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Longitudinal training dams mitigate effects of shipping on environmental conditions and fish density in the littoral zones of the river Rhine

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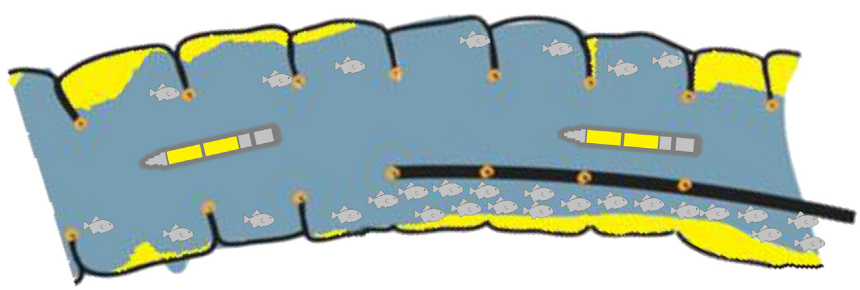
HIGHLIGHTS

- Impacts of passing ships on abiotic conditions in the littoral zone of rivers were reduced in shore channels behind LTD.
- Flow stability was enhanced in the shore channel along the LTD compared to traditional groyne fields.
- Fish densities in the littoral zone of the LTD shore channel were significantly higher compared to traditional groyne fields.
- Fish densities in stony habitats along the LTD increased linearly with distance to dynamic sections (such as in- and outlet).
- LTDs allow for ecological rehabilitation of littoral zones of navigated rivers while enabling multiple uses and flood safety.

GRAPHICAL ABSTRACT



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ABSTRACT

The stability of habitat conditions in littoral zones of navigated rivers is strongly affected by shipping induced waves and water displacements. In particular, the increase of variability in flow conditions diminishes the suitability of these habitats for juvenile fishes. Recently, a novel ecosystem based river management strategy has resulted in the replacement of traditional river training structures (i.e., groynes) by longitudinal training dams (LTDs), and the creation of shore channels in the river Waal, the main, free-flowing and intensively navigated distributary of the river Rhine in the Netherlands. It was hypothesized that these innovative LTDs mitigated the effects of shipping on fishes by maintaining the natural variability of habitat conditions in the littoral zones during ship passages whereby shore channels served as refugia for juvenile fishes. Measurements of abiotic conditions showed a significantly lower water level fluctuation and significantly higher flow stability in shore channels compared to groyne fields. Flow velocity did not differ, nor did the variation in flow velocity fluctuation during ship passage between these habitats. Densities of fish were found to be significantly higher in the littoral zones of shore channels compared to nearby groyne fields. Moreover, electrofishing along the inner side of the newly constructed LTD showed a significant linear relationship between fish density and distance from highly dynamic in-

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River training
Water level fluctuations

and outflow sections and to lowered inflow sections in the LTD. Results of our field sampling clearly indicate successful ecological rehabilitation of littoral zones that coincides with a facilitation of navigation in the main river channel and increased flood safety.

1. Introduction

Biodiversity and functioning of riverine ecosystems are increasingly threatened by overexploitation of water and organisms, water pollution, modification of flow, habitat destruction, introduction of invasive alien species and the overarching effect of climate change (Malmqvist and Rundle, 2002; Dudgeon et al., 2006; Leuven et al., 2009; Vaughn, 2010; Arthington et al., 2010).

One of the major causes of habitat degradation in large rivers is the facilitation of navigation through extensive channelization, dredging and the construction of embankments (Gregory, 2006; Kucera-Hirzinger et al., 2009). These measure result in reduced channel sinuosity and habitat diversity. In addition to these impacts, navigation itself affects riverine habitats and biodiversity through increased wave action, shear stress, flow velocity and sediment resuspension (Ten Brinke et al., 1999, 2004; Söhngen et al., 2008; Kucera-Hirzinger et al., 2009; Hofmann et al., 2011; Gabel et al., 2017). Direct and indirect navigation pressures are expected to increase in the near future as inland shipping is considered more sustainable than road transport (Colvile et al., 2001; Rohács and Simongáti, 2007; European Commission, 2011; Gabel et al., 2017).

The decline in habitat diversity due to navigation is characterized by a deterioration in spawning and nursery habitats that results in decreased diversity and productivity of migratory and riverine fishes (Wolter and Arlinghaus, 2003). Navigation is facilitated by, among other things, the construction of groynes with basalt stones and other rocks (Brunke et al., 2002). These groynes provide habitat for several alien species (Leuven et al., 2009; Van Kessel et al., 2016) and are often characterized by an impoverished fish community dominated by alien species (Fladung et al., 2003; Dorenbosch et al., 2017). Conditions in groyne fields are influenced by shipping (Ten Brinke et al., 1999), increasing wave action and flow velocity. These highly dynamic conditions affect the early life history stages of fishes (Kucera-Hirzinger et al., 2009; Schludermann et al., 2014) and limits the swimming performance of adult fishes (Wolter and Arlinghaus, 2003).

The implementation of the Water Framework Directive (Water Framework Directive, 2000/60/EC) changed the focus of river management from technological to sustainable management taking ecological values into account (Nienhuis et al., 2002). In the Netherlands, the WFD culminated in the 'Room for the River' programme that aims at an integrated river basin management approach (Van Stokkom et al., 2005; Rijke et al., 2012). As part of the 'Room for the River' programme the majority of existing groynes in the river Waal, the main branch of the river Rhine, were lowered and existing groynes over a 10 km long stretch in the inner bend of the river were replaced by three longitudinal training dams (LTDs) (Huthoff et al., 2011; Rijkswaterstaat Oost Nederland, 2011; Verbrugge et al., 2017).

LTDs are novel river training structures that are placed parallel to the river bank thereby protecting the littoral zones from navigation induced impacts. It has been suggested that these river training structures decrease the impact of navigation and improve the variety of habitats and density of fishes (Kucera-Hirzinger et al., 2009; Vermeulen et al., 2014). Recently, LTDs have been built in the rivers Elbe, Loire and Rhine, with the aim of maintaining a minimum water depth for navigation (Paalvast, 1995; Brabender et al., 2016). The LTDs in the river Waal were constructed for multiple functions: 1) to increase and maintain the minimum water depth for navigation, 2) to increase discharge capacity for improved flood safety, 3) to facilitate the safe discharge of ice to protect hydraulic infrastructure and river dikes, 4) to reduce fairway maintenance costs (dredging), and 5) to increase habitat diversity and stability by creating sheltered shore channels (Eerden, 2013).

This study aims to assess the influence of the LTD on abiotic conditions and fish density during two seasons characterized by different water levels. We hypothesize that the impact of navigation on flow velocity, water level fluctuation and flow stability behind the LTD is lower than in traditional groyne fields. Moreover, fish density is expected to be higher in the LTD shore channel as the impact of passing ships is expected to be relatively low. From these hypotheses the following research questions have been derived: Does the impact of navigation on flow velocity, water level fluctuation and flow stability differ between groyne fields and the LTD? How does a decrease in the influence of navigation affect fish density near river training structures? In order to answer these questions measurements of abiotic conditions in river training structures were made and fishes were monitored using seine nets and electrofishing equipment.

