20-year cycled hydrograph (i.e., a repeated hydrograph of a 20-year duration with a daily frequency which is equal to measured data at Köln (river km 640) over the period 1967–1986), and is statistically representative of the long-term discharge conditions of the lower Rhine River (Ylla Arbós, Blom, Sloff, & Schielen, 2023; Ylla Arbós, Blom, White, & Schielen, 2023).

For the unisize case, we adopt a sediment size of 11 mm, which corresponds to the geometric mean grain size of the mixed-size case. The latter consists of a gravel mixture of 6 and 15 mm in proportions of 30% and 70% in the substrate, respectively. This composition is loosely based on the characteristics of the gravel reach of the lower Rhine River (Ylla Arbós, Blom, Sloff, & Schielen, 2023; Ylla Arbós, Blom, White, & Schielen, 2023). The model bed surface composition has adjusted due to the narrowing (i.e., it has become slightly finer), though it remains coarser than the substrate sediment. Slight bed surface fining under conditions of narrowing-induced incision is explained by the fact that channel narrowing increases the flow velocity and bed shear stress, thereby reducing the mobility difference between fine and coarse grains (Blom, Arkesteijn, et al., 2017). Under these conditions, the bed surface does not need to coarsen as much to be able to transport the same sediment flux downstream.

The total annual sediment flux equals to 0.126 Mt/a following Frings et al. (2019). The composition of the flux is the same as the composition of the substrate (Parker et al., 1982; Parker & Klingeman, 1982).

We analyze channel response relative to a base case without the erosion-control measure, which responds to narrowing through channel-bed incision. Figure 5a shows the spatio-temporal changes in bed level relative to the base case for the constant discharge-unisize case. Relative to the base case, the measure leads to a downstream-migrating wave of additional incision. Upstream of the measure, the bed elevation is higher than in the base case, which for our narrowed channel means reduced incision rather than net aggradation.

The reduced incision upstream of the erosion-control measure can be partially explained by the presence of an M1 backwater curve, which leads to deceleration of the flow and a reduction of the sediment transport rate (Czapiga et al., 2022b). This backwater curve is due to progressive protrusion of the measure as the surrounding channel bed incises. In addition, as the erosion-control measure is immobile, the sediment flux over the measure is smaller than in the base case, further reducing the flux downstream of the measure, relative to the base case. The reduced sediment flux downstream of the measure, leads to the downstream-migrating incision wave (see also Figure S1 in Supporting Information S1).

The incision wave has a celerity of about 2 km/a (Figure 5a), which is consistent with the 1.2–1.8 km/a migration celerity observed for the field data. In the field, the M1 backwater effects are be enhanced by the fact that the

