Geomorphological development of aquatic mesohabitats in shore channels along longitudinal training dams

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Keywords
Aquatic habitats, deposition, erosion, fish conservation, remote sensing, river Rhine

Abstract
Longitudinal training dams (LTDs) are novel hydraulic engineering structures in the river Waal intended to facilitate intensive navigation and safe discharges in the main channel while providing sheltered habitats for aquatic biota in shore channels. Monitoring data collected using light detection and ranging, multibeam echosounder and aerial photography for the years during and after the construction of the LTDs were analysed in order to determine patterns of erosion and deposition, the retreat rate of steep eroding banks and shoreline length change through time. The LTD shore channels and two traditional groyne fields (references) were divided into nine mesohabitats based on physical attributes. Net erosion was estimated for eight out of the nine mesohabitats for the 2015–2020 period. Generally, there was a pattern of riverbed aggradation towards the LTDs and degradation or bank erosion towards the littoral zones of the LTD shore channels. This kind of continuous behaviour could be indicative of current or eminent channel and thus habitat stability. The bankline erosion in shore channels had mean retreat rates of 1.4–1.6 m/year. The shorelines were longer in sand-dominated mesohabitats, which could be key for habitat heterogeneity. The LTD shore channels offered more complex relatively natural continuous littoral zones than the traditional groyne fields while maintaining the multifunctionality of the river. Thus, the development of sandy shorelines in the LTD shore channels should be encouraged through management in order to enhance biodiversity. Geomorphological monitoring of the shore channels should continue in the future in order to detect any long-term changes in the sedimentary processes and ecological functions.

Introduction
In the European Union (EU), the majority of lowland rivers have been impacted by human activity leading to habitat fragmentation, deterioration of water quality and hydromorphological changes (Schinegger et al., 2012). Furthermore, all of the major rivers in the EU have been heavily modified in order to allow for hydropower production, agricultural uses (i.e. irrigation for crop production and water for livestock farming) and inland navigation, among other human activities, leading to adverse effects for freshwater ecosystems (Uehlinger et al., 2009; Wantzen et al., 2021; Zajicek et al., 2018). Currently, hydromorphological changes represent the major pressure on freshwater ecosystems in the EU (Walter et al., 2016). The shores of freshwater ecosystems have been particularly affected by human activity resulting in shorter, harder, simpler and polluted shores, thus reducing shore heterogeneity and habitat connectivity, which are important for biodiversity (Strayer & Findlay, 2010). Rivers have been altered in order to limit their movement through the landscape, decreasing their habitat diversity and disrupting their flow and sedimentary regimes (Newson, 2002). Due to the European Water Framework Directive 2000/60/EC (European Commission, 2000), efforts have been made in the region to apply sustainable river management practices in order to improve the ecology of heavily modified rivers.

In the Netherlands, the pilot project of the longitudinal training dams (LTDs), completed in 2015 in the river Waal, was one of the many projects resulting from a nationwide ‘Room for the River’ program (Collas, 2019; Eerden, 2013;
This program aimed at fortifying safety against floods and freer movement of rivers through their floodplains, while enhancing navigation and ecology (Rijke et al., 2012; Van Stokkom et al., 2005). The LTDs are dams that run parallel to the river shore, dividing the river into the main channel used for navigation and a shore channel (Collas et al., 2018; Eerden, 2013). According to the Flood Pulse Concept (Junk et al., 1989), a lowland river when connected to its floodplain should bring in more nutrients and sediment into the system allowing for a more dynamic littoral zone resulting in increased biological productivity. The river Waal is a heavily modified lowland river (i.e. construction of summer and winter dikes, groyne and LTDs) with limited lateral and vertical hydrologic connectivity to its floodplain. Hydrologic connectivity varies spatially and has been partially returned through various restoration measures, such as the digging of several floodplain channels, removal of summer dikes and excavation of floodplains (Havinga, 2020; Stoffers et al., 2021; Uehlinger et al., 2009; Wantzen et al., 2021). The LTD shore channels should positively affect biodiversity in the river Waal because they allow the river to locally move more freely through its floodplain than a traditional groyne field. The LTDs are expected to enhance flood and ice discharge safety, be more cost-effective and maintain the water depth required for navigation in the main channel (Eerden, 2013). Furthermore, the LTD shore channels are protected by the dams from the effects of inland navigation, such as wave action and flow velocity fluctuations (Collas et al., 2018). Indeed, positive responses of local aquatic species assemblages have been observed at the LTD shore channels (Collas et al., 2018, 2020; Dorenbosch et al., 2018).

Riverine landscape diversity depends on fluvial processes including the erosion, deposition and transport of sediment (Ward et al., 2002). River habitats are composed of reaches (10^3 m spatial scale) characterized by vegetation succession, bank erosion, riverbed degradation and aggradation. Pool and riffle systems (10^6 m spatial scale) are characterized by sediment sorting and sedimentary formations that change vertically and transversely (Frissell et al., 1986). Understanding the morphological dynamics of these habitats is important because even highly motile biota, such as non-migratory freshwater fish species, are able to complete their entire life cycles in a river reach (Griff et al., 2003; Wolter et al., 2016). In addition, the establishment of healthy populations of sessile biota such as freshwater mussels have been found to be highly dependent on stable substrate (Hamilton et al., 1997; Hastie et al., 2000; Newton et al., 2020). In lotic ecosystems, habitats are determined by temporal and spatial variability of abiotic conditions (i.e. sediment, water depth, flow velocity, etc.) and their heterogeneity and stability ultimately control biodiversity (Poff & Ward, 1990; Schlosser, 1991; Vannote et al., 1980). A channel may be considered stable when it exhibits predictable geomorphic behaviour that changes without reaching tipping points (Newson, 2002). Hence, investigating the geomorphological development of the protected LTD shore channels is essential to detect the stability of these novel aquatic habitats in order to make informed river management decisions. Dividing riverine macrohabitats (e.g. shore channels, main channel) into mesohabitats may help in the ecological assessments of riverine ecosystems (Vadas & Orath, 1998). Furthermore, Wintzenberger (1996) found that fish diversity increased in river reaches with longer and more complex shorelines, hence investigating how the geomorphological changes in the shore channels has altered the shoreline since the construction of the LTDs would provide insight into the heterogeneity of these novel habitats.

Light detection and ranging (LiDAR) is a technique which uses laser pulse technology to measure the elevation of the earth’s surface from an aircraft using two-way travel time. These measurements are referred to as topographic data (Charlton et al., 2003; De Rose & Basher, 2011; Kinzel et al., 2021; Marks & Bates, 2000). Similarly, multibeam echosounders (MBES) are sonars usually mounted on ships that emit and receive sound pulses from which the two-way travel time is used to measure the elevation of underwater terrain, referred to as bathymetric data (Cartwright & Clarke, 2002; Dinn et al., 1995; Eleftherakis et al., 2014; Huizinga, 2010).

Despite the ecological monitoring and modelling of the geomorphology of the LTD shore channels (De Ruijsscher et al., 2018, 2019, 2020; Omer et al., 2019), the stability of the habitats in the shore channels remains unknown. Therefore, this study aims to assess the geomorphological development of the LTD shore channels and implications for these novel aquatic habitats during the 2015–2020 period. The following research questions were postulated: (1) What are the patterns of erosion and deposition within the LTD shore channels? (2) What is the retreat rate of the steep eroding banklines in the LTD shore channels? (3) How does the shoreline length change during months of high fish densities? In order to answer these questions, this study was conducted by using monitoring data collected using LiDAR, MBES and aerial photography by the Directorate-General of Public Works and Water Management (in Dutch Rijkswaterstaat; RWS) during the years after the construction of the LTDs.

