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Efficacy of Longitudinal Training Walls to Mitigate Riverbed Erosion

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Key Points:

- Longitudinal training walls reduce erosion by removing water from the primary channel
- High flows trap sediment within the primary channel and inter-flood periods distribute the sediment, with a net-effect of bed aggradation
- Erosion mitigation increases by increasing auxiliary channel area and reducing entrance weir area

Supporting Information:

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

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Abstract

The Waal Branch of the Rhine River has eroded over the last 150 years following channel straightening and narrowing. In 2014–2015 a pilot project replaced existing groynes over an 11 km long reach with three longitudinal training walls (LTWs) to mitigate channel bed erosion, among other purposes. Walls are lower than the river bank and split the flow between a primary and an auxiliary channel, which are hydraulically connected during floods. Water enters the auxiliary channel at three elevations (from bottom to top): via an entrance weir, through inter-wall notches, and over the wall. Bathymetry and discharge data were collected for 5 years after construction, which is a first indication that longitudinal dams can help mitigate channel bed erosion and analyzed to understand how the walls partition water and sediment and whether erosion is mitigated by LTWs. As the river discharge increases, a larger fraction of flow is diverted from the primary channel into the auxiliary channel. After a flood, sediment is deposited in the primary channel near the upstream end of each wall and localized scour occurs where the auxiliary channel rejoins the primary channel. Between floods, the accumulated sediment disperses and scour pits tend to fill. We observe a net-accumulation of sediment in the study domain 5 years after construction. Erosion is best mitigated when weir flow is minimized to keep bed material in the primary channel, but weir flow remains important at lower flows for ecological purposes.

1. Introduction

Natural rivers are becoming rare as large engineering projects are applied to, for instance, to improve navigation, commerce, water extraction, and to reduce flood risk. Grill et al. (2019) report that only a third of the largest rivers on earth are still free-flowing along their entire reach today. Many others are heavily modified with, for example, groynes, for example, Rhine River (Le et al., 2020), or bank revetments for example, Mississippi River (Biedenharn et al., 2000). Engineering practices may develop unforeseen side effects, which may become evident immediately or over the course of decades and centuries.

One common effect of engineered rivers is long-term channel bed erosion (Simon, 1989). An increase in sediment transport capacity due to, for instance, changes to planform shape or hydrology, initiates erosion as the river tends toward a milder equilibrium slope (Blom et al., 2016, 2017). Long-term erosion has been observed in many large rivers after groyne construction, including the Danube River (Habersack et al., 2016), Loire River (Gasowski, 1994), Mississippi River (Biedenharn et al., 2000; Kesel, 2003), Missouri River (Alexander et al., 2012), Rhine River (Quick et al., 2020; Ylla Arbós et al., 2021), and Rhone River (Petit et al., 1996). This erosional trend causes economic damage if left unmitigated, as it may, for example, negatively affect navigation due to non-erodible reaches increasingly sticking out, as well as ecological damage associated with an increased main channel-floodplain disconnection.

Longitudinal walls separate the river into a primary and an auxiliary channel and typically have an entrance weir, inter-wall notches, and an exit outlet (Havinga et al., 2009) (Figure 1a). Sediment transport capacity of the river is reduced by water discharge reduction within the main channel, which increases the equilibrium slope and mitigates erosion.

The use of in-channel longitudinal walls dates back to, at least, the 18th century in the Loire River (Grivel et al., 2018) and are sometimes called: *langsdammen* (in Dutch), longitudinal dams (Collas et al., 2018; Eerden et al., 2011), *duits* (in French) (Grivel et al., 2018; Paalvast, 1995), longitudinal dikes, or off-bankline revetments (Pokrefke, 2013). In many applications (e.g., the Loire and Oberrhein rivers), longitudinal walls seek to normalize the channel or to align the flow for navigation (Paalvast, 1995). In such situations, walls narrow and confine

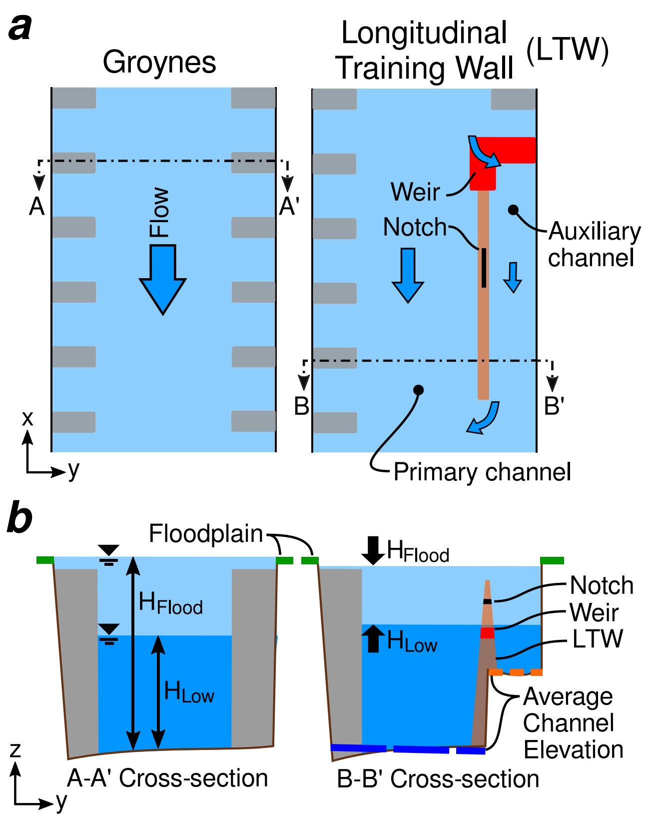

Figure 1. Differences between engineered channels with groynes and longitudinal training walls in: (a) plan view, (b) cross-section view. The longitudinal wall partitions water and sediment between primary and auxiliary channels and tends to increase low-flow depth and decrease peak-flow depth. Water can enter the auxiliary channel through entrance weirs, in-wall notches, and via overtopping the wall.

the flow to increase flow depth. In other applications, walls are built in the littoral zone to provide shelter for fish and other biota (Pokrefke, 2013). In general, fish density increases in more sheltered areas, which in part depends on wall height (Collas et al., 2018).

