Taylor & Francis
Taylor & Francis Group

Journal of Applied Water Engineering and Research

ISSN: (Print) 2324-9676 (Online) Journal homepage: http://www.tandfonline.com/loi/tjaw20

River bank stabilisation by bioengineering: potentials for ecological diversity

Kathrin Schmitt, Michael Schäffer, Jochen Koop & Lars Symmank

To cite this article: Kathrin Schmitt, Michael Schäffer, Jochen Koop & Lars Symmank (2018): River bank stabilisation by bioengineering: potentials for ecological diversity, Journal of Applied Water Engineering and Research, DOI: 10.1080/23249676.2018.1466735

To link to this article: https://doi.org/10.1080/23249676.2018.1466735

Published online: 02 May 2018.

Journal of Applied Water Engineering and Research, 2018
https://doi.org/10.1080/23249676.2018.1466735

River bank stabilisation by bioengineering: potentials for ecological diversity

Kathrin Schmitt*, Michael Schäffer, Jochen Koop and Lars Symmank

Division of Ecology, Federal Institute of Hydrology, Koblenz, Germany

(*Received 30 September 2016; accepted 11 December 2017*)

Riverbanks hold a key position on functionality of floodplains as they constitute the gradual transition between aquatic and terrestrial ecosystems. However, due to technical constructions the majority of riverbanks in temperate regions are far from their ecological potential. This results in the loss of valuable habitats and biodiversity. The need for restoration is high but hardly compatible with economic interests. Bioengineering methods could help to increase the ecological potential of river banks. A comparative investigation on bioengineering bank protection techniques was conducted along two watercourses of different characters of navigation and hydrology (Rhine, Weser). We measured the response of four organism groups to different bioengineering methods. Our results indicate an ecological enhancement of riparian zones by re-establishing of valuable floodplain habitats. The number of terrestrial riparian species increased at both rivers. However, habitat quality for aquatic communities remained limited at due to insufficient extension of measures below mean water level.

Keywords: biodiversity; sustainable river management; floodplain; riparian zone; riprap; river restoration

1. Introduction

Due to high networking and ecosystem functioning, rivers and floodplains in their natural state are among the most species-rich ecosystems (e.g. Tockner & Stanford 2002). River banks hold a key position on functionality of floodplains as they gradually connect aquatic and terrestrial ecosystems (Naiman & Dechamps 1997). However, they are seriously affected by the general loss of biodiversity (Sala et al. 2000). Freshwater biodiversity has decreased more rapidly than marine or terrestrial biodiversity due to an increase in navigation, land use and population density within floodplains during the last centuries (Millennium Ecosystem Assessment, 2005). Navigation still is of considerable economic importance in Central Europe and thus river expansion and the deepening of rivers for increasing transportation of goods were enforced in recent years in Germany (WSV 2016). As a consequence, habitat degradation caused by river regulations was the main driver of biodiversity loss (Tockner & Stanford 2002). The extensive implementation of bank revetment (e.g. riprap) along the vast majority of rivers (Wolter 2001) led to the unification of littoral zones, and loss of structural diversity and ecosystem functionality. Further challenging effects were the increase of flow velocity and soil consolidation within river bodies which result in higher risk of flooding events with negative consequences for the human population (e.g. Wyzga 1993).

Because of these dramatic changes, conservation of rivers and floodplains became increasingly important within international water policy (e.g. Convention on Biological Diversity [CBD] 1992; EU Water Framework Directive [WFD] 2000). As a consequence, multiple floodplain and ecological river renaturation projects have been conducted in recent years. However, the ecological impacts out of several of these projects remain low (e.g. Feld 2013). Most renaturation measures suffer from the lack of sufficient biotic interchange and the lack of recolonisation sources (e.g. Parkyn et al. 2003; Palmer et al. 2010). To increase the success of renaturation projects an interlinkage between faunistic colonisation sources and newly-created habitats has to be established. In this context bank stabilisation by bioengineering measures may serve as ecological stepping stones for riparian and floodplain species.

In this case artificial bank fixation (e.g. riprap) was displaced by biological components while maintaining bank stability (Frothingham 2008). Such measures comprise willow brush mattresses, reed belts or dead wood fascines. Especially willows tended to resist hydraulic stressors well and increase biodiversity (Fischenich & Allen 2000; Cavaille et al. 2013). Despite the increasing popularity of bioengineering stabilisation in recent years (Li & Eddleman 2002), ecological examinations of different measures under variable hydrological conditions has not been carried out to date.

Hence, we present a first comparative analysis of different kinds of bioengineering measures across two river types in Germany to evaluate the ecological impact on vegetation and three animal groups (fish, macrozoobenthos and birds). The rivers differ in hydrological conditions and shipping intensities. Therefore, their riverbanks can

*Corresponding author. Email: kathrin.schmitt@bafg.de

be assumed to underlie different hydraulic stressors. Structural diversity, biodiversity, bank-floodplain connectivity parameters, and bank stability were key aspects in our evaluation. The following three main research questions have been addressed: (i) Do bioengineering bank stabilisation measures increase biodiversity? (ii) Which bioengineering bank stabilisation measures ensure bank stability under navigation pressure? (iii) Which factors limit the ecological improvement induced by bioengineering measures?

To answer these questions, long-term biological monitoring results of the two reaches under study have been comparatively analysed. Our study aims to contribute to an interdisciplinary understanding within the paradigm shift from prevalently technical bank fixation (riprap) towards an extensive application of ecologically sustainable measures on waterways in the future.

2. Material and methods

2.1. Study sites

The study reaches were located at two rivers in Germany with clearly different hydro-morphological characteristics, such as flow velocity, cross section and water level fluctuations (Table 1). The first study reach was located at the Rhine, near the city of Lampertheim. The second study reach was located at the Weser near the city of Stolzenau (Figure 1). The purpose for installation of the study reaches was the ecological improvement of conventional river banks (riprap) with low structural and habitat diversity. Each study reach consisted of several combinations of bioengineering measures (test fields) and reference reaches (riprap) in close vicinity (Figure 1). Within the test fields, large parts of the initial riprap (mainly above mean water level) were removed, some sections of the bank were flattened and bioengineering measures were installed. These measures mainly comprised initially of planting of reed and soft-wood species. Planting of willows was conducted at both study reaches, whereas different other combinations of measures were installed either at the Rhine study reach or at the Weser study reach. Detailed descriptions of test fields are listed in Table 2.

The first study reach was implemented in 2011 within the free flowing section of the Rhine, comprising nine test fields with an overall length of 1 km and two adjacent reference reaches 100 m upstream and downstream, respectively (Figure 1). The study reach is located on the right river bank between Rhine-km 440.6 and 441.6. This section of the river is highly frequented, with approximately 120 ships passing per day, the river has a cross section between 280 and 300 m and navigation moves at a distance of 100 m from the river bank. Enormous intra-annual water level fluctuation (differences of 6 m between equivalent low flow level and the highest navigable water level) could be observed within this section. Flooding events occurred frequently on a yearly basis and often persisted for several weeks in the first half of the year. The installed bioengineering measures were flooded up to 182 days per year in a 10-year average. These long-term flooding events challenged vegetation structures with regard to plant vitality and stability. To cope with the intense hydrological dynamics, the average inclination of bank slopes varies from 1:2 to 1:3 and the initial riprap layer had a thickness between 60 and 90 cm.