Materials and Methods

Study site

The river Waal is the main free-flowing distributary of the rainwater and glacier-fed river Rhine discharging 65%
of its water (Raat, 2001; Uehlinger et al., 2009). This distributary has a mixed riverbed composed of sand and gravel (Kleinhans, 2002). The mean discharge of the river from 2014 to 2020 was 1404 m$^3$/sec (www.waterinfo.nl). The LTDs extend from river kilometer 911–922 and the protected LTD shore channels have a mean width of 80 m. The LTD shore channels have inflows with riprap sills that allow for the modification of flow in the shore channels, outflows into the main channel and permeable lowered sections that allow for mixing with water from the main channel (Collas et al., 2018; De Ruijsscher et al., 2019, 2020; Eerden, 2013). The study sites consisted of the Wamel (N51.878139, E5.458778), Dreumel (N51.849542, E5.430986) and Ophemert (N51.845330, E5.386569) shore channels (reference names are of nearby towns) and two reference groyne field areas referred to as G1 and G2 (N51.888860, E5.451673 and N51.827178, E5.388239 respectively; Fig. 1). The shore channels were divided visually into nine mesohabitats based on differences in shore development, as well as other physical

Figure 1. Map of the Wamel, Dreumel and Ophemert shore channels and two reference groyne field areas (G1 and G2) in the river Waal. The digitized composite vegetation line created for the analysis is depicted in red and the nine mesohabitats are shown as labeled polygons. The arrow shows the main flow direction. Aerial photographs source: Environmental Systems Research Institute (ESRI) Nederland, beeldmateriaal.nl.
Table 1. Summary of mesohabitats.

| Mesohabitat         | Abbreviation | Physical characteristics                                                                 |
|---------------------|--------------|------------------------------------------------------------------------------------------|
| Groyne Field        | G1           | 4 groyne fields with mixed substrate (sand and gravel) located in the outer bend of the river |
| Area 1              |              |                                                                                          |
| Wamel Sandy Area 1  | WSA1         | Most upstream section of the Wamel shore channel with sandy shores and some tree cover     |
| Erosion Area        | WEA          | Middle section of the Wamel shore channel with erosion of the bankline                     |
| Sandy Area 2        | WSA2         | Most downstream section of the Wamel shore channel with sandy shores and limited tree cover |
| Dreumel Sandy Area 1| DSA1         | Most upstream section of the Dreumel shore channel with sandy shores and no tree cover     |
| Erosion Area        | DEA          | Middle section of the Dreumel shore channel with erosion of the bankline                   |
| Sandy Area 2        | DSA2         | Most downstream section of the Dreumel shore channel with sandy shores and some tree cover |
| Ophemert            | O            | The Ophemert shore channel has similar mixed (sand and gravel) substrate and tree cover throughout |
| Groyne Field        | G2           | 3 groyne fields with sandy shores located in a straight section of the river                |
| Area 2              |              |                                                                                          |

The mesohabitats are listed going from upstream to downstream.

characteristics observed in the field (i.e. substrate type, tree cover) and on aerial photographs (Table 1). Three mesohabitats were identified in the Wamel shore channel (Sandy Area 1, Erosion Area, Sandy Area 2), three in the Dreumel shore channel (Sandy Area 1, Erosion Area, Sandy Area 2), one in the Ophemert shore channel and one in each reference groyne field area (G1 and G2).

Patterns of deposition and erosion

Approaches to assess riverine ecosystems and their geomorphologic changes using remote sensing and Geographic Information Systems are commonplace and have included the use of aerial photography, LiDAR and photogrammetry (Charlton et al., 2003; Faux et al., 2009; Lehotský et al., 2017; Middelkoop, 2002). LiDAR and MBES data combination studies have most often been used to map habitats in the marine environment (Costa et al., 2009; Kennedy et al., 2014). MBES is limited by shallow water (≤2 m; Kinzel et al., 2021), which makes the integration of LiDAR and MBES datasets essential for the seamless evaluation of the littoral zone of rivers. LiDAR has previously been used to monitor habitats, evaluate eroding banks and complete topographic studies of rivers and their floodplains (Charlton et al., 2003; De Rose & Basher, 2011; Faux et al., 2009; Grove et al., 2013; Kinzel et al., 2021; Thoma et al., 2005). MBES has mainly been used for bathymetric studies of rivers, but also for substrate classification (Amiri-Simkooei et al., 2009; Cartwright & Clarke, 2002; Eleftherakis et al., 2014; Huizinga, 2010; Muste et al., 2012). These evaluations can be aided by aerial images which have been previously used to determine the retreat rates of eroding banks (De Rose & Basher, 2011; Duró et al., 2018; Khan & Islam, 2003).

LiDAR and MBES datasets collected during monitoring campaigns by RWS were obtained as 0.5 × 0.5 and 1 × 1 m pixel size Digital Terrain Models (DTMs) respectively. The datasets contained elevation (cm or m) relative to the ‘Normaal Amsterdams Peil’ (NAP; where 0 m + NAP is equal to the mean sea level of the North Sea). Datasets included the years 2014, 2015, 2016, 2018, 2019 and 2020 (Table S1). In order to merge each yearly LiDAR and MBES dataset, the data corresponding with the study sites were clipped, converted to XYZ data and gridded in Surfer software (Golden Software, LLC, Golden, CO, USA) using the natural neighbour technique and a 1 × 1 m pixel size (El-Hattab, 2014). This pixel size has provided reasonable volume estimates for eroding river sections in the past (Grove et al., 2013). The gridded yearly DTMs were projected in the Amersfoort/RD New coordinate system and exported as GeoTIFF files. The yearly DTMs were subtracted using the ArcPy package (e.g., 2015 minus 2014) in ESRI ArcMAP 10.3. One of the subtraction DTMs spanned a period of 2 years (i.e. 2016–2018). Aerial photographs were used to manually digitize yearly riparian vegetation lines. Composite vegetated banklines were then created by selecting the most inland sections of each yearly vegetation line (Fig. 1). The composite vegetated banklines were used to separate each study area into the shore channel (mostly submerged) and vegetated bank areas (mostly dry). The volume above the 0.00001 m plane and below the −0.00001 m plane of the subtraction DTMs were calculated using the ‘Surface Volume’ tool from the 3D Analyst toolbox (ESRI, n.d.a). The results were subtracted in order to estimate sediment volume change (AV; m³) for every period (i.e. 2014–2015). The AV per 200 m stretch (the mean distance between groynes) was estimated for the study sites using the linear lengths of the mesohabitats derived from aerial images based on the lengths of the LTDs or the distance between the reference groynes.

Retreat rate of the eroded bankline

Aerial photographs, the yearly DTMs and the subtraction DTMs for the years 2015, 2016, 2018, 2019 and 2020 were
used to do a yearly evaluation of the retreat rate of the bankline within the Wamel Erosion Area and Dreumel Erosion Area mesohabitats (Kessler et al., 2013; Khan & Islam, 2003; Rhoades et al., 2009). The erosion areas consisted of steep walls that regularly collapsed into the shore channels (Collas, 2019). The aerial photographs had pixel sizes equal to 0.05 × 0.05 or 0.1 × 0.1 m, thus were very detailed, clear and with minimal to no noise that could impact visual interpretation. The banklines were manually digitized in ArcMap for each yearly dataset by using a combination of bank shadows, vegetation lines and high points next to the eroding banklines (Boak & Turner, 2005; Gens, 2010; Parthasarathy et al., 2018). The same number of vertices (34 for the Wamel erosion area and 84 for the Dreumel erosion) were used to digitize every yearly bankline to simplify the correlations. The ‘Generate Near Table’ tool from the Analysis toolbox was used to compute the absolute distances between the nearest vertices (ESRI, n.d.b). Since the 2017 data were missing, the results for the 2016–2018 period were divided by two. The mean yearly retreat rate (m/year) of the banklines were calculated using the absolute distances between the vertices.

**Shoreline length change**

Mean water level rasters (1 × 1 m pixel size) for the months April–September (Grift et al., 2003) were obtained from RWS based on the data at the Tiel RWS monitoring station for the 2014–2020 period (www.waterinfo.rws.nl). The rasters represented the estimated change in water level slope per kilometer (≈10 cm/km; Rijkswaterstaat Oost-Nederland, 2019). The yearly DTMs for the period after the construction of the LTDS (2015–2020) were subtracted from each monthly water level raster. The year 2014 was excluded because during the collection of this dataset the construction was ongoing and only small sections of the LTDS were visible. Contours were created from the subtraction results and all that equalled zero were selected as the shorelines at each given water level. The boulder areas such as the LTDS, the groyne fields and the walls at the ends of the shore channels were removed from the shorelines. The shorelines were separated by mesohabitat. The shoreline length for all the mesohabitats were divided by the linear lengths in order to obtain the shoreline-linear length ratio.

