Test stretch with technical-biological bank protection measures

Rhine km 440.6 to km 441.6, right bank

Final report of the monitoring phase 2012 to 2017

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List of abbreviations

ADV measurement	Acoustic Doppler Velocimeter measurement
AHP	Analytic Hierarchy Process
AZW	Rhine-specific water level for hydraulic constructions which is about 20 cm below mean water level (roughly corresponds to MW)
BAW	Bundesanstalt für Wasserbau (Federal Waterways Engineering and Research Institute)
BfG	Bundesanstalt für Gewässerkunde (German Federal Institute of Hydrology)
BfN	Bundesamt für Naturschutz (Federal Agency for Nature Conservation)
BiolFlor	Database on biological and ecological traits of the flora of Germany
BMU	Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety; since 2021 BMVU – Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection)
BMVI	Bundeministerium für Verkehr und Infrastruktur (Federal Ministry for Transport and Infrastructure; since 2021 BMDV – Federal Ministry for Digital and Transport)
BOKU	University of Natural Resources and Life Sciences, Vienna
BrE	Development of breeding potential
BrP	Breeding potential
CI	Consistency Index
CR	Consistency Ratio
EPTCBO species	Species of the orders Ephemeroptera (mayflies), Plecoptera (stoneflies), Trichoptera (caddisflies), Coleoptera (beetles), Bivalvia (bivalve shells) and Odonata (dragonflies and damselflies)
FWZ	Shallow water zone
GBB	Grundlagen zur Bemessung von Böschungs- und Sohlensicherung an Binnenwasserstraßen' ('Principles for the Design of Bank and Bottom Protection for Inland Waterways')
Gew.	Weighting (Wt.)
GlW	Equivalent low water level
GOK	Ground surface (= top edge of the slope)
HL	Hedge layer
HMULV	Hessisches Ministerium für Umwelt, ländlichen Raum und Verbraucherschutz (Hessian Ministry for the Environment, Rural Areas and Consumper Protection; current designation: Hessian Ministry for the Environment, Climate Change, Agriculture and Consumer Protection)

HSW	Highest navigable water level
HW	High water
HWMI	High water level I
HWMII	High water level II
i.e.S.	narrow definition (narr. def.)
i.w.S.	broad definition (br. def.)
Lfd m	per running metre
LfU	Bayrisches Landesamt für Umwelt (Bavarian State Office for the Environment)
LFV	Landesfischereiverband Bayern (Fisheries Association of the State of Bavaria)
$LMB_{10/60}$ / $LMB_{5/40}$	(Light Mass Category B – light-mass armourstones)
MEA	Millennium Ecosystem Assessment
MNW	Mean low water level
MP	Monitoring period
MS Worms	Patrol boat of the Waterways and Shipping Office Upper Rhine
MW ± SD	Mean value ± Standard Deviation (= standard deviation)
MW	Mean water level
MB	Macrobenthos
N	Non-riparian
n. erf.	Not separately recorded
NHN	Standard elevation zero
NMDS	Non-metric multidimensional scaling
MSL	Mean Sea Level
PET	Polyethylenterephthalate
GZ	Gauge zero
PP	Polypropylene
RI	Random Index (= mean consistency index)
RaP	Resting/feeding potential
Ref	Reference stretch
RG	Reed gabions
RL	Red list
rmANOVA	Repeated measures Anova
SE	Standard error

SM	Stone mattresses
StS	Riprap
Stk	Piece
TLW	Technical delivery conditions for armourstones
U	Riparian (typical)
TF	Test field
WFD	European Water Framework Directive
WSA	Waterways and Shipping Office
WSA-MA	Waterways and Shipping Office Mannheim (since 2019 part of the WSA Upper Rhine)
WSL	Willow brush mattress

Authors contributing to the report

Behrendt, Katja	Federal Institute of Hydrology, Koblenz, Department Vegetation Studies, Landscape Management
Fleischer, Petra	Federal Waterways Engineering and Research Institute, Karlsruhe, Section Earthworks & Bank Protection (lead)
Gesing, Carolin	Federal Waterways Engineering and Research Institute, Karlsruhe, Section Shipping
Hannig, Marc	Waterways and Shipping Office Upper Rhine, Department Shipping
Prof. Dr. Koop, Jochen	Federal Institute of Hydrology, Koblenz, Department Animal Ecology
Schäffer, Michael	Federal Institute of Hydrology, Koblenz, Department Animal Ecology (until 2019)
Schlüter, Volker	Federal Waterways Engineering and Research Institute, Karlsruhe, Section Earthworks & Bank Protection
Schmitt, Kathrin	Federal Institute of Hydrology, Koblenz, Department Vegetation Studies, Landscape Management
Schneider, Agnes	Federal Waterways Engineering and Research Institute, Karlsruhe, Section Earthworks & Bank Protection (until 2019)
Sorgatz, Julia	Federal Waterways Engineering and Research Institute, Karlsruhe, Section Earthworks & Bank Protection
Dr. Soyeaux, Renald (†)	Federal Waterways Engineering and Research Institute, Karlsruhe, Section Earthworks & Bank Protection (until 2018)
Dr. Sundermeier, Andreas	Federal Institute of Hydrology, Koblenz, Department Vegetation Studies, Landscape Management
Wieland, Steffen	Federal Institute of Hydrology, Koblenz, Department Vegetation Studies, Landscape Management

With contributions from

Dr. Esser, Daniel	Federal Institute of Hydrology, Koblenz, Department Vegetation Studies, Landscape Management
Herz, Hans-Werner	Federal Institute of Hydrology, Koblenz, Department Vegetation Studies, Landscape Management
Dr. Taupp, Thomas	Federal Institute of Hydrology, Koblenz, Department Animal Ecology

1 Background

Legal provisions and political guidelines require that the needs of shipping are reconciled with other uses of waterways and ecological developments. The design of riparian zones is an important element for the latter. From an ecological point of view, a bank without any protection measures would be ideal; however, in many places bank protection is indispensable. Studies are therefore required to examine whether technical-biological bank protection measures can enhance the ecology and at the same time maintain sufficient protection, including for adjacent ground, at reasonable maintenance cost.

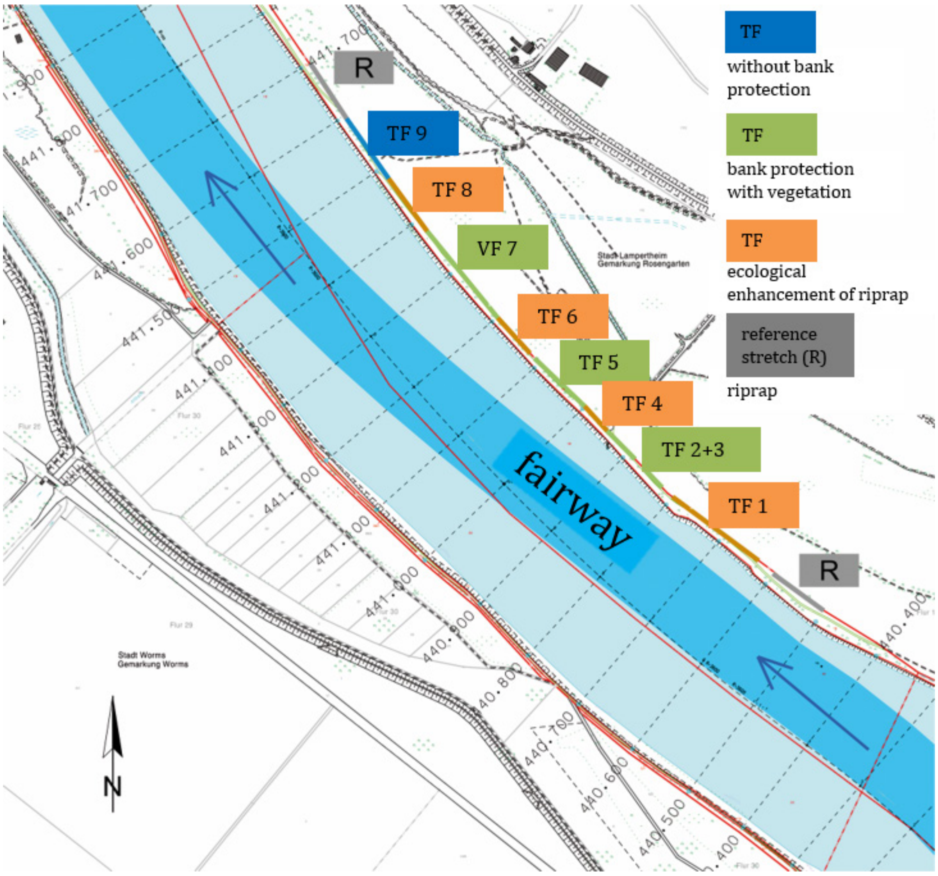
Since 2011 a field test has been conducted on the River Rhine near Worms to find answers to this question. The field test is part of the wider joint research and development project 'Studies on Alternative Technical–Biological Bank Protection Measures Applied on Inland Waterways' that the BAW and BfG have been working on since 2004. The project executing agency responsible for the field test is the former WSA in Mannheim. Nine different technical–biological bank protection measures have been put to test under waterway conditions on a 1-km stretch (km 440.600 to 441.600) on the right river bank of the Rhine in the communal district of Lampertheim. The aim of the new bank protection measures is to provide the same erosion and sliding failure protection to an instable bank as would be ensured by conventional riprap and at the same time achieve ecological enhancement.

The project is accompanied by extensive monitoring. The findings are documented in regular monitoring reports. The boundary conditions and the different designs and their installation are described in the First Interim Report (BAW, BfG, WSA-MA 2012). The Second Interim Report (BAW, BfG, WSA-MA 2013) summarised the initial monitoring results of 2012 and laid important groundwork for evaluations in the subsequent years. The brief third, fourth and fifth interim reports (BAW, BfG, WSA-MA 2014; BAW, BfG, WSA-MA 2015; BAW, BfG, WSA-MA 2016) document the main examinations and events in the relevant periods 11/2012 to 10/2013, 11/2013 to 10/2014 and 11/2014 to 10/2015, respectively.

The present Final Report, which, similarly to the other reports, was prepared to provide information to the BMVI, summarises and evaluates the monitoring results for the period from 01/2012 to 12/2017. After six years of operation, the stability and bank protection provided by the tested measures and their ecological effectiveness are appraised based on developments in this period. Recommendations are made for the future use of the tested measures on inland waterways. Some of the monitoring results have already found their way into guidelines and design recommendations for the Waterways and Shipping Administration.

2 Test Fields

Figure 1 provides a top view of the location of the test stretch, and shows the different test fields on the right river bank and the location of the fairway in the Rhine between km 440.600 and km 441.600. In five bank sections the former riprap was completely removed in the area roughly above mean water level and replaced with vegetations. In one of these sections most of the bank has remained without any protection. In four bank sections different measures were implemented to achieve an ecological enhancement of the existing riprap. There are also two reference sections upstream and downstream of the test stretch, where the old riprap has been maintained.



Reference: Fachstelle für Geodäsie und Geoinformatik der WSV, provided in accordance with GeoNutzV, further processed by BAW.

Figure 1: Geographic location of the test fields (TFs) (BAW, BfG, WSA-MA 2013)

Table 1 provides an overview of the installed bank protection measures and the most important ecological objectives. In test fields (TF) 2, 3, 5 and 7 (highlighted in green in Table 1) the newly installed measures with vegetation components need to ensure bank protection, whereas in TF 1, 4, 6 and 8 (highlighted in brown in Table 1) the existing riprap has been left in place as bank protection. Test field 9, the last test area downstream, has a special function: here, no new slope protection was installed above mean water level after the former riprap had been removed (highlighted in blue in Table 1).

The boundary conditions prevailing on the River Rhine, the design and installation of the individual bank protection measures as well as ecological objectives and the monitoring programme are exhaustively documented in (BAW, BfG 2010) and (BAW, BfG, WSA-MA 2012). The key boundary conditions are summarised in a table in Annex 1.

The paramount ecological objective of all measures is to promote flora and fauna. For TF 1, 2, and 3 the target vegetation consists of woody plants; the same applies to parts of TF 5 (layer of hedges along the shoulder of the slope) and TF 9 (above log groyne and along the maintenance path). In TF 8 the existing woody plant population on the slope was left in place. Reeds and grasses have been specified as the target vegation in TF 5 (reed gabions), 6, 7 and 8 (lower slope area). No target vegetation has been specified for TF 4 and 5 (stone mattresses) and TF 9 (bank slope); here a natural succession of vegetation is allowed.

Table 1: Overview of tested bank protection measures (TF = test field)

TF	Km	Technical–biological bank protection measures	Ensuring the stability of banks Ecological objective	Photograph after installation
1	440.626 to 440.747	Existing riprap complemented with willow branch cuttings, live fascines, brush and hedge layers; off-the-bank stonewall with shallow water zone, dead trunks with root plates	Bank protected by existing riprap Ecological enhancement of riprap through suitable woody plant population, structural diversity and wave-protected shallow water zone Improvement of habitat quality, esp. for fish and macrobenthos, bird species breeding in woody plants, ground beetles, spiders	
2	440.823 to 440.859	Removal of riprap; willow brush mattresses placed at an angle to the flow direction, fixed with crossbars, wooden stakes and wire	Bank protected by vegetation Ecological enhancement through suitable woody plant population, structural diversity Improvement of habitat quality, esp. for bird species breeding in woody plants, ground beetles, spiders	
3	440.874 to 440.945	Removal of riprap; willow brush mattresses placed perpendicular to flow direction, fixed with crossbars, wooden stakes and wire	Bank protected by vegetation Ecological enhancement through suitable woody plant population, structural diversity Improvement of habitat quality, esp. for bird species breeding in woody plants, ground beetles, spiders	

4	440.945 to 441.997	Existing riprap with gravel fill, groups of individual stones, dead wood fascines	Bank protected by existing riprap Ecological enhancement of riprap through structural diversity in order to promote natural succession of vegetation Improvement of habitat quality, esp. for fish and macrobenthos, ground beetles, spiders, reptiles	
5	441.006 to 441.106	Removal of riprap; installation of reed gabions and stone mattresses on granular filters, pre-cultivated plant mats on stone mattresses, hedge layers	Bank protected by a combination of plants and technical components Ecological enhancement through suitable bank vegetation (reed, grasses, woody plants typical of hardwood floodplains), promotion of natural succession of vegetation and creation of habitat structures Improving habitat quality, esp. for bird species breeding in reed areas or in woody plants, ground beetles, spiders, reptiles	
6	441.124 to 441.197	Existing riprap with filling of topsoil-alginate mix, hydro-seeding, individual plants	Bank protected by existing riprap Ecological enhancement of riprap through suitable bank vegetation (reed, grasses), promotion of natural succession of vegetation Improvement of habitat quality, esp. for reed-breeding bird species, ground beetles, spiders, reptiles	
7	441.205 to 441.366	Removal of riprap; installation of pre-cultivated plant mats on various filter mats (nonwoven sheep wool, synthetic nonwoven, coir mat), dead wood fascine, plant rolls, woven coir fabric installed on hydro-seeding; fixed with crossbars, wooden stakes and wire	Bank protected by vegetation Ecological enhancement through suitable bank vegetation (reed, grasses), promotion of natural succession of vegetation and creation of habitat structures Improvement of habitat quality, esp. for reed-breeding bird species, ground beetles, spiders, reptiles	

8	441.369 to 441.480	Existing riprap and paving with reed growth; raising of existing stone wall	Bank protected by existing riprap and paving Ecological enhancement by promoting reed growth in the shelter of the stone wall Improvement of habitat quality, esp. for reed-breeding bird species, ground beetles, spiders, reptiles; at higher water levels also relevant for aquatic organisms	
9	441.480 to 441.598	Removal of riprap; no new bank protection measure in the slope area, log branch cuttings for protecting the maintenance path; log groyne at the downstream end of the test field with willow branch cuttings and fascines	No bank protection measures on the slope, log branch cuttings to set a boundary for erosion in the direction of the maintenance path Ecological enhancement by allowing a limited degree of natural development and succession of vegetation Promoting structural and habitat diversity, esp. for birds, ground beetles, spiders, reptiles	
R	440.510 to 590 and 441.610 to 441.690	Reference stretch: conventional riprap	Bank protected by existing riprap No ecological enhancement	

3 Substudies and Important Boundary Conditions in the Reporting Period

3.1 Completed substudies

The substudies listed in Table 2 were undertaken as part of the monitoring work from 01/2012 to 12/2017, and examined the bank stability, hydraulic loads on banks, weather conditions and water levels, ecological effectiveness and maintenance cost. The BAW collaborated with various universities in special studies investigating the development of individual designs.