Longitudinal training walls were constructed as a pilot project in the Waal branch of the Rhine River, Netherlands in 2014 (Le et al., 2020) to (a) reduce water levels during floods (through increasing flow width during floods); (b) increase water levels during base flows (through decreasing flow width); (c) enhance habitat conditions for ecological development; and (d) reduce a century-long trend in riverbed erosion after wide-spread groyne construction (Figure 1b).

Past research looked into the morphodynamics of longitudinal training walls (LTWs) via laboratory experiments, numerical studies, and local field measurements. Entrance weir shape in laboratory experiments altered deposition patterns in the auxiliary channel, yet weir area did not affect flow partitioning during floods when the wall was over-topped (De Ruijsscher et al., 2019). Further analysis focused on one entrance weir at the Waal River study site (De Ruijsscher et al., 2020). Detailed velocity measurements suggested that suspended sediment was conveyed over the entrance weir, but coarse bed load transport was reduced.

LTW entrance location in the river planform was found to play a role in bifurcation stability in generalized laboratory and numerical experiments (Le, Crosato, & Uijttewaal, 2018; Le et al., 2020). Walls placed at the bend apex or the curvature crossover tended to cause rapid channel closure as one channel fills in with sediment.

Our objective is to understand the primary controls on water and sediment partitioning between the primary channel and auxiliary channel by assessing measurements of hydraulics and morphodynamic change. We assess whether LTWs can be effective at reducing riverbed erosion in the primary channel. The analysis of field data collected on the Waal branch of the Rhine River allows us to compare bed level dynamics before, during, and after construction. These measurements are compared with channel bed elevation along the entire Waal branch since 1926. We incorporate discharge measurements in primary and auxiliary channels during different discharge events to evaluate the relationship between flow partitioning and river discharge.

This paper is organized as follows: we describe the study site and the measurements (Section 2), analyze data to assess LTW performance and its effects on bed level in the primary channel (Section 3), discuss the role of temporal water discharge variation regarding this bed level change (Section 4), and how water and sediment are partitioned by entrance weirs, notches, and walls in LTW systems (Section 5).

2. Field Site and Data Collection

The Waal branch of the Rhine River has been engineered for centuries to ensure flood safety, allow for the safe passage of ships, and to reduce spring ice jams (Le et al., 2020; Ylla Arbós et al., 2021). The channel width was estimated to be 400 m prior to human intervention (Maas et al., 1997) and was progressively narrowed by groynes since 1850 to the modern width of 260 m (Le et al., 2020), initiating a long-term trend in riverbed erosion (Ylla Arbós et al., 2021). Prior to the LTW project, groynes were present on both banks throughout the entire reach from the Pannerden bifurcation at Rhine Kilometer (RK) 867 to the Boven Merwede at Gorinchem, Netherlands (RK 955). In 2014–2015, LTWs were constructed over an 11-km long reach (RK 911–RK 922) with two river bends located in the middle reach of the Waal (Midden-Waal), 40 km downstream from the Pannerden bifurcation (Figures 2a and 2b). The pilot project was thoroughly monitored with periodic surveys of bathymetry, velocity, discharge and sediment size distribution after construction.

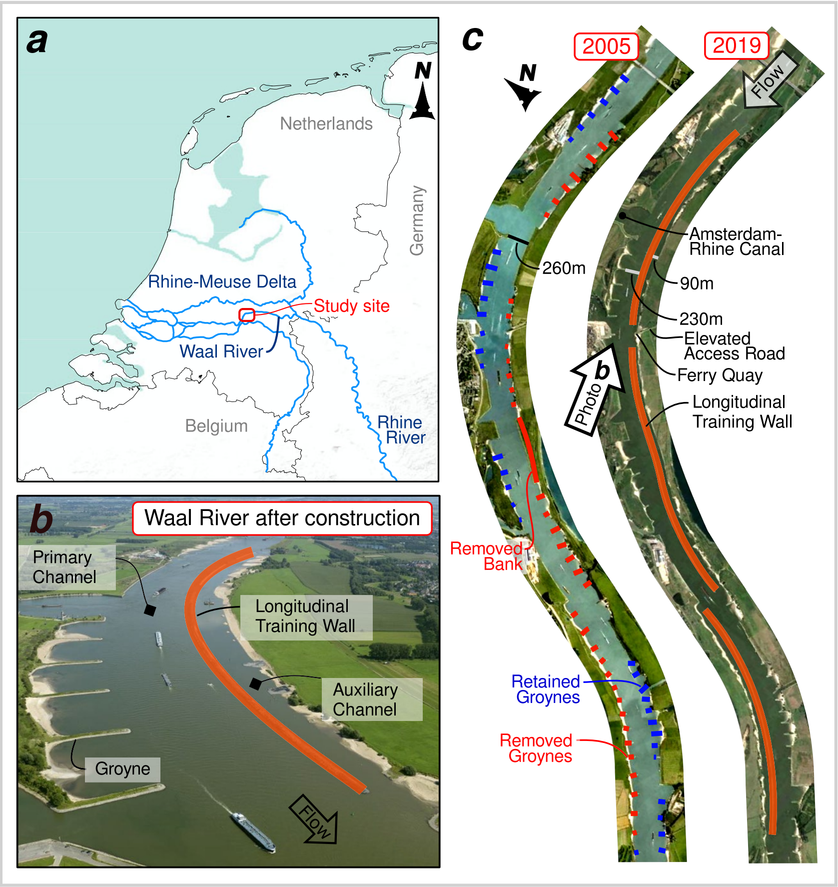

Figure 2. (a) A longitudinal training wall (LTW) pilot project in the Waal River near Tiel, Netherlands was constructed in 2014. (b) Photo, looking upstream at the first LTW (photo by Radboud University (2017); location and orientation is noted in c). (c) The channel was previously controlled by groynes (before 2014, left; from GoogleEarth). Some groynes were replaced with LTWs (After 2015, right). Channel width decreases from 260 m (with groynes) to 230 m (with LTW), but total width across primary and auxiliary channels increases to 320 m (c, right).