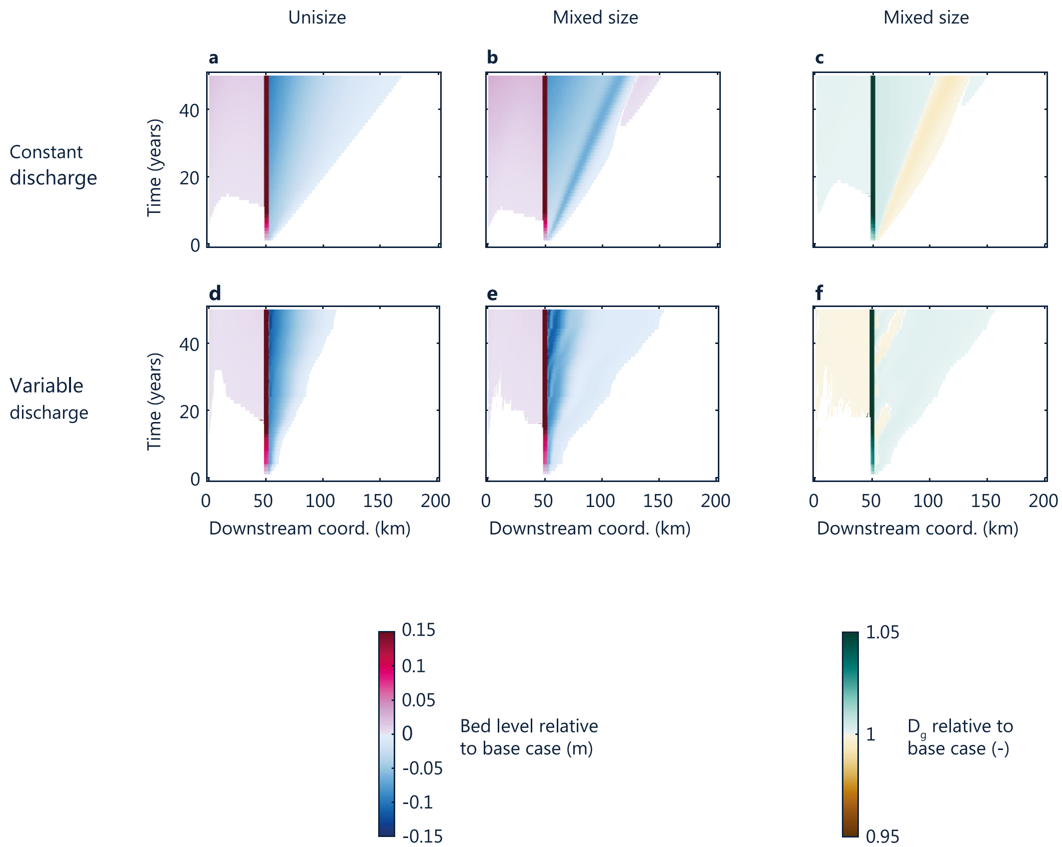

Figure 5. Space-time plots of simulated bed level change (difference) and bed surface grain size change (ratio) due to an erosion-control measure, relative to a base case without the measure: (a) constant discharge-unisize sediment; (b, c) constant discharge-mixed-size sediment; (d) variable discharge-unisize sediment; (e, f) variable discharge-mixed-size sediment. White space on the plots indicates no change in bed level or grain size.

measure is coarser (i.e., rougher), which leads to a larger backwater effect than protrusion alone. This roughness effect is, however, not captured by our simulations given the constant friction coefficient.

In the presence of mixed-size sediment, we observe similar behavior (Figure 5b), with the exception of a downstream-migrating pit that is subsequently (partially) filled. This relatively deep part of the erosion wave is related to entrainment of fines from the substrate, which are exposed as the bed incises, and are more mobile than the relatively coarser material on the bed surface, as illustrated by the fining wave visible in Figure 5c. It is, however, difficult to assess whether the characteristics of the downstream-migrating pit are representative of field conditions or rather a consequence of the limitations of the Hirano (1971) model, especially when considering such a limited amount (two) of grain size fractions.

The fining wave is followed by a mild (almost negligible) coarsening wave (Figure 5c). This net coarsening is likely due to sediment trapping upstream of the erosion-control measure, and non mobility of the measure, which limits the supply to the downstream reach. The resulting incision seems to be preferentially associated with the entrainment of fine material from the surface, which consequently becomes coarser.

Upstream of the measure, the bed surface becomes slightly coarser with time. This seems to be related to the larger share of coarse material in the sediment flux, combined with the sediment trapping due to the M1 backwater curve.

In general terms, the behavior for the case with variable discharge and unisize sediment (Figure 5d) is similar to the constant discharge case. However, while the zone of decreased incision is smaller, the erosion pit is deeper, and the downstream-migrating incision wave is slower (about 1.2 km/a, compared to the 2 km/a of the other cases). The slower wave celerity is due to the variability of the water discharge, as this celerity depends on the

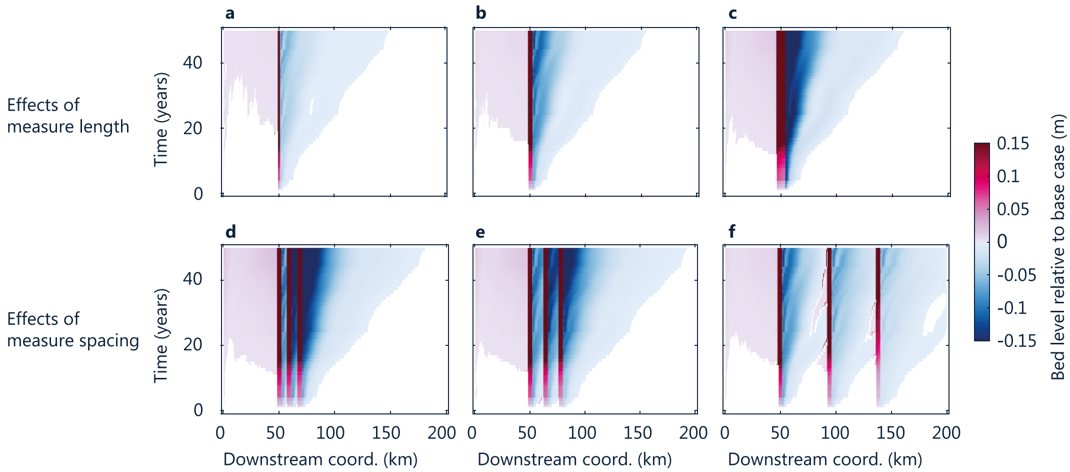

Figure 6. Space-time plots of simulated bed level change relative to a base case without an erosion-control measure, in variable discharge and mixed-size sediment conditions. The top row considers the effects of length, where the length of the erosion-control measure is (a) 2 km, (b) 4 km, and (c) 8 km. The bottom row considers the effects of spacing, where three 4 km long erosion-control measures are spaced (d) 5 km, (e) 10 km, and (f) 40 km.

water discharge (Sloff & Mosselman, 2012). Even though both the constant and variable discharge cases have the same channel-forming discharge, larger discharges are more relevant to channel response and associated with a smaller propagation celerity (Sloff & Mosselman, 2012).