Table 2: Substudies undertaken in the monitoring period

Studies or documentation	Period	Objective and content
Bank stability		
Bank inspections (WSA Upper Rhine, BAW, BfG)	Ongoing	Recording and documenting the status of the new bank protection measures (including photographic documentation), assessment of bank stability
Survey of the bank geometry (WSA Upper Rhine)	2011, 2012, 2015, 2016, 2019	Survey of selected cross sections to determine erosion and sliding of the slope
Pore water pressure measurement (BAW)	2012, 2015,	Pore water pressure measurements in TF 3 during ship traffic (data collected: ship dimensions and ship speeds, distances from banks)
Panorama photos (BAW)	2–3 x per year	Panorama photos from the opposite river bank to document the temporal development of the new bank protection measures
Hydraulic load on the bank		
Traffic monitoring and measuring of hydraulic loads on the bank (BAW and the company Schmid on behalf of the BAW)	2012 2013 2015	Recording of key ship traffic data, measuring of wave heights and flow velocities close to the bank, measuring of flow velocities in the area of willow brush mattresses (TF 3) to determine the influence of willow shoots on flow velocities
Weather conditions and water levels		
Weather records (BAW)	Ongoing	Recording and evaluation of day temperatures and precipitation (data provided by University of Applied Sciences Worms)
Recording of the water levels of the River Rhine (BAW)	Ongoing	Recording, graphic representation and evaluation of Rhine water levels
Ecological studies		
Vegetation (BfG)	2009/2010 (before commencement of construction work), 2012–2017	Recording of plant species and plant abundance for different slope areas parallel to the bank (planting and natural succession), structural parameters (plant cover, layers of vegetation, floating debris, growth of planted woody plants in height and thickness)

Aquatic fauna		
Fish communities (BfG)	2x per year (early summer, autumn)	Electric fishing at survey points along the riparian zones of the test fields and the reference
Macrobenthos (BfG)	Early summer 2013/14 and 2017 Autumn 2016	Determining abundance per sampling area using landing nets in the riparian zones of the test fields and the reference; special structures (especially dead wood) are taken into account
Terrestrial fauna		
Avifauna (BfG)	2013/14 and 2017	Field inspection of the transect, point observation, random observation during 21 and 20 mapping days, respectively, in the study periods; recording of breeding and resting status; comparison to ACTUAL condition survey in 2010
Reptiles (BfG)	2013/14 and 2017	Several visual observations along transects at standardised times during the study periods, especially in combination with pitfall trap activities; comparison to ACTUAL condition survey in 2010
Ground beetles, spiders (BfG)	2013/14 and 2017	Recording by means of pitfall traps at different slope heights; five traps per test field where possible; if required, supplemented by small cup traps and hand-catching; in the herbaceous TF 5 and 7 a sweep net was used as well for catching spiders
Maintenance and repair		
Documentation of works (WSA Upper Rhine)	Ongoing	Type and scope of works executed; execution time and duration; costs
Special studies on development of individual designs		
Root excavation – University of Applied Sciences, Erfurt; part of a student research project, in collaboration with BAW and BfG	4/2015	TF 2/3, 5, 7, 9: production of species inventory and recording of structural parameters within transects; examination of roots of a willow branch cutting
Examination of vegetation – BOKU Vienna, on behalf of BAW	2012–2015	TF 2/3: examinations of growth of planted willows (length of shoots, growth in thickness, vitality, distribution of species, total vegetation coverage)
root excavations – Leibniz University Hannover, part of master theses in collaboration with BAW and BfG	TF 2/3: 11/2012 and 4/2017 TF 7: 4/2017	TF 2/3, 7: Root excavations – recording of root classes, lengths, intensity, mass; increase in shear strength of the soil due to root formation and CO_2 storage for 3 different slope areas parallel to the bank

3.2 Important boundary conditions

3.2.1 Meteorological data and water levels

The meteorological data that were particularly relevant for the development of the plants in the technical–biological bank protection measures (temperature, precipitation, sunshine duration) have been regularly recorded and evaluated since 2011. A detailed overview of the findings is available in the interim report 'Meteorological data and water levels on the River Rhine during the full monitoring period of 2011 to 2016' (BAW 2018). The key meteorological data are summarised in the following.

Temperature

Figure 2 shows the statistical distribution of maximum day temperatures for the period from 2012 to 2016, separately for the phenological winter season (16/10 to 04/04) and the phenological summer season (05/04 to 15/10). Annual distributions are similar; temperature extremes are in the range between − 14°C (2012) in winter and + 39.8°C (2015) in summer.

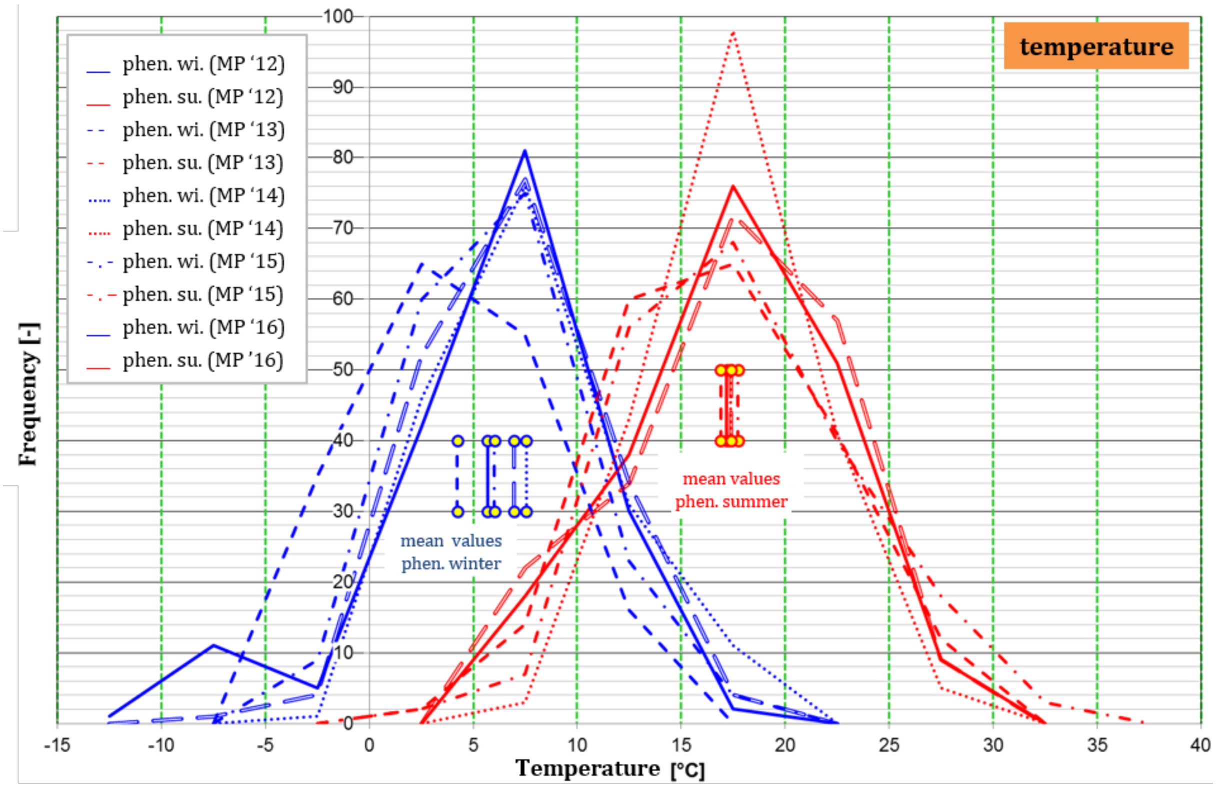


Figure 2: Temperatures (statistical distribution of day maxima) in the years 2012–2016

Precipitation

Figure 3 shows the monthly precipitation from 2011 to 2016. Maximum values of more than 100 mm monthly precipitation were only recorded in the summer months: 2013 (May), 2014 (July and August) and 2016 (May). These are the three years with the highest amounts of annual precipitation as well: 752 mm, 729 mm and 786 mm respectively. In comparison, lower precipitation of only 593 mm was recorded in 2012, and only 468 mm in 2015. Particularly dry months with less than 20 mm precipitation were mainly observed in winter: 2012 (November, February and March), 2013 (January), 2014 (March) und 2015 (April).

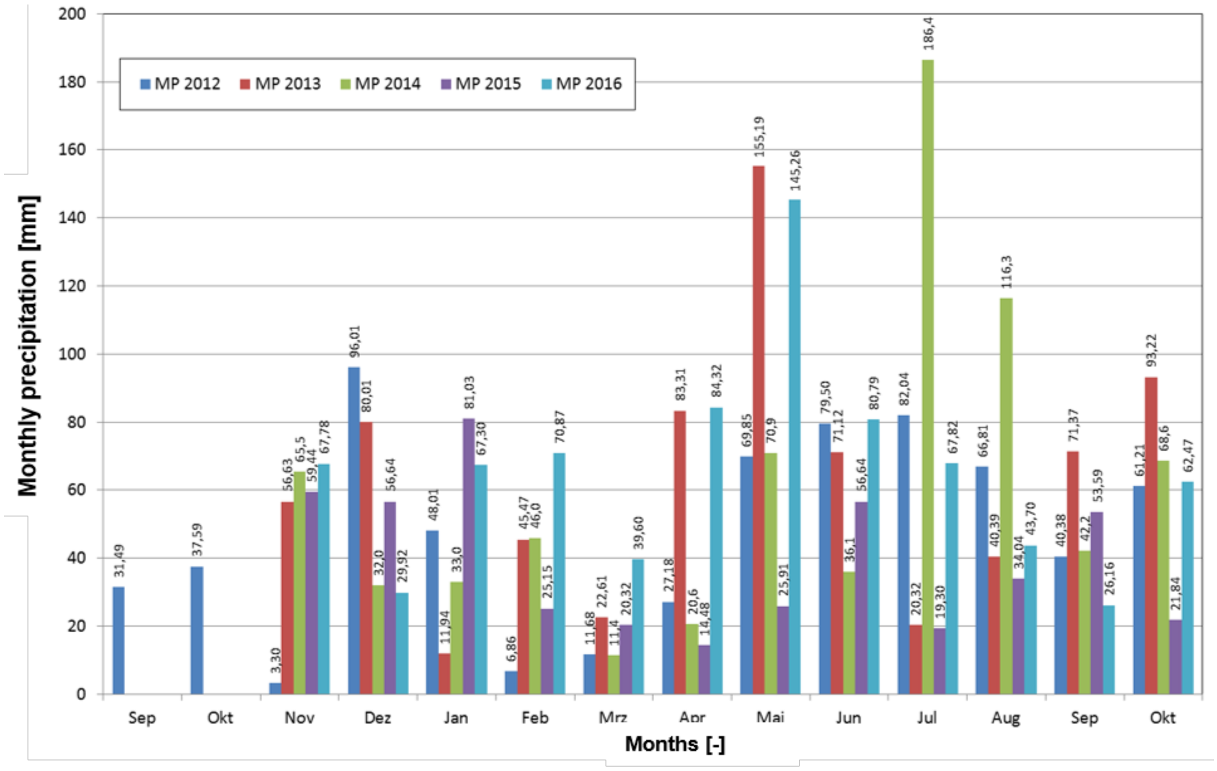


Figure 3: *Monthly precipitation in the years 2011 (September and October on the far left in the chart) to 2016*

The special climate diagram according to Walter & Lieth (Figure 4) represents a combination of precipitation and temperature data, which allows particularly dry and wet periods to be highlighted. The sum of monthly precipitation and the mean monthly temperature are plotted on the ordinates at a ratio of 3 : 1. A precipitation curve below the temperate curve indicates a dry period and reversely a wet period.

Wet and dry periods alternated in the study period, sometimes causing extreme conditions for plants. They correlated with high water and low water periods (Figure 5).

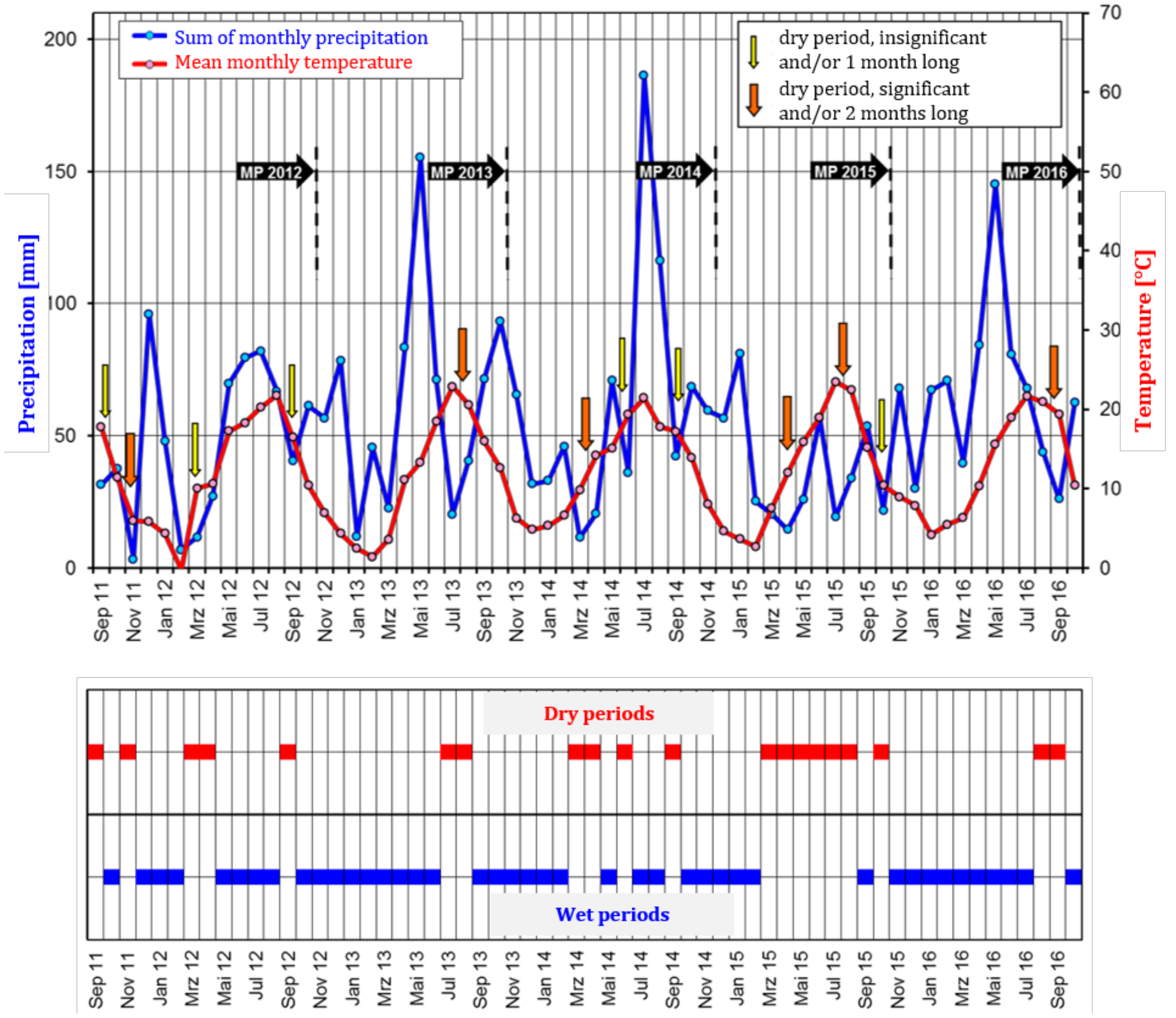


Figure 4: Special climate diagram according to Walter & Lieth (top) and chart showing the dry and wet periods (bottom)

Water levels

Figure 5 shows the hydrograph recorded at the Worms gauging station from 2011 to 2016. The relevant water levels are also shown. It is clear from the picture that the new bank protection measures, which are located in the area highlighted in green between MW (≈ AZW) and the top edge of the slope, have repeatedly been flooded. This has occurred much more frequently and for considerably longer periods in the lower slope area than in the upper zone. Simultaneously, they were exposed to ship-induced loads. In between, periods with low water levels were recorded, which were mostly accompanied by dryness and frequently by high temperatures. Both the high- and low-water times have had an important influence on the development, resistance and vitality of the vegetation. Table 3 provides an overview of the relevant water levels recorded on the test stretch.