Each LTW was designed to include a fixed-elevation entrance weir, an exit outlet, and inter-wall notches (secondary weirs) along the wall. The wall crest was constructed below bankfull water level (Figure 1b). This design allows three pathways for water exchange at different elevations from the river bottom, which include: over-weir, over-notch, and over-wall flows. Low flows are conveyed to the auxiliary channel via over-weir flow, medium discharges additionally pass via over-notch flow, and all three pathways are available during floods. The lateral exchange of water along the longitudinal wall distinguishes LTW from typical side channels constructed in the floodplain (e.g., van Denderen et al., 2018).

Figure 3a shows the study domain, and highlights the location of channels, walls, entrance weirs, and discharge measurements. Groynes attached to the inside bank were removed for LTW construction (Figure 2c), while groynes remained on the outer bank. Walls were back-filled with sand and covered with a layer of immobile boulders. Bed sediment was removed by the contractor and used as backfill in the walls or exported off-site.

Walls narrow the primary channel to 230 m, from the groyne-controlled width of 260 m. Each wall separates the primary channel P from auxiliary channels A_1, A_2, and A_3 (Figure 3). Channels A_1 and A_2 are adjacent to the left bank (looking downstream) and A_3 is adjacent to the right bank. A curvature inflection point lies between A_2 and A_3. Since transverse groynes obstruct the flow, total flow width summed across both channels increased from 260 to 320 m.

Weir and wall elevations were referenced to an agreed low water level profile associated with safe navigation (*Overeengekomen Lage Rivierstand*, (OLR), or "Agreed Low River Level"; Koedijk et al. (2017)). OLR water

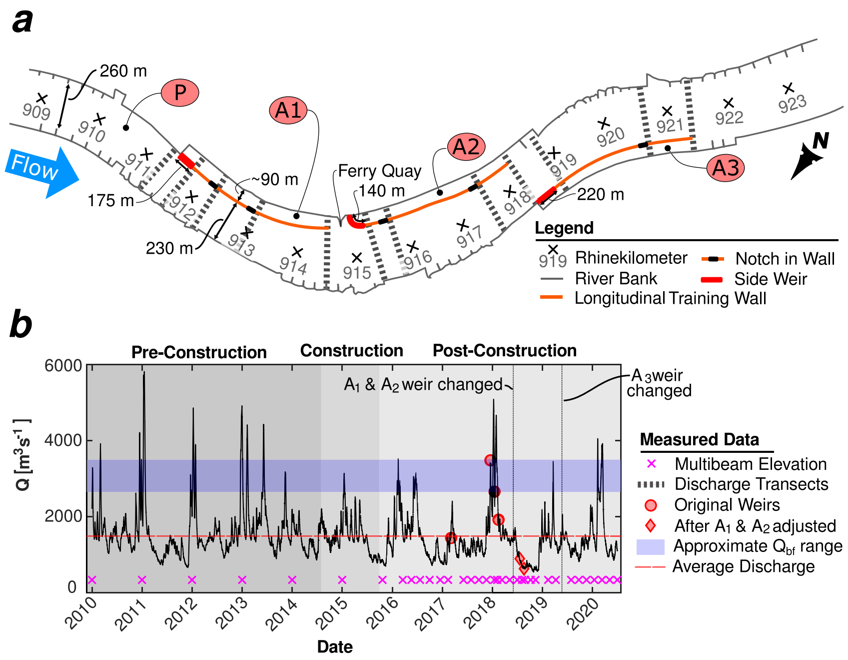

Figure 3. (a) Three longitudinal walls were constructed at the study site over an 11-km reach. Walls separate primary channel P from auxiliary channels A_1, A_2, and A_3. Walls (orange) contain an entrance weir (red) and one or more in-wall notches (black). Bed elevation is measured via multibeam echosounder survey. Transects of water discharge (dashed black lines) are collected from all four channels. (b) Discharge measurements from the Tiel gage, between Rhine kilometer 914 and 915 are plotted with the time of each measurement used in the study. The periods for pre-construction, construction, and post-construction are highlighted with different shades of gray.

level is a government mandated elevation that maintains 2.8 m of flow depth in the navigation channel at Waal River discharge of 700 m^3/s. Wall crest elevation was constructed to decrease downstream, from OLR + 2.78 m adjacent to the A_1 weir to OLR + 2.35 m at the end of the third wall (Sieben, 2020). As such, auxiliary channel A_3 is expected to be inundated more frequently than A_1 for all else held equal.

Weirs were built with a broad crest of immobile sediments at the relative elevation of OLR—1.75 m, such that the flow depth above the weir was equal between the three weirs. In May 2018, the entire A_1 weir and half of the A_2 weir were raised by 2.5 m to OLR + 0.75 m (Sieben, 2020) following rapid sediment deposition in A_1 and A_2 (Figure S6 in Supporting Information S1). Half of the A_3 weir was raised to OLR + 0.75 m in 2019 following rapid sedimentation of coarse sand bed material just downstream of the auxiliary channel entrance (Figures S6 & S7 in Supporting Information S1). Original weir lengths at the original weir level (OLR—2.5 m) were 175, 140, and 220 m for A_1, A_2, and A_3 respectively. Entrance weirs in A_1 and A_3 are side weirs, while the entrance weir in A_2 is curved attaching the wall to its adjacent bank (Figure 3).

In the next sections, we use bathymetric and water discharge data collected before, during and after LTW construction to understand the hydraulic and bed level response to LTWs. We analyze these data to understand bed level trends over a reach longer than the 11 km long pilot project. Multibeam bathymetric data with 1 × 1 m spatial resolution were collected within the study domain at least 4 times per year after LTW construction was completed in 2015.

3. Bed Level Response to LTW Construction

The Midden-Waal had eroded more than 1 m between 1926 and 2014, when LTW construction began (Figure 4). Pre-construction bed elevation changes follow a red-yellow colorbar. Most of the reach considered here, spanning from RK 905 to RK 925, eroded at a more or less uniform rate of about 1–2 cm/yr, which slightly decreased with time. The channel bed downstream of RK 925 aggraded over the last 20 years following construction of a non-erodible fixed layer (St Andries) from 1996 to 1999 (Ylla Arbós et al., 2021).