The overall ecological potential on the river banks was low due to several constraints (ship-induced wave impacts, high flow velocity, poor soil availability and riprap layer). These impacts prevented the development of a characteristic lateral riverbank zoning (pondweed, reed, softwood and hardwood). According to the WFD (2000) this section of the Rhine has been classified as ‘heavily modified’ (ICBR 2009).

The second study reach was implemented in 1989 at the impounded Weser, comprising 14 test fields with an overall length of 750 m and two adjacent reference reaches of comparable extent (Figure 1). An additional reference reach for faunistic studies was chosen on the opposite bank of the study reach (Figure 1). The study reach is located at the right river bank between Weser-km 241.5 and 242.3. With 23 ships per day (BfG & BAW 2008), navigation frequency is markedly lower than that at the Rhine. At the study reach the Weser has a cross section from 77 to 81 m and navigation moves at an average distance of 50 to 55 m from the river bank. Due to hydrological regulation by impoundments, the river is characterised by lower flow velocity and remote water level fluctuations**.** Flooding events occurred rarer than at the Rhine, usually once a year between January and March and persisted for a shorter period. Reed belts in the test fields are flooded between 65 and 365 days per year, willows between 25 and 45 days in a 10-year average. The average inclination of the bank slope was 1:3 with an initial riprap thickness of 60 cm. Due to intensive agricultural land use and resulting nutrient input on the river bank areas, the structural quality of this part of the river was classified as ‘noticeably damaged’ (AG Reinhaltung Weser 1998) and the overall ecological potential was poor.

Although both study reaches gave valuable insights into long-term development and ecological impact of bioengineering stabilisation measures, we are aware that an

Table 1. Main characteristics of investigated study reaches at the rivers Rhine and Weser.

Study reach	Rhine	Weser
Location (river-kilometre)	440.6–441.6	241.5–242.3
Length (m)	1000	750
Year of implementation	2011	1989
Mean flow velocity (m/s)	1.08	0.2
Cross section (m)	290	80
Mean water level fluctuation (m)	6	1.5–2
Shipping frequency (ships/day)	120	23

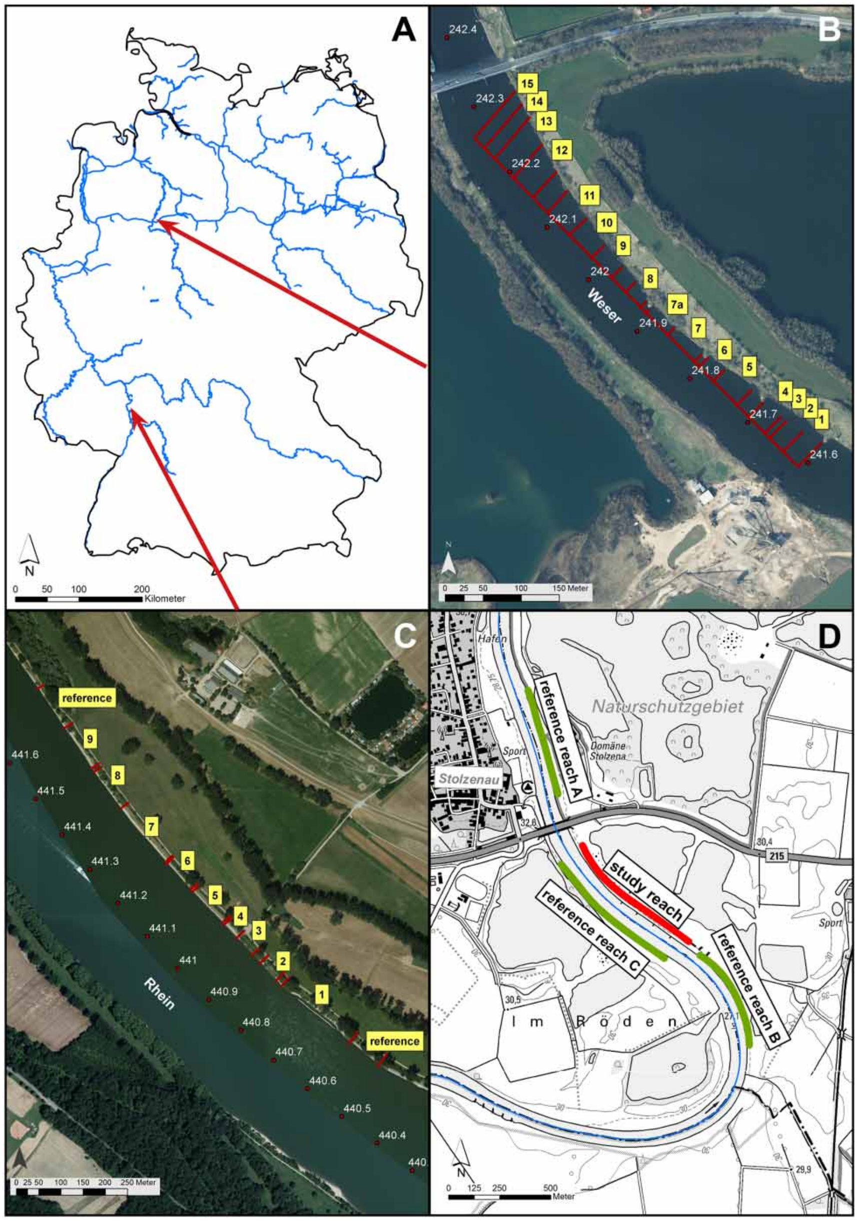

Figure 1. (A) Location of the two study reaches at the German Federal Waterways. (B) Arrangement of test fields within the study reach Weser. (C) Arrangement of test fields and reference reaches at the river Rhine. (D) Position of the study reach and reference reaches at the river Weser. Reference reach A and B: vegetation, reference reach C: fauna.

appropriate and comparable descriptive analysis of the different monitoring programmes can only be carried out partially. Regardless, we tried to delineate methods and results comparably if possible. Due to the high age of the study reach at the Weser (28 years) the initially separated vegetation types (reed and willows) have spread into almost all test fields forming a homogenous vegetation structures today. In comparison to the Rhine, results at the Weser do not apply for single test fields but for the entire study reach. The reason for inconsistence of monitoring programmes was the temporal difference of installation dates of measures. Furthermore the study reach at the Weser was installed for the purpose of ecological compensation of the artificial deepening of the Weser. The study reach at the Rhine instead was set up to test different bioengineering stabilisation measures. Primarily, concepts of both reaches had to fulfil administrative and legal parameters. Only in the case of the Rhine was the approach secondarily elaborated for scientific studies. Although ecological research and ecological river development became popular within the last years, methods of the study reach Weser have not been adjusted to those of the Rhine yet. A comparable monitoring programme for both reaches will start in 2018. Although comprehensive results can only be expected after several years we decided to publish first results here, due to the increasing interests on natural riverbank development

Table 2. Overview of test fields within the study reaches Rhine and Weser.

