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Sediment Nourishments to Mitigate Channel Bed Incision in Engineered Rivers

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Abstract: Engineering modifications of rivers, e.g., dams or groynes, often induce long-term riverbed erosion, which can be mitigated with sediment nourishments. Here, we consider nourishments to mitigate channel bed erosion induced by channel narrowing, as opposed to the more common application downstream of dams. Our objective is to assess and quantify how dumping location, grainsize, and volume are important for mitigation efficacy. Our results show that erosion can be mitigated if nourishments change the sediment flux such that the corresponding equilibrium channel slope is increased. This is achieved by coarsening the sediment flux throughout the reach, increasing magnitude of the sediment flux, or both. Flux is coarsened via additions of sediment at or coarser than the bed surface and nourished sediment should be distributed throughout the incising reach. The second option is nourishing a large volume of relatively fine sediment to increase the equilibrium channel slope. Additions of fine sediment in small volumes decrease the equilibrium channel slope and enhance erosion, because the fine sediment flux makes the gravel more mobile. **DOI: 10.1061/(ASCE)HY.1943-7900.0001977.** *© 2022 American Society of Civil Engineers.*

Introduction

Engineered modifications to natural river channels often develop undesired side effects, including riverbed erosion. Dams cut off sediment supply leading to incision (Dietrich et al. 1989; Kondolf 1997; Brandt 2000). Groynes built, for instance, to deepen navigation channels, increase sediment transport capacity (Erskine 1992), and the channel bed slope slowly adjusts to new conditions governed by a lower equilibrium channel slope (Blom et al. 2017a).

Numerous rivers are experiencing channel bed incision in response to channel modification. Notable examples include the Danube River (Habersack et al. 2016), Elbe River (Gabriel et al. 2009), Rhine River (Gölz 1994; Quick et al. 2020; Ylla Arbós et al. 2021), Rhône River (Petit et al. 1996; Arnaud-Fassetta 2003), Loire River (Gasowski 1994), Missouri River (Alexander et al. 2012), and many Italian Rivers, e.g., Po, Arno, and Brenta (Surian and Rinaldi 2003). The lengthy timescales of channel slope adaptation may mask incisional trends in more recently modified rivers. As such, riverbed incision is expected to become an even more pervasive problem in the future.

Channel bed incision can have significant negative consequences. Decreased floodplain inundation reduces wetland areas, shallow-water habitats, and river-floodplain connectivity, which is important for ecology and agriculture (Baxter 1977; Ward and Stanford 1995; Anderson et al. 2018). Foundations of in-channel structures (e.g., groynes, revetments, and bridge piers) can be exposed, increasing the risk of failure. Water intakes may need to be lowered, and tributaries may experience upstream propagating degradation (Galay 1983). Locally, pipelines and other utility crossings can be exposed and heterogeneous erodibility of the river bed sediment may increasingly expose obstructions to navigation (Ylla Arbós et al. 2021).

Adding sediment to an eroding area is a common mitigation method to combat bed erosion. Examples comprise nourishments along beaches to stabilize the coastline (e.g., Dean 2003), on tidal flats in estuaries (e.g., van der Werf et al. 2015), in rivers downstream of dams, (e.g., Kondolf 1997; Bunte 2004), and in narrowed reaches, (e.g., Dröge et al. 1992; Quick et al. 2020; Ylla Arbós et al. 2021). However, no study has detailed the general large-scale effects of sediment nourishments to mitigate channel bed erosion caused by changes in reach-averaged channel geometry or in the hydrologic regime.

Key variables in the design of sediment nourishments include sediment grainsize distribution, applied volume and frequency, and dumping location. We consider that sediment can be nourished in one location (i.e., point source) or many locations (i.e., distributed). The scheme is static when sediment is dumped at the same location, or placement can be adaptive to river bed changes, e.g., by mainly dumping the most sediment where erosion is highest and small quantities where erosion is lowest. The nourishment grainsize distribution relative to that of the bed surface sediment affects how quickly the nourishment disperses. Nourishments can be placed on the bed, raising the local bed elevation (i.e. exposed), or dumped into low-lying areas such as river bends (i.e. entrenched) (Ock et al. 2013). The former may induce deposition via local backwater effects (Elkins et al. 2007), but also reduce flow depth causing possible hindrance to navigation (e.g., Quick et al. 2020).

Our objective is to assess and quantify the combined effects of these engineering decisions regarding nourishment dumping location(s), grain size distribution, and volume on mitigating channel bed erosion. To this end, we assess the fundamentals of nourishment dispersion relative to their exposure into the flow and compare how adding nourishments with different schemes affects the channel response with a one-dimensional (1D) morphodynamic model that accounts for the nonuniformity of sediment grain size.

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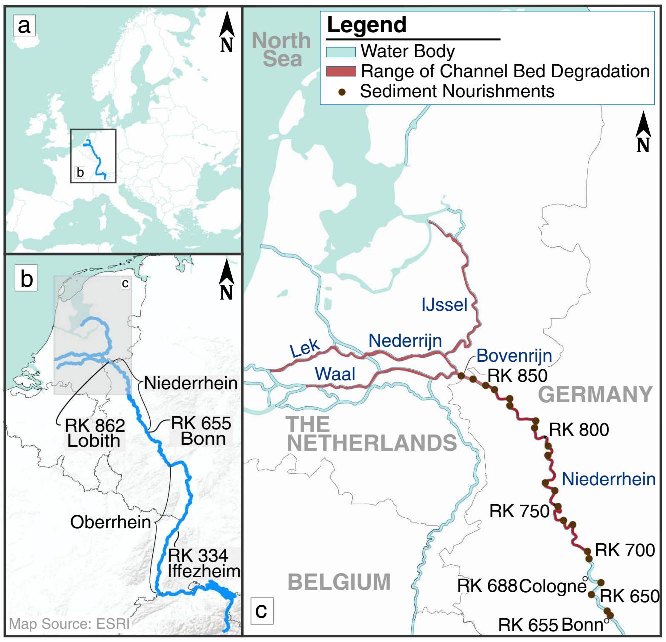

Fig. 1. Widespread erosion and sediment nourishments in the Rhine River: (a) map of Europe showing location of the Rhine River; (b) map of the Rhine River with the locations of two sediment nourishment campaigns (Oberrhein at Iffezheim, Germany, and Niederrhein from Bonn, Germany to Lobith, Netherlands; and (c) the extent of riverbed erosion in the Rhine River downstream of Bonn, Germany, and locations of sediment nourishments from 1985 to 2020 in the Niederrhein [data from Quick et al. (2020)]. (Map source: ESRI.)