2. Methods

2.1. Study sites

Monitoring was performed in the lowland river Waal, the largest, free-flowing distributary of the river Rhine in the Netherlands (Fig. 1a, b). The river Waal is intensively navigated with one of the highest shipping frequencies of all inland waterways in the world (Ten Brinke et al., 1999). Three LTDs have been constructed in the river Waal from river km 911 to 922. The first and second LTD, situated on the left bank, are 3 and 4 km long, respectively (Fig. 2a). The third LTD on the right bank is 3 km long. Each LTD features an in- and outflow, and divides the river into a main channel for commercial navigation and a shore channel where only recreational navigation is allowed (Fig. 1c, d). Along specific sections, the LTDs are lowered by a meter and are more porous, allowing a lateral exchange of sediment, water and biota (Fig. 1e). However, these openings may reduce the shelter effect of the LTD as navigation induced waves may pass through. The first and second LTDs have two lowered sections, whereas the third LTD has one lowered section (Fig. 2a; Supplementary information: Fig. S1). Taking into account the water level fluctuations over the last six years, the longitudinal training dam would have been visible above the waterline for 300 days a year, on average ($\pm$31 days; Supplementary information: Fig. S2). The lowered section would have been visible above the waterline exposed for 211 days, on average ($\pm$51 days; Supplementary information: Fig. S2).

2.2. Navigation induced changes in environmental conditions

Measurements of navigation induced effects on flow velocity, wave action and flow stability were measured at five sites spread throughout Location 5 in the littoral zone directly behind the lowered part of the LTD (Fig. 2a, c, f). This section was most exposed to the potential effects of navigation. Reference measurements were performed at five sites spread throughout location 7 in the littoral zone of a traditional groyne field (Fig. 2b, e). Measurements were performed when the lowered section of the LTD was 1) below and 2) above the water level i.e., < and > + 4.4 m ASL at gauging station Tiel, respectively (Fig. 1e).

A pressure sensor (Water Level Data Logger, Onset HOBO) was used to measure the pressure of the water column at a 1 Hz rate at each of the five measurement sites within each location. The measurements indicated waves generated by navigation and variability in discharge. An additional pressure sensor (Water Level Data Logger, Onset HOBO) was placed in the open air to measure barometric pressure. These measurements were used to transform the pressure measurements of the water column into water levels. Flow stability was measured at one site (S3; Fig. 2e and f) approximately 15 cm above the river bed using a g-force logger (G data logger, Onset HOBO). The position of the logger in the water column on the x, y and z axes was measured at a 1 Hz rate over 1 h. Flow velocity was measured at a 1 Hz rate for at least 5 min at each measurement site within each location using an open channel flow meter (Valeport, model 002). The meter was held 15 cm above the bed surface, perpendicular to the main channel to measure the effect of incoming waves caused by navigation on flow velocity.

A subset of 5 min of data was assigned to every passing ship for flow velocity and water level measurements. Subsets without ship effects were constructed by using the data of time frames without navigation (a period without navigation at least 5min following the last ship passage). The subsets of data were subsequently analysed by deriving the minimum and maximum water level and flow velocity during each ship passage. Flow stability data was not analysed at the level of a single passing ship but was collated for each sampling site during the entire study.

2.3. Fish sampling

Fish sampling was undertaken over four days per month in July and October 2016. Monitoring was performed after sunset in the littoral zone using seine nets (20 × 3 m, smallest mesh size 5 mm stretched) targeting small-bodied fishes (<10 cm) Sampling locations were grouped into three categories: 1) groyne field, 2) shore channel behind sheltered LTD section and 3) shore channel near dynamic LTD section. Locations 1 to 9 were monitored in July 2016; locations 4 to 9 in October 2016. (Fig. 2a). Monitoring was undertaken in both seasons as the lower water level in October compared to July allowed an assessment of the influence of an emergent, lowered LTD section on fish densities. One to three smaller transects were sampled at each sampling location. The length, width and depth of these transects varied between 23.6 and 93.0 m, 1.5 and 14.0 m and 0.2 and 0.94 m, respectively.

The fish assemblages of the stony substrate on the shore channel site of one LTD was sampled using a suitable electrofishing method for sampling small sized fish species in shallow habitats during day time using boat mounted electrofishing equipment (DEKA 7000 N, Mühlenbein, DEKA Gerätebau, Marsberg, Germany). Transect of 50 m were sampled at regular intervals of 200 m along the entire LTD (total length: 4 km), yielding one density for each LTD section. In July, the lowered sections of the dam were submerged and could not be sampled. In October the lowered sections of the LTD were exposed and could thus be sampled. After sampling each transect, all fishes were visually identified, counted, measured and released. All fish surveys and identifications were performed by the same individual, thereby avoiding inter-observer variability.

2.4. Statistical analyses

2.4.1. Navigation induced changes in environmental conditions

A generalized linear mixed effect model (GLMM) was used to analyse the fixed effect of 'navigation' i.e., ship present or absent and fixed effect of 'location' i.e., groyne field, lowered section dam submerged and lowered section dam above water ('emergent') and the random effect of 'measurement site' nested within 'location' on the continuous variable water level fluctuations. A GLMM was also used to analyse the fixed effect of 'location' and the random effect of measurement site nested within 'location' on the continuous variable flow velocity. 'Navigation', 'location' and 'measurement site' were categorical variables. In total 531 and 16,231 measurements of water level fluctuation and flow velocity were available, respectively. Models were fitted using the 'glmer' function from the 'lme4' package in R statistics (Bates et al., 2014; R Core Team, 2015). Distribution of the water level and flow velocity data was checked by deriving a Cullen and Frey graph using the 'descdist' function of the 'fitdistrplus' package (Delignette-Muller et al., 2017) with 1000 iterations. Both datasets depicted a gamma distribution. Therefore, the GLMMs were performed using a gamma distribution with a log link. Model selection was based on the lowest Akaike's information criterion (AICc) value in combination with a significant model improvement using the likelihood ratio test (Field et al., 2012). The best water fluctuation model included 'location' and 'navigation' as fixed factors and included the random factor of 'measurement site' nested in 'location' (supplementary information: Table 1). The best performing flow velocity model included 'location' and the random factor of 'measurement site' nested in 'location' (supplementary information: Table 2). The 'mixed' function of the 'afex' package (Singmann and Bolker, 2014) was used to derive fixed effect significances based on the best fit model for each variable. When necessary, Tukey post hoc comparisons were performed using the 'glht' function of the 'multcomp' package (Hothorn et al., 2016).

The effect of 'navigation' and 'location' and the random effect of 'measurement site' nested within 'location' on range in flow velocity during 5 min time frames was analysed using a linear mixed effect model (LME) using the 'lmer' function from the 'lme4' package (Bates et al., 2014). For all locations combined, 44 time frames with navigation and 6 time frames without navigation were available. Model selection was based on the lowest Akaike's information criterion (AICc) value in combination with a significant model improvement using the likelihood ratio test (Field et al., 2012). The best model included 'navigation' as fixed factor and included the random factor of 'measurement site' nested in 'location' (supplementary information: Table 2). Fixed effect significances were derived using the 'mixed' function of the 'afex' package. In addition, the coefficient of variation (CV) of the flow velocity fluctuation during 5 min time frames was analysed with an asymptotic test using the 'cvequality' package (Marwick, 2016). Flow stability expressed as the position of the g-force logger along the y and z-axes was analysed using the mean position, SD and skewness.