**Statistical analysis**

Using R statistics version 4.0.4 a Shapiro test was used in order to check if the results fitted a normal distribution. For data that were not normally distributed a Kruskal-Wallis test was performed to check for the effects of the mesohabitats and time periods on the ΔV per 200 m stretch (R Core Team, 2021). This test was also performed to check for the effects of the mesohabitats, month and year on the shoreline-linear length ratios. Post hoc pairwise-comparisons were performed using the Wilcoxon Rank Sum test with P-values adjusted using the Benjamini and Hochberg (1995) method to identify significant differences between time periods or mesohabitats (R Core Team, 2021).

**Results**

**Patterns of deposition and erosion**

The combined LiDAR and MBES interpolated yearly elevation datasets included the submerged and dry areas of the LTDS. The subtraction DTMs had some expected sedimentary changes from observations in the field or from the construction of the LTDS. During the construction (2014–2015), features such as dredge lines, groyne fields and new sections of the dams were clearly visible (Fig. S1). During the same time, the elevation of the two reference groyne fields remained relatively constant. After the construction of the LTDS (2015–2020; Fig. 2), a general pattern of erosion towards the shoreline and deposition towards the dams was observed. Erosion was very apparent along the shorelines in the centre areas of the Wamel and Dreumel shore channels. The reference groyne fields showed erosional patterns towards the main channel, this pattern was very noticeable for the period 2015–2016 in G2 (Fig. S2). Another feature first noted in the 2016–2018 dataset that persisted in future datasets was the sedimentation near the inflow of the Ophemert shore channel (Fig. S3).

The ΔV per 200 m stretch results (Fig. 3; Table S2) showed that from 2016 onwards the channel sections in all of the mesohabitats typically lost sediment (≤8090 m³). From 2014 to 2018 the vegetated banks in all of the mesohabitats typically gained small amounts of sediment (≤574 m³; Figs. S4 and S5). The largest loss of sediment for all mesohabitats, except G1 and G2, occurred during the construction of the LTDS (2014–2015) when the channels were dredged (≤56 475 m³ at the Wamel Erosion Area). During the 2015–2020 period, all the mesohabitats suffered sediment losses except for the Wamel Erosion Area mesohabitat, which had sediment deposited in the channel section (4896 m³). The channel section of the Dreumel Sandy Area 2 mesohabitat suffered the most sediment loss out of all of the LTD shore channel mesohabitats (11 379 m³). The study site with the most sediment loss during the 2015–2020 period was the channel section of the G2 reference groyne, this
was likely due to a large sediment loss (11,476 m$^3$) in the 2015–2016 period.

**Retreat rate of the eroded bankline**

The erosion areas at Wamel and Dreumel showed a general inland eroding pattern (Table 2; see Fig. S6). The manually digitized banklines evaluated at Dreumel and Wamel were ~792 and ~547 m long respectively. Visual interpretation of the banklines and the subsequent manual digitization was facilitated by the high resolution of the aerial images and the lack of shadows from vegetation or other objects at the study sites. The shadows casted by the banks on the river below were useful in the interpretation of the banklines. During the construction of the LTDs (2014–2015), the Wamel bankline had small areas of apparent bank accretion. Instances of localized no apparent change were observed. Overall, for the period after the construction of the LTDs (2015–2020), the Wamel and Dreumel banklines had similar mean bankline retreat rates equal to 1.6 and 1.4 m/year respectively.

**Shoreline length change**

Mean shoreline-linear length ratios were comparable for similar mesohabitats (Fig. 4 and Table 3). The Wamel Sandy Area 1, Wamel Sandy Area 2 and Dreumel Sandy Area 2 LTD mesohabitats had the highest mean ratios (1.24–1.30; 2015–2020). The highest ratio (1.70) was seen for Dreumel Sandy Area 2 in September of 2015, a year after the construction of the LTDs. The lowest ratio (0.98) was seen for the Wamel Erosion Area in May and June of 2016. Monthly mean ratios were slightly higher for July, August and September in seven of the nine mesohabitats. Those months frequently had near-mean or below mean flow conditions and the monthly mean water levels used to calculate the shorelines were the lowest for those 3 months (3.2–3.8 m + NAP; Figs. S7 and S8).

**Statistical analysis**

The $\Delta V$ per 200 m stretch ($n = 45; P < 0.001$) and shoreline-linear length ratios ($n = 270; P < 0.001$) were
Figure 3. $\Delta V$ (x-axis; m$^3$) graphs for each study site (y-axis) and year combination including the periods (A) 2015–2016, (B) 2016–2018, (C) 2018–2019, (D) 2019–2020 and (E) 2015–2020. The 2016–2018 period is a 2-year period due to missing data in 2017. In the abbreviations ‘G’ indicates groyne field areas, ‘W’ the Wamel shore channel, ‘D’ the Dreumel shore channel and ‘O’ the Ophemert shore channel. Mesohabitats are listed going from upstream to downstream from top to bottom on the y-axis. ‘SA1’ stands for sandy area 1, ‘SA2’ for sandy area 2 and ‘E’ for erosion areas. The ‘C’ indicates the channel section and ‘V’ the vegetated banks.

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patterns of erosion and deposition

The resulting DTMs showed riverbed aggradation near the dams (LTDs), which is consistent with findings by Van Weerdenburg (2018). Towards the shore, the DTMs often coincided with areas of erosion suggesting littoral zone degradation. It is likely that some of these eroded sediments added to the riverbed aggradation observed near the dams. Preliminary modelled LTD performances for 10, 20 and 30 years after the construction showed deposition and erosion patterns with similar distributions (Omer et al., 2019). Van Denderen et al. (2019) found that riverbed aggradation of some man-made side channels in the river Waal decreased about 5 years after their construction and later continued at a slower rate. Hence, similar timeframes could also apply to the development and stability of the LTD shore channels thus geomorphological monitoring should be continued in the future. Van Weerdenburg (2018) did an analysis of grain size distribution (Dso6; median grain diameter) of the LTD shore channels using sediment samples collected in 2017, the findings showed that for cross-sections of the river kilometers including the LTDs the mean Dso6 was not different from samples collected in 1995. In those samples, the sediment in the upstream section of the Ophemert shore channel consisted of 66% gravel (Van Weerdenburg, 2018). De Ruijsscher et al. (2020) found the Dso6 from 2017 sediment samples did not significantly differ between the main channel and the upstream section of the Ophemert shore channel with sediment fining downstream within that shore channel. Furthermore, mapping of the LTD substrate from side-scan sonar data and grab samples collected in 2019, showed that there was a coarser substrate (i.e. gravel) in the Ophemert shore channel, while the Wamel and Dreumel shore channels were dominated by finer substrate types (Flores et al., 2022). Moreover, elevation data for the main channel for the period 2015–2018 were found to be lower than in the LTD shore channels due mainly to accumulation of sediments in the deepest areas of the shore channels (Van Weerdenburg, 2018). This is consistent with our findings of aggregation towards the dams and near the inflow of the Ophemert shore channel.