We adopt the Rhine River (Fig. 1) as an analogue for this study due to its long history of both widespread erosion and sediment nourishments. Channel modifications in the Rhine date back to the early 19th century (Buck 1993). Sediment nourishments have been used to mitigate erosion throughout the German Rhine since 1978 (Kuhl 1993; Quick et al. 2020): first, downstream of dams in the Oberrhein (Gölz et al. 2006) and later in the narrowed Niederrhein reach (Quick et al. 2020). Input parameters and erosion rates in our 1D model runs are inspired by the Niederrhein (Fig. 1) to provide realistic conditions.

Former field experiments and observations with sediment nourishments in the Rhine River are presented in Section 2. 1D components of the hydraulic and morphodynamic channel response to sediment nourishments are explained in Section 3. After providing an overview of model runs in Section 4, we address how mitigation efficiency of riverbed incision is influenced by nourishment scheme and grainsize distribution (Section 5) and nourishment volume (Section 6).

Field Experiments Regarding Sediment Nourishments in the Rhine River

From upstream to downstream, the modern, undammed section of the Rhine downstream of Iffezheim (RK 334) consists of the Oberrhein, Mittelrhein, and Niederrhein in Germany. The Bovenrijn begins at the Germany–Netherlands border, then bifurcates into several channels in the Rhine delta (Fig. 1). Several changes, including construction of groyne fields, channel straightening, and dredging have caused widespread channel bed erosion in the Niedderhein and Dutch Rhine Delta (Quick et al. 2020; Ylla Arbós et al. 2021).

From 1950 to 1977, a series of barrage dams were constructed in the Oberrhein (Kondolf 1997), reducing the sediment supplied to the downstream reaches. As a result, the channel bed downstream of the last dam at Iffezheim, Germany, started eroding (Kondolf 1997). Coarse sediment nourishments were dumped directly downstream of the dam (Weichert et al. 2010; Kuhl 1993), averaging 0.46 Mt/year, which corresponds to about 45% of the total bed material load previously entering this reach (Frings et al. 2014b). Larger volumes were added in flood years (Gölz 2002). These coarse sediment nourishments slowed erosion at the application site, but enhanced downstream degradation, because the added sediment was less mobile than the original bed material and reduced the sediment supply to the downstream reach; as a result, nourishments were modified to include sand after 1991 (Gölz 1994).

Contrary to the Oberrhein, channel bed incision in the Niederrhein and Bovenrijn has been mainly induced by channel narrowing (e.g., Ylla Arbós et al. 2021). Sediment has been nourished to the entire Niederrhein since 1985 (Ylla Arbós et al. 2021; Quick et al. 2020; Frings et al. 2014a) and has slowed bed erosion. Gravel nourishments supplementing the bedload (sediment size between 4 and 32 mm) amount to 0.1 T/year, and coarse gravel nourishments filling scour holes (sediment size between 8 and 150 mm) amount to 0.33 T/year. Because the total sediment supply to this reach averages 0.5 T/year (Frings et al. 2014a), sediment nourishments represent a major portion of the sediment supply.

One-Dimensional Channel Response to Sediment Nourishments

Four factors characterize the 1D initial response of a mildly sloping channel to a sediment nourishment (Fig. 2): (1) local increase in bed elevation leading to a flow pattern associated with subcritical flow over a sill (i.e., the Bernoulli effect); (2) local increase in bed elevation leading to an M2 drawdown over the nourished reach and M1 backwater upstream of it; (3) locally increased hydraulic roughness (and normal flow depth) due to increased bed surface grain size resulting from coarse sediment nourishment, leading to an M2 drawdown curve over the nourished sediment and an M1 backwater upstream from it; and (4) locally decreased mobility of the bed surface sediment due to increased bed surface grain size.

The initial channel response to nourishments is a combination of these effects, and the relative magnitude determines which effects are dominant. The net channel response, however, is not necessarily the sum of the four effects because they may affect each other. The combined effects are investigated through numerical modeling in the remainder of our analysis. In the subsequent sections, we assess the four effects in more detail.

Effect I

A locally elevated river bed leads to a flow pattern similar to subcritical flow over a sill (i.e., the Bernoulli effect). An increase in the flow velocity over the sill corresponds to an increase in kinetic energy, which is associated with lowering of the water level over the sill [Fig. 2(a)]. The associated initial morphodynamic response is the formation of a pit at the upstream end of the elevated section and a hump at its downstream end. Mild erosion over the upstream part of the elevated section and mild deposition over its downstream part are also expected to occur [Fig. 2(b)]. The upstream pit and mild erosion are associated with bed surface coarsening, whereas the downstream mild deposition and hump are associated with bed surface fining.