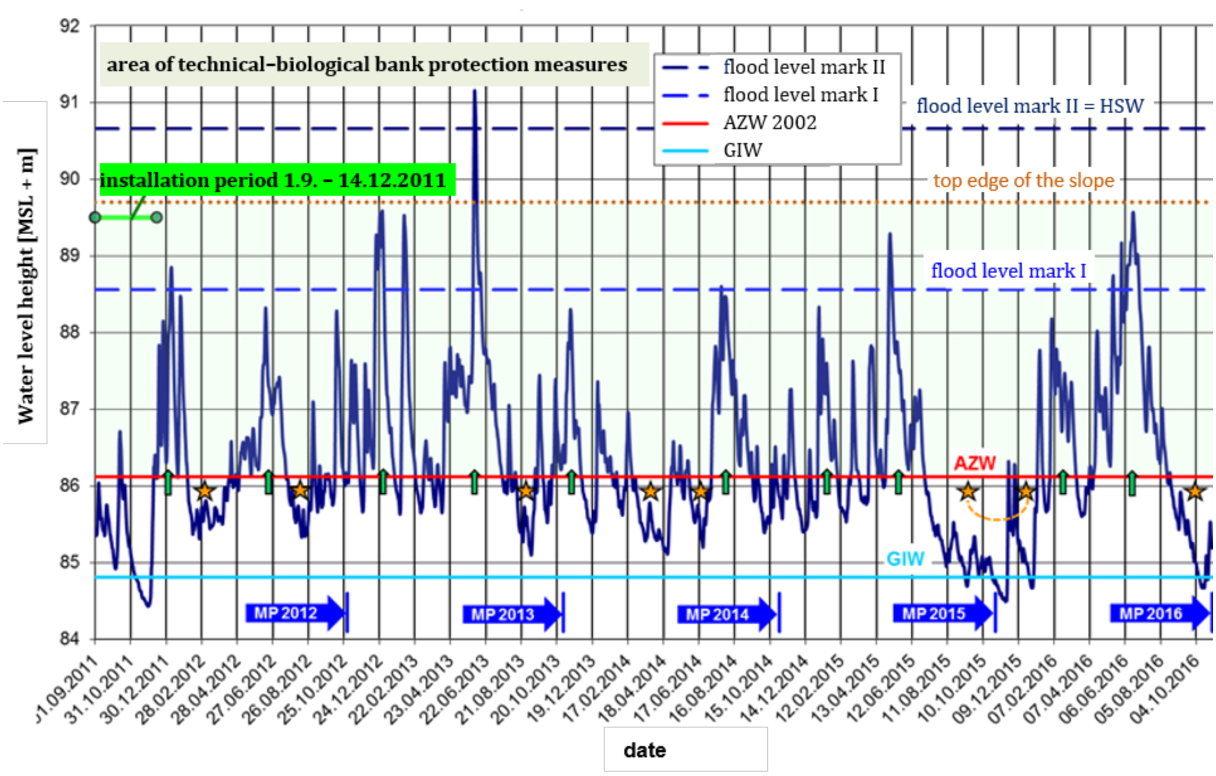


Figure 5: Hydrograph of water levels (daily mean values) at the Worm gauging station (GZ: 84.112 m above NHN (standard elevation zero), German height reference system (DHHN2016/status 170); MW (period 2009/2018) ≈ 200 cm, AZW ≈ MW)
⇧ Periods with high water level above AZW (> 4 weeks)
☆ Periods with low water level below AZW (> 4 weeks)

Table 3: Relevant water levels in the area of the test stretch (key data recorded at the Worms gauging station in 2013)

	km 440.600 (TF 1)	**km 441.100** (TF 5)	**km 441.600** (TF 9)	**km 443.400** Worms gauging station
GlW	MSL + 85.12 m	MSL + 85.06 m	MSL + 85.02 m	MSL + 84.81 m
MW (≈ AZW)	MSL + 86.50 m	MSL + 86.43 m	MSL + 86.36 m	MSL + 86.12 m
HWMI	MSL + 88.90 m	MSL + 88.85 m	MSL + 88.79 m	MSL + 88.56 m
HWMII (HSW)	MSL + 91.04 m	MSL + 90.92 m	MSL + 90.90 m	MSL + 90.66 m
GOK*	~ MSL + 90.00 m	~ MSL + 91.00 m	~ MSL + 89.50 m	

*Top edge of the adjacent ground (top edge of the slope)

3.2.2 Pore water pressure

The drawdown caused by passing ships (Chapter 3.2.3) can cause excess pore water pressure in the in-situ soil of the bank. This can reduce the effective stresses in the soil to the extent that sliding failure near the slope surface or hydrodynamic soil displacement occurs. Dimensioning revetments by sufficient weight per unit area prevents these effects.

Relevant excess pore water pressure is a determining factor when deciding whether bank protection with weight per unit area is required, i.e. whether it will be sufficient to stabilise the bank only with vegetation, such as willow brush mattresses, or whether supplementary technical components with additional weight per unit area must be used as, for example, in reed gabions.

Table 4: Data obtained from pore water pressure measurements

Measurement	Day of measurement	Water level at km 440.900 during measurement (MW: MSL + 86.46 m)	Recorded vessels (of which evaluable)
1	24.01.2012	MSL + 88.74 m (MW + 228 cm)	24 (6) cargo vessels
2	12.06.2012	MSL + 87.89 m (MW + 143 cm)	13 (7) cargo vessels
3	16.10.2012	MSL + 88.06 m (MW + 160 cm)	22 (6) cargo vessels 11 (9) MS Worms
4	19.02.2014	MSL + 87.09 m (MW + 63 cm)	29 (15) cargo vessels
5	06.05.2015	MSL + 89.68 m (MW + 322 cm)	23 (8) cargo vessels
			∑:122 (51) cargo vessels

A total of five measurement campaigns were conducted at different water levels at km 440.9 in TF 3 to measure the pore water pressure in the bank when ships were passing. For this purpose, pore water pressure sensors were installed at different depths in the soil during the construction stage. For each campaign all measurements were made in one day (Table 4). Of a total of 122 recorded ships, 51 showed drawdown values that could be used for evaluation purposes. The domain-specific background, the methodology and the measuring system are exhaustively documented in (BAW 2014).

The results of all five measurement campaigns – i.e. the respective water level drawdown measured at the bank and the associated maximum excess pore water pressure measured in the soil in a depth of 58 cm below the top edge of the slope immediately after the drawdown event – are shown in Figure 6.

Overall, the drawdown levels z_a measured for the relevant 51 vessels were relatively small at a maximum of 20 cm. Larger values (27 to 42 cm) were only observed during measurements in 2012 for which the patrol boat 'MS Worms' of the WSA Upper Rhine specifically navigated close to the bank. Allowance must be made for the fact that 51 ships represent only a small portion (around 0.1%) of the around 40,000 cargo vessels navigating through the test field every year. In general, it can be assumed that substantially larger loads occur as well; according to computations with GBBSoft+, drawdown values of up to around 70 cm are to be expected at km 440.9 (Table 7).

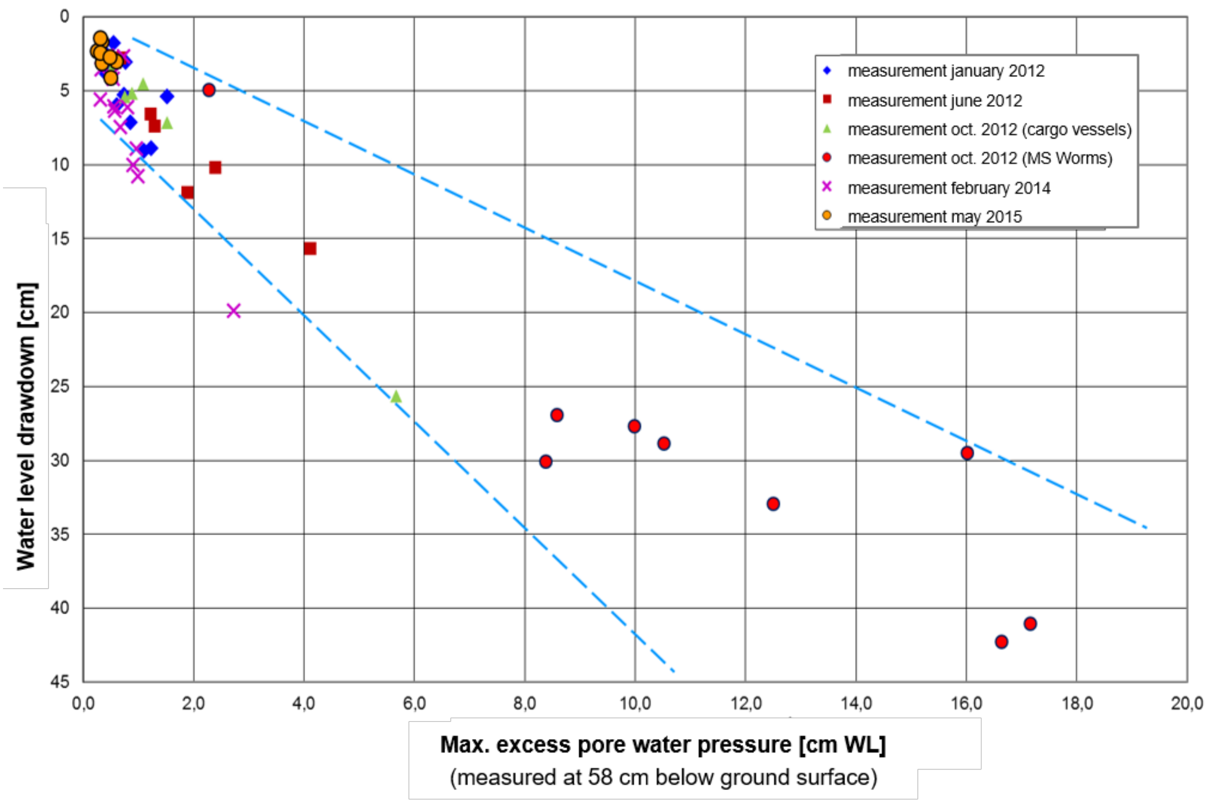


Figure 6: Results of the pore water pressure measurement campaigns

Figure 7 shows a schematic diagram of the development of excess pore water pressure Δu(z) in the soil in relation to the depth z below the top edge of the slope immediately after the drawdown event (green area), and the related formula according to (BAW 2011). The development of excess pore water pressure is mainly a function of the permeability of the soil k_f and the velocity of the water level drawdown v_{za} (value of b in the formula in Figure 7). Excess pore water pressure levels cannot exceed the magnitude of the pressure change resulting from water level drawdown. The excess pore water pressure measured for the drawdown values at a depth of 58 cm (Figure 6) amount to around 1/10 to 1/3 of the pressure change resulting from drawdown in the case of the cargo vessels, and to 1/3 to 1/2 of the pressure change occurring while the MS Worms navigated close to the bank. No measurements were made at a greater depth. A comparison of the measured drawdown velocities ($v_{za} = 3 \cdot 10^{-3}$ m/s to $9 \cdot 10^{-2}$ m/s) with the permeability of the in-situ soil in the area of the probes (gravelly sands: $k_f \approx 1 \cdot 10^{-4}$ m/s to $1 \cdot 10^{-3}$ m/s) shows that drawdown velocities are sometimes only marginally higher than the permeability of the soil. Consequently, the low measurements of excess pore water pressure seem plausible. However, it is evident that in the test field with the willow brush mattresses (TF 3) excess pore water pressure in the soil occurs, depending on ship-induced water level drawdown, and can impact the stability of the bank.

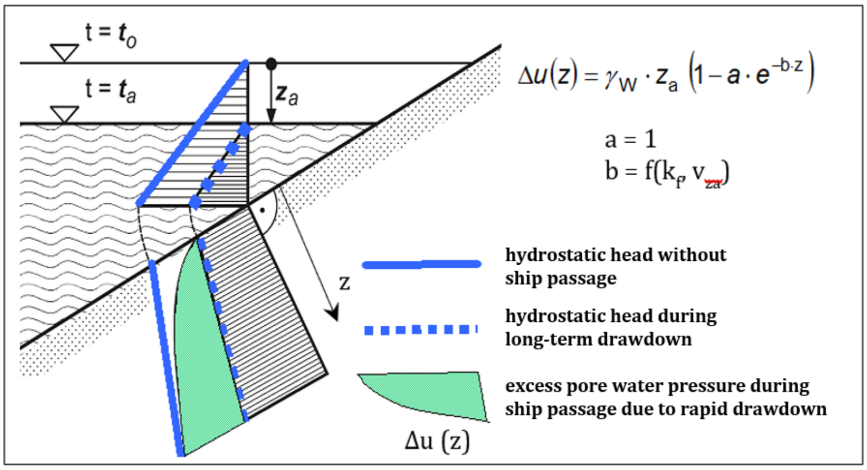


Figure 7: Schematic diagram of excess pore water pressure build-up in the soil when ships are passing the bank; computation formula according to (BAW 2011)

3.2.3 Hydraulic load on the bank

Measurement of the hydraulic load

Measurements of the hydraulic loads acting on the installed technical–biological bank protection measures are an important element of the monitoring programme. Waves, currents and the fast water level drawdown in the area of the test stretch were recorded in a total of five measurement campaigns. The first two campaigns took place before the new bank protection was installed. There are two different types of measurements: flow measurements focusing on loads resulting from natural currents, and traffic observations, which additionally include ship-induced loads. A list of the measurement campaigns conducted on the test stretch with the measurement results is provided in Table 5. The procedure and measuring equipment used in the campaigns and the evaluation methodology are explained in detail in (Schmid 2009). With the exception of the 2009 measurement campaign (water level of 20 to 70 cm below MW), all measurements were carried out at water levels just below high water level I (HWMI) (campaign in 2012) or between HWMI and high water level II (HWMII) (campaigns in 2011, 2013 and 2015) (see Chapter 3.2.1).

Table 5: Measurement campaigns conducted to determine hydraulic loads on banks due to natural current and shipping

Date	**Type of campaign**	**Measurement profiles**	**Measurements /measurands**	**Water level at the Worms gauge**
19.-26.08.2009	Traffic observation	440.600 441.100 441.600	Heights of bow, stern and secondary waves Return flow, slope supply flow velocity Bow and stern drawdown (times)	≈ MSL + 85.7 m
20., 22. and 24.08.2009	Flow measurement	440.600 to 441.600	Flow velocities in longitudinal profiles at 5, 10 and 15 m distance from the bank Cross-sectional surveys	
15.01.2011	Flow measurement	440.600 to 441.600	Flow velocities in longitudinal profiles at 5, 10 and 15 m distance from the bank Cross-sectional surveys	≈ MSL + 89.8 m
15.–17.06.2012	Traffic observation	440.650 440.920 441.550	Heights of bow, stern and secondary waves Bow and stern drawdown (times)	≈ MSL + 88.1 m
15.06.2012	Flow measurement	440.600 to 441.600	Flow velocities in longitudinal profiles at 5, 10 and 15 m distance from the bank Cross-sectional surveys	
06. and 11.06.2013	Flow measurement	440.600 To 441.600	Flow velocities Vertical profiles in 28 cross sections close to bank Cross-sectional surveys	06.06.2013: ≈ MSL + 90.4 m 11.06.2013: ≈ MSL + 88.6 m
07.-09.05.2015	Traffic observation	440.690 440.920 441.050 441.275 441.525	Heights of bow, stern and secondary waves Bow and stern drawdown (times)	≈ MSL + 89.0 m
07., 08. and 09.05.2015	Flow measurement	440.600 to 441.600	ADV measurements in TF 3 Flow velocities in longitudinal profiles at 5, 10 and 15 m distance from the bank Cross-sectional surveys	

Results

Close to 1,000 vessels were recorded during the three traffic observation campaigns. In each measurement campaign, the greatest wave heights were recorded at the beginning of the test stretch at km 440.600 (TF 1), in particular because of the short distance between the fairway and the bank. Further downstream, measured wave heights decreased as the distance between the fairway and the bank became greater. A comparison of the different measurement campaigns also shows that the wave heights are clearly a function of the prevailing water level. Table 2 provides an overview of the maximum bow, stern and secondary wave heights (H_{Bow}, H_{Stern}, H_{Sec}) recorded in the three measurement campaigns. In 2009 the maximum wave height was 81 cm at km 440.600. At the downstream end of the test stretch at km 441.600, maximum values of around 40 cm were measured. In contrast, the maximum wave heights measured during the traffic observations in 2012 and 2015 were 24 cm and 30 cm respectively. The measurement values of 2015 tended to be lower than those of 2012. The reason was that HWMI was exceeded, which meant that certain restrictions applied to shipping according to the Shipping Police Regulations (Rheinschifffahrtspolizeiverordnung, RheinSchPV): for example, the permitted ship speed was limited to 20 km/h (over ground), and the vessels were only permitted to navigate in the centre of the navigation channel (downstream navigation) or in the central third of the river (upstream navigation).

Table 6: Measured maximum wave heights in two cross sections

		Maximum wave height [m]			Water level [MSL + m]
Year	km	H_{Bow}	H_{Stern}	H_{Sec}	
2009	440.600	0.51	0.81	0.57	85.7
	441.600	0.40	0.43	0.43	
2012	440.650	0.22	0.24	0.14	88.1
	441.550	0.12	0.14	0.11	
2015	440.690	0.08	0.10	0.30	89.0
	441.525	0.09	0.09	0.22	

In general, it can be said that, considering the various ways in which ships navigate as a result of HMWI regulations, wave heights in the area of the new bank protection structures installed above MW are higher, the lower the water level. Moreover, the values tabulated in Table 6 show that with the higher water levels in 2015, maximum loads were caused by secondary waves and not by primary waves.

Natural currents and ship-induced flows are superimposed on each other. It is therefore very difficult to separately measure ship-induced flows near banks. For instance, the evaluation of the 2009 measurement campaign revealed that a turbulent natural current superimposed itself on the ship-induced flow velocities. As a result, no reliable data on ship-induced flow velocities could be obtained.

The flow velocities close to the bank that resulted from the natural current without any influence from passing ships were determined in the measurement campaigns for longitudinal profiles at 5, 10 and 15 m distance from the bank using depth averaging. Only the measurements made in 2011, 2012, 2013 and 2015 are relevant for the technical-biological bank protection measures as water levels were above MW in these years and thus in the area of the new bank protection structures (Figure 8).