2.4.2. Fish density

Based on the sampled area fish density was calculated and checked for normal distribution using the 'shapiro.test' function in R. Data that were not normally distributed were $\log_{10}$ transformed and subsequently checked for normality. An Anova model was used to analyse the fixed effect of 'location' i.e., groyne field, LTD dynamic and sheltered shore channel, and 'month of sampling' i.e., July and October on 1) fish density and 2) fish density of native, rheophilic and eurytopic fish species caught using the seine net. Fish guild classification followed Aarts and Nienhuis (2003) and, for recently introduced species, Van Kessel and Kranenbarg (2012) (Table 2). Inclusion of 'sampling transect' nested in 'site' and 'site' nested within 'location' did not significantly improve the model. Post hoc comparisons were performed using the 'TukeyHSD' function in R statistics.

Overall and native fish densities near stony substrate of training structures were analysed using an Anova model that included 'location' i.e., groynes and LTD as fixed effect. Only data from July was available for the groynes, therefore the analysis was restricted to July data. As densities were normally distributed, no $\log_{10}$ transformation was required. The effect of the continuous factor 'minimum distance to dynamic section' and the fixed factor 'month of sampling' i.e., July and October on the continuous variable fish density near stony substrate were analysed using the 'lm' function in R statistics. Model selection was based on the lowest Akaike's information criterion (AICc) value in combination with significant model improvement. The best model included 'minimum distance to dynamic section', 'month of sampling' and the interaction between the two aforementioned factors (Supporting information: Table 3).

Community similarity and temporal patterns were analysed using permutational multivariate analyses of variance (PERMANOVA), taking into account the fixed effect of 'location' i.e., groyne field, LTD dynamic and sheltered shore channel and 'month of sampling' i.e., July and October on fish diversity caught using the seine net. The analyses was performed using the 'adonis' function of the 'vegan' package in R statistics with 1000

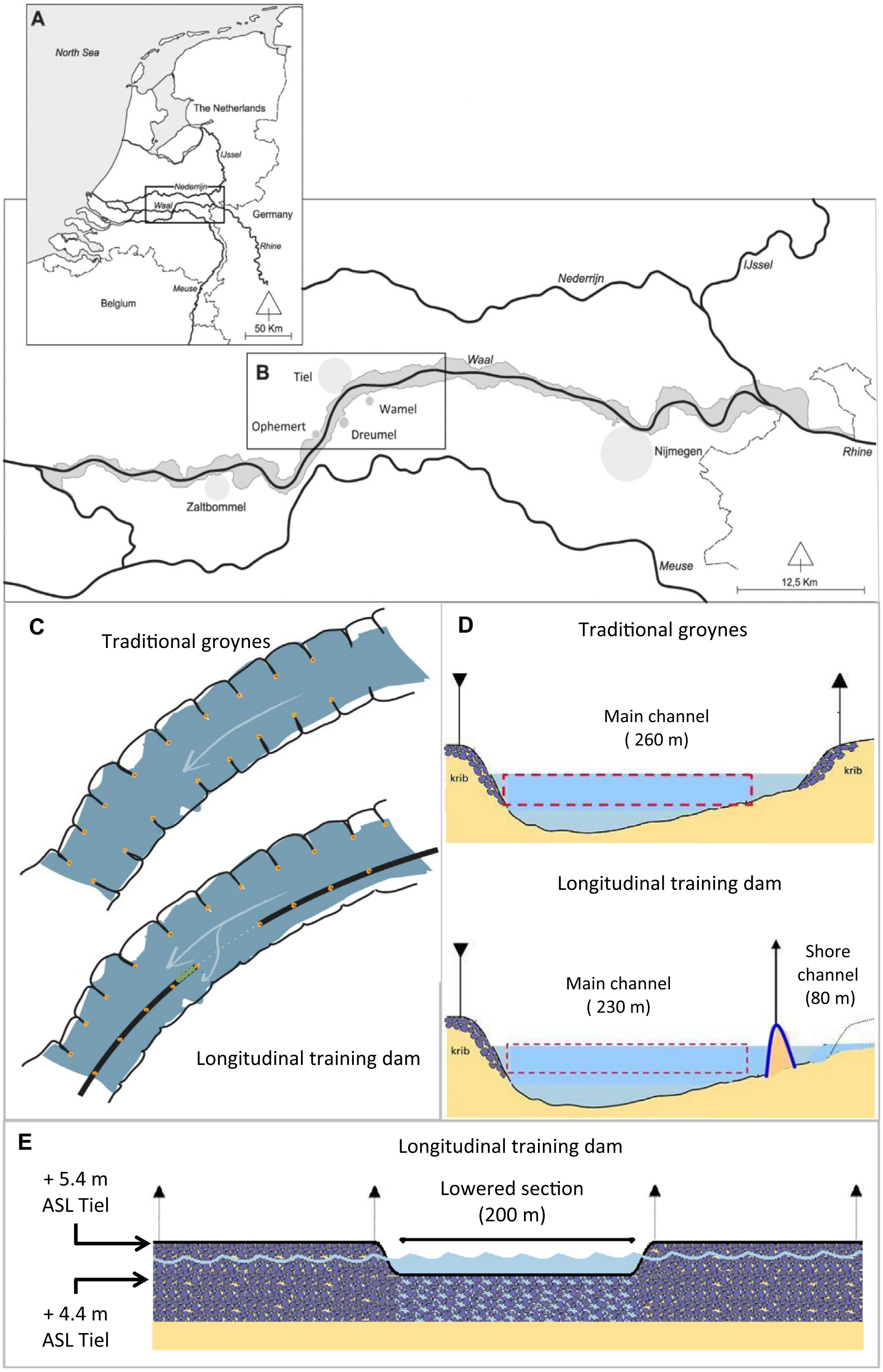

Fig. 1. Schematic overview of the Netherlands (a), the longitudinal training dam study area (b) in the river Waal in the Netherlands, (c) helicopter view of traditional groynes and a longitudinal training dam, and (d) cross section of the study site with traditional groynes and with a longitudinal training dam, and (e) side view of a submerged, lowered section in the longitudinal training dam.
(Adapted from Eerden, 2016 and Verbrugge et al., 2017).

permutations (Oksanen et al., 2017). The adonis function is sensitive to the order in which variables are added, so multiple permutations of each model verified that the predictors that we identified were consistently the most important. In October, fewer sites were sampled resulting in an unbalanced sampling design. Therefore, an additional PERMANOVA was performed including only the fish diversity in July and the fixed effect of 'location' i.e., groyne field, LTD dynamic and sheltered shore channel.