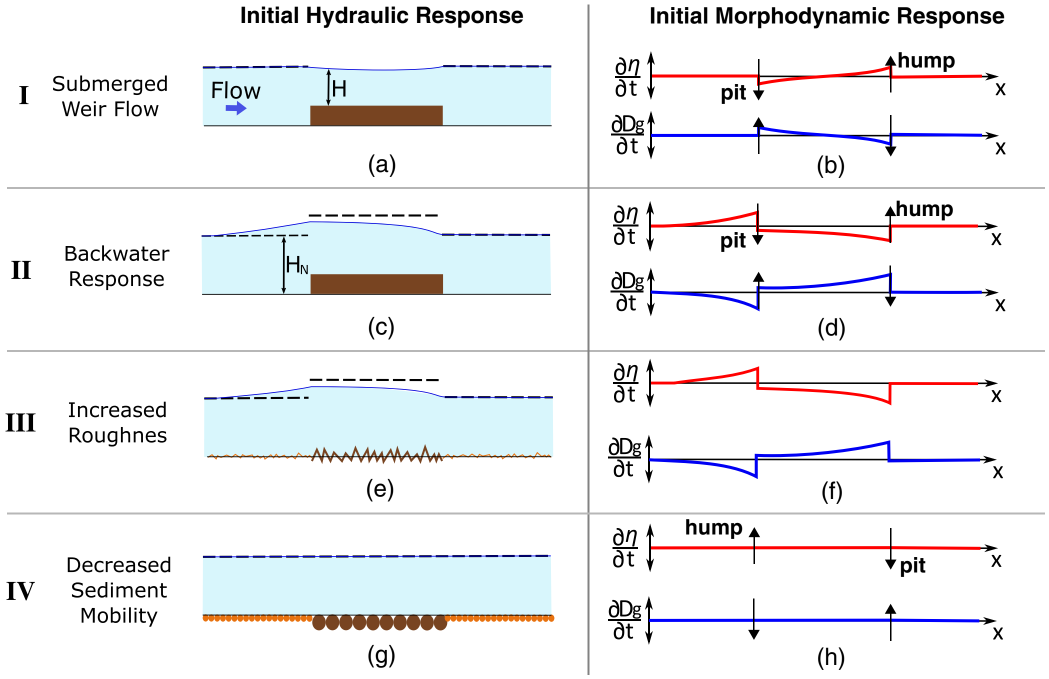

Fig. 2. (a, c, e, g) Short-term channel response regarding hydraulic change; (b, d, f, h) rate of bed level change, and rate of change of the geometric mean grain size of the bed surface sediment to a sediment nourishment. The channel response is subdivided into four relevant factors: (I) local increase in bed elevation resulting in subcritical flow over a sill (a and b); (II) local increase in bed elevation resulting in M1 backwater and M2 drawdown effects (c and d); (III) locally increased hydraulic roughness and normal flow depth due to increased bed surface grain size, and associated M1 backwater and M2 drawdown effects (e and f); and (IV) locally decreased mobility of the bed surface sediment due to increased bed surface grain size (g and h). Dashed lines in the first column indicate the water level that corresponds to the normal flow depth, while solid lines denote the actual water level.

Effect II

A locally elevated reach induces an M2 drawdown curve over the elevated section and an M1 backwater curve upstream of it [Fig. 2(c)]. This flow pattern causes sediment deposition upstream of the elevation section due to the M1 water surface profile, the formation of an erosion pit (and surface coarsening) at the upstream end of the elevated section, erosion of the elevated section increasing in magnitude with streamwise position (with surface coarsening), and shoaling (with surface fining) immediately downstream at the sudden flow expansion [Fig. 2(d)].

Effect III

Supplementing coarse sediment is expected to increase the hydraulic roughness and the normal flow depth, because skin friction scales with a representative coarse sediment fraction of the bed surface sediment (e.g., Parker 1991). This results in an M2 drawdown curve over the elevated reach and an M1 backwater curve upstream of it [Fig. 2(e)] with consequential erosion (and bed surface coarsening) of the elevated reach and deposition upstream of it [Fig. 2(f)].

Effect IV

Supplementing coarse sediment creates changes in sediment mobility at the boundaries of the nourished section. As a result, an erosion pit forms (with surface coarsening) immediately downstream of the nourishment and sediment deposits (with surface fining) at the upstream end of it [Figs. 2(g and h)].

The initial channel response to a sediment nourishment, as illustrated in Fig. 2, is followed by changes in bed level and surface texture that here we refer to as transient response. The transient response is described in Fig. 3 with 1D numerical runs for three types of sediment nourishments: a single exposed nourishment, an entrenched nourishment, and spaced exposed nourishments. Entrenched nourishments are introduced here to represent nourishments that fill a locally incised reach [resembling the ones in the Niederrhein; Frings et al. (2012)].

The runs are made with the 1D research code Elv (Blom et al. 2016, 2017a, b; Chavarrías et al. 2018a, b, 2019; Arkesteijn et al. 2019, 2021) (Appendix S1). It combines the backwater equation (e.g., Parker 2004), a Manning-Strickler roughness closure (Parker 1991), the Hirano equation (Hirano 1971), the regularization strategy proposed by Chavarrías et al. (2019), and a bookkeeping system for storage of stratigraphy (Viparelli et al. 2014). The regularization strategy prevents the model from being ill-posed when degrading into a subsurface that is finer than the bed surface. Simplifications are the following: the sediment consists of three grain size classes (sand, fine gravel, and coarse gravel), the channel is rectangular and the presence of floodplains is not accounted for in the calculation. Flow rate is constant and based on a formative water discharge, and the prenourishment state is an equilibrium state (Blom et al. 2016, 2017a).

The transient response to an exposed nourishment (Fig. 3, column 1) shows some typical features:

1. Downstream translation of the nourished sediment hump forming via Effects I and II, along with associated bed surface coarsening, because the nourished sediment is coarser than the original bed surface material;