Test field	Implemented bioengineering measures
Rhine	
TF1	***WC***, living fascines, brush and hedge layers, ***SW*** with ***SZ***, dead wood trunks with roots
TF2	***R, WM*** diagonally to the flow direction
TF3	***R, WM*** transversally to the flow direction
TF4	application of gravel and single rock groups, ***DF***
TF5	***R***, Tf5a →***RS*** on the lower slope, soil covered ***SM*** onto the upper slope Tf5b →***SM***, lower slope with ***PM***, upper slope covered with soil, Tf5a/5b → hedge layers on the upper edge of the slope
TF6	injection of topsoil alginat composition into riprap cavities, hydroseeding, local planting of ***RS*** into the riprap
TF7	***R***, Tf7a1, Tf7a2, →***RS*** Tf7b,c →***PM*** on different fleeces/geotextiles
TF8	elevation of ***SW*** to protect existing reed
TF9	***R***, free succession, wooden fanshaped groyne fixed within the slope and application of ***WC***
Weser	
TF1	***R, BF, SW, SZ, RS, DF***
TF2	***R, BF, SW,SZ, RS***
TF3	Different groynes modified by ***R, BF, RS, WC***
TF4	***R, BF, SW, WC***
TF5	***SW, SZ, RS***
TF6	***SW, SZ, WC***
TF7	***R, BF, SW, RS,*** coating with plant fleece
*TF7*a	***R, BF, SW, RS, WC, WM***
TF8	***R, RS,*** coating with plant fleece
TF9	***R, BF, SZ, RS, WC, DF***
TF10	***R, WM***
TF11	***R, BF, SZ, RS***
TF12	***WC***
TF13	***RS, DF***
TF14	Planting of alders (*Alnus glutinosa*)

Note: BF: bank flattening, DF: deadwood fascines, PM: plant mattresses or rolls, R: removal of riprap, RS: different types of reed and sedge plantings, SM: stone mattresses, SW: stone wall, SZ: shallow water zone, WC: willow branch cuttings, WM: willow branch mattresses (for a detailed description, see BfG & BAW 2008, 2014).

(e.g. CBD and WFD) and high ecological potential of bioengineering measures.

2.2. *Field sampling and data analysis*

2.2.1. *Vegetation*

Before installing the study reach at the Rhine, a pre-construction t_0 monitoring of the test fields and the reference sites upstream of the measure was conducted in 2009. Braun-Blanquet method (1964) was applied, using the modified abundance scale from Reichelt and Wilmanns (1973) with 9 cover classes (r, +, 1, 2m, 2a, 2b, 3, 4, 5) (Tremp 2005). The method requires a homogenous vegetation structure within the sampling area and a preliminary distinction of vegetation height and coverage of the common vegetation layers (herb layer, shrub layer, and tree layer). After implementation of the measures, over the entire study reach, vegetation surveys were performed twice a year in 2012 and 2014 and only once a year in 2013 and 2016. In the latter years, a second vegetation survey could not be performed due to permanent flooding events. Plant species of each test field were sampled and determined to species level if possible. For the current analysis, only presence/absence data derived from the Braun-Blanquet surveys were used.

At the Weser, presence–absence surveys of vegetation were conducted in 1989, 1999 and 2005 and only from installed bioengineering measures to determine long-term development of vegetation. Plant samples were determined to species level. For an assessment of native riparian plant species development we used additional presence/absence surveys conducted in 2013 across the overall study reach including reference reaches A and B.

The evaluation of habitats developed in the study reach is based on the German Red List of threatened habitat types (Riecken 2006). Regarding the minimum sizes of threatened habitats a national concept does not currently exist. However, we used the guidelines of the Federal State of Lower Saxony (Drachenfels 2011), where the study reach is located, to determine valuable habitat structures. The author stipulates a minimum length/width of 100/10 m for reed and 20/5 m for softwood.

2.2.2. *Fauna*

To evaluate the ecological consequences of the bioengineering measures in different development stages, three faunistic components have been surveyed, i.e. avifauna, fish and macroinvertebrate communities. This data has been compared between test fields and the riprap reference for both rivers respectively. At the Weser faunistic surveys were conducted within reference reach C on the opposite river side (Figure 1).

2.2.2.1. Avifauna Avifaunistic data has been collected using visual and acoustic mapping approaches during six field surveys in the morning hours from 5 to 10 am or during the evening hours from 8 pm to 1 am between April and June 2006 at the Weser. At the Rhine, nine field surveys mainly in the morning hours between March and June 2014 were conducted and, additionally, qualitative observations were included. Species were identified, breeding and migrating individuals were distinguished and if possible activity was recorded.

2.2.2.2. Fish Fish communities were sampled using electro-fishing equipment (Weser: EFGI 4000, Bretschneider, Chemnitz, Germany; Rhine: EL 65 II, Hans Grassl, Schönau, Germany) with direct current and the point abundance method. Sampled points were located in the close vicinity to the river banks and in a distance of approximately 5–10 m from each other. Caught fish individuals were identified, sized and immediately released. In addition, benthic substrate, water depth, distance from bank, and presence/absence of macrophytes occurrence were recorded as general habitat information at each sampling point. Electro-fishing took place in June 2006 in the Weser, whereas the study reach at the Rhine was sampled twice a year between May and October from 2013 to 2015. This data was pooled per year to include the spring and autumn aspect and improve comparability. Presence/absence and dominance data was used to compare the suitability of the test field and the reference reach for fish fauna.

2.2.2.3. Macroinvertebrates Benthic macroinvertebrates were sampled in 2013 at the Rhine and in 2006 at the Weser. Quantitative samples were taken using a kick-sampling method (net frame of 1/16 m^2, aperture of 0.5 µm) or by sampling manually collected blocks (riprap) of a defined area of 0.125 m^2, depending on bottom substrate grain size. In total, 0.375 m^2 were sampled per test field in the Rhine. In the Weser, altogether 30 samples (20 from test fields, 10 from reference) of 0.125 m^2 each were taken using a Surber sampler. Macroinvertebrates were brushed carefully from larger mineral substrates and washed from finer ones, preserved in 80% ethanol and were brought to the laboratory for identification. Individuals were usually identified to species level, chironomids to subfamily level. Characteristic oligochaete species were only identified during the Rhine sampling campaings, otherwise this group was not further distinguished. All macroinvertebrate samples were taken from wadable areas with a maximum depth of 0.5 m. Since only test TF1 and TF4 included measures at the mean water level (TF1: stone wall with low current zone, TF4: dead wood root elements or dead wood fascines), only these test fields have been included into the analysis for aquatic fauna (Table 2). To evaluate the ecological impact of the applied bioengineering bank stabilisation measures on macroinvertebrate communities, different metrics and indices were calculated. In particular, the species richness, the Potamon-Typie-Index (PTI, Schöll et al. 2005), the dominance structure and the Saprobic index (DIN 38410) were calculated.

3. Results

3.1. Vegetation

Regarding the Rhine, test fields and correlated results were still strongly influenced by small scale effects. This is especially true for fast frequencies and changes of drought periods and flooding events, observed within the first five years of plant growth. After building activities in 2011 and remediation work in the following monitoring years

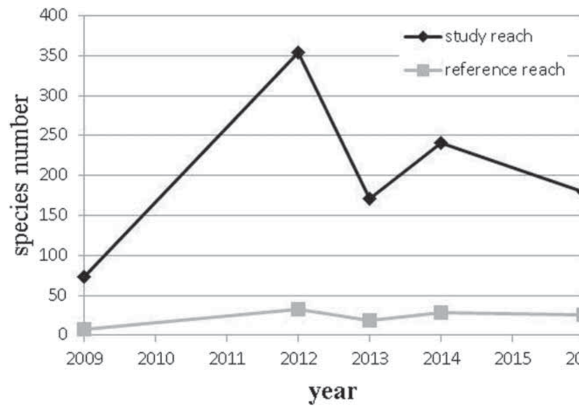

Figure 2. Temporal development of plant species numbers within the study reach (black) and the reference reach (grey) at the Rhine from 2009 to 2016.