3. Results

3.1. Navigation induced effects on environmental conditions

During water level measurements 106 ships passed. Water level fluctuations significantly differed between 'locations' ($\chi^2 = 23.76$, DF $= 2$, P-value <0.001; Fig. 3a) and were significantly influenced by

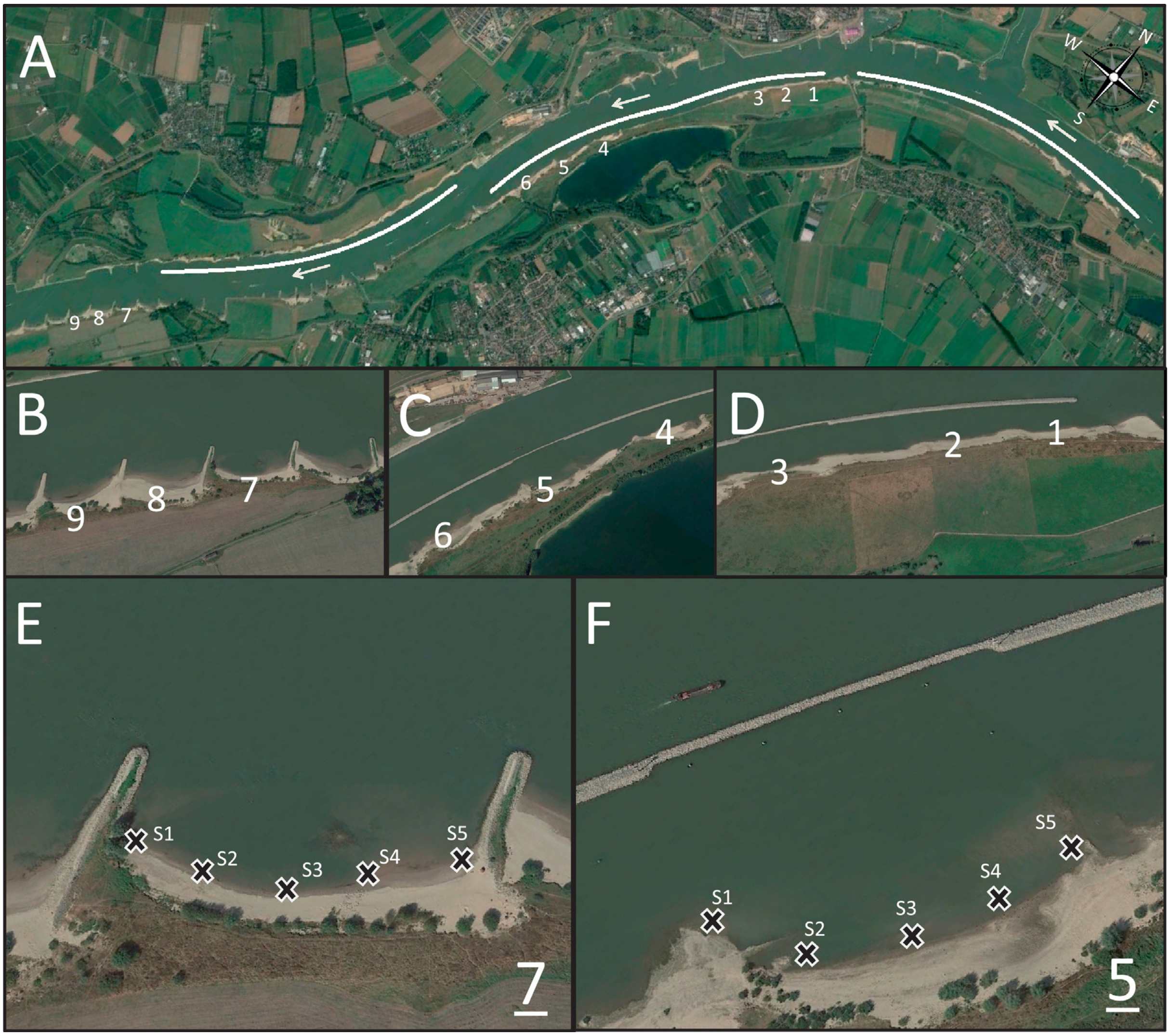

Fig. 2. (a) Locations of the longitudinal training dams (LTDs) and sampling sites of fishes, (b) close-up of groyne fields where fishes were sampled (reference sites), (c) and (d) close-up of fish sampling sites near the LTD, (e) sites of abiotic measurements in groyne field at location 7, and (f) abiotic measurement sites in shore channel along LTD at location 5. Locations behind the LTD are categorized as dynamic (1, 3, and 5) and sheltered (2, 4, 6) shore channel; location 7, 8 and 9 are categorized as groyne fields. Arrows indicate river flow direction.

'navigation' ($\chi^2 = 64.52$, DF = 1, P-value <0.001; Fig. 3b). Water level fluctuations were significantly higher in the groyne field compared to sites behind the lowered parts of the LTD (*Z*-value = 6.407, P-value ≤0.001). Water level fluctuations significantly decreased during periods with low river discharge when this LTD section was above water compared to periods with higher river discharges when this section was submerged (Z-value = −3.722, P-value ≤0.001).

Flow velocity ranged between 0.02 and 0.35 $m.s^{-1}$ and did not significantly differ between the three study 'locations' ($\chi^2 = 0.04$; DF = 2; P-value = 0.98; Fig. 4a). Variation in flow velocity during ship passages ranged between 0.05 and 0.32 $m.s^{-1}$ and did not significantly differ between the presence or absence of ships (F-value = 1.34; DF = 1, 44.67; P-value = 0.25). The CV of the flow velocity fluctuation during ship passage was higher in the groyne field than in the shore channel, but this difference was not significant (Test value: 4.89; DF = 2; P-value = 0.09; Fig. 4b).

Flow stability significantly differed between the three locations (Fig. 5). The mean position of the g-force logger in the groyne field along the Y axis was 95°, close to the position of 90°, indicating low flow. Mean logger positions for the submerged and emergent lowered LTD section were 66° and 58°, respectively. These positions indicate that the loggers were on average push downstream, on average, which was in accordance to the local natural flow conditions in the absence of passing ships. The average position of the logger along the Z axis was 80°, 74° and 80° for the groyne field, and submerged and emergent lowered LTD section, respectively. All three average logger positions were below 90°, indicating a flow mainly directed towards the littoral zone. The distribution along Z axes of logger positions in groyne fields showed clear signs of bimodality (Fig. 5). Standard deviations of logger position along the Y and Z axes were highest for the groyne field location, followed by the emergent and the submerged lowered LTD section (Table 1). All three locations showed skewness along the Z axis towards the right side of the distribution (Table 1). Skewness along the Y axis was towards the right for the groyne field location, but towards the left for the two lowered LTD section locations.

Table 1
Descriptive statistics of logger positions along the Y and Z axes for the groyne field and lowered LTD location under submerged and emergent conditions.

Location	Axis	Mean	SD	Skewness
Groyne field	Y	95°	19°	0.26
	Z	80°	54°	0.31
Submerged lowered LTD location	Y	66°	14°	−0.58
	Z	74°	24°	0.07
Emergent lowered LTD location	Y	58°	14°	−0.73
	Z	80°	30°	0.37

Table 2
Overview of the density (ind.100 m^{-2}) of all fish species, guild and origin caught during sampling with seine nets.