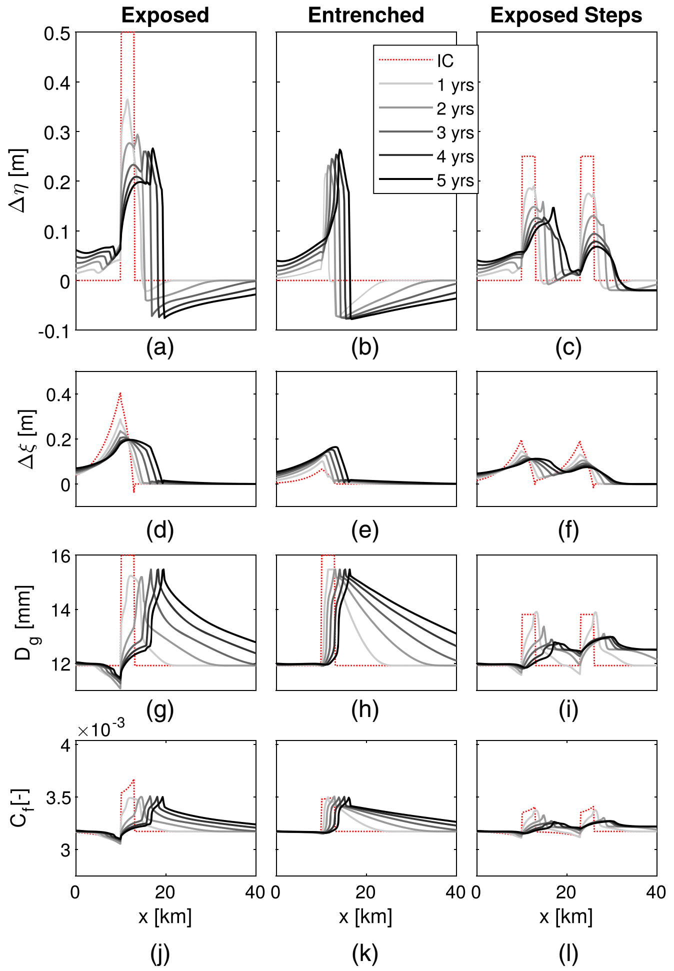

Fig. 3. Channel response to a single exposed nourishment (Column 1; subplots a, d, g, and j), entrenched nourishment (Column 2; subplots b, e, h, and k), or spaced exposed nourishments (Column 3; subplots c, f, i, and l). Nourished sediment is coarser than the bed surface sediment. Row 1 (subplots a–c) shows change in bed elevation relative to the initial state, $\Delta\eta$; Row 2 (d–f) the change in water level relative to the initial condition, $\Delta\xi$; Row 3 (g–i) the change in geometric mean grain size of the bed surface sediment, Dg; and Row 4 (j–l) the dimensionless friction coefficient Cf.

2. Upstream deposition via the backwaters of Effects II and III and associated fining of the bed surface sediment due to preferential deposition of fines;
3. Erosion and dispersion over the nourished reach via the M2 drawdown curve of Effects II and III, which is associated with slight bed surface coarsening;
4. Incision directly downstream of the nourishment, and its downstream translation, via the mobility reduction of Effect IV. These effects migrate faster (order 10 km/year) than the displacement of the nourished sediment (order 1 km/year); and
5. The downstream translation of the deposition at the upstream edge of the nourished sediment via Effect IV, and its downstream translation. This effect is associated with local bed surface fining, and its downstream translation.

The transient response to the entrenched nourishment (Fig. 3, Column 2) is similar to the exposed nourishment (Fig. 3, Column 1), despite the bed's not being initially elevated. This implies that, under current settings, it is Effect IV (and, to a smaller extent, Effect II) that dominates the transient channel response. The sediment wave grows throughout the five-year simulation as upstream sediment continues to deposit at the nourishment site. Sediment deposition at the upstream end of the nourished sediment via Effect IV (and to a smaller extent Effect III) does induce an upstream backwater effect, as illustrated by Effect II (Fig. 2) and associated upstream sediment deposition. Overall, the sediment wave developing from an exposed nourishment is larger, yet the entrenched nourishment captures more of the passing sediment. A secondary difference relates to negligible upstream bed surface fining with the exposed nourishment as the upstream M1 backwaters via Effect II and (initially) Effect III are weaker for the entrenched case.

Channel response to a sequence of exposed nourishments (Fig. 3, Column 3) shows significant differences compared to the single exposed nourishment (Fig. 3, Column 1). For simplicity, the volume of nourished sediment is subdivided between two sections with nourishment thickness equal to one half of the single exposed nourishment. Distributing sediment to two locations means that the bed surface at each nourishment is finer relative to the single exposed nourishment case. Incision immediately downstream of the downstream nourishment is reduced, compared to the single nourishment. Furthermore, incision downstream of the first nourishment is absent due to the M1 backwater and associated sediment trapping subject to the second nourishment.

The schematic runs in Fig. 3 illustrate that, with our current settings, sediment mobility effects (Effect IV) dominate the transient channel response. Effects I and III are less significant. Effect IV by itself (i.e., hump formation at the upstream end of the nourished reach) leads to the backwater effects of Effect II, which explains why channel response to entrenched and exposed nourishments is similar. For this reason, we focus on only exposed nourishments in the remainder of this paper.

Overview of Model Runs

We expand the schematic runs of the previous section to understand the channel response to nourishments with different characteristics. We do so within the context of sediment nourishments used to mitigate channel bed incision due to channel narrowing.

We select the four schemes in Fig. 4 to compare the effects of point source and distributed nourishments with static or dynamic implementations. A schematic explaining how nourishments are applied is included in Appendix S2 (Fig. S1).

The *upstream scheme* places nourishments at the upstream end of the considered domain, similar to typical measures applied downstream of dams (e.g., Kondolf 1997; Bunte 2004). The *spaced deposit scheme* distributes sediment throughout the reach with equal nourishment height, length, and spacing. Similar distributive approaches have been applied in the Niederrhein (Quick et al. 2020) and the Elbe (Gabriel et al. 2009). The *steepest slope scheme* dumps sediment immediately downstream of the location with the steepest slope, intending to fill erosion pits related to the reduced sediment mobility of Effect IV (Fig. 2). The *reference profile scheme* dumps sediment where elevation falls below a selected reference bed level profile. The total nourishment volume is divided relative to the difference between the current and reference elevation, which implies that more sediment is added to regions further below the reference profile; this scheme has also been tested numerically for application to the Dutch Bovenrijn (Ottevanger et al. 2015).