Table 3. Absolute plant species numbers across all test fields within the study reach and the reference reach at the Rhine from 2009 to 2016 (BfG & BAW 2016).

Year	River Rhine study reach	River Rhine reference reach
2009	72	8
2012	354	32
2013	171	19
2014	241	29
2016	179	26

Table 4. Species richness of study reach and reference reaches of the Weser in 2013 (BfG & BAW 2016).

River Weser	Richness
study reach	9.53
Reference A	9.14
Reference reach B	13.00

the occurrence of ruderal vegetation was still affecting present results. However, our results showed a first trend of ecological improvement. The overall number of plant species increased considerably across all test fields since the implementation of measures. Increase of the species numbers across the test fields was comparably higher than the increase of plant species within the reference reaches (Figure 2, Tables 3 and 4). The highest numbers of species were detected for plant mats (TF7). Here, installed plant mats did not resist prevailing flooding intensities and constantly needed to be remediated throughout the monitoring period leading to varying establishing of allochthonous taxa. The lowest plant diversity was detected within the willow brush mattresses (TF2, TF3), where shrubby vegetation dominated and thus inhibited the development of the ground vegetation layer.

Moreover, a typical vegetation zonation trend within the monitoring period could be detected. Species adapted

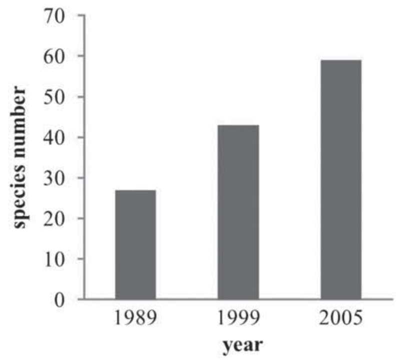

Figure 3. Temporal development of plant species within the Weser study reach from 1989 to 2005.

to moisture (e.g. *Phalaris arundenacea*) developed bank-typical habitats in the lower part of the slope and less flooding resistant species persisted in the upper parts of the test fields. Furthermore installed willow brush mattresses (TF2, TF3) developed well and can provide valuable softwood habitats for riparian fauna in the future. In another case the installed plant mats (TF7) did not resist prevailing flooding intensities and constantly needed to be remediated throughout the monitoring period. In the upper part of TF9, a site-typical hardwood structure was (*Cornus sanguinea*) established spontaneously. Additionally, *Silene baccifera* was found, which is classified as a threatened species according to the regional Red List (Hesse; BVNH 2008).

At the Weser study reach plant diversity within the test fields increased considerably since realisation of the restoration measures (Figure 3) and species numbers more than doubled by 2005. Some species were able to establish occasionally and disappeared again, most likely due to expansion of highly competitive plants like reed or willows. Two threatened species (*Inula britannica*, *Ranunculus sardous*) according to the regional Red List (Lower Saxony, Ludwig & Schnittler 1996) were introduced spontaneously. However, spatial analyses from the year 2013 showed even higher diversity rates within reference reach B and similar diversity within reference reach A compared to the study reach (Table 4).

Reed, sedge and willow species planted in 1989 rapidly spread into other sections where no vegetation was initially introduced. Especially reed growth was initialised successfully due to lower hydraulic stress at the Weser compared to the Rhine. Within the different sections, the aspired habitats, such as near-natural reed and softwood, developed well and constituted highly valuable structures according to the German Red Data Book on endangered habitats (Riecken 2006). In contrast, only one small patch of endangered habitat (softwood) appeared in reference reach A and B, respectively (Figure 4(B) and 4(C)). Minimum habitat size according to Drachenfels (2011) was frequently reached (Figure 4(A), marked red), whereas other habitats could not meet size requirements due to the small scale design of the test field area (Figure 4, yellow dashed).

3.2. Avifauna

The overall basic richness of avian species was lower at the Rhine reach compared to the higher values at the Weser River reach. Nevertheless the recorded species richness of the avifauna in both study reaches was higher in the test fields compared to the references reaches (Table 5). Species abundance of breeding bird-individuals followed a similar distribution pattern between study and reference reaches. In this context the structure of vegetation in the Weser study reach especially seems to offer suitable breeding habitats for numerous bird species. In contrast, the Rhine test fields were mostly inhabited by resting or by migrating bird individuals. Further the abundance of protected species (Südbeck et al. 2009) appeared to be slightly higher in both study reaches compared to the reference sites.

Figure 4. Occurrence of endangered habitats within the study reach Weser according to the German Red Data Book on endangered habitats (Riecken 2006). (A) Study reach, (B) reference reach A, (C) Reference reach B. Red: actual endangered habitats complying minimum size according to Drachenfels (2011). Yellow (dashed): potential valuable habitats of relevant species composition but not complying with minimum size due to fragmentation of the test fields.

Table 5. Bird species recorded during field surveys in the two study reaches compared between reference and testing fields (BfG & BAW 2016).

	River Rhine		River Weser	
	Reference	Study reach	Reference	Study reach
Taxa number	11	33	26	52
Breeding	0	2 (5)	18	30
Resting/Migrating	11	31 (28)	8	22
Red list species	5	9	1	6

Note: Species numbers in brackets including species with suspected breeding.

3.3. *Fish*

The fish communities from the test fields at the Rhine with riprap removal above mean water level (TF2-3, TF5-9; Figure 5) expectedly did not display any difference compared to the riprap reference sites. In contrast, TF1 and TF4 are characterised by measures at mean water level. Here, the ratio between native species and non-native species (neozoa) was quite different compared to the reference situation (Figure 5). In the test fields the yearly caught number of fish species ranged between 12 and 23 during the study period from 2013 to 2015. In contrast, in bank areas with riprap, invasive fish species, i.e. round goby (*Neogobius melanostomus*) and Kessler's goby (*Ponticola kessleri*), distinctly dominated the ichtyofauna with proportions of about 70–75% (Figure 5). However, native fish species appeared to benefit from structural enhancement due to dead wood application (TF1 and TF4) and especially from the current slackening behind the longitudinal stone wall in TF1. Their mean relative frequency was increased to approximately 60% at these two test fields (Figure 5). The relation between native and neozoa seemed to be relatively stable over the sampling period in TF1 (Figure 6). In the reference reach the proportion of neozoa increased clearly from 2013 to 2014 and decreased slightly in 2015. The invasive species proportion in TF4, in contrary, increased from 2013 (9%) to 2014 (33%) to 2015 (88%) (Figure 6). Additionally, the number of individuals caught decreased in the same time period from 235 individuals in 2013 to 60 individuals in 2014 and only 25 individuals in 2015. The low fish density of the latter two years were likely due to exceptionally dry summers and thus low water levels during the fishing campaigns. Under these conditions the relevant dead wood structures at mean water level were not wetted and therefore not effective. Sampling then was most likely influenced by habitat uniformity and did not reflect the actual fish stock.