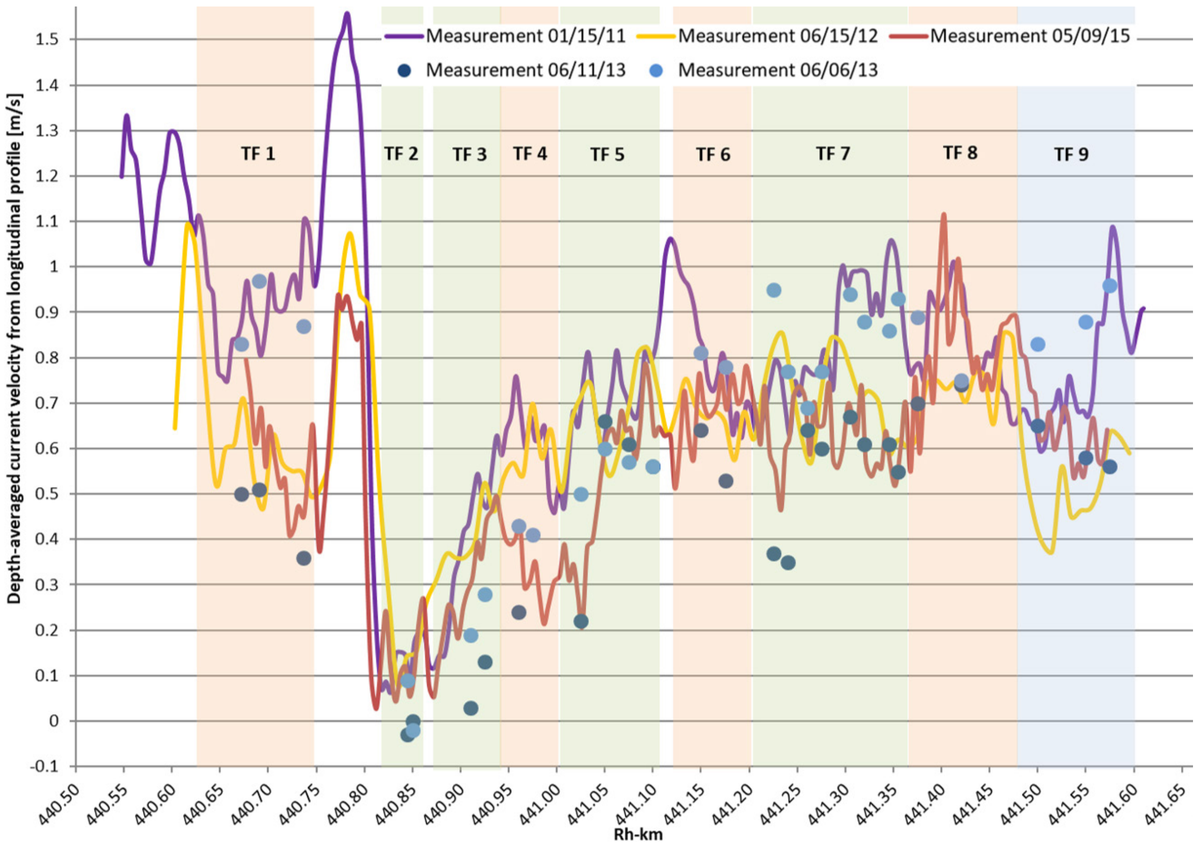


Figure 8: Longitudinal profiles of the measured depth-averaged natural current velocities at a distance of approximately 5 m from the bank (positive values in flow direction of the Rhine)

Flow velocities close to the bank vary widely in the first part of the stretch up to the end of TF 4, which is due to the bank geometry. In the area of TF 1 the bank is set back by several metres. A stone wall was built to a height of up to MW + 0.5 m and extends the bank line. The following projection of the bank initially causes the flow to accelerate to a maximum of 1.5 m/s and diverts it to the middle of the river. As a result of this, TF 2 is a flow-reduced area with very low or almost no flow velocities; spot measurements conducted in 2013 even showed flows opposite to the main channel's flow direction. In TF 3 and 4 the flow characteristics become gradually balanced again although the loads resulting from the flows are still somewhat smaller than in the test field further downstream. Velocities near the bank remain roughly at the same level (0.5 m/s to 1.1 m/s) throughout the remainder of the test stretch. Invidual peaks measured in the different years may be due, amongst other things, to the respective measuring position which was more to the middle of the stream than with other measurements and thus caused velocity values to be higher (e.g. TF 8 in 2015). It is important to note that any passing ship may cause higher loads close to the bank as the ship-induced flow velocities are superimposed on the currents.

Loads on banks resulting from water level fluctuations

Water levels and the length of the time during which they prevail determine the times when bank protection is exposed to hydraulic loads. These factors consequently have a significant impact on plant growth and stability and thus on the stability of the bank. Water level fluctuations are discussed above in Chapter 3.2.1.

Conclusion

Hydraulic measurements have shown that, in addition to ship-induced waves and flows, the natural current and fluctuating water levels impose high loads on river banks. However, it is not possible to say as yet whether these measurement data are representative of the typical ship- induced loads in this reach of the River Rhine since the traffic observations conducted only covered short periods of between three and seven days. It may be assumed that the maximum loads are not necessarily captured during such short measurement periods. The traffic observations on the test stretch recorded only around 1,000 of a total of 40,000 vessels a year. A single peak of 81 cm wave height was recorded in 2009, which is in the same magnitude as the maximum value computed by the program GBBSoft+ for the dimensioning of bank protection. The theoretically possible maximum loads computed with GBBSoft+ are tabulated in Table 7 for the examples of two cross sections.

Table 7: Computed, theoretically possible maximum ship-induced loads

	Rhine-km 440.90	Rhine-km 441.50
Maximum wave height [m]	0.88	0.40
Maximum water level drawdown [m]	0.73	0.19
Maximum flow velocity [m/s]	1.99	1.10

4 Results regarding stability and vegetation

4.1 Clustering of the test fields

This section presents the most significant results of the monitoring period from 01/2012, i.e. immediately after completion of construction, to 12/2017. The individual measures' stability and their effectiveness in ensuring bank protection, and the rehabilitation and maintenance measures carried out are described for each test field. The vegetation development is evaluated for its function in enhancing stability; findings regarding ecological effectiveness are contained in Chapter 5. The measures were tested to verify whether they can replace conventional riprap and have the same technical effectiveness as bank protection and under which conditions they can be recommended as alternatives. Special attention is paid to test fields 2, 3, 5 and 7, where the existing riprap was removed, so that the stability of the bank now depends on the new technical–biological bank protection structures (Chapter 4.2). In test fields 1, 4, 6 and 8, where the riprap was kept as bank protection structure and was ecologically enhanced, the primary focus will be on plant development (Chapter 4.3). Test field 9 is special in that the riprap was removed and no new protection structure was installed. In this test field the stability, progress of erosion and natural succession of vegetation was studied (Chapter 4.4).

Annex 4 contains specifications (M1–M15) which provide an overview of the measures installed in test fields 1–9, showing the progress of bank stability and ecological conditions achieved since the beginning of the measures, when the state of the bank was critical, until today. The annex also lists the maintenance and rehabilitation actions.

4.2 New bank protection measures after removal of riprap (test fields 2, 3, 5, 7)

4.2.1 Test fields 2 and 3 – M1 Willow brush mattresses

Willow brush mattresses are bank protection measures consisting of live willow branch material possessing no significant self-weight. They were used deliberately in TF 2 and 3, even though the necessity of a distributed surcharge load maximally corresponding to 30 cm-thick riprap was calculated (theoretically possible water level drawdown when a ship passes: 70 cm, see Chapter 3.2.3). Excess pore water pressures in the soil were measured in TF 3 during measurement campaigns for individual ship passages (see Chapter 3.2.2). In addition, protection against surface erosion caused by wave and current loads is necessary. The measure serves to study whether willow brush mattresses – even if lacking significant weight per unit area – are able to meet the requirements specified for bank protection (Table 8).

Table 8: Ensuring the stability of banks using willow brush mattresses

Requirements	**How/by what means should bank protection be ensured?**	
	Initial state (without roots or shoots)	**Long-term (with roots and shoots)**
Root growth into the subsoil	Installation of shoot-forming willow branches completely covering the bank and firmly secured to the soil (crossbars and stakes in a tight grid), covered with topsoil to ensure good surface contact	No more aids required
Erosion protection	Gapless coverage of the slope surface with willow branches firmly attached to the ground	Above-ground shoots and surface-covering, near-surface root system
Filter stability	Gapless coverage of the slope surface with willow branches firmly attached to the ground or additional installation of a biodegradable geotextile filter between the soil and the willow branches	Cohesive and sufficiently dense root system near the surface of the soil (root architecture)
Protection against sliding failure (only relevant in case of excess pore water pressure)	Problematic, as virtually no self-weight; increased stability from sufficiently long and closely positioned stakes (soil nailing)	Sufficiently strong and deep-reaching, densely branched roots in the ground (individual roots, root architecture)
Protection against hydrodynamic soil displacement (only relevant in case of excess pore water pressure)	Cannot be guaranteed, as virtually no self-weight at the beginning; downward soil displacement limited by crossbars tightly arranged parallel to the bank line	Cohesive and sufficiently dense root system near the surface of the soil (root architecture)

Native (autochthonous) and site-typical shrubs such as the purple willow (*Salix purpurea*) or, more rarely, osier (*S. viminalis)* and willow tree species (white willow, *S. alba*) were received as a donation from a property close by. Willow trees and shrubs were introduced with the aim of achieving a larger diversity in the woody plant structure. The white willow is the most frequent willow tree along the Rhine, the purple willow was chosen for its good resistance to dryness and less vigorous growth (advantages regarding maintenance). After removal of the riprap, the willow branches were installed on the 1 : 3 sloping bank without an additional filter, either perpendicular (TF 2) or at an angle (TF 3) to the flow direction. They were then secured with stakes and crossbars, and embedded 2 to 3 cm in gravelly sand. Since especially the purple willow's branches are relatively thin, only branches with diameters of 0.5 cm to 3 cm were available and, as a result, it was not possible to achieve a complete surface coverage as was originally specified. Already during the first flooding events with simultaneous ship-induced loads not only the sand cover but even the local soil was eroded under the willow branches. Even the brushwood, which had been placed as a layer over the willow branches and secured with wire bracing to provide additional erosion protection in the lower slope zone (up to approx. 1.70 m above MW), was largely ineffective due to buoyancy and was unable to prevent erosion. Stakes that had not been installed deeply enough because of stones in the ground came loose or were even pulled out. The very small weight per unit area favoured instabilities in the rather critical initial period during which roots and shoots necessary for bank protection are only about to develop.

After some remedial work had been undertaken (i.e. driving the stakes back into the ground, renewing the soil cover), the willows developed well (Figure 9) and the bank's stability improved with the growth of roots and shoots. The willows' growth initially appeared to be somewhat weaker in the lower slope zone up to approximately 1 m above MW and in the upper third of the slope. At the lower end, the willows are exposed to high stress resulting from ship-induced loads and often persistent flooding. However, in the upper third of the slope, dryness and shade pressure from the nearby poplars have an adverse effect on shrub growth. Moreover, the much thinner shoots were caused to die off locally due to infestation with parasitic dodder (*Cuscuta lupuliformis,* Figure 10), whose flooding tolerance is only very low.

Figure 9: Overview: development of willow brush mattresses in TF 3 – 4/2012 (left), 7/2012 (centre), 7/2017 (right) (photos: BAW)

Figure 10: Infestation of young willow shoots with dodder in TF 2, 8/2016 (left); local shoot dieback, 8/2016 (right) (photos: Katja Behrendt, BfG)

It could generally be observed that root and shoot growth occurred preferably close to the crossbars and stakes, i.e. where the branches had been firmly pressed into the ground and thus remained in good contact with the soil throughout. The left photo in Figure 9 shows the first shoots developing along the crossbar. Between the crossbars, the growth of roots and shoots remains rather poor to date.

Three years after installation, maintenance work was carried out for the first time in February 2015 for test purposes. The willows were pruned to approximately 10 cm above the slope surface; this was done in larger areas in TF 2 and in smaller, more fractioned areas in TF 3, for comparison purposes. Some individual shoots showing strong growth were not pruned and selected to be cultivated as future 'target trees'. From a technical point of view, the aim of the maintenance work was to preserve the elasticity of the willow shoots that had grown to be thick for better flood discharge, and to promote shoot and root growth for better bank protection. In ecological terms, the aim of pruning was to develop a willow population of mixed ages, with multiple layers and rich structures.

Figure 11 shows TF 2 approximately six weeks (left) and 10 weeks (right) after pruning. The transition to areas where the willows were not pruned is clearly visible in both pictures. Even 2½ years after pruning, the different heights of the willow trees are clearly visible (cf. Figure 9, right).

Figure 11: State of TF 2 shortly after pruning on 10.04.2015 (left) and on 11.05.2015 (right) (photos: BAW)

Immediately after pruning, a longer period of high water resulted in the willows being flooded to up to 3 m above MW (cf. Figure 5). Simultaneously, they were exposed to ship-induced loads. While the grown shoots had been able to slow down the flow velocities, this was no longer possible with the pruned willows. Erosion of the flotsam that had deposited between the willow shoots and of the in-situ soil increased, especially in the larger areas with pruned willows in TF 2 (Figure 11 left). The pruned willows were additionally weakened due to persistent flooding and a dry period with high temperatures which immediately followed the flooding. In this most strongly affected slope area some willows were lost locally and soil erosion caused hollows under the willow branches. In August 2016 the remaining coverage of the willow stand was only approximately 20 to 30%. The willows were able to recover only in the lower and upper slope zones. Here, the total coverage of the willow stand in August 2016 was approximately 70–80% (in the lower slope zone) and approximately 70% (in the upper slope zone). The highest shoots of the pruned white willows reached up to 3.50 m. The lower slope zone continued to provide sufficient water supply even at low water or when the weather was hot.

In the upper slope zone, the willows were generally less frequently flooded, and for shorter periods of time. However, with the onset of the dry period, the willow shoots in the upper slope zone were infested with parasitic dodder – similarly as in previous years – causing the dieback of individual willow shoots (Figure 10). By August 2016 the infestation had caused the dieback of shoots in large areas and also spread to many other shoots. Depending on the length of a dry period, an infestation with dodder can adversely affect the vitality of major parts of a willow population. This development will therefore be monitored closely. The vital willow portions, in particular in the lower slope zone, offer some bank protection as they slow down the flow; however, they are unable to prevent erosion once water levels are higher.

In TF 3, where smaller areas were pruned, the willows showed better regeneration capabilities and were largely able to recover well. Here, the total coverage of the willow stand in 2016 reached 80% in the lower slope zone and in the middle area, and approximately 65% in the upper slope zone. Infestation with dodder was observed in the latter, the willows there are generally less growthy and vital. Overall, individual shoots of unpruned willow trees (white willow) measured up to 6 m in length and up to 8 cm in diameter.

The situation in TF 2 and 3 is also reflected in the repeated cross-sectional surveys conducted by the WSA Upper Rhine (Figure 12 and Figure 13). Figure 12 shows that a limited degree of erosion had occurred in TF 2 as early as between 2012 and 2015/16 (up to a maximum depth of approximately 20 cm). After the large-scale pruning in 2015/16 erosion intensified strongly, especially in the middle slope area. Until now, up to 70 cm of soil have been carried away as high water levels occurred repeatedly. Less erosion was observed in TF 3 (Figure 13), where only limited portions of the population had been cut back. For future maintenance this means that pruning should be limited to smaller portions of the willow stand.