We use the same 1D numerical research code as in the previous section. The length of the model domain is 160 km. It consists of a 100-km study reach where nourishments are applied, a 50-km downstream buffer reach that reduces or eliminates backwater

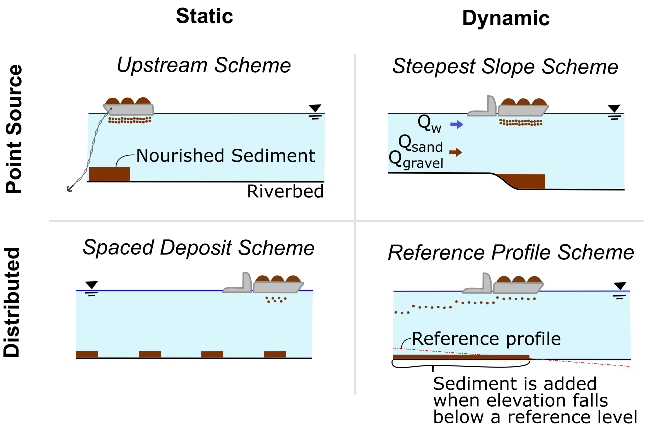

Fig. 4. Four nourishment schemes are adopted to test their mitigation efficacy. Each scheme is characterized by its application domain (point source versus distributed) and consistency (static versus dynamic). The upstream scheme (static, point source) dumps sediment at the upstream end of the affected domain, the steepest slope scheme (dynamic, point source) places sediment downstream of the location with the steepest slope within the domain, the spaced deposit scheme (static, distributed) places sediment at various locations within the domain, and the reference profile scheme (dynamic, distributed) places sediment wherever the bed falls below a reference profile.

effects from the basin, and a 10-km upstream buffer reach to account for upstream backwater effects of nourishments placed at the beginning of the study reach. Narrowing is applied to the entire 160-km domain.

Sediment is discretized into three grainsize classes: $D_1 = 1.5$ mm, $D_2 = 6$ mm, and $D_3 = 16$ mm. The dimensionless friction factor $C_f = 0.015(H/k_s)^{-1/3}$ is computed as in Parker (1991), where roughness height is related to the geometric mean grainsize of the bed surface sediment (D_g) as $k_s = 3D_g$. Form drag is neglected.

Sediment flux equals 0.3 t/year, and the representative water discharge is set to 3,000 $\mathrm{m}^3\ \mathrm{s}^{-1}$. Volume fraction contents of the three grainsize classes in the sediment supply are 0.66, 0.17, and 0.17, respectively. These values are loosely based on measured data in the Niederrhein (Frings et al. 2014a).

An initial equilibrium condition is assumed (Blom et al. 2016, 2017a) with a prenarrowed channel width equal to 400 m. The Ashida-Michiue sediment transport relation (Ashida and Michiue 1972; Wong and Parker 2006) is used to compute the bed load transport capacity (sensitivity to the sediment transport relation is included in Appendix S6). This result sets the initial channel slope equal to $2.9 \cdot 10^{-4}$, and the volume fraction contents of the three grainsize classes in the bed surface sediment (F_{1-3}) to 0.11, 0.03, and 0.86. The difference in grain size distribution between the sediment supply and the bed surface sediment indicates that conditions of grainsize-selective transport are prevailing (i.e., the bed surface is coarser than the sediment supply to provide sufficient transport capacity of the coarse grain size fraction).

The subsurface composition is finer than the bed surface and coarser than the sediment supply. The volume fraction contents of the three grainsize classes in the subsurface are set to 0.25, 0.25, and 0.50, respectively. This composition was selected because it reproduced long-term degradation rates similar to those seen in the Niederrhein around 2 cm/year (Quick et al. 2020).

Numerical parameters include the active layer thickness (0.5 m) (sensitivity analysis in Appendix S7), spatial step (1 km), time step (1 day), and Hoey-Ferguson (Hoey and Ferguson 1994) coefficient (0.3), indicating that the grainsize distribution of sediment transferred to the subsurface during aggradation is composed of 70% bed load sediment and 30% active layer sediment (Toro-Escobar et al. 1996), which moves finer sediments below the surface.

Degradation is imposed by narrowing the channel by 40% from 400 m to 280 m. Decreasing channel width reduces the equilibrium channel slope and yields a finer equilibrium bed surface sediment (Blom et al. 2016, 2017a). This is because a narrow channel has higher transport capacity than a wide channel at the same slope. Therefore, a small channel slope suffices to transport the same sediment supply in a narrow channel.

In response to channel narrowing, a downstream migrating degradational wave forms and rapidly causes erosion in the entire model domain, with erosion rates decreasing over time. Sediment nourishments are applied over a 30-year period in which the erosion rate ranges from 1.5–3 cm/year with average rate of 2 cm/year. Bed elevation and composition at the beginning of this period is the initial condition for all model runs. Due to differential erosion prior to the nourishments, bed slope varies in the reach. In particular, the upper subreach has a milder slope than the downstream subreach because more erosion occurred in the upstream portion of the model reach. Further details for initial conditions of nourishment model runs are included in Appendix S3 (Fig. S2).

Sediment is nourished at 1-year intervals as 2-km-long exposed nourishments that instantaneously raise the local bed elevation. Nourishment length with the reference profile scheme varies up to the entire length of the study domain, depending on how much of the reach falls below the reference profile set by the bed level immediately prior to the first nourishment. Nourishments are spaced by 10 km in the spaced deposit scheme. The nourishment rate $Q_N = 0.30$ t/year corresponds to 100% of the upstream sediment feed $Q_{b,f}$. Nourished sediment composition varies from a distribution matching the sediment feed (finest) to 100% of the coarsest grainsize in the model (coarsest).

Effects of Nourishment Scheme and Composition on Mitigation Efficiency

In this section, we analyze the effect of the four nourishment schemes of Fig. 4 and nourishment grainsize distribution on mitigation efficiency. Elevation change $\Delta\eta$ is referenced to the bed level at the beginning of the 30-year period. Erosion is (partly) mitigated when the channel bed erodes less than in the base case, and the magnitude of mitigation is defined as the difference in bed elevation between the simulation with sediment nourishments and the base case (no nourishment) results. Here, nourished sediment consists of the coarse gravel only.

No nourishment scheme is able to completely stop degradation within the considered 30 years (Fig. 5), but all schemes reduce channel bed erosion. When coarse gravel is applied via the upstream scheme, sediment mobility is reduced in the nourished reach (Effect IV in Fig. 2), thus reducing sediment supply downstream and enhancing degradation in the downstream reach.