In contrast, fish communities from the Weser study reach in 2006 were exclusively composed of seven native species (Figure 7). Five species were equally identified in all sampling reaches (study and reference reach), the species ide (*Leuciscus idus*) was found only in the study reach, the species perch (*Perca fluviatilis*) was only caught in the reference reach. The dominance structure between the test fields and the reference reach was comparable: both have been dominated by cyprinids of the species roach (*Rutilus rutilus*) and dace (*Leuciscus leuciscus*) comprising approximately 75% in the reference reach and 85% in the test fields. The individual density was lower in the reference reach (43 individuals) compared to the test fields (120 individuals), taking the double effort at the latter into account. A clear influence of the bioengineering bank stabilisation on fish fauna could not be detected at the Weser study reach.

3.4. *Macroinvertebrates*

The macroinvertebrate communities from the test fields of both study reaches were heavily dominated by invasive

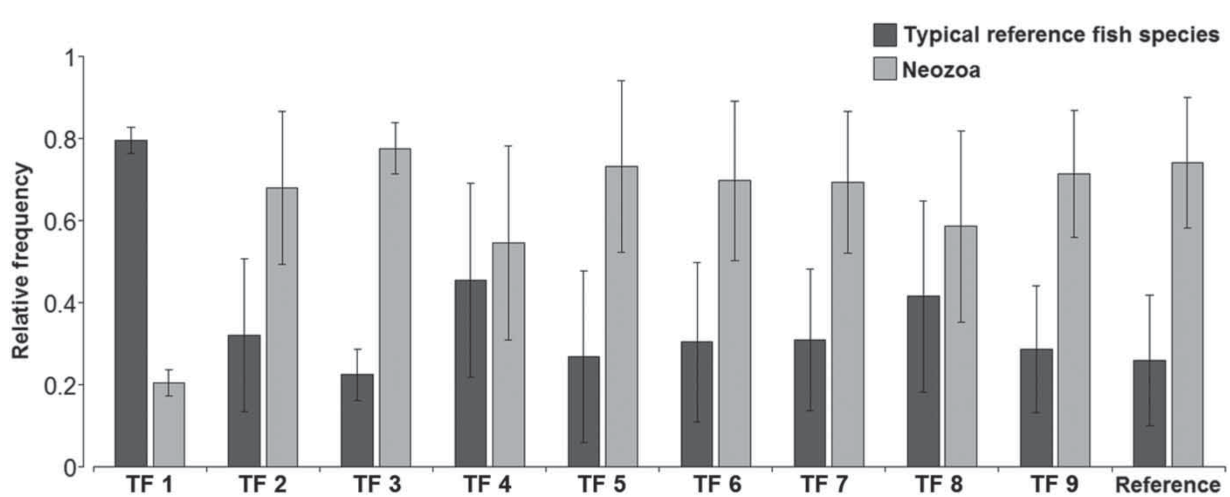

Figure 5. Relative frequency (%) of native fish species and neozoa within the test fields (TF) on the Rhine with (TF1 and 4) and without ecological enhancement (TF2, 3, 5–9) at mean water level compared to the riprap reference.

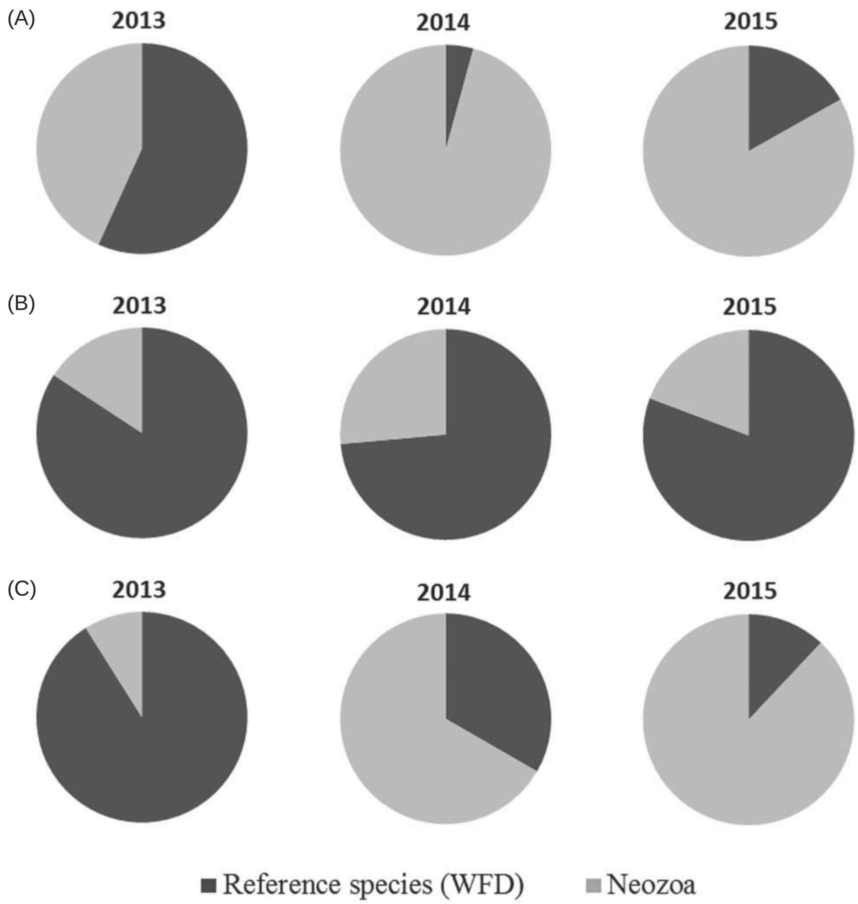

Figure 6. Relative proportion of native fish (reference species according WFD) and invasive species (Neozoa) during the three sampling years at the Rhine study reach in (A) the riprap reference, (B) test field 1 (TF1) containing slow flowing area with dead wood elements and (C) test field 4 (TF4) with dead wood fascines at mean water level.

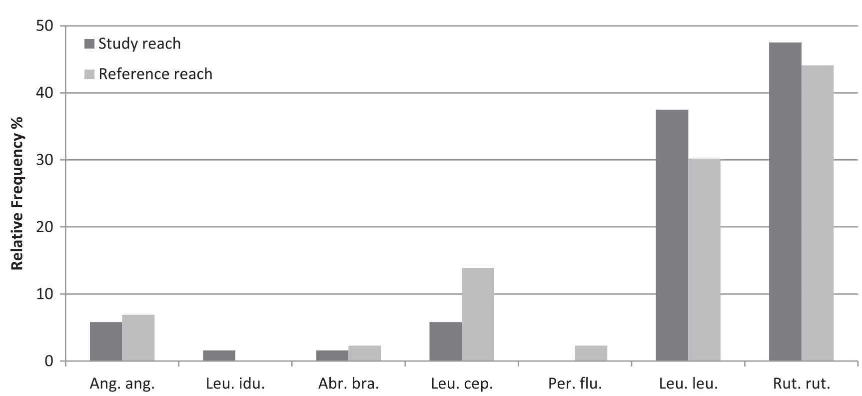

Figure 7. Relative frequency of fish species within the study reach compared to the reference reach at the Weser. Note: *Ang. ang.* = Eel (*Anguilla anguilla*), *Leu. idu.* = ide (*Leuciscus idus*), *Abr. bra.* = bream (*Abramis brama*), *Leu. cep*. = chub (*Leuciscus cephalus*), *Per. flu*. = perch (*Perca fluviatilis*), *Leu. leu*. = dace (*Leuciscus leuciscus*), *Rut. rut*. = roach (*Rutilus rutilus*).

crustacean species representing dominance values of neozoa up to 96% from parts at the Weser and up to 100% from special wooden structures in TF1 and in TF4 at the Rhine. The taxa richness was slightly increased at the test fields TF1, TF3 and TF4 with mean values from 14 to 15 compared to all other test fields which did not differ from the reference reach at the Rhine study reach. At the Weser, macroinvertebrate taxa richness was increased at the test fields compared to the reference reach (Table 6). The values of the Potamon-Typie-Index at the Rhine study reach ranged between 2.9 and 3.6, indicating a moderate to poor ecological state with no clear differences between test fields and the reference site. At the Weser study reach the PTI was 2.7 at the reference reach (moderate) and 4.4 at the

Table 6. Mean species richness of macroinvertebrates at Rhine and Weser within the study reaches compared to the reference reaches.