Kleinhans (2002) suggested that rivers like the Waal could have considerable sediment transport occurring during low flow conditions through the mobilization of sand formations (i.e. ripples and dunes) and that gravel could be mobilized in dunes during peak flow conditions. Further, Flores et al. (2022) visually classified the substrates at the LTD shore channels using SSS backscatter images and sediment samples obtained from dunes composed of sand, gravel or mixed substrate. Flow conditions are a main driver of geomorphology, thus if the goal is to slow down riverbed aggradation in the shore channels it is essential to not limit the flow in the LTD shore channels, but to allow for continuous flow (Van Denderen et al., 2019). There were high water levels from peak river discharges (>3000 m³/sec) in the beginning of 2016 and 2018 (Figs. S7 and S8) and such discharges have the potential for more sediment mobilization (Kleinhans, 2002). Yet, the elevation datasets were collected in the fall and winter of those years and therefore the
immediate after effects of the high water levels on the sedimentary dynamics of the LTD shore channels were likely no longer noticeable. In the Wamel shore channel the erosion area showed continuous bed aggradation towards the dam even though the entire channel showed net sediment loss. The sill of the Wamel inflow was open in 2017, allowing more flow through the channel, and then it was completely closed from April 2018 onwards. Later in April 2020, a small opening was made in this sill (Personal communication with H. Eerden; project manager of RWS; 21 March 2022). The sill closure restricted the flow into the Wamel shore channel which could have contributed to the bed aggradation. This was also likely intensified by the location of this shore channel on the

**Figure 4.** Shoreline-linear length ratio (x-axis) graphs for all of the study sites per month (y-axis) and year (line colour) combination including (A) G1, (B) Wamel Sandy Area 1, (C) Wamel Erosion Area, (D) Wamel Sandy Area 2, (E) Dreumel Sandy Area 1, (F) Dreumel Erosion Area, (G) Dreumel Sandy Area 2, (H) Ophemert and (I) G2.
Table 3. Summary of the mean shoreline-linear length ratios for the mesohabitats evaluated in the river Waal.

| Parameter | G1     | G2     |
|-----------|--------|--------|
|           | Mean   | Mean   |
| Shoreline-| 1.20 ± | 1.12 ± |
| Linear    | 0.04   | 0.04   |
| Length Ratio | 1.30 ± | 1.05 ± |
| Area 1    | 0.12   | 0.02   |
| Sandy     | 1.01 ± | 1.24 ± |
| Erosion   | 0.02   | 0.14   |
| Area 2    | 1.24 ± | 1.12 ± |

The statistical analysis of the sediment ΔV per 200 m stretch suggested that the patterns of erosion and deposition in the shore channels have been stabilizing after their construction, since no significant differences in the ΔV were seen between the subsequent time periods. In fact, the longest shorelines and highest sediment losses were seen for the 2015–2016 period right after the construction of the LTDs and then it seems to stabilize. Later, the LTD shore channels seem to behave similarly from year after year even through yearly flooding events and an extreme flooding and draught event in 2018. Net erosion was seen in eight out of the nine mesohabitats for the entire study period (2015–2020). However, this kind of continuous geomorphologic behaviour, that is, yearly net gains and losses in specific locations (i.e. towards the dams, littoral zone) adding up to net losses for the entire study period, could also indicate current or eminent channel stability according to Newson (2002). Furthermore, the shore channels showed developmental characteristics consistent with those described by Frissell et al. (1986) for riverine reaches (i.e. bank erosion, aggradation and degradation). This temporal and spatial variation in sediment leads to habitat heterogeneity, which enhances biodiversity (Poff & Ward, 1990; Schlosser, 1991; Vannote et al., 1980).

Benthic macroinvertebrate communities in lowland river reaches have been improved by habitat restorations that allow for more natural geomorphological dynamics (Pedersen et al., 2014). For fish, the LTD shore channels may offer continuously varying geomorphological units that are required during early life stages or for transitory use, as riverine fish species are highly adapted to hydro- and geomorphological dynamics (Wolter et al., 2016). Aarts and Nienhuis (2003) found that in large rivers different fish species have also been found to prefer either erosional, intermediate or depositional environments. All these environments may be found within the LTD shore channels. Erosional, depositional and neutral areas seem to remain relatively constant through the study period at the LTD study sites, also suggesting habitat stability. The groyne areas on the other hand, seem to experience more dynamic changes in the spatial distribution of the sedimentary processes year to year. Fish assemblages have previously been shown to have higher population densities in the LTD shore channels than in the groyne fields (Collas et al., 2018). In lowland rivers, submerged macrophytes lower flow velocity and retain sediment. However, in spatially limited ecosystems, such as a shore channel,
Macrophytes often do not play a large geomorphological role (Verschoren, 2017). According to Collas et al. (2020), establishments of three semi-submerged or submerged macrophyte species, common water moss, hornwort and longroot smartweed (Fontinalis antipyretica, Ceratophyllum demersum and Persicaria amphibia respectively), have been observed mostly in the Wamel and Dreumel shore channels which have nutrient input from ongoing bank erosion and lower flow velocities than the Ophemert shore channel. Thunnissen et al. (2019) found that 50% of macrophyte species were negatively affected by ship induced fluctuations in flow velocity in the river Rhine, hence the protection of the littoral zone provided by the LTDs seems very important for macrophyte establishment. Therefore, these two shore channels and their distinct mesohabitats seem to offer the heterogeneity in abiotic parameters (i.e. substrate type, flow velocity) necessary for the establishment of macrophytes.

A limitation of the analysis was the missing 2017 dataset, which meant that two temporal comparisons could not be performed (i.e. 2016–2017 and 2017–2018); however, although this likely led to an overestimation of the 2016–2018 period volumes and limited the comparisons between yearly datasets, it did not impact the start- to end-comparison for the entire period (2015–2020). Another limitation is that the yearly datasets were not collected on the same month every year. The intervals varied between 11 and 16 months, leading to over- or underestimations of volumes for each period. Additionally, high net erosion was seen during the 2016–2018 period in the channel of the Wamel Sandy Area 1 and Dreumel Sandy Area 2 mesohabitats. The Dreumel and Wamel shore channels had 30 000 m$^3$ of sediment removed through dredging in April 2018. While the exact volumes removed from each shore channel are unknown (Personal communication with K. van Korlaar; technical manager of RWS; 11 March 2021), this likely resulted in an overestimation of the erosion during the 2016–2018 period of ~24% of the total erosion seen in these two shore channels. Also, long-term geomorphological consequences of the dredging are likely present in the 2019 and 2020 datasets and probably persist beyond the time period covered in this study. Since the dredging of sediments is a common maintenance and management measure for river channels, their development will likely repeatedly be impacted by this activity. Finally, our approach was based on yearly datasets which limited this analysis to large-scale geomorphological changes occurring through the entire study period (2015–2020) and was too sparse to give insight into short-term changes and processes (e.g. dredging volumes, the consequences of changes to the sills and the immediate after effects of floods).

**Retreat rate of the eroded bankline**

Data resolution commonly used to track bankline changes have been as low as 1 by 1 m in the past (Duró et al., 2018), hence the pixel size used in our study is not expected to have caused any major discrepancies. Some possible sources of error for the analysis are that the vertices were not completely parallel and the oblique distance was not added to the absolute distances between the vertices. The DTM showed erosion in the submerged areas right below the bankline. In ADCP data collected in 2019, Flores et al. (2022) found relatively low (~0.4–0.8 m/sec) near-bottom flow velocities towards the littoral zones of the LTD shore channels. This retreat process seems consistent with the three steps of bankline erosion described by Thorne and Tovey (1981) that take place during several peak flow events consisting of erosion at the bottom of the bank, failure of the top and erosion of the collapsed section.

The shoreline retreat rates at the two erosion areas in the Wamel and Dreumel shore channels behave similarly likely due to both sites being located on the inner bend of the river. Meandering is the natural dynamic state of lowland rivers and streams; this behaviour has been limited through modifications (i.e. groynes) and would normally involve bank erosion (Pedersen et al., 2014; Uehlinger et al., 2009; Walker & Cant, 1984; Wantzen et al., 2021). Channels of meandering streams are expected to migrate at a mean rate of 1% of their width per year (Walker & Rutherfurd, 1999). Based on the mean width of the shore channels in our study, the erosion is taking place at a slightly higher mean rate (i.e. ~1.8–2% shore channel widths per year). Walker and Rutherfurd (1999) found yearly channel migration rates as high as 6% channel widths; hence our migration rates are within these limits. Since most of the banks in the erosion areas are covered with herbaceous vegetation the lack of woody vegetation lowers bank stability (De Rose & Basher, 2011). Bank erosion is an essential process in riverine ecosystems as it curbs geomorphological dynamics, serves as a substrate source (i.e. sediment and woody debris), stimulates riparian vegetation succession and increases habitat heterogeneity (Florsheim et al., 2008). Additionally, monitoring of the biota in the LTD shore channels showed that the eroding banklines serve as habitats for beavers and birds (Collas et al., 2020).