Distributed nourishment schemes evenly coarsen the sediment flux and mitigate erosion throughout the entire reach. By distributing coarse sediment over the study reach, the downstream degradation pits resulting from locally reduced sediment supply (Fig. 2, Effect IV) do not develop, which confirms the results for distributed nourishments in Fig. 3. The analysis also agrees with past studies in which distributed gravel injections into the sediment load were superior to nourishing at a single location in the Niederrhein (Schwerdtfeger 2004; Sloff and Sieben 2008) and with

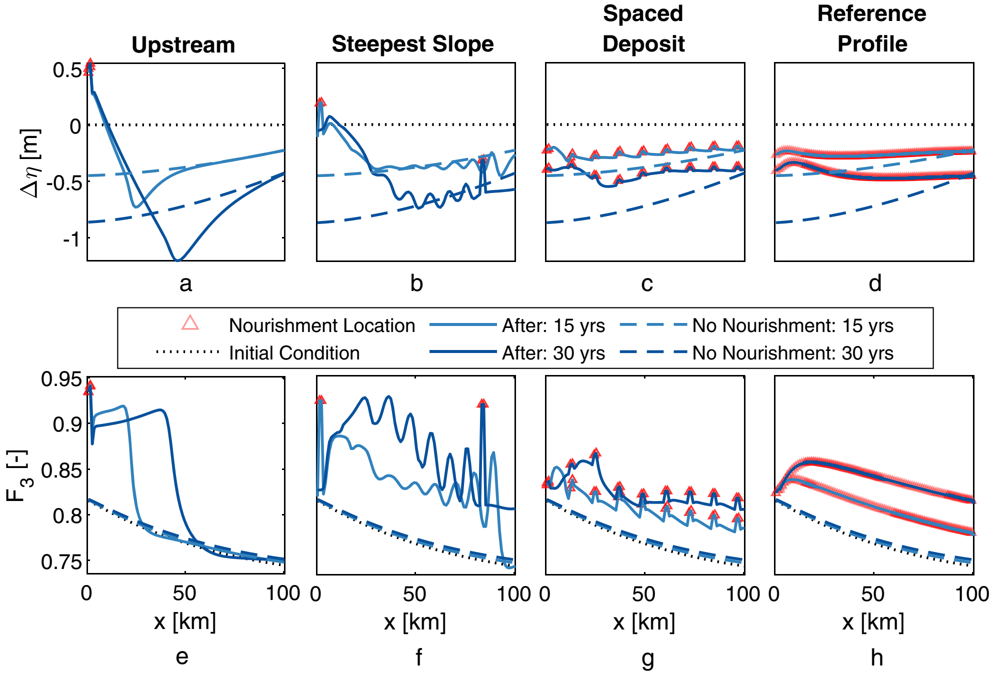

Fig. 5. Mitigation effectiveness for four sediment nourishment schemes (Fig. 4); nourishments (solid lines) against the base case where no nourishments are added (dashed lines), after 15 and 30 years of model runs. The initial condition is drawn as a dotted line and the triangles denote the nourishment location at each time horizon. Subplots (a–d) show the temporal change in bed elevation relative to the initial bed elevation, $\Delta\eta$, and subplots (e–h) the volume fraction content of the coarse grainsize class in the bed surface sediment, F_3. Nourished sediment consists of the coarse (16 mm) grain size only at $Q_N = 0.30$ t/year, doubling the sediment supply rate to the domain.

respect to the reference profile scheme in the Dutch Rhine Delta (Ottevanger et al. 2015).

In the steepest slope scheme [Figs. 5(b and f)] a series of coarse sediment waves develop throughout the domain, but mitigation remains limited to the upstream end of the domain despite strong bed surface coarsening. Results of spaced deposit and reference profile schemes are similar, implying that adapting the nourishment dispersal in distributed schemes is not an important factor under the considered conditions.

Next, we consider five different grainsize distributions of the nourishment mixture to assess the effect on mitigation efficiency. The added sediment in Fig. 6 descends from coarsest (first row) to finest (bottom row): (1) coarse gravel (16 mm) (same as Fig. 5); (2) bed surface sediment prior to nourishment; (3) equal portions of fine gravel (6 mm) and coarse gravel (16 mm); (4) equal portions of sand (1.5 mm) and coarse gravel (16 mm); and (5) the same grainsize distribution as the sediment feed. In Fig. 6, all nourishments are at or coarser than the feed, but only the 100% coarse gravel nourishment (first row) is coarser than the bed surface. We consider the equilibrium bed surface sediment distribution as a reference value, such that *coarse* nourishments as coarser and *fine* nourishments as finer than the bed surface sediment.

Point source schemes with mixtures at or finer than the average bed surface sediment eliminate the downstream scouring present with nourishments coarser than the bed surface in Fig. 6(a). When sediment matching the bed surface composition is added, all nourishment schemes improve against the base case [Figs. 6(d–f)], but point source schemes mitigate erosion over the upstream segment only, while distributed schemes mitigate erosion across the entire reach.

Results of distributed schemes worsen as fine sediments are added to the mixture, matching field observations of nourishments in the Elbe River (Gabriel et al. 2009) and modeling applied to the Niederrhein (Alexy 2018). Mixtures finer than the bed surface sediment cause more erosion than the base case [Figs. 6(j–o)]. This is because sand is not only relatively more mobile than gravel, but it also enhances the mobility of gravel due to its increased exposure when surrounded by sand (Iseya and Ikeda 1987; Jackson and Beschta 1984; Ferguson et al. 1989; Montgomery 1999; Wilcock and Crowe 2003; Venditti et al. 2010a, b; Hill et al. 2017; Miwa and Parker 2017; An et al. 2019). The increased gravel mobility caused by the addition of a limited volume of fine sediment further reduces the equilibrium slope, and thus enhances rather than mitigates erosion. The reference profile scheme [Figs. 6(l and o)] causes the most erosion here due to a negative feedback loop between the scheme and sand content of the nourishment. This scheme delivers more sand to a location as it erodes, which increases the degradation rate.

In other words, under our current settings, distributed schemes are useful for coarse nourishments only, because the schemes distribute the sediment too strongly and the volume of added sediment is not large enough for fine additions to enhance the equilibrium slope and be useful.

Several factors are relaxed and described in the Supplemental Materials, e.g., mitigation efficiency is not affected by degradation rate (Appendix S5, Fig. S4).