	River Rhine			River Weser	
	Study reach (TF1, 3, 4)	Study reach (TF2, 5, 6, 7, 8, 9)	Reference	Study reach	Reference
Species richness (mean)	14–15	9–11	10	44	30

test fields (poor) but, due to the partly low classified taxa numbers the meaningfulness of these values at all sampling sites was restricted. The saprobic index values ranged between 2.1 and 2.4 at all studied sites (except for two test fields of the Rhine study reach which were spatially influenced, due to a temporary sewage outflow) representing the general status of the rivers but not the influence of the measures.

4. Discussion

Living plants have been used for riverbank stabilisation for centuries. However, they have largely been displaced by artificial bank fixation methods (e.g. riprap) during the twentieth century (Evette et al. 2009). Both study reaches are, next to single small-scale measures, two out of only a few examples for the implementation of bioengineering bank stabilisation on navigable waterways in Germany. To our knowledge, the ecological impact of such measures has not been investigated sufficiently so far. With this manuscript therefore we go a first step to close this gap of knowledge and to get more insight into the role of bioengineering on the ecological potentials of large rivers and waterways. However, due to large temporal difference and thus varying quality of methods (e.g. experimental design, size of test fields) several uncertainties need to be considered.

The ecological improvement and the colonisation of target species are based on the establishment of site specific habitats. Valuable structures like softwood and reed are still extensively underrepresented along navigable waterways. The successful establishment of target habitats requires several years (or even decades) of undisturbed development. The study reach Weser offers the unique facility to evaluate bioengineering measures after a duration time of more than a quarter of a century. Although monitoring programme started more than 25 years ago and does not meet today's research standards, the results can help us to increase our knowledge of long-term development of bioengineering methods along rivers.

Compared to the reference reaches, site specific structures have been established in the test fields at the Weser, serving as valuable habitats for potential floodplain species. The willow brush mattresses within the test fields developed into broad softwood copse which can be attributed to the (critically) endangered habitat type softwood alluvial forest (Riecken 2006). The same applies to several reed beds (Red List status: vulnerable) even though they do not meet minimum size of endangered habitats (Drachenfels 2011). No bank erosion could be detected, proving the suitability of bioengineering measures for bank stabilisation. In contrast, only two small softwood structures occur in the reference reaches. Here, the purely technical bank fixation (riprap) and the steep bank inclination hampered the establishment of near-natural vegetation structures. Since the realisation of the measures, the abundance of plant species increased continuously within the test fields and two threatened plant species colonised spontaneously. However, species abundance of reference reach A was comparable to the study reach. Species abundance of reference reach B was even higher. This pattern complied with a recent study of several other river banks of navigable waterways in Germany (Harvolk et al. 2015). The reference reaches imply conventional riverbank fixations. Here the steep gradient (bank inclination) and riprap lead to a very pronounced moisture gradient and the consecutive settlement of various adapted species. On the other hand plant diversity of reference reach A was negatively influenced by agriculture within the riverine area (e.g. Feld 2013). This affected a different species composition but a comparable species number as in the study reach. Generally, high species numbers of riprap are composed of allochthonous taxa which in most instances are not target species of river restoration projects. In contrast, species of the test fields at the Weser were autochthonous in large parts, with higher moisture and nutrition indicator values (Ellenberg et al. 1991). Furthermore, target habitats such as reed beds and softwood were typically consist of very few dominant species such as *Phragmites australis* and willows (*Salix spec.*) which naturally inhibit species-rich vegetation.

However, well-developed habitats such as reeds, tall forbs and willows provided more breeding and resting places for various bird species in the study reaches compared to uniformous riprap at the reference reaches. The higher species numbers of breeding birds in the test fields compared to the reference reaches were most likely caused by the progressed vegetation development and a resulting mosaic of suitable habitats within an overall monotonous landscape. This hypothesis is also supported by the generally higher taxa numbers in the test fields. Additionally, the removal of riprap and the flattening of the riverbank might have attracted species of the amphibian zone, such as waders. Furthermore, the number of Red List species

(Südbeck et al. 2009) is considerably higher within the test fields.

However, regarding the macroinvertebrate communities no clear differences were detected between the study reaches and the references reaches. This was very likely due to the fact that measures have not been installed underneath mean water level, where submerse bank protection is still dominated by riprap. Similar patterns could be detected regarding the fish communities. Furthermore, the prevailing technical bank fixation seemed to predominantly attract neozoa. The experimental site at the Rhine is considerably younger in age and has not developed stable target habitats so far. In the first two years, the vegetation was strongly influenced by building activities. This resulted in an extreme short-term increase of plant species numbers in 2012, which included many species that were not characteristic for river banks. Furthermore, small scale effects due to extreme hydrological dynamics (e.g. long-term flooding in 2013, extreme droughts in 2015), regular maintenance and remediation work in single test fields could clearly be observed. However, indications of ecological improvement could also be detected. The overall number of species in the test fields increased compared to the initial state of the bank from 2009 until today. This pattern could not be observed within the references reaches where species numbers remain low. It has to be addressed that the sampling size of reference species compared to the entire number of test fields is clearly smaller. However, in case of a linear relation between species number and size of sampling field, which is highly improbable, plant species numbers within the reference reach would still be markedly lower. Further it has to be conceded that installing various bioengineering bank stabilisation measures generally suggests increased structural diversity and an increase of species numbers. Future study reaches should include a lower number of measure types but instead be larger in size. Despite these uncertainties in the experimental design, various bioengineering bank protection measures could be evaluated under extreme hydrological and navigational conditions. The entire removal of riprap without bank fixation above mean water level (TF9) on the one hand strongly supported the development of a near-natural zonation of the river bank but on the other hand showed strong erosion effects under extreme hydrological conditions at the Rhine. Especially willow brush mattresses (TF2, TF3) and willow branch cuttings (TF1) developed well and so far resisted navigation impacts according to monitoring results (BfG & BAW 2015). Hence, they so far provided sufficient bank stability by simultaneously enhancing the structural diversity. On a long-term perspective, a similar development of these structures as seen at the Weser can be assumed at the Rhine as well if maintenance will be restricted to low levels.

In contrast to the test fields at the Weser, the suitability for bird species at the Rhine was limited by frequent observations and regular maintenance work. Even if these influences will be reduced in the future, anthropogenic disturbances remain due to the vicinity of a footpath (walkers, dog owners) and fishing activities in this densely populated area. However, first results show that bird species numbers are higher in the test fields than in the reference reach suggesting that enhanced structural diversity can provide suitable habitat structures.