**Shoreline length change**

The statistical analysis of the shoreline-linear length ratios suggested that sand-dominated mesohabitats had longer shorelines than the other mesohabitats assessed. The ratios were often slightly higher in July, August and
September, which suggested that longer shorelines often coincided with months of high biological productivity. This is important since longer shorelines give way to habitat heterogeneity that lessens the impacts of floods and provides refuge for fish species (Pearson et al., 1992; Wintersberger, 1996). Collas et al. (2018) found that in the LTD shore channels, fish densities were higher in July than in October, thus longer shorelines also seem to coincide with higher fish densities. Littoral areas provide many ecosystem services that enhance biodiversity, such as energy dispersion and the redistribution of organic matter (Strayer & Findlay, 2010). The LTD shore channels offer lateral movement of the shoreline into the floodplain during different water levels and hence appear to provide the heterogeneity and connectivity necessary for the development and functioning of riverine ecosystems. Junk et al. (1989) noted the importance of moving littoral zones in riverine ecosystems, which would allow high biological productivity through the prevention of water stagnation and the fast cycling of nutrients. Additionally, the LTD shore channels provide more continuous littoral zones (680–3188 m of continuous shorelines in one mesohabitat) than the traditional groyne fields (~200 m). This offers fish species the opportunity to avoid exposure to inland navigation effects (i.e. wave action and flow velocity fluctuations) by utilizing protected home ranges within the shore channels (Collas et al., 2018; Grift et al., 2003; Wolter et al., 2016; Zajicek et al., 2018).

Wintersberger (1996) related longer shorelines to higher Shannon–Wiener indices for fish diversity, which increases as both the fish species richness and evenness of abundances increase (Hixon & Brostoff, 1983; Shannon, 1948; Wintersberger, 1996). The study included both natural and heavily modified shorelines of another large European river (i.e. the Danube). The linear regression equation for this relation was used to estimate biodiversity indices per 100 m of river for each mesohabitat in this study. The estimated mean species diversity indices were relatively low for eight out of the nine mesohabitats assessed (<1) with the higher values (0.8–1.0) corresponding with the sand-dominated mesohabitats in the LTD shore channels (Hixon & Brostoff, 1983; Wintersberger, 1996). This suggests that these more heterogeneous shorelines should also host a higher number of aquatic species than the other mesohabitats. The findings correlate with data from Collas et al. (2018, 2020), showing that the shore channels have higher fish densities and diversity than surrounding groyne fields. In data collected using different sampling methods from 2016 to 2019, 36 fish species were observed in the shore channels while only 28 were observed in the main channel and groyne fields. From those samples, the majority of the fish caught in the LTD shore channels were juveniles including diadromous species, such as the Atlantic salmon (Salmo salar; Collas et al., 2020). Additionally, in 2021 endangered species such as the houting (Coregonus oxyrinchus) and European eel (Anguilla anguilla) were caught in the Dreumel shore channels during seine net sampling (Flores & Collas, 2021). A direct comparison between fish as monitored by Collas et al. (2020) and Flores and Collas (2021) and the various mesohabitats defined in this study was not possible since not all mesohabitats were monitored at the same times. Furthermore, macroinvertebrates, including rare species of mussels, mayflies and dragonflies, have also been observed to be more abundant and diverse in the LTD shore channels than in the groyne fields, this is aided in part by the accumulation of organic matter (Collas et al., 2020; Dorenbosch et al., 2018; Flores & Collas, 2021).

Habitats found in the river Waal include channels, river banks, softwood and hardwood forest, oxbow lakes, marshland and swamp forests (Duel et al., 2003). In addition to the different river bank types, a section of the bank in the Ophemert shore channel was observed to be colonized by reed (Collas et al., 2020). More complex, heterogeneous and relatively natural continuous habitats such as those observed along the LTD shore channels should provide a continuum of environmental variables and pockets of suitable habitats for the different life stages of riverine fauna, thus improving biodiversity in a multifunctional river (Erős & Bányai, 2020; Pätzig et al., 2018; Pearson et al., 1992; Stoffers et al., 2021; Strayer & Findlay, 2010; Wolter et al., 2016). Some sandy shorelines in the LTD shore channels, such as the Dreumel Sandy Area 2, also have established riparian vegetation (i.e. bushes and trees) which are partially submerged during high water providing further habitat complexity. Nonetheless, this vegetation is often removed to decrease resistance during flooding events, as the combination of higher elevations from sand dunes and woody vegetation could increase water levels (Duel et al., 2003). It is important to note that the boulder structures of the LTDs and groynes, which were excluded in this study, also serve as habitats for various aquatic species (Collas et al., 2018; Flores et al., 2022). The LTD shore channels would always have longer shorelines than the groyne fields if these walls were included. Furthermore, it is noteworthy to mention that the physical development and quality of riverine habitats are also dependent on other abiotic parameters such as water temperature, flow velocity, water depth, light intensity, dissolved oxygen and inland navigation effects, all of which may also affect fauna and flora, but were beyond the scope of this study (Collas et al., 2018, 2020; Grift et al., 2003; Junk et al., 1989; Stoffers et al., 2021; Strayer & Findlay, 2010; Vannote et al., 1980).
In the future, the development of longer shorelines should be encouraged by river managers in order to secure higher biodiversity in these novel habitats. This should fall within a decision-making process that not only secures the development of complex habitats to improve ecology, but also financially weights in the future effects of climate change, new restoration projects and the maintenance of the main channel for navigation in a complete evaluation of river functions such as that completed by Hiemstra et al. (2020). This should also include the repair and maintenance of old restoration projects which have been shown to lose their ecological functions over time (Stoffers et al., 2021). Such an approach may help to secure the multifunctionality of heavily modified rivers in the future.

Conclusions

The LTD shore channels showed a general pattern of riverbed aggradation towards the dams and degradation or bank erosion towards the littoral zones. From 2015 to 2020, there was net sediment loss in all three shore channels with Wamel having the least and Dreumel the most. The bank erosion areas in the Wamel and Dreumel shore channels had mean retreat rates of 1.4 and 1.6 m/year respectively. Sand-dominated shoreline mesohabitats in the LTD shore channels provided longer shorelines than other mesohabitats. These rehabilitation measures have the potential to provide more complex, heterogeneous and relatively natural continuous littoral zones for biota than traditional groyne fields without compromising the multifunctionality of the river. The development of sandy shorelines in the LTDs shore channels should be encouraged through management in order to enhance biodiversity. Hydrogeomorphological monitoring of the shore channels should be continued in the future with the simultaneous monitoring of biota and other abiotic parameters that affect habitat quality and development in order to detect any changes in the ecological functionality and geomorphological processes within these novel habitats.

Acknowledgements

Rijkswaterstaat (RWS) Oost Nederland financially supported this study (RWS reference number 31153573). We are very thankful to Daniël van Putten (RWS) for providing the water level data and valuable advice for the shoreline length analysis. Special thanks to Bert Go (RWS) for his help in procuring the datasets and to Margriet Schoor (RWS) and Henk Eerden (RWS) for their valuable guidance and suggestions during the completion of this study.

References

Aarts, B.G. & Nienhuis, P.H. (2003) Fish zonations and guilds as the basis for assessment of ecological integrity of large rivers. Hydrobiologia, 500, 157–178. doi:10.1023/A:1024638726162

Amiri-Simkooei, A., Snellen, M. & Simons, D.G. (2009) Riverbed sediment classification using multi-beam echosounder backscatter data. The Journal of the Acoustical Society of America, 126(4), 1724–1738. https://doi.org/10.1121/1.3205397

Benjamini, Y. & Hochberg, Y. (1995) Controlling the false discovery rate: a practical and powerful approach to multiple testing. Journal of the Royal Statistical Society: Series B (Methodological), 57, 289–300. https://doi.org/10.1111/j.2517-6161.1995.tb00203.x

Boak, E. & Turner, I. (2005) Shoreline definition and detection: a review. Journal of Coastal Research, 21, 688–703. https://doi.org/10.2112/03-0071.1

Busnelli, M., Schuurman, F., Sieben, A., Van der Wal, M. & Huub, H. (2011) Morphodynamic responds of groyne fields to the lowering of crest level of the groyne in the Waal River, The Netherlands. River, Coastal and Estuarine Morphodynamics, RCEM2011, 1450–1463.