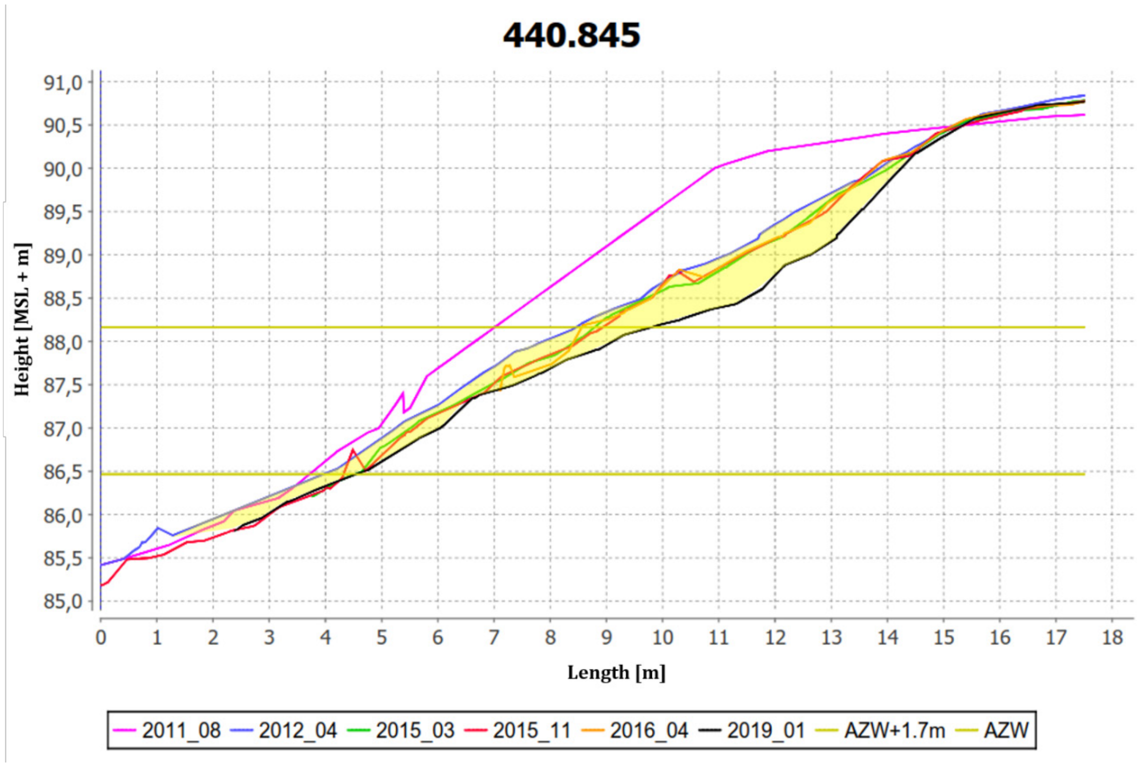


Figure 12: Cross section at km 440.845 (TF 2, large-area pruning) – highlighted in yellow: eroded area in the period from 04/2012 to 01/2019

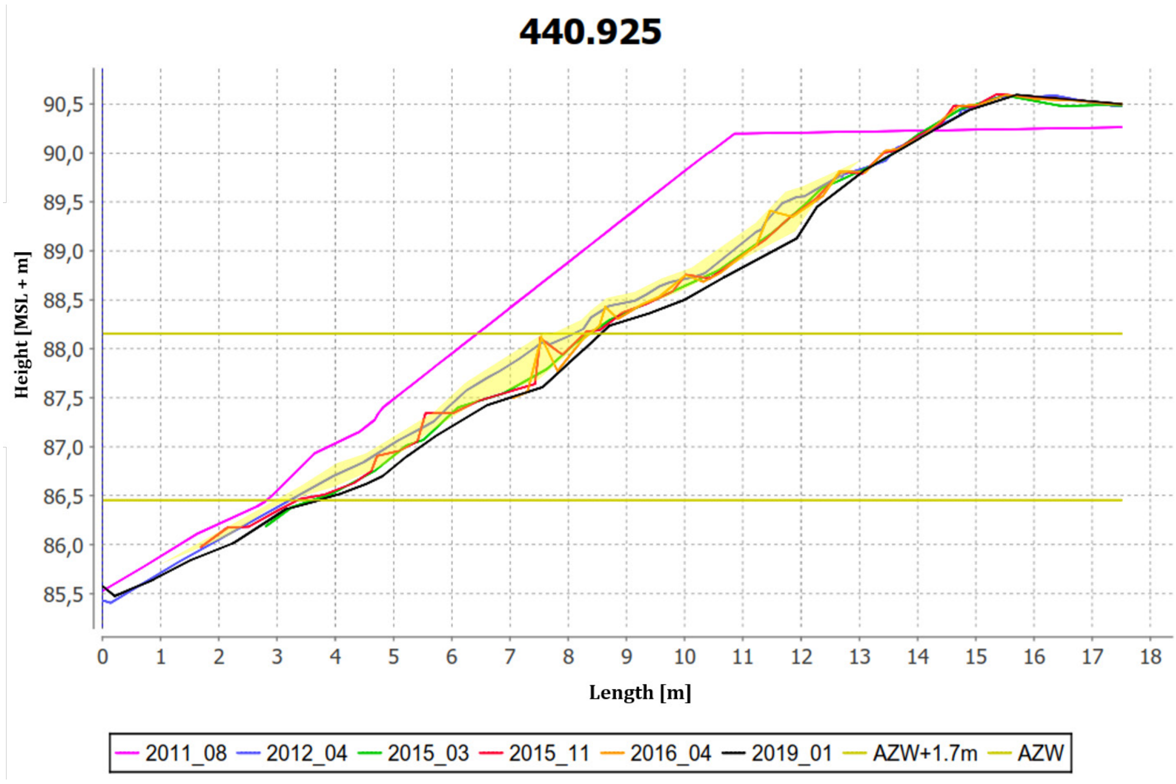


Figure 13: Cross section at km 440.925 (TF 3, limited pruning) – highlighted in yellow: eroded area in the period from 04/2012 to 01/2019

Different rehabilitation measures have been tested since 2018 to counteract the progressive erosion in TF 2. In early 2018, scattered willow branch cuttings and, in the upper slope zone, common dogwood (*Cornus sanguinea*), a site-typical alluvial hardwood, were planted in order to achieve denser vegetation. Unlike the willow branch cuttings, the common dogwood failed to establish in the dry year 2018. In addition, a new willow brush mattress was installed on a limited area of approximately 6 m² in the middle of the slope in February 2019 as a local rehabilitation measure. As an experiment, willow branches were fixed to the ground; the results are still outstanding. Rehabilitations like these are necessary since willows do not develop from root shoots. The rootstock is very vital and durable thanks to good regeneration following mechanical damage (pruning, cuts); however, should it die back, the empty space will only be stabilised by the spreading root systems of neighbouring plants; there will be no overground shoots of new rods from the root system. Since willows only sprout on wet, open raw soil, there is little chance that new willows will establish from seeds.

After the very dry year 2018, a dieback of willows in the upper slope zone was observed, which will be further monitored.

Results of root excavation

The local stability of banks protected by means of willow brush mattresses depends to a large degree on the growth of shoots and roots. The near-surface root system can protect the soil, prevent surface erosion and ensure filter stability in the slope area. In addition, roots can increase the shear strength of the soil and thus prevent sliding failure of the slope caused by water level drawdown during a ship's passage. The state of the willow roots was examined in 2012 and 2017 in cooperation with Leibniz University Hannover to assess the stability of the bank slope in TF 2 and 3. To this end, roots were excavated in a zone not affected by pruning at the downstream end of TF 3.

In November 2012 the first willow roots were excavated at km 440.940 to evaluate their development one year after their planting. In two locations at different heights of the slope, roots were exposed on an area of approximately 1.0 m x 0.5 m. It could be observed that already after the first vegetation period a relatively dense root system with root lengths of up to 60 cm had developed (Schneider 2013).

In April 2017 root excavation was repeated after 5 years of an initial growth phase in the vicinity of the first excavation (Ziegenhorn 2017). The root development of the purple and white willows predominating in this zone was assessed in three areas at different heights of the slope between mean water level (MW) and high water level I – HWMI (MW + 2.40 m). A deep-reaching and densely branched root system with root lengths of up to 1.70 m was found (Figure 14). The roots were taken to the BAW lab for examination and measuring. The root mass was determined in relation to the depth under the ground surface. The roots' stabilising effect was quantified by consulting the results derived in laboratory experiments carried out by the BAW in cooperation with the Vienna University of Natural Resources and Life Sciences (Eisenmann 2015).

Willow brush mattresses had been pre-cultivated in boxes made of osier and purple willow branches for one vegetation period; the increase in the soil's shear strength attributable to the roots as a function of their dry root mass was determined by means of a large-scale shear test at the BAW's foundation engineering laboratory (Figure 15). Based on the correlation found and neglecting the age difference between the willows from the laboratory and from the field, it may be assumed that after around five years of initial growing the willows from the field test on the Rhine achieved an increase in the soil's shear strength compared to the unrooted soil. This increase may be assumed to be at least 10 kN/m^2 up to a depth of 10 cm under the ground surface (dry root mass: 4,500 g/m^3); 4 kN/m^2 in the range of 10 cm to 40 cm of depth (dry root mass: 1,000 g/m^3) and 1 kN/m^2 in the range of 40 cm to 70 cm of depth (dry root mass: 550 g/m^3). Numerical computations with the finite element program PLAXIS for modelling slope stability show that under the given boundary conditions these shear strengths of the rooted soil can prevent sliding failure of the slope caused by a fast drawdown of 70 cm during a ship's passage. This is approximately the maximum drawdown expected to occur around the willow brush mattresses. This means that there is evidence that willow brush mattresses as installed in the field test are able to protect the bank against sliding failure.


Figure 14: Exposed roots of willows in TF 3 (photos: BAW)

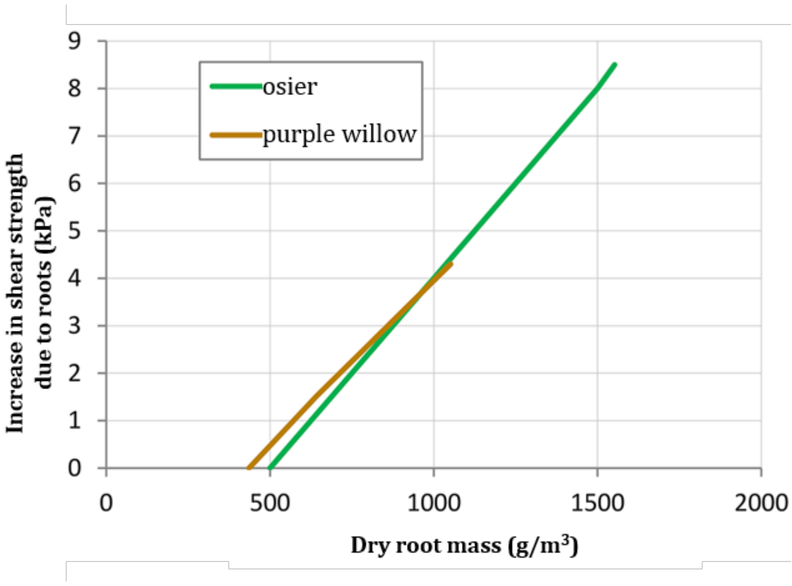


Figure 15: Shear strength increase of the soil as a function of dry root mass (Eisenmann 2015)

A further important finding derived from root excavation was that willow branches form significantly more root mass if their diameters are larger than 2 cm. Moreover, stronger root growth was found around the crossbars and stakes, i.e. where the willow branches were placed and attached so that they were firmly pressed to the soil right from the beginning. Even if roots were also expanding somewhat to the sides, the spaces between the crossbars remained significantly less rooted.

Intensive near-surface rooting was found around the branches, retaining soil and thereby improving filtering and surface erosion protection. This could also be confirmed simultaneously by means of filter experiments carried out at the foundation engineering laboratory of the BAW in cooperation with the Vienna University of Natural Resources and Life Sciences (Sokopp 2017). Branches of osier and white willows were pre-cultivated in boxes and tested after installation, and again after an initial growth phase of one, three and six months, using test equipment specifically developed for this purpose. The specimens consisting of willow branches and soil (fine-gravelly sand) were subjected to seepage under waterways conditions and loss of soil was measured (Figure 16). Immediately upon installation, and even with almost complete surface coverage, soil retention achieved by the installed willow branches was insufficient. However, after an initial growth phase of three months, the root system of the willows had developed to such an extent that soil loss could be prevented almost completely.

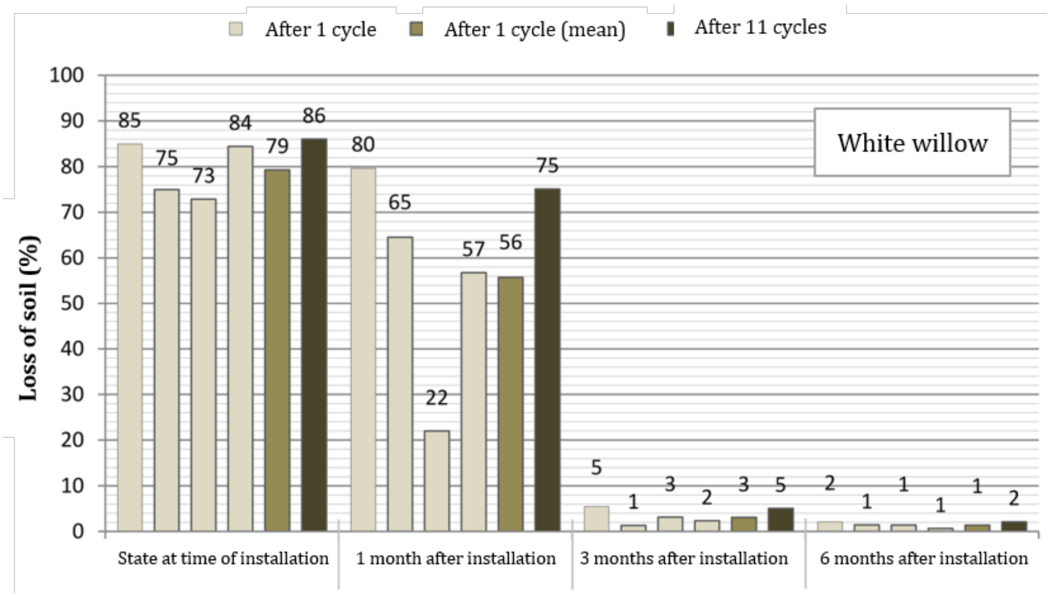


Figure 16: Soil retention achieved by willow brush mattresses of various ages determined in the laboratory (Sokopp 2017)

This means that additional measures may be necessary temporarily, at least during the critical initial growth phase. Therefore, a cooperation project of Fraunhofer-Institut UMSICHT Oberhausen, FKuR Kunststoff GmbH, Trevira GmbH, BNP Brinkmann GmbH & Co. KG and the BAW has recently been initiated to develop a geotextile filter nonwoven with defined biodegradability. The technical properties required (strength, permeability, filter stability) must remain intact for three years; after that the fleece is intended to biodegrade completely. First prototypes are currently being tested at the BAW and have been tested since early 2020 at a spot of the test stretch (TF 6).

Dense, herbaceous undergrowth did not occur, because the willows' competition pressure was too strong. The hedge layer planted in two rows on the adjoining plane at the top of the slope of TF 2, which consists of guelder rose (*Viburnum opulus*), common hawthorn (*Crataegus monogyna*), common dogwood (*Cornus sanguinea*), European spindle (*Euonymus europaea*) and common hazel (*Corylus avellana*), developed well over the entire monitoring period and showed good vitality. The hedge layers can additionally contribute to bank stability thanks to their subsoil root growth.

The willow brush mattresses have shown to be effective in general under the conditions of the test stretch. The target vegetation has developed as planned. Bank protection is ensured to a suf-

ficient degree. It is instrumental to the success of the measure that the willows are installed optimally from the start: they need to be placed with good soil contact of the branches, so that the roots and shoots grow over the entire area. Instructions for design and installation are provided in the specifications for 'Living Brush Mattresses' drawn up based on the experience with the test stretch for purposes of future planning (https://ufersicherung-baw-bfg.baw.de/binnenbereich/en/arbeitshilfen/kennblaetter). Annex 3 contains further instructions regarding the optimisation of the design and application recommendations.
An important finding from the field test is that careful and gentle maintenance measures are required to ensure the long-term vital development of the willows. This is particularly necessary where maximum discharge must not be negatively influenced by the growing willows. Optimal maintenance strategies are therefore an important aspect of continued monitoring (Chapter 9).

No significant difference was found in the development of the willow branches between the designs where the mattresses were installed perpendicular to the flow direction and the designs where they were installed at an angle. From a technical point of view the use of willow brush mattresses is recommended where bank protection without weight per unit area is required and the inclination of the slope does not exceed 1 : 3. With increasing root development, willow brush mattresses can also ensure bank stability when excess pore water pressures occur, i.e. when weight per unit area is required. In the initial phase without roots, however, slope instabilities and a need for corresponding maintenance are to be expected.

4.2.2 Test field 5 – M2 Reed gabions; M3 and M4 Stone mattresses with or without plant mats

Reed gabions

Reed gabions (vegetation gabions) filled with small armourstones made of quartz–porphyry ($CP_{45/125}$, ρ = 2,650 kg/m3) and with soil, covered with coir mats and wire mesh, pre-cultivated with herbaceous plants from the reed and softwood zone, are bank protection measures that consist of technical and plant components. They protect the bank using plants and through the structure and the weight per unit area of the total gabion. Calculations show that although ship–induced loads are lower than in the area of the willow brush mattresses (due to the greater distance between the navigation channel and the bank), the relatively steep slope of 1 : 2.5 in TF 5 also requires bank protection with a weight per unit area. Depending on the water level, this corresponds to a maximum weight of around 30 cm-thick riprap (theoretical maximum possible drawdown when a ship passes: approximately 50 cm). Protection must also be provided against surface erosion caused by wave and current loads. Table 9 shows how reed gabions can be used on the test stretch to ensure that banks are protected.

Table 9: Using pre-cultivated reed gabions to protect banks

Requirements	**How/by what means should bank protection be ensured?**	
	Initial state (without roots or shoots)	**Long-term (with roots and shoots)**
Root growth into the subsoil	The self-weight of the gabion elements provides good surface contact	The self-weight of the gabion elements provides good surface contact
Erosion protection	The structure of gabion elements is itself erosion-resistant; installation across the entire area on dimensioned granular filter	The structure of gabion elements is itself erosion–resistant; installation across the entire area on dimensioned granular filter; long-term additional erosion protection is provided by above-ground plant parts and roots
Filter stability	Filter–stable structure between the subsoil, granular filter and gabion elements and of the gabion elements themselves	Filter–stable structure between the subsoil, granular filter and gabion elements and of the gabion elements themselves; additional long-term protection provided by the root system
Protection against sliding failure (only relevant in case of excess pore water pressure)	Through sufficient weight per unit area of the gabion elements and granular filter	Through sufficient weight per unit area of the gabion elements and granular filter; in the long term also through root growth into the subsoil
Protection against hydrodynamic soil displacement (only relevant in case of excess pore water pressure)	Through sufficient weight per unit area of the gabion elements and granular filter	Through sufficient weight per unit area of gabion elements and granular filter; in the long term also through near-surface root system and root growth into the subsoil

The reed gabions were installed with a layer thickness of 30 cm in the lower half of the slope between mean water level – 0.5 m and mean water level + 1.70 m on a 30 cm-thick granular filter (chippings) in TF 5a. The gabions were prefabricated in April 2011 and pre-cultivated with different species for two planting zones over one vegetation period, so that they were fully vegetated and rooted at the time of installation. Planting zone 1 (mean water level – 0.5 m to + 0.5 m) was predominantly planted with slender tufted and greater pond sedges *(Carex acuta, C. riparia*, up to 60 to 75%) and additionally with a mixture of other species of the reed/softwood zone, and planting zone 2 (mean water level + 0.5 m to + 1.70 m) mainly with tall fescue (*Festuca arundinacea*), reed canary grass *(Phalaris arundinacea*) (60 to 75%) plus a mixture of other species of the reed/softwood zone. However, during cultivation individual species were arranged in groups or ‘clumps’ rather than mixed as was originally specified. Some of the adverse effects on the function of the reed gabions described below may have been exacerbated by this type of planting.