Electro-fishing campaigns at the test fields with measures in the (semi-) aquatic zone were difficult to perform at low water levels and thus collected data partly do not reflect the actual fish stock situation in these test fields. In these cases measures applied at mean water level are not effective and the riprap layer mostly is the only remaining refuge for local fish populations even if this was covered by pebble material applied during the installation of TF4. From results of the electro-fishing campaigns in the years 2013, 2014 and 2015 at the Rhine only test fields including measures at mean water level tended to inhabit lower relative proportions of invasive fish species. Especially round goby (*Neogobius melanostomus*) widely colonise riprap structures within heavily modified waterways (Borcherding et al. 2013) and appear to be better adapted to this habitat than native fish species. At the same time, relative proportions of reference species according to the WFD (2000) were low within the reference reach and decreased within the sampling years in TF4. Continuous water level data from the nearby gauging station Worms (Rhine-km 443.4) indicated that flooding frequencies of the fascines in TF4 was 260 days in 2013, 182 days in 2014 and only 156 days in 2015. Considering also the decreasing individual numbers caught in TF4, a positive relationship between flooding frequency of the fascines, as an important structural element for aquatic communities in this test field and the number of caught fish is suggested. At the same time a negative relationship between the flooding frequency and the proportion of neozoa, which were caught in the permanently flooded riprap below the dead wood fascines can be assumed. Consequently, the ecological efficiency of dead wood fascines appears to be strongly dependent on flooding frequency and therefore can be expected to be highest when flooding occurs permanently. On the other hand, native fish individuals were recorded frequently in larger proportions in the shallow water zone with dead wood trunks (TF1). Lower stream velocities, increased sediment deposition and enhanced structural diversity by these dead wood trunks were very likely to attract autochthonous fish species. As discussed for TF4 low water levels inhibited sufficient sampling at this test field and limit the valuable function of the shallow water zone as shelter for nursery of young site-typical fish species compared to mean or even high water levels. Thus, effectiveness of measures including shallow water zones would have been higher if single deep water areas were provided serving as retreats during periods of low water levels.

Until now macroinvertebrate data analysis did not give clear indications for bioengineering bank protection measures resulting in increased biodiversity or ecological quality. Communities of both rivers were dominated by invasive crustacean species, which seem to better cope with riprap habitat. Our data suggested that this might be different if measures that enhance structural diversity would have been installed deeper into the aquatic environment (below mean water level) to ensure consistent effectiveness. This is indicated by more diverse colonisation of wooden habitats in the test fields at the River Rhine.

5. Conclusions

With regard to the three initial research questions, valuable conclusions can be derived from our investigations.

(I) Concerning the ecological impact of bioengineering stabilisation measures, our results show, that both study reaches do increased biodiversity of river banks especially by forming valuable habitat structures for native plant and bird species.

(II) In particular, willow brush mattresses appear to support structural diversity and served to secure bank stability and flood protection even under high hydrological pressure (e.g. Rhine). Reed belts secured stabilisation of river banks under moderate hydrological conditions (e.g. Weser) and provided valuable habitat structures for birds and organisms of the amphibian zone. Thus, if hydrological conditions are suitable for the installed plant species, our results responded positively to the second research question.

(III) However, the impact of measures on fish and macrozoobenthos is strongly limited if measures are only installed above mean water level. The respond of organisms on bioengineering measures within the aquatic zone still remains unsolved and needs further investigations. Additionally, it can be assumed that the particulate low species numbers (e.g. fish) and the dominance of invasive macroinvertebrates were also due to the lack of accessible source populations needed for successful recolonisation of bioengineered reaches. For adequate ecological evaluation of the effectiveness of bioengineering measures, further long-term examinations across different river systems under varying navigation intensities are needed.

Acknowledgements

We thank the engineering office Björnsen Consulting Engineers for collection of field data. Furthermore we thank our colleagues from the Ecology Division (BfG) for field sampling and their great support regarding species identification and data analysis, especially Katja Behrendt, Andreas Sundermeier and Steffen Wieland. Additional we thank Kevin Jewell, Andre Terwei and Björn Hoppe for valuable support during the preparation of this publication. Moreover we thank Maria Maag for analysis of vegetation data. We are grateful to the Waterways and Shipping Administration Offices in Mannheim and Verden for enabling the installation of the study reaches and providing their valuable management experience on both federal waterways. The present research project 'Alternative technical-biological bank protection measures on federal waterways' is funded by the Federal Ministry of Traffic and Digital Infrastructure Germany.

Notes on contributors

Kathrin Schmitt is a scientist at the Department of Vegetation Studies and Landscape Management at the German Federal Institute of Hydrology. She graduated from the Technical University Munich (TUM) in Germany within the field of engineering ecology and environmental planning. Her current research interests focus on ecological interactions (biotic, abiotic) and biodiversity of river bank habitats along human-modified waterways.

Michael Schäffer is a research scientist at the German Federal Institute of Hydrology. He graduated from the Technische Universität Dresden, Germany (Institute of Hydrobiology) and is specialized in ecology of macroinvertebrate and fish communities. His current research interests are focused on ecological interactions between river bank structures and aquatic and terrestrial animal diversity.

Dr. Jochen H.E. Koop studied Biology focused on Zoology, Zoophysiology and Limnology at the Heinrich–Heine–University, (Düsseldorf, Germany). He graduated with diploma in biology and obtained his PhD with Prof. Grieshaber at the local Institute of Zoophysiology. Thereafter, he became assistant Professor of Prof. Benndorf at the Institute of Hydrobiology of the Technische Universität Dresden. Since 2002, he is head of the Department of Animal Ecology at the German Federal Institute of Hydrology. He obtained his habilitation at the University of Koblenz–Landau (venia legendi zoology) on the competition of aquatic organisms in streams and rivers with attention to the importance of species-specific ecophysiological traits. Subsequently, he was appointed as extraordinary Professor. His main focus is on the understanding of colonization structures of aquatic and terrestrial animals (biodiversity) of large rivers with biotic and abiotic stressors and the ecological interactions.

Dr. Lars Symmank is working at the Department of Vegetation Studies and Landscape Management at the German Federal Institute of Hydrology. He obtained his PhD in biology at the Technische Universität Dresden, Germany (Institute of Botany). His current research includes investigation of biodiversity of human-modified riparian zones and floodplains with special focus on regulating and cultural ecosystem services.

References

AG Reinhaltung Weser. 1998. *Karte zur Gewässerstrukturgüte der Flüsse Weser, Werra, Fulda [Map of river structural quality of the rivers Weser, Werra, Fulda]*. Wassergütestelle Weser: Hildesheim.

[BfG & BAW] Federal Institute of Hydrology and Federal Waterways Engineering and Research Institute. 2008. Untersuchungen zu alternativen technisch-biologischen Ufersicherungen an Bundeswasserstraßen, Teil 2: Teststrecke Stolzenau/Weser [Investigations to alternative technical-biological bank protection measures on Federal Waterways, Part 2: Study reach Stolzenau / Weser]. Karlsruhe / Koblenz. (BfG- Nr.: 1579).