Cartwright, D.S. & Clarke, J.E.H. (2002) Multibeam surveys on the Fraser River Delta, coping with an extreme refraction environment. Canadian Hydrographic Association. Proceedings of the Canadian Hydrographic Conference, Ottawa, Canada.

Charlton, M.E., Large, A.R.G. & Fuller, I.C. (2003) Application of airborne LiDAR in river environments: the River Coquet, Northumberland, UK. Earth Surface Processes and Landforms, 28, 299–306. https://doi.org/10.1002/esp.482

Collas, F.P.L. (2019) Preferences and bottlenecks – predicting riverine species occurrences under changing abiotic conditions. PhD dissertation, Radboud University, pp. 228.

Collas, F.P.L., Buijse, A.D., Van den Heuvel, L., Van Kessel, N., Schoor, M.M., Erden, H. et al. (2018) Longitudinal training dams mitigate effects of shipping on environmental conditions and fish density in the littoral zones of the river Rhine. Science of the Total Environment, 619–620, 1183–1193. https://doi.org/10.1016/j.scitotenv.2017.10.299

Collas, F.P.L., Flores, N.Y., Van Aalderen, R., Bosman, F., Schoor, M.M., Verbrugge, L.N.H. et al. (2020) Rapportage natuurgegevens langsdammen Waal 2016–2020. Series of reports on animal ecology and physiology 2020–2. Nijmegen: Radboud University, pp. 44–83 (in Dutch).

Costa, B., Battista, T. & Pittman, S. (2009) Comparative evaluation of airborne LiDAR and ship-based multibeam SoNAR bathymetry and intensity for mapping coral reef ecosystems. Remote Sensing of Environment, 113, 1082–1100. https://doi.org/10.1016/j.rse.2009.01.015

De Rose, R.C. & Basher, L.R. (2011) Measurement of river bank and cliff erosion from sequential LIDAR and historical
aerial photography. *Geomorphology*, **126**(1–2), 132–147. https://doi.org/10.1016/j.geomorph.2010.10.037

De Ruijsscher, T., Hoitink, A.J., Naqshband, S. & Paarberg, A.J. (2019) Bed morphodynamics at the intake of a side channel controlled by sill geometry. *Advances in Water Resources*, **134**, 103452. https://doi.org/10.1016/j.adwatre.2019.103452

De Ruijsscher, T., Naqshband, S. & Hoitink, T. (2018) Flow bifurcation at a longitudinal training dam: effects on local morphology. ESS Web of Conferences, *River Flow 2018*, 40, 05020. https://doi.org/10.1051/esconf/20184005020

De Ruijsscher, T.V., Vermeulen, B. & Hoitink, A.J.F. (2020) Diversion of flow and sediment towards a side channel separated from a river by a longitudinal training dam. *Water Resources Research*, **56**(6), e2019WR026750. https://doi.org/10.1029/2019WR026750

Dinn, D.F., Loncarevic, B.D. & Costello, G. (1995) The effect of sound velocity errors on multibeam sonar depth accuracy. Institute of Electrical and Electronics Engineers. *Proceedings of the OCEANS’95 MTS/IEEE Conference*, San Diego, USA, pp. 1001–1010. https://doi.org/10.1109/OCEANS.1995.528595

Dorenbosch, M., Van Kessel, N. & Collas, F. (2018) Kritische benthische soorten in de Waal. Onderzoek naar het voorkomen van larvale rivier- en zeeprik, rivierrombout en volwassenen naajden. Bureau Waardenburg Rapportnummer 18-038. Bureau Waardenburg, Culemborg, pp. 38–40 (in Dutch).

Duel, H., Van der Lee, G.E.M., Penning, W.E. & Baptist, M.J. (2003) Habitat modelling of rivers and lakes in The Netherlands: an ecosystem approach. *Canadian Water Resources Journal*, **28**, 231–247. https://doi.org/10.2429/cwrj2802231

Duró, G., Crosato, A., Kleinmans, M.G. & Uijttewaal, W.S. (2018) Bank erosion processes measured with UAV-SfM along complex banklines of a straight mid-sized river reach. *Earth Surface Dynamics*, **6**, 933–953. https://doi.org/10.5194/esurf-6-933-2018

Eerden, H. (2013) Pilot langsdammen Waal: projectplan realisatiefase II monitoren & inregelen – projectfase MIRT4. Concept Projectplan versie 1.0. Bijlage D: Monitoringplan Pilot Langsdammen Waal. Ministerie van Infrastructuur en Milieu, Rijkswaterstaat Oost Nederland, Arnhem (in Dutch).

Eleftherakis, D., Snellen, M., Amirí-Simkooei, A., Simons, D.G. & Siemes, K. (2014) Observations regarding coarse sediment classification based on multi-beam echo-sounder’s backscatter strength and depth residuals in Dutch rivers. *Journal of the Acoustical Society of America*, **135**, 3305–3315. https://doi.org/10.1121/1.4875236

El-Hattab, A.I. (2014) Single beam bathymetric data modelling techniques for accurate maintenance dredging. *The Egyptian Journal of Remote Sensing and Space Science*, **17**(2), 189–195. https://doi.org/10.1016/j.ejrs.2014.05.003

Environmental Systems Research Institute (ESRI) (n.d.a) Surface volume (3D Analyst). ESRI. Available at: https://pro.arcgis.com/en/pro-app/tool-reference/3d-analyst/surface-volume.htm#L [Accessed 14th January 2020].

Environmental Systems Research Institute (ESRI) (n.d.b) Generate near table (Analysis). ESRI. Available at: https://pro.arcgis.com/en/pro-app/tool-reference/analysis/generate-near-table.htm [Accessed 20th January 2020].

Faux, R.N., Buffington, J.M., Whitley, M.G., Lanigan, S.H. & Roper, B.B. (2009) Use of airborne near-infrared LiDAR for determining channel cross-section characteristics and monitoring aquatic habitat in Pacific Northwest rivers: a preliminary analysis. In: Bayer, J.M. & Schei, J.L. (Eds.) *Remote sensing applications for aquatic resource monitoring*. Cook: Pacific Northwest Aquatic Monitoring Partnership (PNAMP) special publication, pp. 43–60.

Flores, N.Y. & Collas, F.P.L. (2021) Mitigation of inland navigation effects on biodiversity by longitudinal training dams. Series of Reports on Animal Ecology and Physiology 2021–9. Nijmegen: Radboud University, pp. 36–46.

Flores, N.Y., Collas, F.P.L., Mehler, K., Schoor, M.M., Feld, C.K. & Leuven, R.S.E.W. (2022) Assessing habitat suitability for native and alien freshwater mussels in the river Waal (The Netherlands), using hydroacoustics and species sensitivity distributions. *Environmental Modeling & Assessment*, **27**, 187–204. https://doi.org/10.1007/s10666-021-09776-4

Florsheim, J.L., Mount, J.F. & Chin, A. (2008) Bank erosion as a desirable attribute of rivers. *Bioscience*, **58**(6), 519–529. https://doi.org/10.1641/B380608

Frissell, C.A., Liss, W.J., Warren, C.E. & Hurley, M.D. (1986) A hierarchical framework for stream habitat classification: viewing streams in a watershed context. *Environmental Management*, **10**(2), 199–214. https://doi.org/10.1007/BF01867358

Gens, R. (2010) Remote sensing of coastlines: detection, extraction and monitoring. *International Journal of Remote Sensing*, **31**(7), 1819–1836. https://doi.org/10.1080/01431160902926673

Grift, R., Buijse, A.D., Van Densen, W., Machiels, M., Kranenbarg, J., Breteler, J. et al. (2003) Suitable habitats for 0-group fish in rehabilitated floodplains along the River Rhine. *River Research and Applications*, **19**, 353–374. https://doi.org/10.1002/rra.711