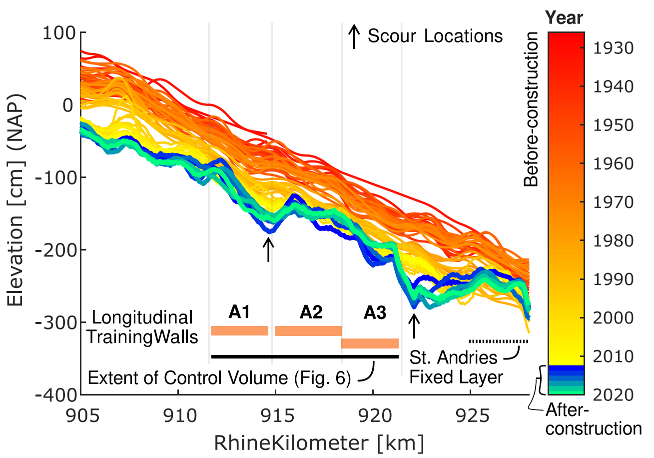

Figure 4. Width averaged bed level of the primary channel along the Midden-Waal. The position of each wall is noted by thick orange lines along the *x*-axis. Measurements before longitudinal training wall construction follow a color shift from red to yellow, while post-construction data from 2015 to 2019 follow a blue-green color bar. The extent of the control area (Figure 5) is drawn here with a sold black line and the St. Andries fixed layer (RK 925–928) is drawn with a dotted black line. Scour locations are noted with an arrow.

Long profile changes after LTW construction (blue-green colorbar in Figure 4) illustrate that LTW construction has led to the formation of several scour pits. The scour downstream of the study site was the largest, spanning 3 km and more than 1 m below pre-LTW elevation, while other scour depths were on the order of 50 cm. The downstream most scour pit expanded downstream through 2020, but appears to have stopped at RK 925, where the St. Andries fixed layer (RK 925–928) prevents erosion. The channel abruptly transitions back to groynes at RK 921.5 (Figure 3a) where auxiliary channel flow merges into the narrowed primary channel.

A scour pit also developed between auxiliary channels A_1 and A_2, but not between channels A_2 and A_3, where the walls were built on opposite banks. The scour between A_1 and A_2 is related to the floodplain ferry access road and a ferry quay near RK 914.5 (Figure 3a). These locally narrow total channel width from 320 m (spanning the primary and auxiliary channels) to 250 m at the ferry quay. The floodplain access road also appears to reduce overbank flow during floods (Figure S5 in Supporting Information S1), leading to spatial flow acceleration between A_1 exit and A_2 entrance weir. In general, scour pits develop where total flow width is abruptly narrowed. Hydrodynamics in such sections resemble a river confluence where flow combination from upstream channels cause secondary flows and flow width contractions that often develops similar scouring patterns (Best & Rhoads, 2008). River confluences of parallel channels do not develop secondary flows regardless of the discharge ratio between feeder channels (Sukhodolov & Sukhodolova, 2019), which implies the width contraction alone causes the observed local scouring.

We consider the mean bed elevation change in a control area within the primary channel to assess the river response to LTW construction. The control area spans the regions between groyne toes and is limited to the total length or extent of the three LTWs as illustrated in Figure 4 (i.e., entrance and exit effects upstream and downstream from the LTWs are excluded). To this end, we evaluate how the channel bed elevation averaged over the control area has changed before and after LTW construction (Figure 5). Details regarding our methods to process bed elevation data are included in Supporting Information S1 (Section S2).

Before construction, the control area eroded at a rate of 1.0 cm/yr (Figure 5), which confirms the degradation rate from the reach-scale analysis of Ylla Arbós et al. (2019). Average bed elevation in the control area rapidly dropped by nearly 10 cm during construction. This lost volume equates to nearly 50% of the annual bed material load (Frings et al., 2014). Immediately after construction, the reach rapidly aggraded toward pre-LTW levels. After this adjustment period, the bed aggraded at an average rate of 1.0 cm/yr with intra-annual oscillations that averaged ±2 cm. The 2020 mean bed elevation was 5–6 cm higher than the extrapolated pre-construction trend of average bed elevation (Figure 5), suggesting LTWs are mitigating erosion. Expanding our control volume to include the entrance weir and exit outlet slightly reduces this aggradation magnitude, but aggradation is still evident (Figure S3 in Supporting Information S1).

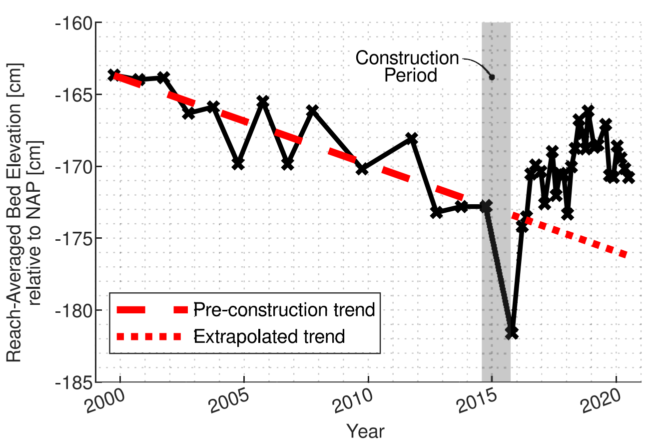

Figure 5. Mean bed elevation within a control area ranging from RK 911.5 to RK 921.7 as a function of time. The long-term channel bed erosion rate prior to construction (from 1999 to 2014) is 1.0 cm/year. A linear regression of data from 1999 to 2014 (dashed red line) is extrapolated to 2020 (fine dashed line).

4. Importance of Water Discharge Variation in Time

Here we investigate the effects of variation of water discharge in time on the river response to LTWs. Based on the hydrograph at Tiel, we identify five periods after LTW construction (Figure 6a): (a) 2016 flood period, (b) inter-flood period 1, (c) 2018 flood period, (d) inter-flood period 2, and (e) 2020 flood period.