[BfG & BAW] Federal Institute of Hydrology and Federal Waterways Engineering and Research Institute. 2014. Einrichtung einer Versuchsstrecke mit technisch-biologischen Ufersicherungsmaßnahmen, Rhein-km 440,6-441,6, rechtes Ufer [Establishment of a study reach with technical-biological bank protection measures, Rhine-km 440,6–441,6, right bank], 4th Interim Report, Monitoring results 2013. Karlsruhe / Koblenz. (BfG-Nr.: 1677).

[BfG & BAW] Federal Institute of Hydrology and Federal Waterways Engineering and Research Institute. 2015. Einrichtung einer Versuchsstrecke mit technisch-biologischen Ufersicherungsmaßnahmen, Rhein-km 440,6-441,6, rechtes Ufer [Establishment of a study reach with technical-biological bank protection measures, Rhine-km 440,6–441,6, right bank], 4th Interim Report, Monitoring results 2014. Karlsruhe / Koblenz. (BfG-Nr.: 1677)

[BfG & BAW] Federal Institute of Hydrology and Federal Waterways Engineering and Research Institute. 2016. Einrichtung einer Versuchsstrecke mit technisch-biologischen Ufersicherungsmaßnahmen, Rhein-km 440,6-441,6, rechtes Ufer [Establishment of a study reach with technical-biological bank protection measures, Rhine-km 440,6–441,6, right bank], 4th Interim Report, Monitoring results 2014. Karlsruhe / Koblenz. (BfG-Nr.: 1677).

Borcherding J, Dolina M, Heermann L, Knutzen P, Krüger S, Matern S, van Treeck R, Gertzen S. 2013. Feeding and niche differentiation in three invasive gobies in the lower Rhine, Germany. Limnologica – Ecol Manag Inland Waters. 43:49–58.

Braun-Blanquet J. 1964. *Pflanzensoziologie – Grundzüge der Vegetationskunde [Phytosociology – main features of vegetation studies]*. Vienna: Springer.

[BVNH] Botanische Vereinigung für Naturschutz in Hessen. 2008. *Rote Liste der Farne und Gefäßpflanzen [Red list of ferns and vascular plants]*. 4th ed. Wiesbaden: Hessisches Ministerium für Umwelt, ländlichen Raum und Verbraucherschutz.

Cavaillé P, Dommanget F, Daumergue N, Loucougaray G, Spiegelberger T, Tabacchi E, Evette A. 2013. Biodiversity assessment following a naturality gradient of riverbank protection structures in French prealps rivers. Ecol Eng. 53:23–30.

CBD. 1992. Convention on biological diversity. [accessed 2016 Sept. 30]. http://www.cbd.int/doc/legal/cbd-en.pdf.

Drachenfels O. 2011. *Kartierschlüssel der Biotoptypen Niedersachsens [Mapping key for habitat types of lower saxony].* 7th ed. Norden: Niedersächsischer Landesbetrieb für Wasserwirtschaft, Küsten- und Naturschutz.

Ellenberg H, Weber HE, Dull R, Wirth V, Werner W, Paulisen D. 1991. Zeigerwerte von Pflanzen in Mitteleuropa [Indicator values of plants in Central Europe]. Scripta Geobotanics. 18:248.

Evette A, Labonne S, Rey F, Liebault F, Jancke O, Girel J. 2009. History of bioengineering techniques for erosion control in rivers in Western Europe. Environ Manage. 43: 972–984.

Feld CK. 2013. Response of three lotic assemblages to riparian and catchment-scale land use: implications for designing catchment monitoring programmes. Freshwater Biol. 58:715–729.

Fischenich JC, Allen H. 2000. *Stream management*. Vicksburg: Engineering Research and Development Centre Vicksburg (No. ERDC/EL-TR-SR-W-00-1).

Frothingham KM. 2008. Evaluation of stability threshold analysis as a cursory method of screening potential streambank stabilization techniques. Appl Geogr. 28:124–133.

Harvolk S, Symmank L, Sundermeier A, Otte A, Donath TW. 2015. Human impact on plant biodiversity in functional floodplains of heavily modified rivers – A comparative study along German federal waterways. Ecol Eng. 84: 463–475.

[ICBR] International Commission for the Protection of the Rhine against Pollution. 2009. Internationally coordinated management plan for the international river basin of the Rhine (part A). Koblenz.

Li MH, Eddleman KE. 2002. Biotechnical engineering as an alternative to traditional engineering methods: A biotechnical streambank stabilization design approach. Landscape Urban Plan. 60:225–242.

Ludwig G, Schnittler M. 1996. *Rote Liste gefährdeter Pflanzenarten [Red list of threatened plant species]*. Bonn: Federal Agency of Nature Conservation.

Millennium Ecosystem Assessment. 2005. Ecosystems and human well-being: Synthesis. The millennium ecosystem assessment series. Washington (DC): World Resources Institute.

Naiman R, Decamps H. 1997. The ecology of interfaces: riparian zones. Ann Rev Ecol Syst. 28:621–658.

Palmer MA, Menninger HL, Bernhardt E. 2010. River restoration, habitat heterogeneity and biodiversity: a failure of theory or practice? Freshwater Biol. 55:205–222.

Parkyn SM, Davies-Colley RJ, Halliday NJ, Costley KJ, Croker GF. 2003. Planted riparian buffer zones in New Zealand: do they live up to expectations? Restor Ecol. 11:436–447.

Reichelt G, Wilmanns O. 1973. *Vegetationsgeographie [Phytogeography]*. Braunschweig: Georg Westermann.

Riecken U. 2006. *Rote Liste gefährdeter Habitattypen in Deutschland [Red list of threatened habitat types of Germany]: Ed. 34*. Bonn: Federal Agency of Nature Conservation.

Sala OE, Chapin FS, Armesto JJ, Berlow E, Bloomfield J, Dirzo R, Huber-Sanwald E, Huenneke LF, Jackson RB, Kinzig A, et al. 2000. Global biodiversity scenarios for the year 2100. Science. 287:1770–1774.

Schöll F, Haybach A, König, B. 2005. Das erweiterte Potamontypieverfahren zur ökologischen Bewertung von Bundeswasserstraßen (Fließgewässertypen 10 und 20: kies- und sandgeprägte Ströme, Qualitätskomponente Makrozoobenthos) nach Maßgabe der EU-Wasserrahmenrichtlinie. *Hydrologie und Wasserwirtschaft*. 49(5):234–247.

Südbeck P, Bauer H-G, Boschert M, Boye P, Knief W. 2009. Rote Liste und Artenliste der Brutvögel (Aves) in Deutschland [Red list and species list of breeding birds (aves) of Germany]. Nat Conserv Biodivers. 70:159–227.

Tockner K, Stanford JA. 2002. Riverine flood plains: present state and future trends. Environ Conserv. 29:308–330.

Tremp H. 2005. *Aufnahme und Analyse vegetationsökologischer Daten [Survey and analysis vegetation data]*. Stuttgart: Verlag Eugen Ulmer.

WFD. 2000. Water framework directive (2000/60/EC). [assesed 2016 Sept. 30]. http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri = CELEX:32000L0060&from = EN.

Wolter C. 2001. Conservation of fish species diversity in navigable waterways. Landscape Urban Plann. 53:135–144.

[WSV] Federal Waterways and Shipping Administration. 2016. Statistischer Verkehrsbericht 20104/20154 [Navigational traffic report 2014/2015]. WSV.

Wyzga B. 1993. River response to channel regulation: case study of the Raba river, Carpathians, Poland. Earth Surf Proc Landforms. 18:541–556.