A reason for the slightly reduced upstream sediment trapping in the variable discharge case (compare Figures 5d and 5a) may be the fact that the backwater effects are relatively less pronounced in the case of moderate and high flows than in the case of base flows. This is because the ratio of the protrusion-related bed level step height (which causes the M1 backwater curve) to flow depth is larger for base flows than for peak flows, making the latter relatively less effective at trapping sediment.

In the case of variable discharge and mixed-size sediment, we notice two types of incision waves: one that is faster and shallower, and one that is slower and deeper (Figure 5e). The faster and shallower wave may be associated with the presence of finer material, which moves faster in the downstream direction. Figure 5f shows slight general coarsening of the bed surface, which we attribute to the same reasons as that explain coarsening in the constant discharge-mixed-size case. We also notice two fining waves at about 10 and 30 years. These fining waves are associated with peak flows (see Figure S2 in Supporting Information S1), which lead to entrainment of fines from the substrate.

In contrast to the constant discharge case, in the variable discharge case the bed surface upstream of the measure becomes slightly finer. This may be due to the fact that upstream backwater effects are relatively more pronounced for base flows than for peak flows, making the first relatively more efficient at trapping sediment. The sediment transported by base flows is finer than the sediment transported by peak flows, resulting in slight net bed surface fining.

6. Length and Spacing of Erosion-Control Measures

In this section we analyze the effects of length and spacing of erosion-control measures on channel response. To this end, we consider a case with variable discharge and mixed-size sediment.

Figures 6a–6c show space-time plots of bed level relative to the base case for one erosion-control measure with a length of 2, 4 and 8 km respectively, centered at the same location. We note that the longer the measure, the more pronounced the additional incision downstream. This can be explained, on the one hand, by the fact that a longer measure leads to stronger backwater effects. Upstream of the measure, the stronger backwater traps more sediment, further reducing the sediment supply to the downstream reach. In addition, a longer measure reduces the sediment mobility over a longer reach. First, backwater-related sediment trapping at the upstream end of the erosion-control measure increases with the length of the measure (Figures S3a and S3b in Supporting

Information S1). Second, in our eroding river (decreasing slope in response to channelization), the sediment flux increases in the downstream direction. As the fixed bed prevents the bed from eroding, the sediment flux is constant along the fixed bed. This means that, the longer the erosion-control measure, the more reduced the sediment flux is, relative to what it would be without the erosion-control measure.

To assess the effects of spacing, we model three erosion-control measures of 4 km length, spaced 5, 10, and 40 km apart (Figures 6d–6f). The differences in upstream effects are negligible across configurations. However, the downstream incision is more pronounced when the measures are closer together. This is because the incision waves interfere and amplify. The case with the smallest measure spacing (Figure 6d) largely resembles the case of one long measure (Figure 6c), as it creates an upstream backwater zone, and a zone of reduced sediment mobility similar to what a long erosion-control measure would create (see also Figure S4 in Supporting Information S1).

7. Discussion

Our study shows that large-scale channel response to erosion-control measures consists of enhanced and reduced incision downstream and upstream of the measures. The deep erosion pits downstream of the measures are particularly problematic, and illustrate the need for monitoring as well as opportunities for optimized installation and maintenance of the measures.

Problems are most pronounced for the fixed bed at Nijmegen due to the continued large-scale incision of the surrounding bed. The increasing protrusion of this fixed bed repeatedly disrupts navigation during low flows. Water management authorities have considered reducing the surface elevation of this fixed layer by removing or scraping off its top layer. This would aid navigation thanks to the decreased protrusion of the fixed bed, and would lead to smaller backwater effects, hence reducing the additional downstream incision. This is because smaller backwater effects lead to less sediment trapping upstream of the erosion-control measure and thus a smaller reduction of the sediment flux to the downstream reach.

However, a lower elevation of the fixed-bed surface may be detrimental to the upstream reach. This is because fixed beds mitigate upstream erosion through backwater-related flow deceleration. This effect is generally overlooked. The reduction of the upstream backwater effects given by a lower elevation of the fixed bed surface results in less sediment trapping upstream of the fixed bed, which implies less erosion mitigation over the upstream reach or, depending on the specific conditions, even channel-bed incision. Operations to reduce the fixed-bed surface elevation may need to be repeated over time, if the large-scale channel-bed incision that leads to fixed bed protrusion is expected to continue over the next decades (e.g., Ylla Arbós, Blom, Sloff, & Schielen, 2023; Ylla Arbós, Blom, White, & Schielen, 2023).