			Groyne field		Dynamic LTD shore channel		Sheltered LTD shore channel	
Species	Guild	Origin	July	October	July	October	July	October
Abramis brama	Eurytopic	Native	0.37	0.12	0.38	0.48	1.04	7.19
Alburnus alburnus	Eurytopic	Native	0.43	1.47	0.55	0.64	1.07	0.09
Aspius aspius	Eurytopic	Alien	0.27	0.51	0.72	0.32	0.97	0.53
Barbus barbus	Rheophilic[a]	Native	–	–	0.04	–	–	–
Blicca bjoerkna	Eurytopic	Native	0.07	–	–	–	–	–
Chelon labrosus	–	Native	–	0.67	–	–	–	–
Chondrostoma nasus	Rheophilic[a]	Native	–	0.04	0.17	0.32	0.36	0.79
Cyprinus carpio	Eurytopic	Alien	–	–	–	–	0.06	–
Esox lucius	Eurytopic	Native	–	–	0.08	–	–	–
Gasterosteus aculeatus	Eurytopic	Native	0.17	–	0.08	–	0.03	–
Gymnocephalus cernua	Eurytopic	Native	0.13	–	0.30	–	0.23	0.96
Leuciscus idus	Rheophilic	Native	1.04	1.19	0.89	2.24	1.43	0.53
Leuciscus leuciscus	Rheophilic	Native	–	0.04	0.04	–	0.16	–
Neogobius fluviatilis	Rheophilic[a]	Alien	0.60	0.08	2.17	2.88	3.83	18.42
Neogobius melanostomus	Rheophilic[a]	Alien	0.23	–	1.15	–	3.31	0.18
Perca fluviatilis	Eurytopic	Native	0.17	–	2.46	0.16	7.31	0.18
Platichthys flesus	Rheophilic	Native	–	–	–	–	–	0.26
Ponticola kessleri	Rheophilic[a]	Alien	1.24	–	3.78	–	2.05	0.09
Proterorhinus semilunaris	Eurytopic[a]	Alien	–	–	–	–	0.03	–
Romanogobio belingi	Rheophilic[a]	Alien	0.03	–	0.51	–	3.96	–
Rutilus rutilus	Eurytopic	Native	1.74	0.28	2.12	5.77	4.25	7.72
Sander lucioperca	Eurytopic	Alien	1.34	0.04	3.53	0.96	3.80	0.70
Squalius cephalus	Rheophilic	Native	–	–	–	–	0.03	–
Vimba vimba	Rheophilic[a]	Alien	0.03	0.04	0.08	–	–	–
		Native species:	8	7	11	6	10	8
		Alien species:	7	4	7	3	8	5
		Total number of species:	15	11	18	9	18	13
		Sampled area:	2991	2525	2354	624	3080	1140

All guilds defined according to Aarts and Nienhuis (2003), except [a]: Van Kessel and Kranenbarg (2012).

3.2. Fish density

In total, 24 fish species were caught using the seine net (Table 2). Fish density per transect varied between 0.01 and 0.79 ind.m^{-2}. Overall fish density significantly differed between 'locations' (F-value = 14.02, DF = 2, P-value <0.001). Fish densities in the sheltered section of the LTD were significantly higher (0.43 ± 0.25 ind.m^{-2}) compared to the groyne field (0.08 ± 0.06 ind.m^{-2}) (P-value <0.001; Fig. 6a). The density of native fish species significantly differed between 'locations' (F-value = 6.01, DF = 2, P-value <0.01). Native fish density in the sheltered section of the LTD were significantly higher (0.20 ± 0.15 ind.m^{-2}) compared to the groyne field (0.05 ± 0.03 ind.m^{-2}) (P-value <0.01; Fig. 6b). The density of rheophylic fish significantly differed between 'locations' (F-value = 12.362, DF = 2, P-value <0.001), having a significantly higher density in the sheltered section of the LTD (0.21 ± 0.14 ind.m^{-2}) compared to the groyne field (0.03 ± 0.04 ind.m^{-2}) (P-value <0.01; Fig. 6c). Eurytopic fish density significantly differed between 'locations' (F-value = 10.351, DF = 2, P-value <0.001; Table 3) and were significantly higher in the sheltered shore section (0.22 ± 0.15 ind.m^{-2}) compared to the groyne field (0.04 ± 0.03 ind.m^{-2}) (P-value <0.001; Fig. 6d). Fish density did not significantly differ between July and October for eurytopic fish (F-value = 3.548, DF = 2, P-value = 0.07; Supplementary information: Fig. S3) or rheophilic fish (F-value = 0.146, DF = 2, P-value = 0.71; Supplementary information: Fig. S3). The interactions between 'date' and 'location' did not add significant value and was therefore not included in our model. Overall fish density derived from catches using electrofishing equipment near stony substrate was significantly higher near the LTD (1.28 ± 0.54 ind.m^{-2}) than on groynes (0.44 ± 0.32 ind.m^{-2}) (F-value = 12.33, DF = 1, P-value <0.01). The density of native fish species was significantly higher near the LTD (0.86 ± 0.40 ind.m^{-2}) than on groynes (0.14 ± 0.11 ind.m^{-2}) (F-value = 18.39, DF = 1, P-value <0.001).

The ordering of factors influenced the outcome of the PERMANOVA analysis (Table 4), indicating the unbalanced sampling design that resulted from the lower number of sampling sites in October compared to July. The F-value and R^2 of the fixed factor 'date' were higher compared to 'location' in both models including all fish diversity data. Fish community structure significantly differed between sampling dates for both models (Table 4). Significant differences between 'locations' varied. However, in general the effect of 'location' was less important than the effect of 'date'. No significant difference in fish diversity between locations was found when data obtained in July was compared (R^2: 0.11; P-value 0.39).

Fish density near stony substrate along the LTD varied depending on the sampling time (Fig. 7a and b), showing the effect of different water levels on fish densities near the stony habitat of the LTD. In total 19 species were caught with an average density (±SD) of 1.28 ± 0.54 ind.m^{-2} and 0.32 ± 0.15 ind.m^{-2} in July and October, respectively (Supplementary information: Table S4). Fish density increased significantly with increasing distance from dynamic sections (F-value = 49.279, DF = 1, P-value <0.001; Fig. 7d and e) and were significantly higher in July compared to October (F-value = 115.608, DF = 1, P-value <0.001). The effect of distance from dynamic sections differed significantly between July and October (F-value = 29.101, DF = 1, P-value <0.001; Fig. 7d and e).

Table 3
Anova-results of the overall fish density, native fish density, rheophilic fish density and eurytopic fish density with fixed factors 'location' and 'date'.

	Source	DF	Sum Sq	Mean Sq	F-value	P-value
Overall fish density	Location	2	3.73	1.87	14.02	<0.001
	Date	1	0.18	0.17	1.31	0.26
	Residuals	25	3.33	0.13		
Native fish density	Location	2	2.30	1.15	6.01	<0.01
	Date	1	0.02	0.02	0.09	0.77
	Residuals	25	4.79	0.19		
Rheophilic fish density	Location	2	5.27	2.63	12.36	<0.001
	Date	1	0.29	0.29	1.34	0.26
	Residuals	25	5.33	0.21		
Eurytopic fish density	Location	2	3.15	1.57	10.35	<0.001
	Date	1	0.54	0.54	3.55	0.07
	Residuals	25	3.80	0.15		