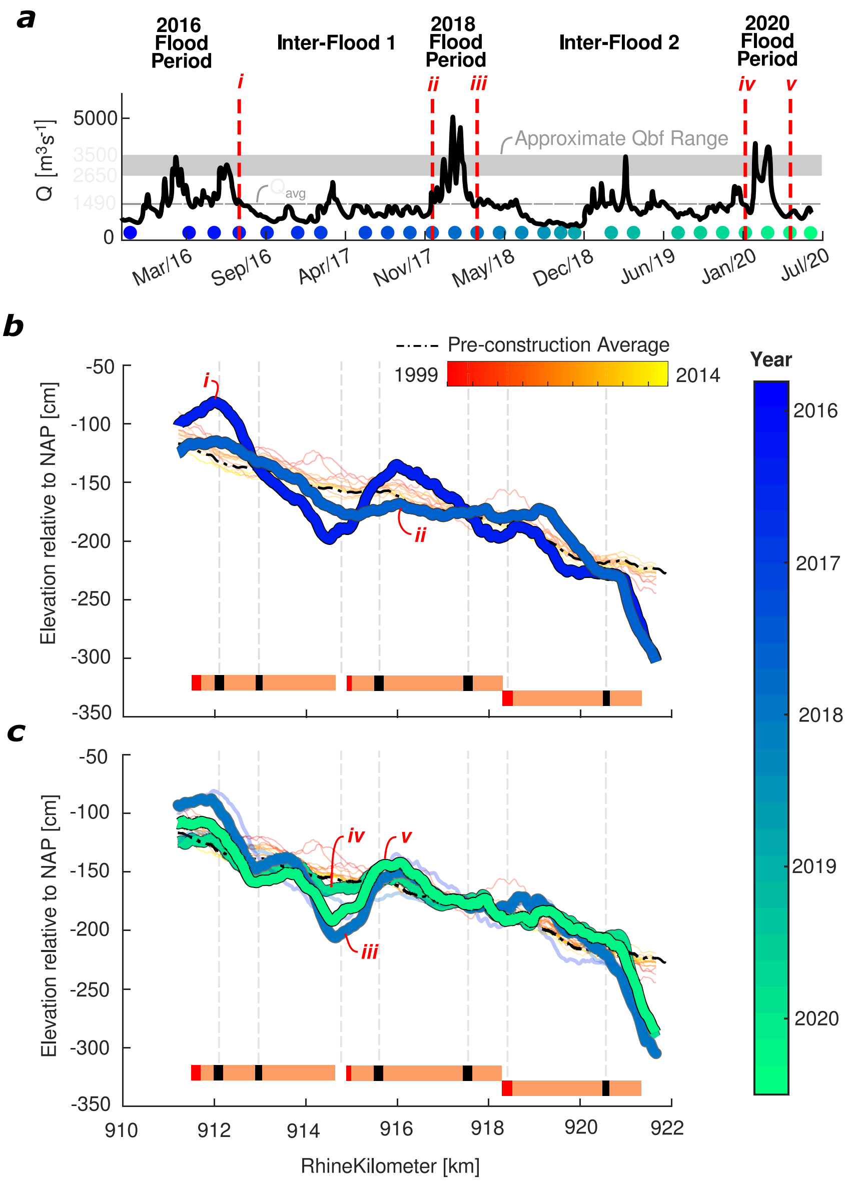

Figure 6. Cyclic patterns of aggradation and scouring during flooding periods and riverbed diffusion during inter-floods following construction of the Longitudinal training walls (LTWs): (a) The hydrograph at Tiel gage (RK 915). The mean-annual discharge Q_{avg} (Le et al., 2020) is drawn with a dashed gray line. Approximate Bankfull discharge is drawn as a gray rectangle ranging from 2,650 m^3/s (Le et al., 2020) to 3,500 m^3/s (Figure 7). Node color matches the color bar in b and c. Five times are highlighted: (i) 2016 flood period; (ii) after inter-flood 1; (iii) after the 2018 flood period; (iv) after inter-flood 2; (v) after the 2020 flood period. A video with all data is included in Supporting Information (Movie S1). (b) The first flood/inter-flood cycle. Elevation at times *i* and *ii* is plotted with pre-construction measurements in red-yellow shading and the 5-year (2009–2014) average elevation (black dash-dotted line). LTWs are drawn as in Figure 3 with entrance weirs (red) and notches (black); vertical lines are drawn from these locations. (c) The second flood/inter-flood cycle, after the 2018 flood, at time (iii), after inter-flood 2 at time (iv), and after the 2020 flood at time (v).

The profiles in Figures 6b and 6c highlight single bathymetric measurements at the end of each of the five periods and explain how variability of the water discharge affected local bathymetry. All data have been compiled into a video that can be downloaded as Supporting Information; Movie S1. The 2018 flood was the largest discharge in our study period and nearly doubled the bankfull discharge of 2,650 m^3/s (Le et al., 2020). Meanwhile, the average inter-flood discharge in both periods was lower than mean-annual discharge of 1,490 m^3/s (Le et al., 2020).

Aggradation and scour were observed after the 2016 flood period (time *i*), after the 2018 flood (time *iii*), and after the 2020 flood period (time *v*; Figures 6b and 6c). Sediment deposition in the primary channel occurred at