The weight per unit area of the gabions and the granular filter, which together exceeded the theoretically required maximum, and the way they were tightly arranged to exclude any gaps between the gabions, enabled them to be positioned effectively on the slope right from the start.

No additional fastenings were required. It was only necessary to rework the lower edge of the gabions into the existing riprap after the gabions initially slipped on the relatively steep slope (1 : 2.5). Once the reed gabions were firmly in place the pre-cultivated plants initially developed very well (Figure 17, left). The vegetation was then supplemented by other species that migrated in the course of natural succession.

However, with regularly recurring higher water levels, resulting in long periods of complete flooding, and simultaneous ship-induced loads, vegetation was progressively lost, primarily in the lower, often water-loaded slope area to begin with and later across the entire area of the reed gabions as well. Initially, some plant species recovered repeatedly between individual flooding events. However, almost 10 weeks of uninterrupted flooding of all the gabions in spring 2013 (cf. Figure 5) combined with ship-induced loads and a subsequent dry period that lasted several weeks led to major losses of certain plant species (planting zone 1: reed canary grass, creeping bent *(Agrostis stolonifera*), common club-rush *(Schoenoplectus lacustris*), gypsywort *(Lycopus europaeus*), purple loosestrife *(Lythrum salicaria*), yellow iris *(Iris pseudacorus*); planting zone 2: predominantly reed canary grass) and thus to large bare areas where there was no vegetation in the gabions as a result of the 'clump' planting. Extreme events in subsequent years led to an even greater loss of vegetation. Only the large sedges dominating the lower area exhibited a high level of vegetative regenerative capacity under the prevailing conditions. This was due to their high flooding tolerance. However, owing to the planting arrangement applied, they tended to form isolated clumps (Figure 17, centre). In dry periods, the relatively coarse plant substrate and the granular filter under the gabions made it increasingly difficult for the plants to regenerate. Spontaneous immigration of plants proved to be all but impossible on this substrate.

Figure 17: Development of the gabions, from left: 07/2012 – 07/2013 – 07/2017 (condition rehabilitated with one stone layer) (photos: BAW)

The large amount of vegetation lost played a role in the destruction and dissolution of the coir lining and the increasing discharge of material from the gabions during flooding and consequent damage to the gabions themselves. Damage was exacerbated by the stones that were no longer stable slipping down the slope inside the gabions, so that the underlying granular filter was also no longer sufficiently protected from local erosion (Figure 18).

Figure 18: Reed gabions on 10.11.2015, vertical edge due to stone displacements within the gabions (photos: BAW)

The partially ‘empty’ wire mesh lining protruded from the slope and became a danger for animals, especially for fish during flooding events. Vegetation (both spontaneously occurring species and the remaining sedges) could no longer be expected to spread. At the end of 2016, all the reed gabions were therefore rehabilitated by covering them with chippings and a layer of armour stones. The highly regenerating and flood-tolerant sedges have since grown through gaps in the stone layer (Figure 17, right) and benefit from the stability provided by the surcharge load. The map of the rehabilitated area made in 2017 showed that reed canary grass, purple loosestrife and tall fescue – also originating from the original planting – were also sporadically present between the sedges. This means that the desired vegetation may still be able to establish in the medium term following rehabilitation.

The conclusion may therefore be drawn that, owing to the combination of plant species used and the planting mistakes (planting of individual species in clumps), the reed gabions were not stable enough for the conditions prevailing on the test stretch. In principle, however, vegetation gabions are suitable from a technical point of view for ensuring bank stability along inland waterways. Their long-term stability largely depends on the enduring vitality of the pre-cultivated plants in the gabions. This means that it is not only important to have an optimal filter-stable and erosion-resistant structure as well as sufficient gabion weight per unit area, the right selection and mix of plant species must also be made – especially with regard to required flooding tolerance. Field tests successfully identified plants that are suitable or unsuitable for use in vegetation gabions in areas with large water level fluctuations, long flooding periods and simultaneous ship-induced loads alternating with dry periods (see Annex 2). The dominantly planted sedges (slender-tufted sedge, greater pond sedge) exhibited the greatest resistance to the above-mentioned boundary conditions along the test stretch. Depending on planting (clumps), construction methods and hydraulic loads, species such as reed canary grass, tall fescue and purple loosestrife, which grow naturally in this slope zone, have not proved successful. However, as these species reappeared after rehabilitation, it may be assumed that they have protection potential if banks are planted and constructed in the right way. Notes on optimum design, information about the selection of plants and installation can be found in the ‘Vegetation Gabions (Reed Gabions)’ specification that has been produced by BAW and BfG based on experience derived from the test stretch (https://ufersicherung-baw-bfg.baw.de/innenbereich/en/arbeitshilfen/kennblaetter). Vegetation gabions can be installed in areas impacted by water level drawdown and relevant excess pore water pressures if they have the required weight per unit area and are filled with the appropriate plants. Further information can be found in Annex 3.

Stone mattresses

Stone mattresses – high-strength elongated cylindrical plastic nets that are filled with small armourstones made of quartz-porphyry ($CP_{45/125}$, ρ = 2,650 kg/m^3) and joined together to form mattresses – are bank protection measures consisting of technical components that are intended to grow over through a process of natural succession. Like the reed gabions they are arranged in TF 5a and 5b in an area where bank protection is required with a weight per unit area which, depending on the water level, theoretically corresponds to a maximum weight of 30 cm-thick riprap (theoretically maximum possible drawdown when a ship passes: approximately 50 cm). Protection must also be provided against surface erosion caused by wave and current loads. Initial and long-term bank protection is guaranteed by an erosion-resistant and filter-stable structure (installation on granular filter) and by the weight per unit area of the stone mattresses and the granular filter.

Stone mattresses with a layer thickness of 25 cm were installed in TF 5a above the reed gabions between mean water level + 1.70 m and the top edge of the slope and in TF 5b between mean water level – 0.5 m and the top edge of the slope without any gaps on a 30 cm-thick granular filter (chippings) on the 1 : 2.5 sloping bank. In TF 5b, the lower edge was tied into the riprap that remained under water. No additional fastenings were required. In TF 5b, pre-cultivated plant mats (species and zonation as for the reed gabions, see Annex 2) were planted on the stone mattresses in the lower bank area (up to MW + 1.70 m) and secured on the stone mattresses with crossbars and cable ties. Chippings were first flushed into the gaps between the stones. Vegetation was intended to emerge by natural succession on the upper part of the bank slope in TF 5a and 5b. The stone mattresses were earthed with several centimetres of alluvial loam as a precaution against the plastic nets being cut by vandals (which would be easy to do with a pocketknife).

During the monitoring period, the soil cover was successively washed away at the level of the water level lines during flooding periods. Although, as expected, much more vegetation overall grew on the areas initially covered with soil, biodiversity was lower with just a few nitrogen-loving species in particular, such as common mugwort *(Artemisia vulgaris*), dominating. In addition to mugwort, stable colonies of species such as cock´s foot *(Dactylis glomerata*), common couch *(Elymus repens*), common soapwort *(Saponaria officinalis*), cypress spurge (*Euphorbia cyparissias*), Canadian fleabane (*Conyza canadensis*), greater burdock (*Arctium lappa*), hedge mustard *(Sisymbrium officinale*), etc. also settled. On the uncovered stone mattresses, these species were joined by a number of plants with indicator values for moisture in particular, such as purple loosestrife, reed canary grass and tall fescue.

A mix of nitrogen-loving ruderal species, grassland species and species that thrive in dry and wet soils thus grew on the stone mattresses, and the water body itself and the adjoining plane at the top of the slope both had an observable radiating effect on the surrounding environment. The main neophyte trees to appear were ashleaf maple *(Acer negundo*) and London plane *(Platanus x hispanica*), which are cut back once a year. The roots of successive herbaceous plants that grew into the subsoil can additionally contribute to slope stability.

The weight per unit area of the stone mattresses, which together with the granular filter exceeds the theoretically required maximum, and the absence of gaps in the arrangement of the mattresses gave them a good and stable position on the slope from the very beginning. Up to now, the self-weight of the mattresses and their erosion-resistant and filter-stable structure, both internally and in relation to the subsoil, have ensured bank stability regardless of vegetation. The evaluation of the regular cross-sectional surveys documents the stable position (Figure 19).

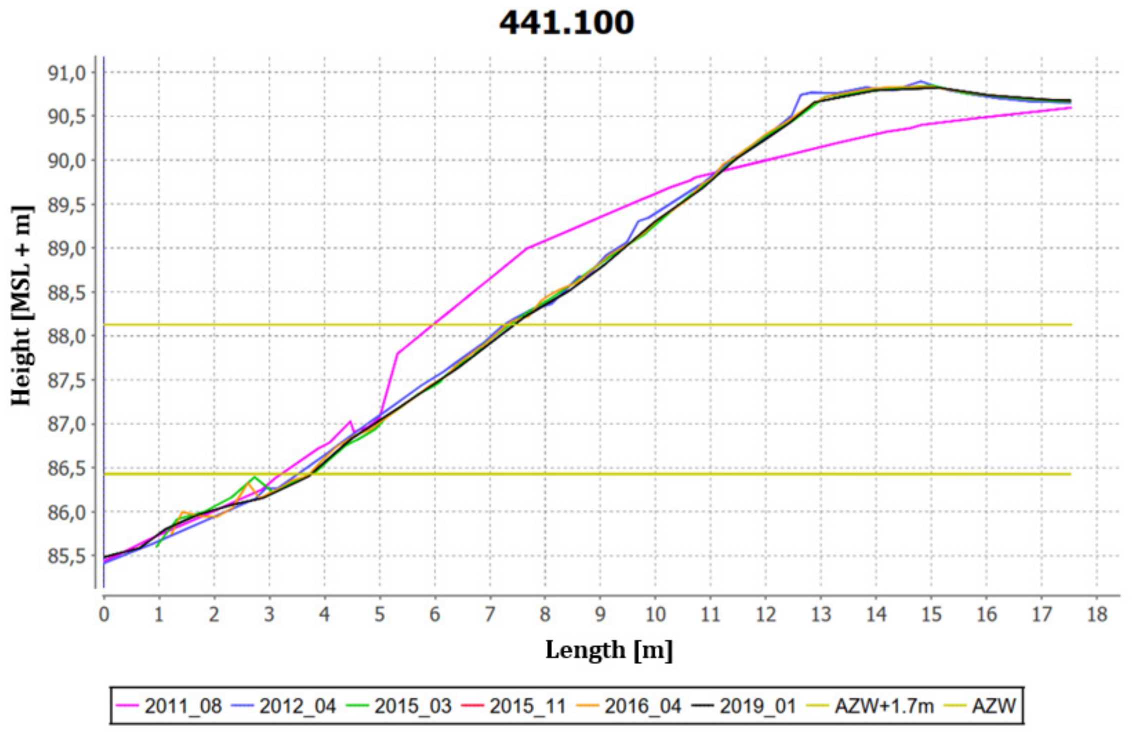


Figure 19: Cross section at km 441.100 (TF 5b, stone mattresses from MW – 0.5 m to GOK)

The plant mats in the lower slope area of TF 5b, which were fixed on a test basis to establish vegetation on the stone mattresses, have not proved successful. Just 1 ½ years after installation, all the pre-cultivated plants – including the highly regenerating sedges – had completely failed (see Annex 2). The main reasons are the 'pumping effects' that act on the almost weightless plant mats due to buoyancy and simultaneous wave and current loads during flooding. The up and down movement of the mats between the fixings prevented them establishing close contact with the soil to enable roots to grow into the stone mattresses and subsoil. In addition, owing to the weak growth of roots, the plants were irreversibly damaged in the initial dry phase when water levels were low.

The remains of the plant mats were removed in 2013, leaving the lower part of the slope to natural succession. Figure 20 shows the condition of the stone mattresses two years later in 2015. There is still a sharp contrast in the appearance of the upper and lower areas. Compared to the already reasonably well vegetated upper part, which was relatively seldom flooded, there is almost no vegetation at all in the lower area.

Figure 20: TF 5b – Stone mattresses, well vegetated on the upper half of the slope and with almost no vegetation on the lower half (2.7.2015) (photo: BAW)

Figure 21: Condition of the stone mattresses (20.6.2018) (photo: BAW)

Although more vegetation managed to establish on the lower part of the bank as well by 2018 (Figure 21), fluctuating water levels up to about 1 m above MW clearly prevent the natural succession of intensive vegetation due to frequent flooding and hydraulic loads.

Overall, it can be stated that stone mattresses provide sufficiently stable bank protection under the conditions along the test stretch. The particular arrangement of plant mats on stone mattresses on the lower slope area is not recommended. Compared to riprap, the gaps in the relatively slender stone mattresses (25 cm) are far finer and fill up with alluvial substrate when water levels are high. This favours the establishment and growth of plants, which is evident in the test field area – at least in the middle and upper slope areas that are subject to less load.

In the long term, the vegetation could protect the plastic nets from damage and vandalism and, with roots that grow into the subsoil, contribute to the stability of the structure and the bank. Further guidance on the application of this design is available in Annex 3.

The layer of hedge planted towards the adjoining plane at the top of the slope, consisting of hazel, European spindle, field maple *(Acer campestre*), common dogwood, hawthorn and guelder rose

(Figure 21), grew strongly over the monitoring period and now forms a dense woody structure that provides the bank with additional stability (see Annex 2).
No specifications were made for the vegetation desired on the stone mattresses; the idea was for vegetation to develop spontaneously through natural succession. As vegetation was not planted on the mattresses, the ensuing vegetation was expected to be sparser than in the case of reed bed planting or seeding. The vegetation has grown much as expected, except to some extent in the lower, frequently flooded slope zone and as far as the emergence of neophytic woody plants is concerned.

4.2.3 Test field 7 – M5 Plant mats on geotextiles; M6 Coir on hydroseeding; M7 Reed rolls

Plant mats

Pre-cultivated woven coir fabric plant mats, laid on the 1 : 3 sloping bank on various filter mats, are bank protection measures that consist primarily of plant components without any significant self-weight. The woven coir fabric is encased in fine woven polyethylene netting for added stability. Current computations with GBBSoft+ show that the bank in TF 7 only needs to be protected against surface erosion, because ship-induced loads decrease further downstream (see Chapter 3.2.3). Excess pore water pressures caused by water level drawdown resulting from the passage of ships are not relevant here. Weight per unit area is not required. Table 10 shows whether and how bank protection can basically be ensured using plant mats.

Table 10: Ensuring bank protection with pre-cultivated plant mats

Requirements	How/ by what means should bank protection be ensured?	
	Initial state (without roots or shoots)	**Long-term (with roots and shoots)**
Root growth into the subsoil	Sufficient fixing in a tight grid (crossbars and stakes) to ensure good and continuous contact of mats to the soil	No more aids required
Erosion protection	Gapless (overlapping) covering of the slope surface with erosion-resistant vegetation and filter mats	Above-ground shoots and surface-covering, near-surface root system
Filter stability	Gapless (overlapping) coverage of the slope surface with filter mats adapted to the soil (arrangement between plant mat and soil)	Surface-covering, near-surface root system
Protection against sliding failure (only relevant in the event of excess pore water pressure)	Problematic, as virtually no self-weight; increased stability from sufficiently long and closely positioned stakes (soil nailing)	Sufficiently deep and densely branched roots in the subsoil
Protection against hydrodynamic soil displacement (only relevant in the event of excess pore water pressure)	Cannot be guaranteed, as virtually no self-weight; downward soil displacement limited by crossbars tightly arranged parallel to the bank line	Cohesive and sufficiently dense root system near the surface of the soil (root architecture)

The plant mats were installed in TF 7a between MW and MW + 1.70 m and in TF 7b and 7c between mean water level and the top edge of the slope on various filter mats (synthetic nonwoven, nonwoven sheep wool or woven coir fabric) and fixed to the slope with stakes and crossbars. The plant mats were also planted over one vegetation period with pre-cultivated herbaceous plants typical of reed and softwood zones (see Annex 2). Of the plants used, 60–75% consisted of slender-tufted and greater pond sedges, reed canary grass and tall fescue and around 25–45% of a mixture of less dominant species, such as creeping bent, purple loosestrife, meadowsweet *(Filipendula ulmaria*), yellow iris, reed sweet-grass *(Glyceria maxima*), gypsywort (cf. BAW, BfG, WSA-MA 2012). Clearly discernible differences in the extent of rooting and the viability of the plants (significantly lower quality than in reed gabions) were already apparent at the time of delivery. One possible cause might have been the high summer temperatures prevailing during cultivation. As a result, the nonwoven sheep wool, which had been previously laid below the plant mats in the growing basin, began decomposing sooner than expected. Decomposition also degraded the water quality and consequently the plant growth in the growing basins. The initial condition quickly became very critical.