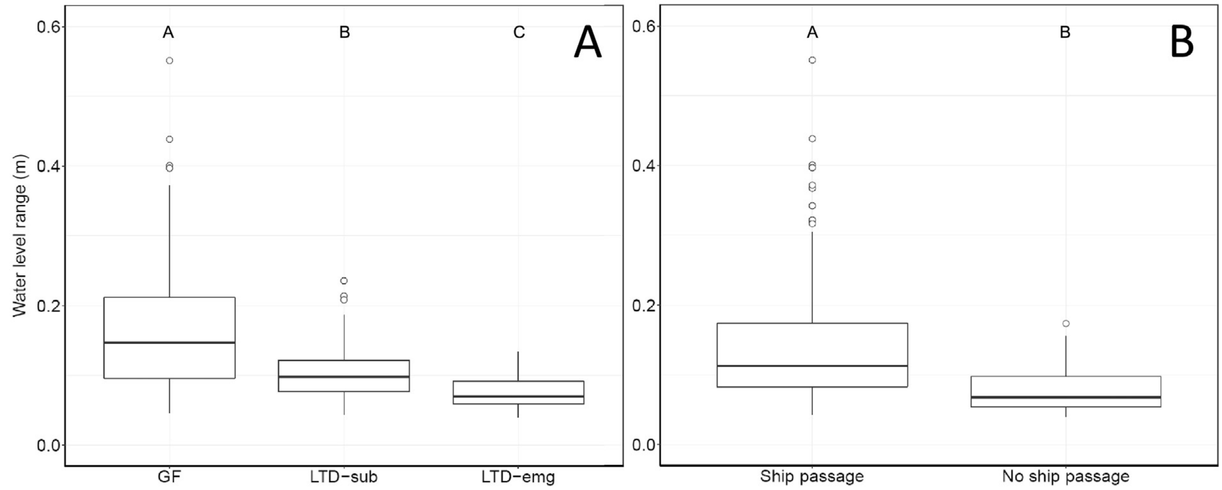

Fig. 3. Whisker plots of range of water level fluctuations a) in the groyne field location (GF, Location 7 Fig. 2e), submerged lowered LTD location (LTD-sub, Location 5 Fig. 2f) and emergent lowered LTD location (LTD-emg, Location 5 Fig. 2f), and b) during periods with and without ship passages (Different letters depict significant differences). The bands in the middle of the boxes are the median; the lower and upper bands of the boxes are the 25th and 75th percentiles, respectively; the upper and lower whiskers were derived using the standard setting in R statistics, and the dots represent outliers.

4. Discussion

Environmental conditions in the littoral zones of shore channel behind the LTD were less exposed to ship induced waves and water displacements compared to the traditional groyne field. Even when the lowered LTD section was submerged and lateral water exchange occurred, water level fluctuation was reduced significantly, indicating that refuge is provided from the effects of navigation during a major part of the year (at least 300 days a year on average; see supplementary information: Fig. S2). The maximum observed water level fluctuations of 0.54 m in the groyne field was in accordance with previous studies of the river Rhine (Ten Brinke et al., 1999, 2004), but higher than the value (0.18 m) reported for groyne fields in the river Elbe (Brunke et al., 2002). This difference is likely explained by the higher intensity of navigation and the larger ship size on the river Rhine compared to the river Elbe (Central Commission for the Navigation of the Rhine, 2014).

Average flow velocities in littoral zones were not significantly lower in the shore channel compared to the groyne field. Conversely, the variation in flow velocity fluctuation during ship passages was substantially and almost significantly ($P < 0.1$) higher in the groyne field compared to the submerged and emergent sections of the shore channel. Additional measurements are expected to result in a significant difference in the variation of flow velocity fluctuation. Brunke et al. (2002) measured a change in flow velocity in groyne fields of 0.6 $m.s^{-1}$ during ship passage in the river Elbe. Similar changes in flow velocity during ship passage have been reported in groyne fields along the river Danube in Austria (Kucera-Hirzinger et al., 2009) and the river Rhine (0.4 $m.s^{-1}$; Ten Brinke et al., 1999). The difference in flow velocity fluctuation between the river Elbe and river Waal is likely due to the river Elbe's narrow width (Gabel et al., 2017).

The higher standard deviation in g-logger position along the Y and Z-axes in the groyne field compared to the lowered LTD section indicates more unstable and disturbed flow conditions in the groyne field compared to the littoral zones of the shore channel. The absence of a bimodal distribution near the lowered LTD section in combination with a g-logger position in accordance to the a flow regime not disturbed by shipping indicate that flow conditions in the shore channel can be considered near natural.

The lower magnitude in flow velocity fluctuation in the littoral zone of the LTD during ship passage indicates that conditions behind the LTD are more stable compared to groyne fields. Combined with higher flow

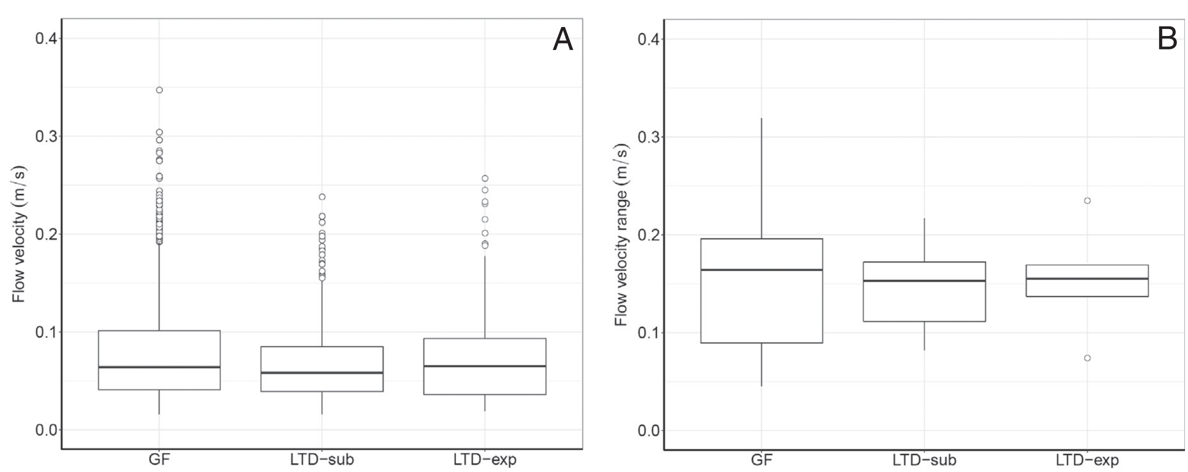

Fig. 4. Whisker plots of measurements at the groyne field location (GF, Location 7 Fig. 2e), submerged lowered LTD location (LTD-sub, Location 5 Fig. 2f) and emergent lowered LTD location (LTD-emg, Location 5 Fig. 2f) of a) all flow velocity measurements and b) range in flow velocity during passage of ships. The bands in the middle of the boxes are the median; the lower and upper bands of the boxes are the 25th and 75th percentiles, respectively; the upper and lower whiskers were derived using the standard setting in R statistics, and the dots represent outliers.