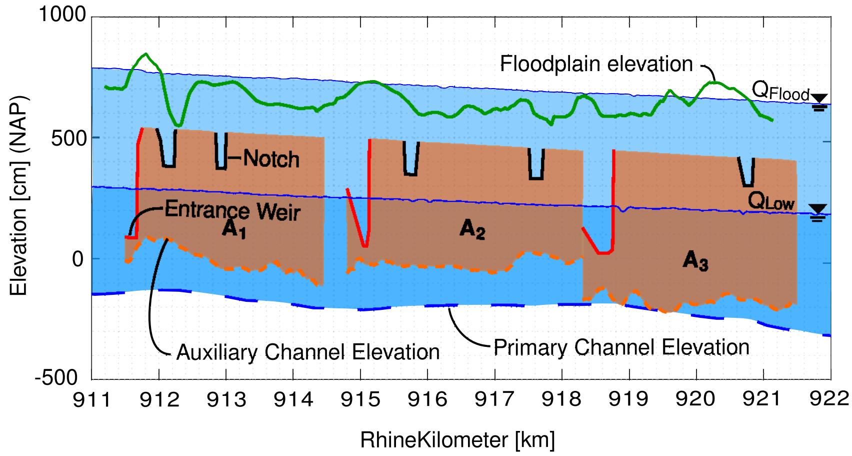

Figure 7. Longitudinal profile of wall, weir, bed, floodplain, and water surface elevations. Walls are shaded in orange with entrance weirs (red) and inter-wall notches (black). Auxiliary (dashed orange lines) and primary channel elevations (long-dashed blue line) are from 2018. Floodplain elevation is extracted from a national Lidar survey along the bank adjacent to each wall and smoothed via moving-window scheme for clarity. Measured water surface elevation is drawn with shades of blue at low flow ($Q_{\mathrm{Low}} \approx 1{,}000$ m^3/s) and flood flow ($Q_{Flood} \approx 3{,}500$ m^3/s). At low flows, water is only exchanged via the weir and channel exit, while the entire wall is overtopped at flood stage.

the upstream part of the first LTW (around RK 912.2) and just downstream of the first inter-wall notch of A_2 (RK 916). The 2016 flood period contained smaller, longer duration peaks (around 3,300 m^3/s) than the 2018 flood, but developed the largest sediment deposition in the primary channel (Figure 6b).

Significant scour occurred during the three flood periods (see times *i*, *iii*, and *v*) between auxiliary channels A_1 and A_2, as was also evident in annual bathymetric surveys (Figure 4). This scour pit is associated with the local channel narrowing effect due to the ferry quay.

Sediment deposits in the primary channel during floods are dispersed during inter-floods (i.e., deposits are eroded and scour holes are filled, see times ii and iv). At moderate and low flows, drawdown conditions form (i.e., an M2 backwater curve) over the deposits, which aid the downstream migration of the previously deposited sediment. During these conditions, water is conveyed through the 230 m wide primary channel. At low flow, the scour pit between A_1 and A_2 acts as a sediment sink because of local flow expansion from 230 to 250 m, rather than the width contraction from 320 to 250 m that occurs during floods. In general, these measured patterns of sedimentation and dispersion agree with schematic numerical modeling efforts (Mosselman et al., 2007; Spies, 2009).

5. Water and Sediment Partitioning

Here we assess the interplay of flow discharge to the auxiliary channel and discharge capacity of the auxiliary channel on water partitioning. Discharge into the auxiliary channels is controlled by three levels of weirs (from bottom to top): the entrance weir, inter-wall notches, or over the wall (Figure 7). Entrance weir elevations in Figure 7 represent the original post-construction levels (see Section 2). The drawn floodplain elevation relates to the elevation along the top of bank adjacent to each LTW. Actual floodplain elevation varies, but most of the bank adjacent to all three auxiliary channel is 7–8 m above Normaal Amsterdams Peil, the vertical datum of the Netherlands (Figure S5). The wall crest is 1–2 m below the floodplain. Notches and entrance weirs are approximately 1 and 4 m below the wall crest, respectively.

Discharge partitioning depends on both water level and location along the wall. At low discharge, flow enters auxiliary channels over the entrance weir and leaves at the downstream end of auxiliary channels (Q_{Low} in Figure 7). As discharge increases, flow additionally enters via notches, then over the wall. During bankfull flood discharge, the water surface rises to ≈2.5 m above the wall (Q_{flood} in Figure 7).

As discharge and water level increase, a larger portion of the flow is diverted into the auxiliary channels (Figure 8a), agreeing with laboratory experiments (De Ruijsscher et al., 2019) and a field analysis of the A_3

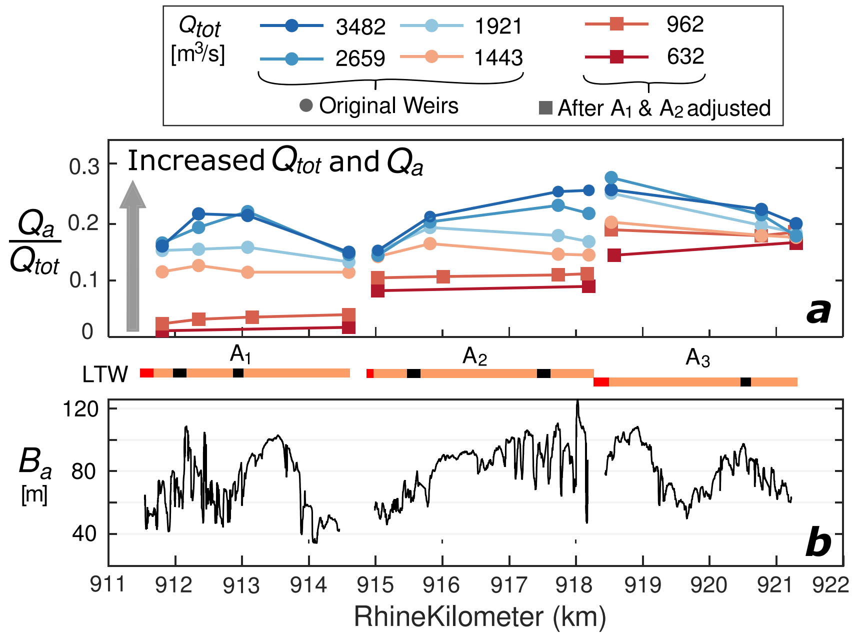

Figure 8. (a) Measured discharge in the auxiliary channels Q_a, normalized by the total discharge entering the study domain Q_{tot} ranging from about 600 to 3,400 m^3/s. Discontinuities in the lines reflect the gaps between longitudinal training walls. Flows over 1,000 m^3/s were measured with the original weir elevations, which had equivalent relative elevation. Flows lower than 1,000 m^3/s were measured after A_1 and A_2 (RK 912–918) were raised, which reduced their discharge level. (b) Auxiliary channel width measured in all three auxiliary channels.

weir alone (De Ruijsscher et al., 2020). Entrance weirs control auxiliary channel discharge at conditions below 1,500 m^3/s where water level is below notches and the wall crest.