Necessary Nourishment Volume to Mitigate Erosion

Our results indicate that a large volume of fine sediment is required to mitigate erosion in an eroding reach. This requires further examination. To this end, we compare the combined effects of nourishment grainsize distribution, rate Q_N and scheme on the quantity of erosion mitigated at two representative locations for the upstream half ($x = 25$ km) and the downstream half ($x = 75$ km)

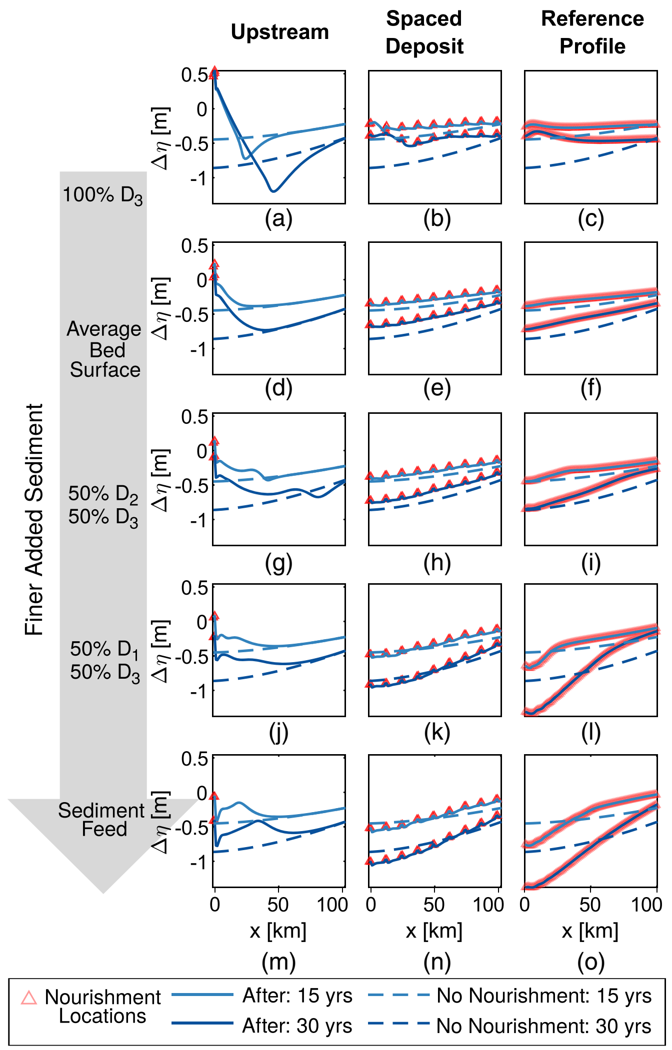

Fig. 6. Mitigation effectiveness for nourishments with sediment characterized by five grainsize distributions; nourishments (solid lines) against the base case in which no nourishments are added (dashed lines), after 15 and 30 years of model runs. Each row represents a grainsize distribution of nourished sediment (from coarsest to finest): (1) the coarse gravel (16 mm) (same as Fig. 5) (subplots a–c); (2) the bed surface prior to nourishment (d–f); (3) equal portions of fine gravel (6 mm) and coarse gravel (16 mm) (g–i); (4) equal portions of sand (1.5 mm) and coarse gravel (16 mm) (j–l); and (5) the same grainsize distribution as the sediment feed (m–o). Results are compared across three nourishment schemes: the upstream scheme, the spaced deposit scheme, and the reference profile scheme in Fig. 4.

of the 100-km study domain (Fig. 7). The upstream (point source) and spaced deposit (distributed) schemes are used here. We consider a nourishment rate $Q_N = \alpha Q_{b,f}$, where α ranges from 1 (as used in previous figures) to 3. The five grainsize distributions used in Fig. 6 are ordered by the geometric mean size of the nourished sediment and normalized by the bed surface sediment $D_{g,N}/D_{g,surf}$. The magnitude of mitigated erosion (shown on the vertical axis of Fig. 7) is the difference between the bed level after 30 years of sediment nourishments and the base case.

The trends illustrated in Fig. 6 are exacerbated by increased sediment nourishment rate (Fig. 7). The upstream point source scheme mitigates more erosion in the upstream subreach [$x =$ 25 km; Fig. 7(a)] as the nourishment rate increases. Mitigation effectiveness does not depend on grainsize here, as illustrated by the flat slope of each line.

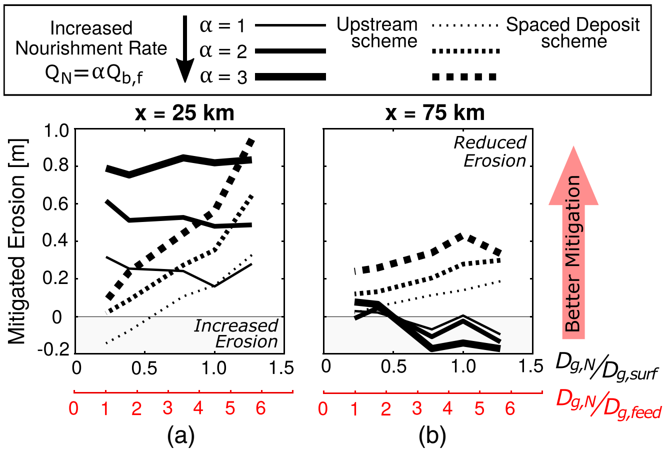

Fig. 7. Mitigated erosion (i.e., the difference in bed elevation between nourishment runs and the no-nourishment base case) after 30 years at: (a) $x = 25$ km; and (b) $x = 75$ km. Upstream point source nourishments (solid) and distributed spaced deposit nourishments (dashed). Line thickness increases with increased nourishment rate. Values below zero mean the nourishment increases erosion relative to the base case. Two x-axes are drawn where the geometric-mean grainsize of the nourishment is normalized by the surface sediment (top) and the feed sediment (bottom).

The upstream scheme is ineffective in the downstream section [$x = 75$ km; Fig. 7(b)] regardless of the nourishment rate. Fine nourishments at or near the composition of the sediment feed mitigate some erosion, but increasing the nourishment rate does not improve mitigation. Coarse nourishments increase erosion relative to the base case, worsening with increased α. The three coarsest nourishment distributions increase erosion here for $\alpha = 3$, including a distribution finer than the bed surface.