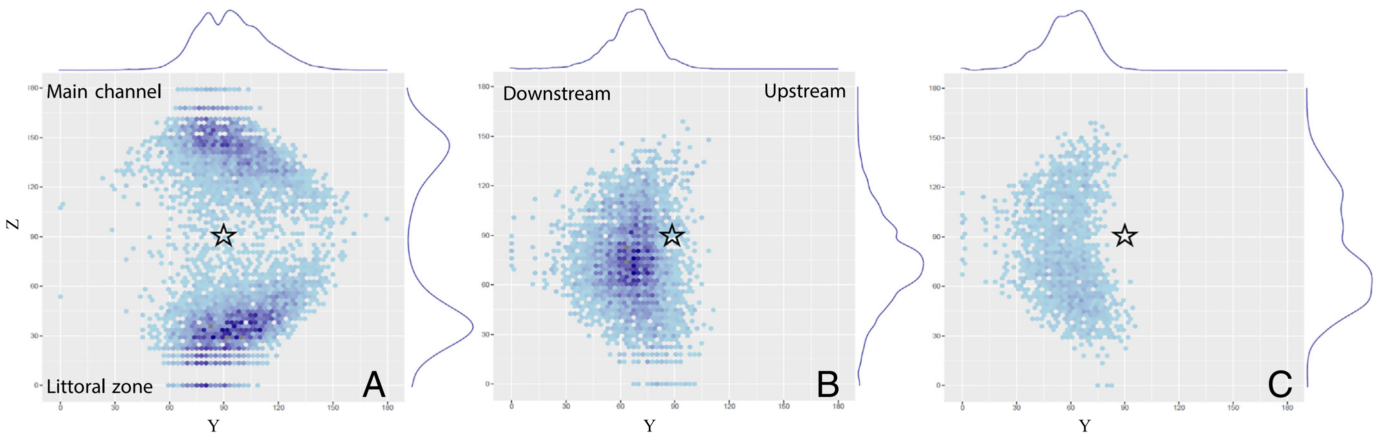

Fig. 5. Scatter plot of the position of the g-force logger in the littoral zone of a traditional groyne field (a), and at the submerged (b) and emergent (c) lowered LTD locations. Density plots are included next to the two axes. The star indicates the position of the logger when no flow is present. Axes represent the position of the logger in space based on a z (main channel – littoral zone) and y (up- or downstream) value.

stability, this observation allows us to conclude that an LTD significantly mitigates wave action and water displacement caused by navigation in the littoral zones in intensively used rivers like the river Rhine. Our results regarding the positive effect on stability of environmental conditions in the shore channel behind an LTD can be considered generalizable. Improved hydrodynamic conditions will decrease energy expenditure in relation to swimming and reduce the risk of wash-out for fishes (Schiemer et al., 2003; Tudorache et al., 2008; Lechner et al., 2014; Trinci et al., 2017). Therefore, the sheltered shore channels provide refuges for (juvenile) fishes that support their survival.

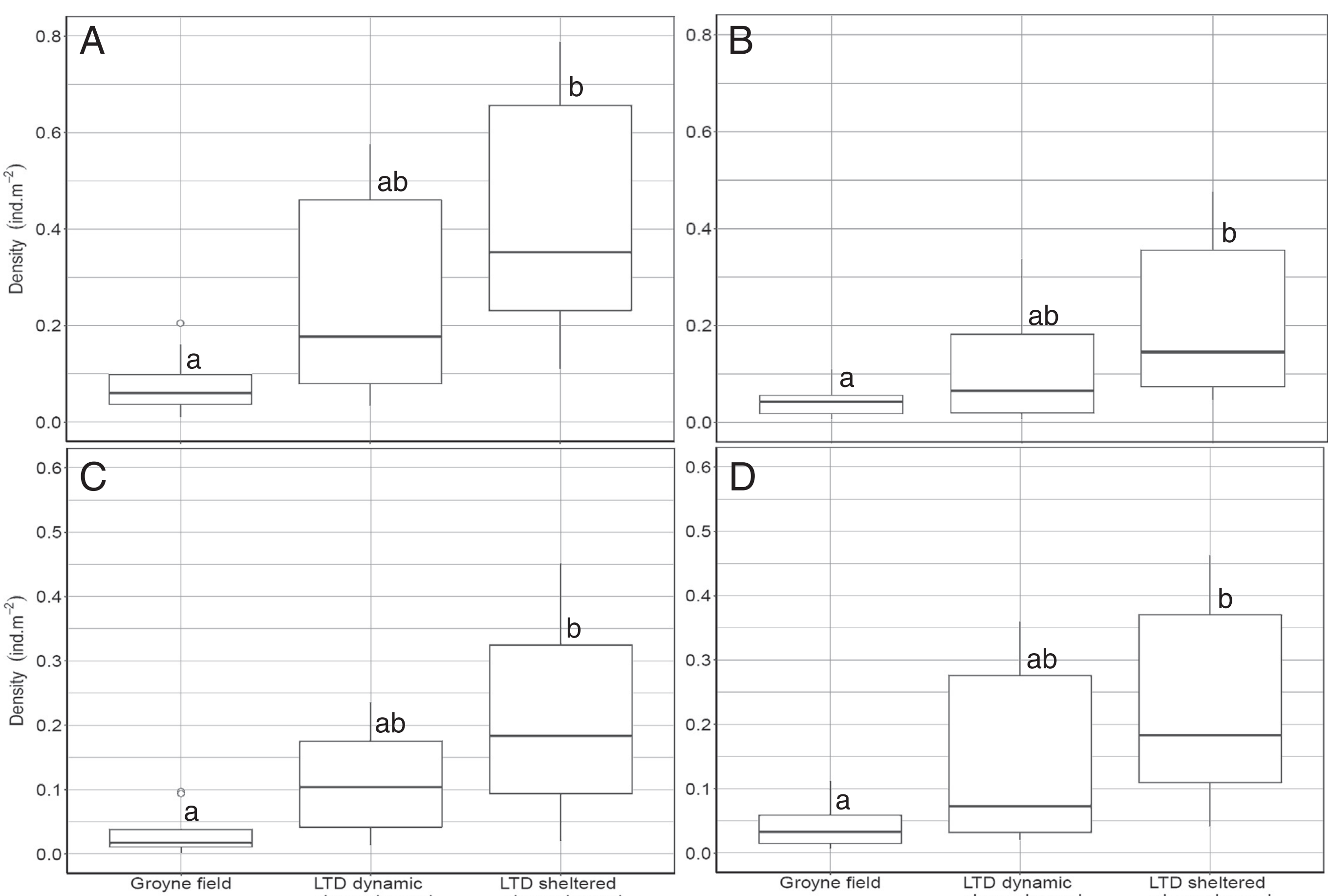

Fig. 6. Whisker plots of fish density caught with a seine net at the groyne field location, LTD dynamic shore channel location and LTD sheltered shore channel location for a) all species pooled, b) native fish species pooled; c) rheophylic fishes pooled and d) eurytopic fishes pooled (Different letters depict significant differences $P < 0.05$). The bands in the middle of the boxes are the median; the lower and upper bands of the boxes are the 25th and 75th percentiles, respectively; the upper and lower whiskers were derived using the standard setting in R statistics, and the dots represent outliers.

Table 4
Results of PERMANOVA of fish community structure.

	Source	DF	Sum Sq	Mean Sq	F-value	R^2	P-value
All data	Location	2	0.41	0.21	2.51	0.14	<0.05
	Date	1	0.44	0.44	5.34	0.15	<0.01
	Residuals	25	2.05	0.08		0.71	
	Total	28	2.90			1.00	
All data	Date	1	0.54	0.54	6.64	0.19	<0.001
	Location	2	0.31	0.15	1.86	0.11	0.06
	Residuals	25	2.05	0.08		0.71	
	Total	28	2.90			1.00	
July subset	Location	2	0.11	0.06	1.09	0.11	0.39
	Residuals	18	0.91	0.05		0.89	
	Total	20	1.03			1.00	

Fish densities in sheltered habitats behind the LTD was significantly higher than ingroyne fields. The positive influence of flow stability on fish density is also exemplified by a higher fish density in the sheltered compared to the dynamic sections of the shore channel. However, this result was not significant. Higher fish densities can also be the result of a higher resource availability. As phytoplankton and zooplankton production reduces with decreasing water retention time (Eddy, 1929; Basu and Pick, 1996; Reckendorfer et al., 1999; Engelhardt et al., 2004), one could argue that increased mixing of water in groyne fields due to navigation reduces phytoplankton and zooplankton production and thus resource availability. The absence of navigation effects in the shore channel of the LTD will likely increase retention time thereby positively influencing resource availability, though additional research is necessary to explore this. Fish densities are also influenced by predation pressure which is likely to be higher in the shore channel as higher densities of fish predating birds were observed here compared with groyne fields (personal observation F. Collas). Additional research is required in order to fully understand the impact of predation in the shore channel.