Water exchange patterns vary downstream and with discharge level (Figure 8a). Entrance weir flow is significantly larger through the longest entrance weir A_3. During the largest flow event in channel A_2, discharge doubled via inter-wall flows relative to the entrance weir discharge. Conversely, under the same conditions, inter-wall flows halve the entrance weir discharge in A_3 via a return flow to the primary channel. Channel A_1 shows a combination of both patterns. These trends match spatial width variation (Figure 8b), suggesting that discharge in auxiliary channels is limited by local auxiliary channel width B_a during floods.

Discharge partitioning during floods is set by the auxiliary channel area. Thus, if the auxiliary channel widens, the discharge capacity increases, and the over-wall flow is directed from the primary to the auxiliary channel (case of A_2). If the auxiliary channel becomes narrower, its discharge capacity decreases and water is directed from the auxiliary to the primary channel (case of A_3).

During the early morphodynamic response, channel width seems to be the main factor governing the discharge capacity, which agrees with schematic numerical results (Spies, 2009). However, this correlation likely reduces once the auxiliary channel bed or banks have been able to adapt. By 2020, auxiliary channel bank erosion (Flores et al., 2021) (Figure S4 in Supporting Information S1) and deposition in wider sections of auxiliary channels (Figure S6 in Supporting Information S1) tend to reduce the downstream changes in auxiliary channel area. As a result, auxiliary channel discharge capacity would tend toward quasi-uniform, which would reduce the inter-wall flow exchange.

Auxiliary channel water discharge is limited by flow entering the channel at low flow and the discharge capacity during flood flows. The transition between such limiting controls occurs when the wall is over-topped. However, wall elevation does not significantly affect discharge capacity, as shown by similar partitioning ratios in the largest measured discharge levels (Figure 8a).

Bed material can be removed from the primary channel when flow passes over the entrance weir, which is much shallower than the notches or wall crest (Figure 4). This effect is clearly observed downstream of the A_3 weir, where bed material was deposited immediately downstream of the entrance weir (De Ruijsscher et al., 2020)

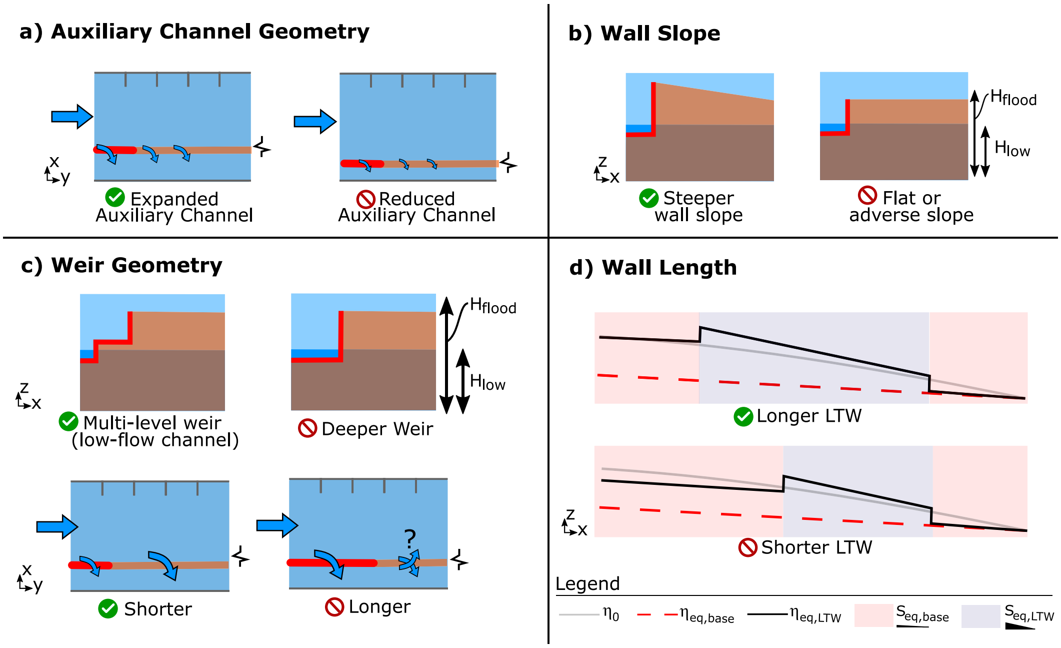

Figure 9. Schematic illustrating the design criteria to mitigate erosion with longitudinal training walls. The criteria relate to: (a) auxiliary channel area, (b) wall slope, (c) weir area and geometry and (d) wall length.

(Figures S6 & S7 in Supporting Information S1). Flows through notches or over the wall come from the upper half of the water column (Figure 7), where the concentration of suspended bed material is typically much lower than near the bed. Over-notch and over-wall flows are thus likely to carry less sediment, but aggradational waves that develop adjacent to notches in A_1 and A_2 indicate that some sediment is also transferred via notches (Figure S6 in Supporting Information S1).

Sediment accumulations in the primary channel adjacent to A_1 and A_2 during floods develop at the first inter-wall notch. These deposits imply conditions where: (a) bed material is maintained in the primary channel, and (b) sediment transport capacity in the primary channel abruptly declines. Both A_1 and A_2 channels have reduced entrance weir flow relative to A_3, meaning that flood flows enter auxiliary channels at higher elevations via the notches or over the wall. Sediment accumulates where flow is rapidly removed from the primary channel as illustrated in Figure 8a as steep gradients in Q_a/Q_{tot}. Increasing the gradient then likely increases the accumulation height.

These conditions suggest that the magnitude of sediment extraction directly relies on entrance weir area and local discharge capacity behind the entrance weir. Downstream discharge capacity does not limit entrance weir flow, but rather forces a return flow as in A_3 (Figure 8a). Bed material bypasses entrance weirs with smaller area (A_1 and A_2) and stays in the primary channel. While the controls on water partitioning rely on the wall geometry and auxiliary channel discharge capacity, sediment flux partitioning primarily depends on entrance weir area.