Grove, J.R., Croke, J. & Thompson, C. (2013) Quantifying different riverbank erosion processes during an extreme
flood event. *Earth Surface Processes and Landforms*, 38, 139–1406. https://doi.org/10.1002/esp.3386

Hamilton, H., Brim Box, J. & Dorazio, R.M. (1997) Effects of habitat suitability on the survival of relocated freshwater mussels. *Regulated Rivers: Research & Management*, 13, 537–541. https://doi.org/10.1002/rrr.3450110204

Hastie, L.C., Boon, P.J. & Young, M.R. (2000) Physical microhabitat requirements of freshwater pearl mussels, *Margaritifera* (L.). *Hydrobiologia*, 429, 59–71. https://doi.org/10.1023/A:1004068412666

Havinga, H. (2020) Towards sustainable river management of the Dutch Rhine River. *Water*, 12, 1827. https://doi.org/10.3390/w12061827

Hiemstra, K.S., Van Vuren, S., Vinke, F.S.R., Jorissen, R. & Kok, M. (2020) Assessment of the functional performance of lowland river systems subjected to climate change and large-scale morphological trends. *International Journal of River Basin Management*, 1–22. https://doi.org/10.1080/15715124.2020.1790580

Hixon, M.A. & Brostoff, W.N. (1983) Damselfish as keystone species in reverse: intermediate disturbance and diversity of reef algae. *Science*, 220, 511–513. https://doi.org/10.1126/science.220.4596.511

Hoffmans, G.J.C.M. & Verheij, H.J. (1997) Scour manual. Rotterdam: A.A. Balkema, pp. 156–162.

Huizinga, R.J. (2010) Bathymetric surveys at highway bridges crossing the Missouri River in Kansas City, Missouri, using a multibeam echo sounder, 2010. Report 2010-5207. U.S. Geological Survey, Reston, pp. 61.

Junk, W.J., Bayley, P.B. & Sparks, R.E. (1989) The flood pulse concept in river-floodplain systems. *Canadian Special Publication of Fisheries and Aquatic Sciences*, 106, 110–127.

Kennedy, D.M., Ierodiaconou, D. & Schmel, A. (2014) Granitic coastal geomorphology: applying integrated terrestrial and bathymetric LiDAR with multibeam sonar to examine coastal landscape evolution. *Earth Surface Processes and Landforms*, 39, 1663–1674. https://doi.org/10.1002/esp.3615

Kessler, A.C., Gupta, S. & Brown, M.K. (2013) Assessment of river bank erosion in Southern Minnesota rivers post European settlement. *Geomorphology*, 201, 312–322. https://doi.org/10.1016/J.GEOMORPH.2013.07.006

Khan, N.I. & Islam, A. (2003) Quantification of erosion patterns in the Brahmaputra-Jamuna River using geographical information system and remote sensing techniques. *Hydrological Processes*, 17, 959–966. https://doi.org/10.1002/hyp.1173

Kinzel, P.J., Legleiter, C.J. & Grams, P.E. (2021) Field evaluation of a compact, polarizing topo-bathymetric LiDAR across a range of river conditions. *River Research and Applications*, 37, 513–543. https://doi.org/10.1002/rra.3771

Kleinhans, M. (2002) Sorting out sand and gravel: sediment transport and deposition in sand-gravel bed rivers. PhD dissertation. Netherlands Geographical Studies, 293. The Royal Dutch Geographical Society, Utrecht University, pp. 20–28.

Lehotský, M., Rusnák, M. & Kidová, A. (2017) Application of remote sensing and the GIS in interpretation of river geomorphic response to floods. In: Radecki-Pawlik, A., Pagliara, S., Hradecký, J. & Hendrickson, E. (Eds.) *Open channel hydraulics, river hydraulics structures and fluvial geomorphology*. Boca Raton: Taylor & Francis Group, pp. 388–399.

Marks, K. & Bates, P. (2000) Integration of high-resolution topographic data with floodplain flow models. *Hydrological Processes*, 14(11–12), 2109–2122. https://doi.org/10.1002/1099-1085(20000815/30)14:11/123.0.CO;2-1

Middelkoop, H. (2002) Application of remote sensing and GIS-based modelling in the analysis of floodplain sedimentation. In: Leuven, R.S.E.W., Poudveigne, I. & Teeuw, R.M. (Eds.) *Application of geographic information systems and remote sensing in river studies*. Leiden: Backhuys Publishers, pp. 95–117.

Muste, M., Kim, D. & Merwade, V. (2012) Modern digital instruments and techniques for hydrodynamic and morphologic characterization of river channels. In: Church, M., Biron, P.M. & Roy, A.G. (Eds.) *Gravel-bed rivers: processes, tools, environments*. Chichester: John Wiley & Sons, Ltd, pp. 315–341.

Newson, M.D. (2002) Geomorphological concepts and tools for sustainable river ecosystem management. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 12, 365–379. https://doi.org/10.1002/aqc.532

Newton, T.J., Zigler, S.J., Schrank, P.R., Davis, M. & Smith, D.R. (2020) Estimation of vital population rates to assess the relative health of mussel assemblages in the Upper Mississippi River. *Freshwater Biology, 65*, 1726–1739. https://doi.org/10.1111/fwb.13575

Omer, A., Ottevanger, W. & Yossef, M. (2019) Modelling the morphological effects of longitudinal dams in the Midden-Waal. Reference 11203681-002. Deltares, Delft, pp. 45–51.

Parthasarathy, K.S.S., Subbarayan, S. & Abijith, D. (2018) Shoreline change detection using geo-spatial techniques- A case study for Cuddalore Coast. 6th International Symposium on Advances in Civil and Environmental Engineering Practices for Sustainable Development (ACEPS), Galle, Sri Lanka, pp. 33–39.

Pitzig, M., Vademoncœur, Y. & Bruns, M. (2018) Lakeshore modification reduces secondary production of macroinvertebrates in littoral but not deeper zones. *Freshwater Science*, 37, 845–856. https://doi.org/10.1086/700885

Pearson, T.N., Hiran, W.L. & Lamberti, G.A. (1992) Influence of habitat complexity on resistance to flooding and resilience of stream fish assemblages. *Transactions of the American Fisheries Society*, 121, 427–436. https://doi.org/10.1577/1548-8659(1992)121<0427:OHCOR>2.3.CO;2

Pedersen, M.L., Kristensen, K.K. & Friberg, N. (2014) Re-meandering of lowland streams: will disobeying the laws of...
geomorphology have ecological consequences? *PLoS One*, **9**(9), e108558. https://doi.org/10.1371/journal.pone.0108558

Poff, N. & Ward, J. (1990) Physical habitat template of lotic systems: recovery in the context of historical pattern of spatiotemporal heterogeneity. *Environmental Management*, **14**, 629–645. https://doi.org/10.1007/BF02394714

R Core Team. (2021) *R: a language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing. Available at: https://www.R-project.org/ [Accessed 20th April 2021]

Raat, A.J.P. (2001) Ecological rehabilitation of the Dutch part of the River Rhine with special attention to the fish. *Regulated Rivers: Research & Management*, **17**, 131–144. https://doi.org/10.1002/rrr.608

Rhoades, E.L., O’Neal, M. & Pizzuto, J.E. (2009) Quantifying bank erosion on the South River from 1937 to 2005, and its importance in assessing Hg contamination. *Applied Geography*, **29**, 125–134. https://doi.org/10.1016/J.PRAGEOG. 2008.08.005

Rijke, J., Herk, S., Zevenbergen, C. & Ashley, R. (2012) Room for the River: delivering integrated river basin management in The Netherlands. *International Journal of River Basin Management*, **10**, 369–382. https://doi.org/10.1080/15715124.2012.739173

Rijkswaterstaat Oost-Nederland. (2019) Betrekkingslijnen_2018_h-Lobith_650-1780_rkm. Rijkswaterstaat Oost Nederland, Arnhem (in Dutch).