The density of native fish was significantly higher in the shore channel than in the groyne fields, though alien fish species were still found in the shore channel. A similar effect has been observed near other river rehabilitation measures (Schmutz et al., 2014; Dorenbosch et al., 2017). Alien species diversity is not expected to decrease in the future as the LTD is connected to the main river thereby facilitating continuous influx of alien species from upstream sections (Burgess et al., 2012; Schmutz et al., 2014).

Native fish densities near the stony substrate of the LTD were significantly higher than those found in the traditional groyne fields. The difference is likely the result of measures that filled crevices between the stones of the LTD with sand, thereby decreasing the available habitat of alien species and increasing habitat for native species. In 2017, relative high discharge washed the majority of this sand away (personal observation F. Collas). Therefore, additional sampling may further elucidate the effect of this sandy fill on the establishment of native and alien fish species near the stony substrate of the LTD. The linear relationship between fish density in stony habitats and distance from dynamic sections of the LTD further underlines the impact of navigation on the hydrodynamics of littoral zones. In July 2016, fish densities close to the stony substrate of the LTD were lowest at and near dynamic sections. Stony substrate monitoring in October, when the lowered LTD sections were above water, revealed a more homogenous fish density distribution. An increase in fish density associated with a decrease in the dynamic nature of the habitat was observed for both rheophilic and eurytopic species. In addition, eurytopic juvenile and adult density has been found to be higher in the river Elbe behind LTDs compared to traditional groyne fields (Fladung et al., 2003). The higher density of rheophilic fish in the littoral zone of the shore channel is of particular

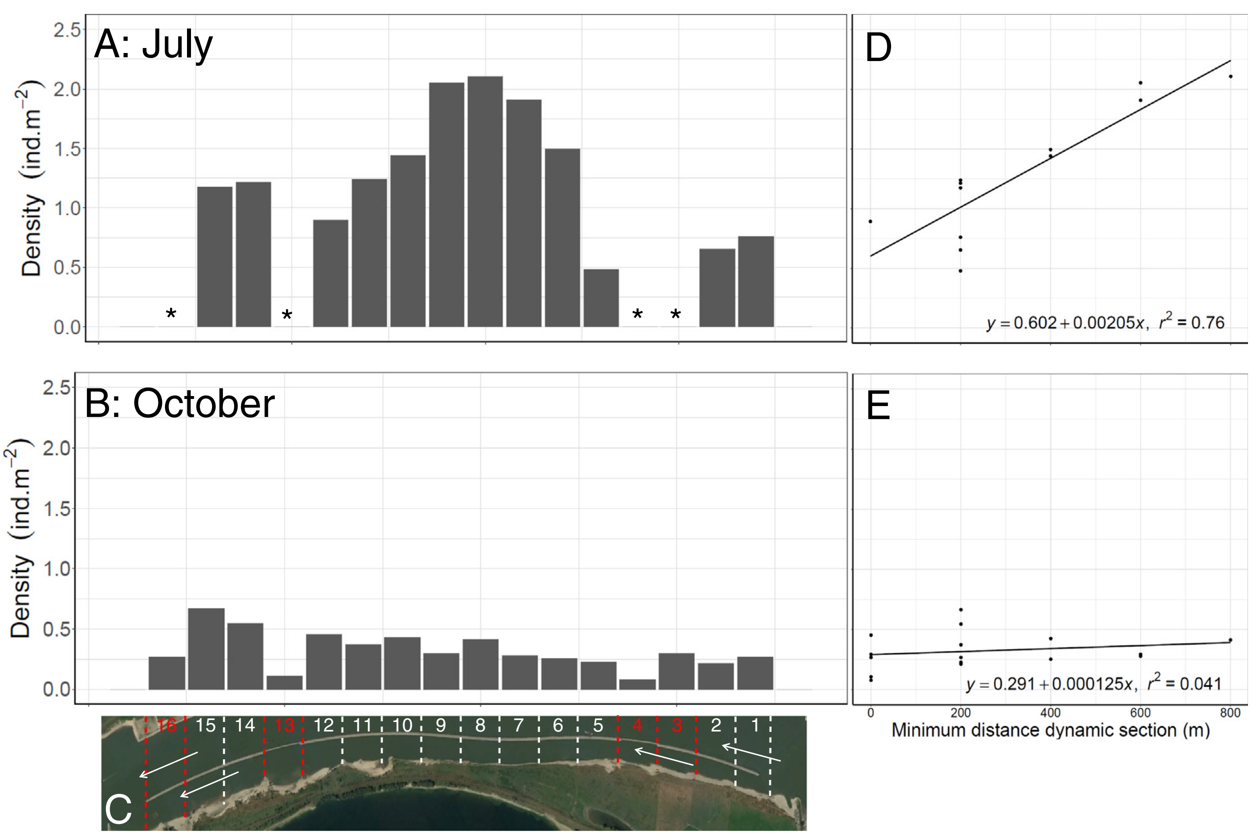

Fig. 7. Density of fish species caught by electrofishing along the shore channel site of the LTD during a) July and b) October for 50 m transects at regular intervals of 200 m (c), and the relation between minimum distance to a dynamic section (see Fig. 2) and fish density during d) July and e) October (*: sections that could not be sampled due to dynamic conditions caused by flow or navigation (indicated in red in c); arrows in c indicate flow direction). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

rehabilitation interest as these species have strongly declined in the river Rhine (Raat, 2001). Fish diversity observed during the seine net sampling in July was not significantly different between locations (Table 1, Table 4). This is contrary to the effect observed by Fladung et al. (2003) near LTDs in the river Elbe and a meta-analyses of the effect of rehabilitation measures on fish assemblages in the Austrian river Danube (Schmutz et al., 2014). The difference in effect can be caused by: 1) low habitat variability near the LTD due to its recent construction and 2) the time lag that occurs prior to colonisation by rare species.

Erosion and sedimentation processes are expected to increase habitat diversity in the shore channel over the coming years. This may result from changes in depth, flow velocity and substrate variation that lead to increases in fish species density as well as diversity. Therefore, continued monitoring of geomorphological processes in shore channels and the spatial distribution of fish species is highly recommended. Such increases in habitat diversity may provide the required conditions for the early ontogenetic development of fishes (Schiemer et al., 2001), increasing the ecological value of the shore channel behind the LTD.

It is of vital importance that river training structures are not only designed to serve socio-economic functions (e.g., increased flood safety and navigation potential) but also to facilitate the ecological rehabilitation of regulated rivers. Our results show that the LTDs along the river Waal contribute to the ecological rehabilitation of a river used intensively for transport. The considerable length of the 10 km shore channel will provide a substantial area with more ecologically favourable flow and habitat conditions compared to groyne fields. However, additional measurements of hydrodynamic conditions in the shore channel are required during periods of overtopping of the entire dam to fully grasp the ecological potential of the LTD throughout the entire year. Monitoring is required in future years to assess whether habitat in the shore channel diversifies and how this will benefit fish species.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2017.10.299.

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