The first longer flooding phases in the lower slope area (between MW and around MW + 1.70 m) combined with simultaneous ship-induced loads already resulted in significant damage Figure 22, left). Stakes and crossbars became loose and were pulled out. Changes in pressure during flooding due to buoyancy and simultaneous wave and current loads caused the almost weightless mats to rise and fall between the fixings, and the roots were unable to grow into the subsoil or broke off again. Ultimately, most of the pre-cultivated plants died off (see Annex 2). At the same time, the nonwoven sheep wool installed in the lower area very quickly dissolved completely and only the areas in which synthetic nonwovens had been installed were protected against erosion. Long-term local bank stability was no longer sufficiently guaranteed, and the lower slope area had to be rehabilitated with a single layer of armourstone as early as 2012/2013. The remains of the plant mats were well stabilised by the distributed surcharge load, so that the few remaining plants, in particular reed canary grass, sedges and purple loosestrife, benefited and have since grown out of the gaps in the stone layer. Here, too, as with the design of the reed gabions, these plant species have been shown to have real bank protection potential under optimal planting and with the right design. In addition, there is a natural succession of plants such as beggarticks *(Bidens frondosa*), creeping yellow-cress *(Rorippa sylvestris*) and meadow fleabane *(Inula britannica*) (Figure 22, centre).

Figure 22: Damage in the lower slope area 5/2012 (left); rehabilitated condition 7/2017 (centre); good development in the upper slope area (right) 7/2017 (photos: BAW)

As can be seen in Figure 22 on the right, the plant mats in the upper area that is rarely flooded and subject to fewer loads (between mean water + 1.70 m and the top edge of the slope) developed well in the critical initial period after some remedial work had been undertaken (extensive hydroseeding, laying of sod). Today, the extensive and dense vegetation consists predominantly of grassland species (various grasses and herbs, such as false oat-grass (*Arrhenatherum elatius*), cock's foot, Yorkshire-fog (*Holcus lanatus*), perennial rye-grass (*Lolium perenne*), common bird's-foot-trefoil (*Lotus corniculatus*), hedge bedstraw (*Galium mollugo*), common couch and species of the original vegetation (especially reed canary grass, tall fescue, yellow iris, tall sedges and creeping bent). The mature development of the test field is evident from the increasing distribution of species according to their natural habitat requirements along the hydrological gradient. The upper bank is then colonised by plants typical of dry-warm sites, such as red fescue *(Festuca rubra*), cypress spurge (*Euphorbia cyparissias*), salad burnet *(Sanguisorba minor*), lady's bedstraw (*Galium verum*), crown vetch (*Securigera varia*) and brown knapweed (*Centaurea jacea*).

The target vegetation has established along the upper zone; vegetation has yet to develop in the lower area of the bank. In the long term, it will only be possible to maintain the vegetation along the upper slope, which is dominated by grasses and herbs, by regular mowing. This is carried out by the branch office Worms/Oppenau in coordination with the BfG. Mowing serves in particular to push back hazel-leaved dewberry (*Rubus corylifolius*).

Results of root excavation

The local stability of the bank slope that is protected with pre-cultivated plant mats depends not only on the above-ground parts of plants but also on the development of their roots. The root system near the surface can protect the soil and thus prevent surface erosion and ensure long-term filter stability in the slope area. In order to assess the local stability of the bank slope in TF 7, root excavations were carried out in 2017 in cooperation with the Leibniz University Hannover in various areas in which synthetic nonwoven, nonwoven sheep wool and woven coir fabric are used as filters. Specifically, excavations were carried out in four individual fields, all of them in the upper, rarely flooded, well-developed half of the slope, above approximately MW + 1.70 m:

- U1: plant mat on nonwoven sheep wool (km 441.327, elevation approximately 2 m above MW)
- U2: plant mat on woven coir fabric (km 441.327, elevation approximately 3 m above MW)
- U3/U4: plant mat on synthetic geotextile (km 441.300, elevation approximately 2 m above MW)

The main plant species identified in the study areas were greater pond sedge, reed canary grass, tall fescue, red fescue and common couch. The nonwoven sheep wool (U1) had already biodegraded when samples were taken while much of the woven coir fabric (U2) had weathered. Only the synthetic nonwoven in fields U3 and U4 was still completely present.

Maximum root lengths of 50 cm to 70 cm were detected in fields U1 and U2 (Figure 23). At these rooting depths, roots had developed relatively uniformly over the area with dry root mass of 900 g/m³ to 2,700 g/m³. Most roots are to be found in the upper 10 cm to 15 cm (Figure 23) where they resemble a dense mat of roots, which is particularly important with regard to the filter function and for providing protection against surface erosion.

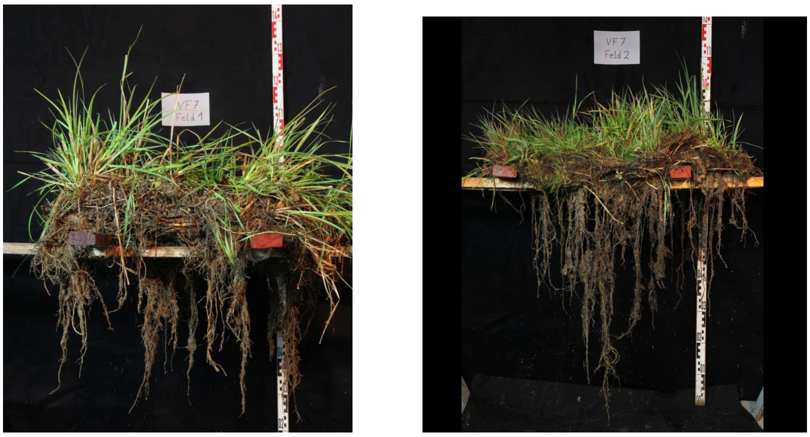


Figure 23: Excavated roots in study areas U1 and U2 (plant mats, filter mats no longer present) (Heinzner 2017b)

The roots of greater pond sedge were found to have developed particularly strongly and deeply. Tall fescue, red fescue and common couch also provide very effective protection. As each plant species develops its own specific root system, a combination of different root systems develops in the species-rich plant mats. Overall, the roots have developed well for bank protection purposes through a combination of grasses (large elastic root mass with a dense horizontal mat of roots close to the surface) and herbs (dowel effect produced by sporadic larger roots).

Root development and the impact of geotextiles on the roots have also been studied in the fields in which synthetic nonwoven geotextiles were used (U3/U4). The roots of the herbs and grasses were easily able to penetrate the synthetic nonwoven geotextile (consisting of PP and PET, with a weight per unit area of 300 g/m^2) (Figure 24). In total, root lengths of up to 45 cm were found (Figure 24, right). At this depth, roots had formed relatively uniformly over the entire area with total root dry masses of 2,700 g/m^3 (U4) to 3,400 g/m^3 (U3). However, some roots appeared to have been constricted by the geotextile, and these could prove to be weak points under load. A 3 cm to 5 cm thick mat-like ‘tangle’ of fine roots was present immediately below the synthetic nonwoven, and a dense 5 cm to 10 cm thick mat-like root system had also formed above it.

The roots have developed to such an extent that it may be assumed that they are already effectively retaining soil and protecting the slope from surface erosion. Greater pond sedge, common couch and tall fescue have proved to provide particularly effective bank protection. The roots of tall fescue in particular are able to anchor the geotextile to the soil and help to stabilise the plant mats on the slope.

As with willow brush mattresses, the roots of herbaceous plants also grew most prolifically near stakes and crossbars – where the plant mats were in most effective contact with the ground from the very beginning (cf. Figure 24 on the left, where the vegetation has developed in clumps around the stakes).

Figure 24: Roots exposed by water in the study area U3, right: excavated roots in study area U4 (photos: BAW)

The conclusion can therefore be drawn that the plant mats, filter mats and fixings used under the conditions pertaining along the test stretch were only successful in the areas of the upper slope that were subject to less load. This means that the use of plant mats with a suitable selection of pre-cultivated plants is only recommended for waterways on which water levels fluctuate only slightly or not at all. Information on optimum design and installation is contained in the specification prepared by BAW and BfG based on the experience gained on the test stretch (https://ufer-sicherung-baw-bfg.baw.de/binnenbereich/de/arbeitshilfen/kennblaetter). It is also important to realise that roots can grow through synthetic geotextiles. The developing near-surface mat-like root system (above and below the geotextile) can increasingly assume a filter function. This means that use of a fully biodegradable geotextile is recommended as a temporary filter. Just such a degradable geotextile is currently under development in cooperation with the BAW (Chapter 4.2.1).

Use of the tested plant mats with predominantly sporadic fixings is not generally recommended for frequently flooded riparian zones. Based on the experience gained in the test stretch, a possible alternative would be to cover the plant mats with a layer of armourstone to make the position of the plant mats stable and enable good root and overall plant development. At the same time, this provides weight per unit area that has an additional stabilising effect. Further information on optimising the design and recommendations for use are provided in Annex 3.

Woven coir fabric on hydroseeding

The prepared subgrade in the upper slope area between mean water + 1.70 m and the ground surface on the 1 : 3 inclined slope of TF 7a was hydroseeded with site-typical grasses and herbs (see Annex 2, including creeping bent, tall fescue, common couch, reed canary grass, meadow foxtail (*Alopecurus pratensis*), tufted hair-grass (*Deschampsia cespitosa*)), and covered with woven coir fabric for protection. It is a purely plant-based measure without any own weight per unit area. Roots were easily able to grow through the woven coir fabric; however, the coir fabric was not sufficiently filter-stable in relation to the existing soil.

In addition, it was only fixed in a few places with wooden stakes without using crossbars. These conditions meant that the initial state could be expected to be very critical from the outset. This design has therefore only been tested in the rarely flooded upper area.

High water levels occurred repeatedly soon after installation. This led to waterlogging and simultaneous hydraulic loads on the coir mats. As, in contrast to the other areas in TF 7, the coir mats were initially only fixed at certain points, and because of the lack of filter stability, larger quantities of material were washed out and moved, which resulted in large-scale slope deformation (Figure 26). This can be clearly seen in the cross-sectional recordings (Figure 25). The areas that were eroded between installation at the end of 2011 and April 2012 are marked in yellow. There was no protection against surface erosion.

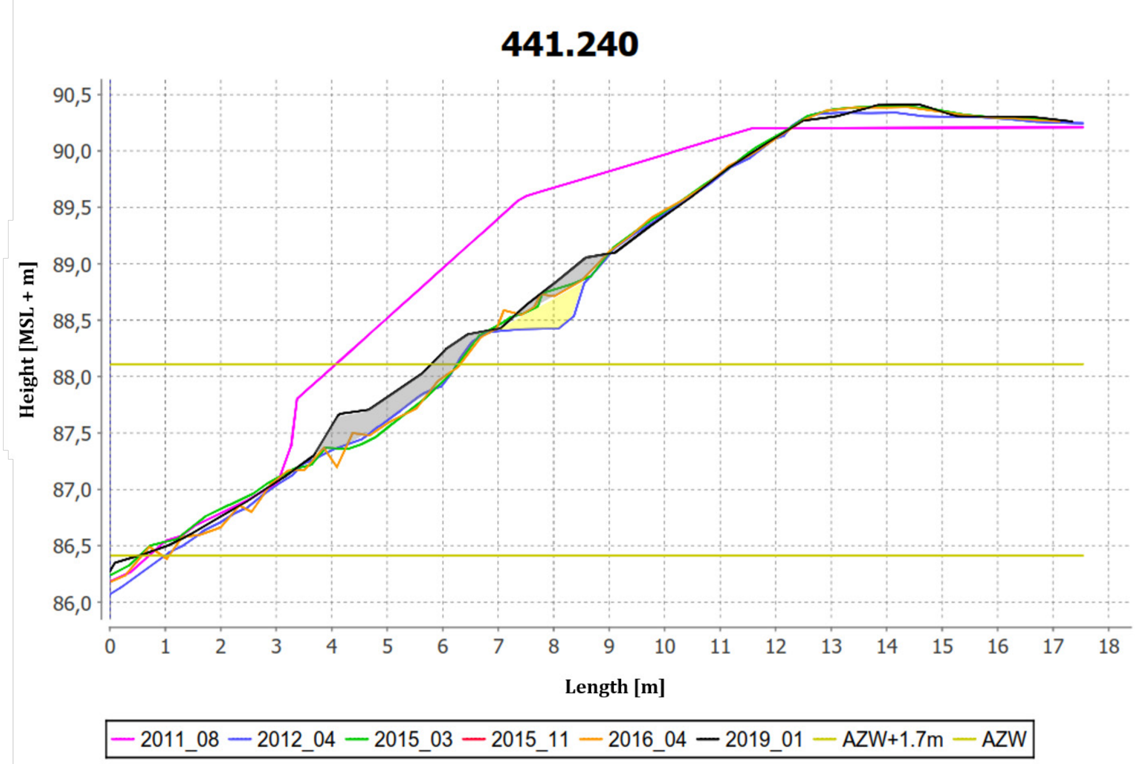


Figure 25: Cross section at km 441.240 (TF 7a, coir mat on hydroseeding between MW + 1.70 m and GOK)

Appropriate rehabilitation work was carried out as early as 2012 to prevent further material being washed away (local installation of grass sods, secured with crossbars; additional hydroseeding (BAW, BfG, WSA-MA 2013)). This area subsequently became somewhat more stable in 2013 due to the infrequent flooding (Figure 27). Grasses and herbs continued to grow and spread; however, no vegetation grew on some areas of the irregularly eroded bank relief, and particularly not on the depressions spanned by the coir mat. These areas increased in size with each successive flood.

Figure 27: Slope deformations after flooding in TF 7a, upper zone (22.3.2012) (photo: BAW)

Figure 26: Vegetation development after rehabilitation in TF 7a, upper zone (4.10.2013) (photo: BAW)

Figure 28 left shows the largest damaged area in 2015 at km 441.200 with an area of almost 20 m^2 and a maximum depth of 45 cm. As the local slope protection was no longer adequate, the depressions were filled with gravel in 2016, and finally almost the entire area was covered with a layer of armourstone (Figure 28, right), which can be seen as a grey area in the 2019 measurements (Figure 25). Following rehabilitation, highly regenerating plant species benefited from the weight of the stones, similarly to the rehabilitated area of the plant mats and reed gabions, and have since grown through the gaps in the stone layer. In addition, growth of site-typical woody plants has been observed since 2014. Individual willows are rejuvenating along the border between the softwood and hardwood floodplains. Single small-leaved elms and hawthorns are colonising the upper slope area. Herbaceous vegetation is growing in the remaining unrestored area as described for the plant mats.

Figure 28: Left: largest damaged area in TF 7a, upper zone, km 441.200 (11/2015); right: condition after rehabilitation (4/2017) (photos: BAW)

The conclusion can therefore be drawn that coir mats on hydroseeding cannot sufficiently guarantee bank stability under the conditions of the test stretch, even in the upper, rarely flooded riparian zones. This measure only appears to be practically effective on slope areas that are not exposed to waves and currents, i.e. in waterways with constant water levels above the wave run-up (see Annex 3). The target vegetation only established after extensive rehabilitation.

Reed rolls

The reed rolls, which are covered with woven coir fabric and filled with gravel and reed bales (see Annex 2, including yellow iris, reed, common club-rush *(Schoenoplectus lacustris*), water mint *(Mentha aquatica*), gypsywort), were installed in TF 7b and 7c in the longitudinal direction of the river between MW and MW + 0.5 m and then selectively ballasted with single armourstones. At the same time, they served as toe protection for the plant mats installed higher up (Figure 29).

Figure 29: Reed rolls during and after installation in 2011 (photos: Katja Behrendt/ Hans-Werner Herz, BfG)

In this area around mean water, the reed rolls were from the very start very frequently and repeatedly flooded for long periods. Simultaneous hydraulic and ship-induced loads very quickly destroyed the woven coir fabric and washed out the gravel and reed bales. The reed rolls had to be covered with armourstone as early as 2012 in order to stabilise the bank and to restore toe protection for the plant mats.

This method would only appear to be conceivable on waterways with very low ship-induced and natural loads and almost constant water levels.

4.3 Ecological enhancements in the existing riprap (test fields 1, 4, 6, 8)

4.3.1 Test field 1 – M8 Preparation of planting trenches perpendicular to the bank; M9 Planting of log branch cuttings; M12 Building of a stone wall running parallel to the bank line; M13 Installation of dead wood structures

Hydraulic loads are highest in this area at the upstream end of the test stretch, because here the bank is undercut and the fairway runs close to the bank. The riprap has therefore been left in place as bank protection. Possibilities to ecologically enhance existing loose riprap are tested by planting vegetation, which can increase bank stability as roots grow deeper into the ground, introducing dead wood and building a stone wall off the bank as an indirect bank protection measure.