Schinberger, R., Trautwein, C., Melcher, A. & Schmutz, S. (2012) Multiple human pressures and their spatial patterns in European running waters. *Water and Environmental Journal*, **26**, 261–273. https://doi.org/10.1111/j.1747-6593.2012.00285.x

Schlosser, L.J. (1991) Stream fish ecology: a landscape perspective: land use, which influences the terrestrial-aquatic interface, can affect fish populations and their community dynamics. *Bioscience*, **41**, 704–712. https://doi.org/10.2307/1311765

Shannon, C.E. (1948) A mathematical theory of communication. *Bell System Technical Journal*, **27**, 379–423.

Stoffers, T., Collas, F.P.L., Buijs, A.D., Geerling, G.W., Jans, L., Van Kessel, N. et al. (2021) 30 years of large river restoration: how long do restored floodplain channels remain suitable for targeted rheophilic fishes in the lower river Rhine? *Science of the Total Environment*, **755**, https://doi.org/10.1016/j.scitotenv.2020.142931

Strayer, D.L. & Findlay, S.E.G. (2010) Ecology of freshwater shore zones. *Aquatic Sciences*, **72**, 127–163. https://doi.org/10.1007/s00027-010-0128-9

Thoma, D.P., Gupta, S.C., Bauer, M.E. & Kirchoff, C.E. (2005) Airborne laser scanning for riverbank erosion assessment. *Remote Sensing of Environment*, **95**, 493–501. https://doi.org/10.1016/j.rse.2005.01.012

Thorne, C.R. & Tovey, N.K. (1981) Stability of composite river banks. *Earth Surface Processes and Landforms*, **6**, 469–484. https://doi.org/10.1002/esp.3290060507

Thunnissen, N.W., Collas, F.P.L., Hendriks, A.J. & Leuven, R.S.E.W. (2019) Effect of shipping induced changes in flow velocity on aquatic macrophytes in intensively navigated rivers. *Aquatic Botany*, **159**, 103–145. https://doi.org/10.1016/j.aquabot.2019.103145

Uehlinger, U., Wantzen, K., Leuven, R.S.E.W. & Arndt, H. (2009) The Rhine river basin. In: Tockner, K., Uehlinger, U. & Robinson, C.T. (Eds.) *Rivers of Europe*. London: Academic Press, pp. 199–245.

Vadas, R.L. & Orth, D.J. (1998) Use of physical variables to discriminate visually determined mesohabitat types in North American streams. *Rivers*, **6**, 143–159.

Van Denderen, R.P., Schielen, R.M.J., Westerhof, S.G., Quartel, S. & Hulscher, S.J.M.H. (2019) Explaining artificial side channel dynamics using data analysis and model calculations. *Geomorphology*, **327**, 93–110. https://doi.org/10.1016/j.geomorph.2018.10.016

Van Stokkom, H., Smits, A. & Leuven, R.S.E.W. (2005) Flood defense in The Netherlands: a new era, a new approach. *Water International*, **30**, 76–87. https://doi.org/10.1080/02508060508691839

Van Weerdenburg, R.J.A. (2018) Measured change in bed elevation and surface texture near longitudinal training dams in the Waal River. Honours programme master thesis. Delft University of Technology, pp. 11–36.

Vannote, R.L., Minshall, G.W., Cummins, K.W., Seden, J.R. & Cushing, C.E. (1980) The river continuum concept. *Canadian Journal of Fisheries and Aquatic Sciences*, **37**, 130–137. https://doi.org/10.1139/f80-017

Verbrugge, L.N.H., Ganzvoort, W., Fliervoet, J.M., Panten, K. & Van den Born, R.J.G. (2017) Implementing participatory monitoring in river management: the role of stakeholders’ perspectives and incentives. *Journal of Environmental Management*, **195**, 62–69. https://doi.org/10.1016/j.jenvman.2016.11.035

Verschooren, V. (2017) Spatial pattern formation of macrophytes: an integrated model for the management of lowland rivers. PhD dissertation. University of Antwerp, p. 119.

Walker, M. & Rutherford, I. (1999) An approach to predicting rates of bend migration in meandering alluvial streams. CRC for Catchment Hydrology, Monash University. Proceedings of the Second Australian Stream Management Conference, Adelaide, South Australia, pp. 659–665.

Walka, R.G. & Cant, D.J. (1984) Sandy fluvial systems. In: Walker, R.G. (Ed.) *Facies models*. Hamilton: Geoscience Canada, p. 72.

Wantzen, K.M., Uehlinger, U., Van der Velde, G., Leuven, R.S.E.W., Schmitt, L. & Beisel, J.N. (2021) The Rhine river basin. In: Tockner, K., Zarfl, C. & Robinson, C.T. (Eds.) *Rivers of Europe*, 2nd edition. London: Academic Press, pp. 331–389.

Ward, J., Tockner, K., Arscott, D. & Clare, C. (2002) Riverine landscape diversity. *Freshwater Biology*, **47**, 517–539. https://doi.org/10.1046/j.1365-2427.2002.00893.x
Wintersberger, H. (1996) Spatial resource utilization and species assemblages of larval and juvenile fishes. *Large Rivers*, 11(1), 29–44. https://doi.org/10.1127/lr/11/1996/29

Wolter, C., Buijse, A.D. & Parasiewicz, P. (2016) Temporal and spatial patterns of fish response to hydromorphological processes. *River Research and Applications*, 32, 190–201. https://doi.org/10.1002/rra.2980

Zajicek, P., Johannes, R. & Wolter, C. (2018) Disentangling multiple pressures on fish assemblages in large rivers. *Science of the Total Environment*, 627, 1093–1105. https://doi.org/10.1016/j.scitotenv.2018.01.307

**Supporting Information**

Additional supporting information may be found online in the Supporting Information section at the end of the article.

**Table S1.** Summary of RWS datasets used for the analysis.

**Figure S1.** Subtraction DTMs map of the study sites in the river Waal for the period 2014–2015 for the (A) groyne field area 1 (G1), (B) Wamel shore channel, (C) Dreumel shore channel, (D) Ophemert shore channel and (E) groyne field area 2 (G2).

**Figure S2.** Subtraction DTMs map of the study sites in the river Waal for the period 2015–2016 for the (A) groyne field area 1 (G1), (B) Wamel shore channel, (C) Dreumel shore channel, (D) Ophemert shore channel and (E) groyne field area 2 (G2). Additionally, profiles of the eroding banklines are shown for the (F) Wamel and (G) Dreumel shore channels.

**Table S2.** The $\Delta V$ (m$^3$) per 200 m of the study sites per yearly subtraction.

**Figure S3.** Subtraction DTMs map of the study sites in the river Waal for the period 2016–2018 for the (A) groyne field area 1 (G1), (B) Wamel shore channel, (C) Dreumel shore channel, (D) Ophemert shore channel and (E) groyne field area 2 (G2).

**Figure S4.** Subtraction DTMs map of the study sites in the river Waal for the period 2018–2019 for the (A) groyne field area 1 (G1), (B) Wamel shore channel, (C) Dreumel shore channel, (D) Ophemert shore channel and (E) groyne field area 2 (G2).

**Figure S5.** Subtraction DTMs map of the study sites in the river Waal for the period 2019–2020 for the (A) groyne field area 1 (G1), (B) Wamel shore channel, (C) Dreumel shore channel, (D) Ophemert shore channel and (E) groyne field area 2 (G2).

**Figure S6.** Digitized banklines for the erosion areas in shore channels at Wamel (top) and Dreumel (bottom) in the river Waal.

**Figure S7.** River discharge at the Tiel RWS monitoring station in the river Waal for the 2014–2020 period (www.waterinfo.rws.nl).

**Figure S8.** Water level at the Tiel RWS monitoring station in the river Waal for the 2014–2020 period (www.waterinfo.rws.nl).

**Table S3.** Results ($P$-values) of the pairwise-comparison of the $\Delta V$ (m$^3$) per 200 m stretch between time periods using Wilcoxon Rank Sum test.

**Table S4.** Results ($P$-values) of the pairwise-comparison of the shoreline-linear length ratio between mesohabitats using Wilcoxon Rank Sum test.