6. Design Criteria

The results of our analysis are summarized into several design criteria to effectively mitigate channel bed erosion and reduce negative side effects. These are illustrated schematically in Figure 9 and include the design of the entrance weir geometry, wall slope, auxiliary channel area, and LTW length.

The wall, and not the entrance weir, acts as the primary weir to mitigate channel bed erosion. While discharge partitioning depends on the auxiliary channel area (Figure 9a), wall height controls the discharge level at which flow is reduced in the primary channel (Figure 9b). Lowering the wall diverts water at lower discharge levels and decreases the cumulative sediment transport capacity in the primary channel (summed over a flow-duration curve). However, since the wall top is closer to the bed, we can also expect more bed material sediment to be transported into the auxiliary channel, which may limit the potential erosion mitigation. The entrance weir area should be reduced to limit the extraction of bed material during floods. Flow exchange during low discharge events can be achieved with a multi-level weir that includes a low-flow channel and a relatively high entrance weir at or near the wall crest elevation (Figure 9c).

During floods, the wall is over-topped and the proportion of discharge diverted to the auxiliary channels directly depends on the auxiliary channel area. Increasing channel area, via dredging or width expansion, then diverts more water, which reduces more erosion (Figure 9a). Auxiliary channels will adapt over time via bank erosion (Flores et al., 2021) or aggradation (Figure S6 in Supporting Information S1), reducing channel area and erosion mitigation effectiveness. Bank revetments, or short remnants of previous groynes, can help reduce bank erosion. Sedimentation in auxiliary channels is reduced by limiting bed material load transport into auxiliary channels by decreasing the entrance weir area. However, build up of washload deposition will eventually require maintenance dredging.

Our results suggest that LTWs increase the equilibrium slope in the region immediately adjacent to the walls. LTW length has a direct influence on both the magnitude of potential erosion mitigation and the response time to reach a new equilibrium state. Slope steepens through sediment deposition in the primary channel, which raises the bed elevation at the upstream end of LTWs (Figure 9d). This effect is proportional to the length and ratio of equilibrium slopes between the upstream and LTW sections. Increasing length requires more bed volume to be filled, which increases the response time. Aggradation to maintain the upstream bed level also reduces the upstream sediment load and exacerbates this trend.

7. Discussion

LTWs promote sediment deposition in the primary channel during floods as a direct result of two combined factors: (a) more sediment is in transport during floods, (b) proportionally more flow is diverted to auxiliary channels during floods causing a sharp reduction of sediment transport capacity. Inter-floods disperse the deposited sediment. The balance between sediment deposition during floods and sediment dispersion between floods is vital for LTW functioning, as well as to maintain all river uses. For example, consecutive floods or relatively long periods of high flow may generate sediment accumulations large enough to hinder navigation.

Channel bed erosion can be mitigated by decreasing sediment transport capacity and increasing the river equilibrium slope. In the presence of LTWs, this is achieved by decreasing water discharge without extracting a significant portion of the bed material load sediment from the primary channel. To this end, water is removed from the primary channel via notches and over the wall, which forces the majority of the bed material to be transported via the primary channel. Thus, equilibrium slope increases by increasing auxiliary channel discharge capacity, which allows more flow to divert from the primary channel and by reducing the bed material flux to the auxiliary channel. This agrees with previous laboratory experiment findings (De Ruijsscher et al., 2019).

Here we focus solely on LTW performance for erosion mitigation. A multi-faceted approach must balance the four typical criteria for design: mitigate riverbed erosion, increase flow depth during low flows (beneficial to navigation), reduce water level and flood risk during high flows, and improve ecosystem well-being. These criteria are largely balanced by selection of wall height and auxiliary channel discharge capacity. Increasing the auxiliary channel width (and thus auxiliary channel discharge) reduces flood risk via expanded flow area and reduces erosion rate via reduced discharge capacity, but may cause sediment accumulations during floods that disrupt navigation. Navigation can be doubly hampered by a sequence of consecutive floods. Early observations indicate that fish ecological health is enhanced by protection from ship-induced waves due to the walls (Collas et al., 2018) and presence of shoreline rugosity (Flores et al., 2021).

Long-term stability of LTWs, or prevention of channel closure, depends on weir and wall placement, along with the maintenance of auxiliary channels. Laboratory experiments and numerical modeling studies suggest all LTW configurations eventually lead to siltation of one channel (Le, Crosato, Mosselman, & Uijttewaal, 2018; Le, Crosato, & Uijttewaal, 2018). However, their experiments and models adopt a wall that cannot be overtopped, the effect of which we have shown to play a major role in how water and sediment are partitioned under LTW conditions. Since flow can exchange along the entire length of the channel, a local blockage, (e.g., upstream sedimentation that clogs entrance flow) does not affect the discharge partitioning. Similarly, inter-wall exchanges reduce the likelihood for one bifurcate to increasingly take more discharge over time. This factor likely improves long-term LTW sustainability, but more investigation is still necessary.

8. Conclusions

Groynes have been replaced with LTWs over an 11-km reach in the Waal branch of the Rhine River, which was previously eroding at 1 cm/yr. Over 5 years after construction of the LTWs, channel bed deposition has exceeded the pre-construction erosional trend. Our results suggest that LTWs have the potential to be effective in mitigating overall channel bed erosion.

Variability of the flow rate, or cyclicity of peak and low flows, is necessary to maintain a sustainable river. Discharge leaves the primary channel during floods, decreasing its sediment transport capacity and causing sediment to deposit near the upstream end of each wall. Between floods, these deposits are dispersed and scour pits are partially filled. In other words, the high flow phase traps sediment within the domain and inter-flood periods distributes the sediment, with net-effect of bed aggradation.

Auxiliary channel area controls discharge partitioning during floods, when most sediment is trapped by the LTWs. Entrance weirs do not affect flow partitioning during floods, but can cause the extraction of bed material from the primary channel. Erosion mitigation is improved by reducing discharge without extracting bed material. As such, the entrance weir area length should be reduced as much as possible to guarantee flow partitioning at low flows that fulfills the wall ecological needs.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Data is available at: https://sites.google.com/view/czapiga-2022-ltw-wrr/home.

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