Distributed schemes are more reliant on grainsize, which is magnified as nourishment volume is increased. When using the coarsest sediment, 80 cm of erosion is mitigated when increasing α from 1 to 3 [Fig. 7(a)]. The finest distributed nourishment increases erosion compared to the base case [also shown in Fig. 6(n)], because applied volume is insufficient to increase the equilibrium slope.

The distributed scheme is less effective in the downstream half of study domain and less dependent on grainsize [Fig. 7(b); $x = 75$ km] relative to the upstream half, but it still reduces erosion. Degradation rates are lower at this location because the rate decreases downstream (Appendix S3, Fig. S2).

Discussion

Dam construction can lead to overcoarsening of the downstream armored bed surface, which reduces the ecological health of the river system, because fish species such as salmon require fine gravel patches as spawning grounds (Kondolf 2000). Nourishments at dams have aimed to improve the in-channel habitat for various fish species (Kondolf 1997). Distributed coarse nourishments are designed to coarsen the sediment flux and bed surface and, therefore, may similarly reduce ecological health. Nourishment design may be modified to increase spatial variability of the bed surface sediment via strategic placement of nourishments (Battisacco et al. 2016). Furthermore, floodplain ecology suffers from continued channel bed incision, because it increasingly disconnects the channel from its floodplain. Mitigation through nourishments that raise the riverbed likely improves floodplain ecology. Still, river management shall include ecological experts to improve nourishment design from an ecological perspective.

Our results focus on the fundamental 1D physics of sediment nourishments, because these factors are most important for reach-scale design decisions. Two-dimensional physics also have implications for nourishment design. Sediment can be added to the channel bottom, along the bank, in a deep outer bend, or on a point bar (Ock et al. 2013). Such placement within the channel cross-section and channel curvature likely plays a role in the pattern and rate of translation or dispersion of the nourished sediment. Nourishments placed along outer banks, for instance, are more mobile than sediments on a point bar due to increased shear stresses (Miwa and Parker 2012; Chardon et al. 2018). Channel curvature and associated secondary flow affect the distribution of shear stress along the bed and induce bend sorting (Baar et al. 2020). These features are expected to affect the longitudinal and lateral dispersion of nourished sediment. Specific applications will require more detailed [for instance, two-dimensional (2D)] modeling efforts.

Our study limits analysis to a representative water discharge, and typical effects of peak flows and discharge variability are not considered. In field studies, dispersion of the nourished sediment dominates over translation and can be enhanced during flood events (Arnaud et al. 2017), and, thus, exacerbated for deposits placed in locations only mobile at peak flows (Ock et al. 2013). As dispersion increases, point source nourishments of fine sediments will resemble distributed schemes that we show are ineffective. Varying water discharge increases nourishment diffusion during lower flows, which lessens the mobility gradient (Effect IV) and reduces typical scouring patterns downstream of coarse nourishments.

Despite theses limitations, our results concerning the efficacy of coarse, distributed nourishments agree with results in the field applications at the Elbe River (Gabriel et al. 2009) and in the Niederrhein Quick et al. (2020), along with past modeling results applied in different site-specific conditions (Schwerdtfeger 2004; Ottevanger et al. 2015). The specific details of the distribution scheme do not affect mitigation efficiency. River managers therefore have flexibility during design in regard to longitudinal placement. Conversely, efficacy of nourishments finer than the bed surface sediment lack a field comparison, and our results indicate that there is a threshold volume required to be mitigate (rather than enhance) erosion. This scheme thus requires future consideration to be verified with laboratory or field experiments.

River managers should select a nourishment scheme and sediment type based on available supply of sediments and an understanding of how the scheme effectively mitigates channel bed erosion. Once a scheme is selected, it must be continued to maintain the mitigation effects. River managers must therefore ensure that sediment sourcing is feasible for the duration of the project.

Conclusions

Sediment nourishments mitigate widespread erosion due to, for example, channel narrowing, provided that they change the sediment flux to increase the equilibrium channel slope. The latter can be achieved in three ways: (1) by coarsening the sediment flux, (2) by increasing the magnitude of the sediment flux, or (3) both. The first option is achieved through distributed addition of sediment with a grainsize distribution similar to or coarser than the bed surface sediment. The distributed aspect is required to avoid a reduced sediment supply and associated enhanced erosion downstream of the nourished and coarsened reach. The second option is achieved through significant-volume addition of sediment.

When using point source fine nourishments, the volume should be sufficiently large to increase the equilibrium channel slope and mitigate channel bed erosion. This is because addition of fine sediment in a relatively small volume enhances (rather than mitigates) channel bed erosion, because it fines the sediment flux and the added sand makes the coarse sediment more mobile. As such, addition of fine sediment in a relatively small volume (such as in a distributed scheme) decreases the equilibrium channel slope and enhances erosion. This pattern is disrupted by increasing the nourishment rate.

When using coarse distributed nourishments, the channel response to entrenched or exposed nourishments is similar, which implies that the effect of the locally reduced sediment mobility is dominant in the channel response to coarse nourishments. Entrenched nourishments tend to trap more upstream sediments than exposed nourishments. Mitigation efficiency depends on the relative difference in grainsize distribution between the bed surface sediment and the nourished sediment. The coarser the added sediment, the more the bed coarsens, the larger the reduction in sediment transport capacity and erosion, the more effective the trapping of feed sediment, the higher the mitigation efficiency per volume of added sediment. At the same time, further increase of grain size of nourished sediment tends to cause downstream-propagating erosion pits between nourishments.

Future studies shall further investigate 2D effects (e.g., lateral variation in shear stress, secondary flow) on nourishment placement within the channel cross section, influence of the substrate composition on mitigation effectiveness, and best practices for defining the grainsize distribution of the nourished sediment.

Data Availability Statement

All data, models, and code generated or used during the study appear in the submitted article. The Elv model code is available at: https://sites.google.com/view/czapiga-et-al-2021-jhe. All data for this paper are cited and referred to in the reference list.

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Supplemental Materials

Appendixes S1–S8 and Figs. S1–S10 are available online in the ASCE Library (www.ascelibrary.org).

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