The erosion-control measures in the Niederrhein have less unwanted effects than those in the Waal. On the one hand, the former are less prone to protrusion than the latter. A reason for this is the fact that water management authorities have succeeded in mitigating large-scale channel-bed incision in the Niederrhein through a combination of scour-filling measures and sediment nourishments (Frings et al., 2014; Ylla Arbós et al., 2021a). Bed level change in the Niederrhein, however, has been milder than in the Waal since, at least, the 1960s, which is prior to the scour filling and nourishment measures since the late 1980s (Ylla Arbós et al., 2021a). Milder incision rates in the Niederrhein may be associated with the coarser bed surface grain size and sediment flux in the Niederrhein, which may limit incision. On the other hand, erosion-control measures in the Niederrhein consist of more numerous scour-filling measures of smaller magnitude, whose characteristics more closely resemble those of the surrounding channel bed. The coarser sediment of the scour-filling measures is covered with finer sediment similar to the surrounding bed surface sediment. Despite the erosion-control measures in the Waal having different goals than those in the Niederrhein, it may be interesting to consider optimized geometries and materials for the fixed beds in the Waal, as this may help in mitigating their unwanted effects.

We note that there are a series of erosion-control measures over the Rhine River's gravel-sand transition (river km 840–930, Ylla Arbós et al., 2021a). By partially inhibiting sediment exchange with the river bed, erosion-control measures may interfere with gravel-sand transition dynamics. In addition, erosion-control measures may disrupt point bars along the river, thereby affecting the habitat of several species (e.g., Wohl, 2005; Yi et al., 2020). Future research may provide additional insight on such processes.

We have not addressed friction changes in our model runs. Given the use of coarse material or even large boulders, erosion-control measures can be associated with increased roughness, and thus lead to larger flow depths over the fixed bed. This leads to an M2 backwater (drawdown) curve over the measure, and an M1 backwater upstream of it (e.g., Czapiga et al., 2022b). The M1 backwater curve is associated with sediment trapping upstream of the measure, and as such, may enhance the observed incision downstream of the measures. Yet similar to Czapiga et al. (2022b), we note that the reduced sediment mobility is the dominant mechanism in the channel response to these erosion-control measures.

In our numerical simulations, erosion-control measures cover the full cross-section of the main channel (i.e., their effects are schematized in a one-dimensional manner). While some erosion-control measures certainly cover the full cross-section of the main channel, the measures in the Dutch Rhine are installed in river bends and cover approximately half of the main channel width. Our one-dimensional modeling approach (i.e., accounting for variations in the streamwise dimension only) does not allow for considering the effects of helical flow, which plays an important role in river bends. Besides, it cannot capture two-dimensional erosion pit dynamics, such as potential localized deepening due to helical flow (Broekema et al., 2018). Future research should focus on how these two-dimensional effects affect the large-scale channel response to erosion-control measures.

8. Conclusions

Erosion-control measures in the lower Rhine River aim to mitigate channel bed erosion or to increase the navigable width. While they have succeeded in achieving these goals, they show signs of unintended large-scale downstream effects, specifically in the form of downstream-migrating incision waves, which enhance the ongoing channel-bed incision. These waves of additional incision have a celerity of about 1.5 km/a, and are more pronounced for the fixed-bed type of measures, such as the ones at Nijmegen and Sint Andries.

Erosion-control measures trap sediment upstream due to backwater effects, related to protrusion of the measure and their increased roughness. This sediment trapping, combined with the non-erodability of the erosion-control measure, reduces the flux of sediment to the downstream reach, resulting in a downstream-migrating incision wave. The reduction of sediment flux downstream of the measure and the magnitude of the associated downstream incision both scale with the length of the measure. When erosion-control measures are placed close together, their downstream incision waves interfere and amplify.

These results shed light on the often-ignored large-scale effects of erosion-control measures, which are traditionally planned with a local focus. Our findings suggest that while such measures may solve river management issues at local scale, they may worsen channel bed incision over tens of kilometers downstream of them.

Data Availability Statement

Two-dimensional bathymetric data from the period 1999–2020 are available through the 4TU.ResearchData repository (Ylla Arbós, Blom, Sloff, & Schielen, 2023; Ylla Arbós, Blom, White, & Schielen, 2023). We have used the transect extraction functions in https://github.com/shelbyahrendt/transect-functions/tree/main to extract longitudinal and transverse profiles from the two-dimensional bathymetric data. One-dimensional bed elevation data over the period 1980–2020 are accessible at (Ylla Arbós et al., 2021b). Model simulations are performed with the code Elv (Chavarrías et al., 2019), accessible at https://oss.deltares.nl/web/riverlab-models/elv.

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