According to the natural zonation of the water body and river bank, woody plants typical of alluvial softwood forests (purple and white willow and osier, ('Hutchinsons Yellow')) were planted in 17 trenches perpendicular to the bank in the slope zone MW to MW + 1.70 m. Woody plants of the alluvial hardwood forest were planted (ash (*Fraxinus excelsior*), guelder rose, common hazel, bird cherry (*Prunus padus),* field maple, hawthorne, European spindle) were planted in the zone above

MW + 1.70 m (see Annex 2). For this purpose, shoot-forming willows found on site (native to the area) were used and installed as log branch cuttings, fascines or brush layers (willow rods without roots). Bare-rooted seedlings (hedge layers) were used in the upper bank areas. The trenches were then filled with soil and covered with armourstones to restore a uniform slope surface.
All plantings showed a good and vigorous development in the monitoring period. The willow branch cuttings reacted to the frequent and sometimes long flooding periods in the lower slope zones by intensively forming adventitious roots to compensate for the lack of oxygen (Figure 30, left). In the second year after their planting, the willow shoots already had lengths of up to 4 m (Figure 30, right). The strongest shoots – mainly white willows – had a diameter of up to 3.5 cm. The vitality of the shoots was the same for both long and short branch cuttings.

Figure 30: Left: willow branch cutting with adventitious roots (07/2013); right: vigorous development of willow plantings (06/2014) (photos: Katja Behrendt/Hans-Werner Herz, BfG)

In February 2015 maintenance pruning of the willow branch cuttings and fascines was carried out for the first time. Different types of pruning were specified with the aim of obtaining a richly structured multi-layer woody plant population in the long term. To this end, the shoots of some of the log branch cuttings have been regularly cut back since 2015, so that they could develop into 'pollarded willows'. The strongest shoots of an additional number of defined branch cuttings are maintained to develop into future 'willow trees'. In places, branch cuttings were cut diagonally to a height of approximately 10 cm above the riprap to form 'willow bushes'. Within the fascines the strongest shoots were cut back to maintain the willows' elasticity for flood protection purposes. All other branch cuttings were left unpruned. All these activities were carried out manually in close cooperation between the branch office Worms/Oppenheim, BAW and BfG. The waste was removed.

The pruned plants have since developed into a vital and dense vegetation cover. The different woody structures (pollarded willows and willow trees, bushes of willow shrubs) aimed at by the different maintenance strategies can be seen in Figure 31. The target vegetation has established as planned.

In the lower and central areas of the slope the riprap between the plantings has largely remained without any vegetation. In the upper slope zone a herbaceous layer has grown which is dominated by hazel-leaved drewberry (*Rubus corylifolius agg.*) and includes a mix of moisture-loving species (e.g. reed canary grass, gypsywort, hop (*Humulus lupulus*), tall fescue); nitrogen-loving species (greater burdock, common nettle (*Urtica dioica*), hedge bindweed (*Calystegia sepium),* mugwort and others); grassland species (false oat-grass, common couch, cock's foot and others); and species typical of short-lived weed meadows and farm fields (e.g. field horsetail (*Equisetum arvense*), prickly lettuce (*Lactuca serriola*), field bindweed (*Convolvulus arvensis*)). The roots of successive herbaceous plant growth grow into the subsoil and can thus make an additional contribution to the stability of the slope.

Figure 31: Richly structured woody plant population after maintenance pruning (07/2015) (photo: Hans-Werner Herz, BfG)

In the area of the test field the bank is set back and, as a result, it was possible to build a stone wall off the bank, which extends the bank line and, for water levels up to MW + 1 m, creates a shallow water zone protected against the wash from waves. The structure of this shallow water zone was enhanced on the bank side by the placing of dead wood (trunks with root plates), which improves habitat conditions for aquatic fauna and plants.

This has had the additional indirect effect of protecting the bank, and promoted the development of vegetation cover in the lower slope area. Reed initials (sedge, reed canary grass) and willow seedlings were able to establish in this area. In the shallow water zone, aquatic plants have established. Moreover, in years with long periods of low water levels, species-rich annual meadows developed (cf. Chapter 5.2).

4.3.2 Test field 4 – M13 Installation of dead wood structures, M14 Placing of gravelly substrate and groups of individual stones

The riprap in TF 4 is left in place as bank protection. It has been ecologically enhanced by filling it with gravel and placing structural elements (groups of large individual granite stones). In the monitoring period the gravel mostly eroded during times of flooding, whereas the large granite stones have largely maintained their original positions.

Two slope zones can be distinguished: the lower/middle slope zone, which is largely without vegetation, and the more vegetated upper slope zone (Figure 32). In the recording period, dominating species were hazel-leaved dewberry, with an increasing proportion, followed by nitrogen-loving and ruderal species, such as mugwort, fat-hen, common couch, field bindweed and amaranth species (*Amaranthus bouchonii, A. retroflexus).* Recurrent growth of neophytic ashleaf maple was removed manually every year.

No specifications were made for a target vegetation in the test field; the idea was for vegetation to develop spontaneously through natural succession.
In the mean water level area, dead wood fascines (consisting of birch) were installed in the slope as dead wood structures (visible along the waterline in Figure 32). Since their installation in 2011, the fascines have decomposed into small pieces of wood and now need to be replaced with new structures, so that the positive ecological effect is maintained.

Figure 32: Lower/middle slope zone without vegetation and more vegetated upper slope zone subject to lower hydraulic loads (06/2017) (photo: Steffen Wieland, BfG)

4.3.3 Test field 6 – M10 Introduction of topsoil alginate and subsequent hydroseeding; M11 Planting of reed bales into the riprap

The riprap in TF 6 has been left in place as bank protection. It is ecologically enhanced by filling the gaps in the riprap with a topsoil–alginate blend and subsequent hydroseeding, and by the local planting of reed bales (see Annex 2) into the riprap in the area around the MW line.

As early as in the 2012 and 2013 monitoring periods, only a small quantity of the topsoil alginate and the subsequently added gravel were left in the gaps in the riprap due to erosion during high water levels. Twelve months later, the reed bales had eroded as well. The grass and herb cover on the remains of the alginate in the upper slope area, which had been sparse from the beginning, did not develop any further in the monitoring period. Today, the alginate has been completely washed away. In this test field, the ecological enhancement measures failed due to the Rhine's hydraulic loads. Regarding its vegetation cover, the test field can no longer be distinguished from the reference stretch.

4.3.4 Test field 8 – M12 Building of a stone wall running parallel to the bank line

The remaining riprap and the old paving protect the bank in this test field. Here, ecological enhancement is to be achieved by raising the riprap in the paved toe area (stone wall) and promoting the existing reed cover on the berm and the adjoining lower slope zone. As long as water levels stay below the top edge of the stone wall (MW + 0.5 m), the hydraulic load on the bank is reduced. As a result, a species- and flower-rich reed zone expanded over the past six years, with tall forbs typical of humid sites, flood-meadow species and short-lived pioneer plants typical of muddy soils (e.g. round-fruited rush (*Juncus compressus*), creeping yellow-cress, creeping bent, reed canary grass, tall fescue, slender-tufted sedge, yellow loosestrife (*Lysimachia vulgaris*), pale persicaria (*Persicaria lapathifolia),* purple loosestrife, etc.; Figure 33, Figure 34).
A cm-scale mud layer, which has deposited behind the stone wall on the paved berm in this test field as well (cf. TF 1), provides a substrate for the growth and establishment of vegetation.

The development shows the effectiveness of the higher stone wall in reducing the impact of waves and flows on bank vegetation. The target vegetation of reed and grasses has developed as planned.

Figure 33: Muddy soil pioneer vegetation with flowering yellow-cress (06/2012) (photos: Katja Behrendt, BfG)

Figure 34: Well-developed reed zone in the shelter of the stone wall (05/2017)

4.4 Without bank protection measures after removal of riprap (test field 9)

M15 – No bank protection above MW, willow branch cuttings on the slope crest, log groyne

After removal of the riprap, the slope profile was designed with an inclination of 1 : 2 to 1 : 3 in the area between mean water level and the top edge of the slope. The slope was left unprotected (Figure 35, left). In the last test field downstream, the distance between the fairway and the bank is the greatest (approximately 140 m). As a result, ship-induced loads on the bank are relatively small. Calculations show that excess pore water pressures in the soil are not relevant, so that no weight per unit area is required for bank protection – mere protection against surface erosion would be sufficient; however, it was decided to leave the slope without any protection. The aim was to allow for the natural succession of vegetation in this test field and to simultaneously monitor and evaluate erosion. In the area between the shoulder of the slope and the maintenance path, two rows of white willow branch cuttings were installed, offset from each other, to examine whether the growing roots can protect the maintenance path against erosion. At the downstream end of the test stretch, a log groyne consisting of tree trunks and armour stones and vegetated with willow branch cuttings was installed (see Annex 2).

Since early 2012, flood events with water levels sometimes higher than the adjoining terrain and the simultaneous ship-induced loads have led to the anticipated progressive increase in erosion in the entire slope area. Finer soil constituents in the sand or gravel grain size range were eroded especially in the lower slope areas, which were frequently flooded for long periods. This has had the effect that larger stones with edge lengths exceeding 5–10 cm became exposed as water washed away the subsoil, and now dominate the bank appearance (Figure 35, centre and right). At the downstream end of the test field in front of the log groyne, turbulences orientated towards the bank have caused major local erosions up to the top edge of the slope. Depending on the water levels during high water, this led to the formation of terraces in the upper 2 m area of the in-situ alluvial loam.

The cross-sectional surveys at km 441.575 in Figure 36 show that, after removal of the riprap, the slope edge at the end of the test field shifted approximately 5 m further inland until 2019. The eroded area is highlighted in yellow.

Figure 35: Development in TF 9 – 12/2011 (left, after completion of construction), 7/2013 (centre), 3/2014 (right) (photo: BAW)

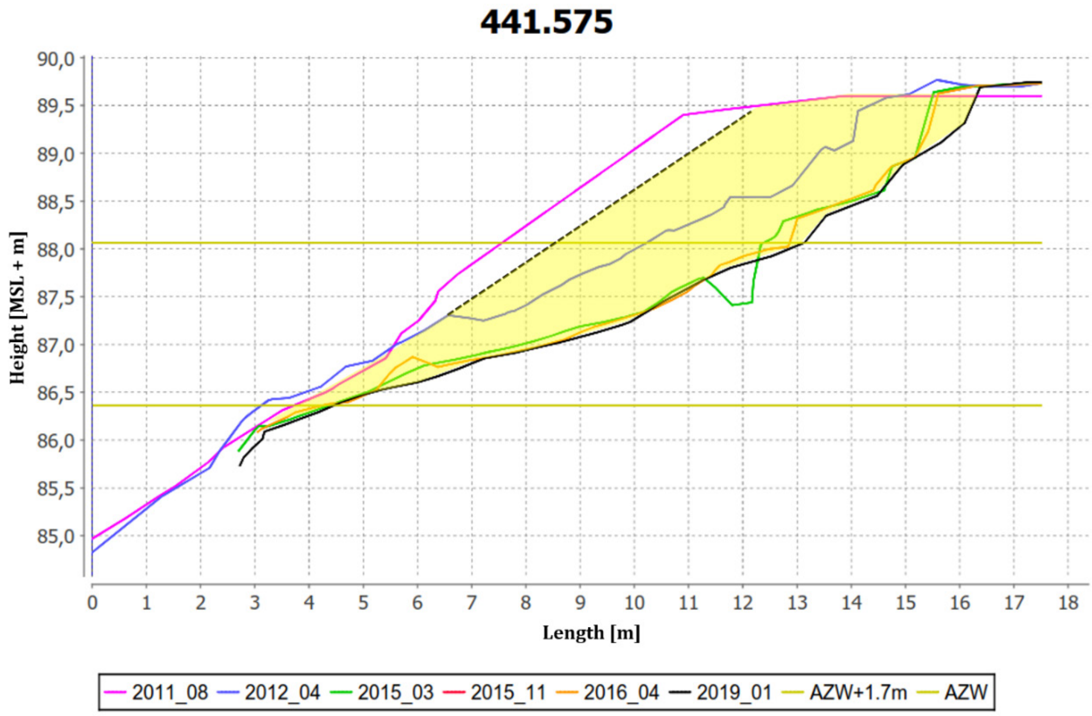


Figure 36: Cross-section at km 441.575 (TF 9, end of test field near log groyne)

Figure 37: Left: *old armourstones in the ground exposed by water in TF 9 (8.9.2016); right:* log branch cuttings exposed by water (26.04.2018) (photos: BAW)

Figure 38 shows a similar development for the cross-profile at km 441.500, where the 500 m-sign is located at the top edge of the slope (Figure 35, centre and left). Although erosion was less pronounced overall in this area, it had already proceeded thus far in 2015 to reach the km-sign. In 2016 the sign was newly installed and secured with armourstone (Figure 39). The slope has levelled off across the entire test field, except for the upper slope area where nearly vertical scarps have formed in the alluvial loam. The result was that on the riverside some of the overall well-developed log branch cuttings on the adjoining plane at the top of the slope were exposed by water erosion up to the lower edge (Figure 35, right, and Figure 37, right). They no longer provide any protection to the bank. A third row of willow branch cuttings was therefore planted on the landward side in 2014.

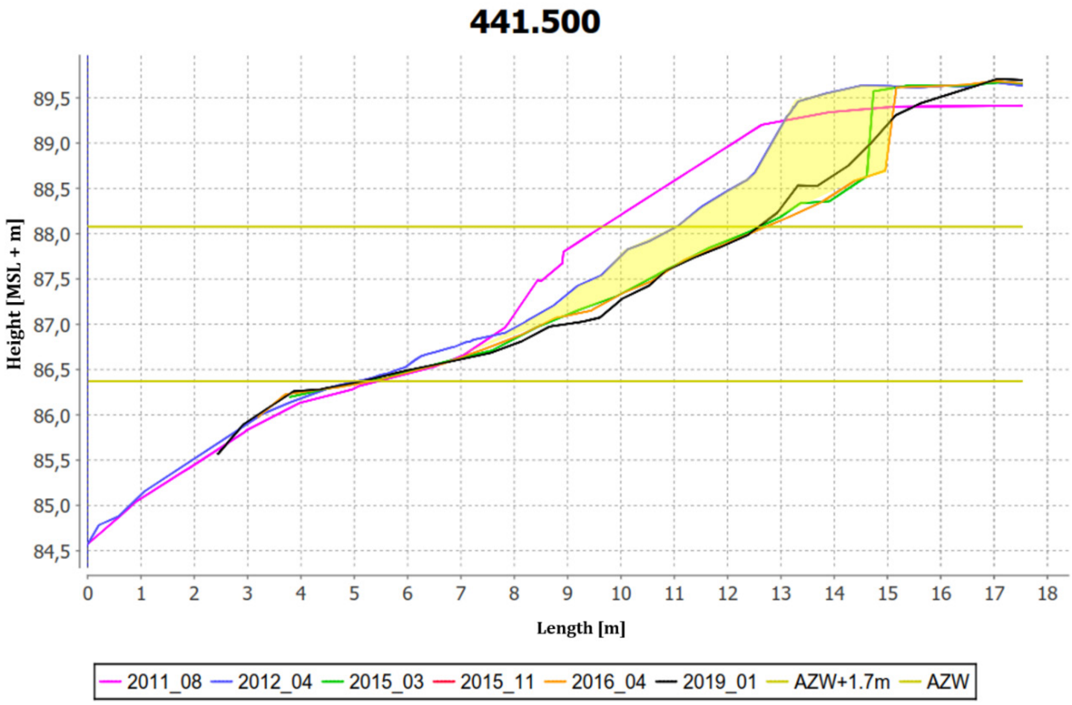


Figure 38: Cross-section at km 441.500 (TF 9)

However, the cross-sectional surveys also show that since 2015 only insignificant changes occurred in the lower slope area, i.e. the slope is largely stable at its current inclination of around 1 : 6 to 1 : 7. This stability is due to smaller armourstones from aged bank protection structures built in the past 150 years, which have been exposed by water and now protect the bank (Figure 35, centre and Figure 37, left)

Root excavations that were carried out on a log branch cutting at km 441.590 in cooperation with the FH Erfurt in 2015 revealed that no extensive root system has developed between the branch cuttings planted at distances of approximately 2 m in 2011, so that the progressive erosion between the willows cannot be stopped. The willows grown from the log branch cuttings do not provide sufficient protection for the access road, and it may be assumed that the log branch cuttings will be further exposed by water and ultimately be lost.

Figure 39: Km-sign at km 441.500 secured with armourstones (7.11.2017) (photo: BAW)

In general, the changes that have occurred in this test field show that bank protection measures are always necessary in the area of the test stretch if erosion of the bank is to be prevented. In the upper bank area, which is less frequently flooded, the in-situ alluvial loam will continue to erode during high water, so that the slope edge will move further inland.

The succession of vegetation was highly dynamic in the recording period. The processes of erosion and shifting and redistribution of stone size classes described above led to a permanent rejuvenation (dieback and recolonisation) of plant communities. While the lower slope area remained largely vegetation-free over the entire monitoring period, a sparse vegetation cover established in the middle slope area after long low-water periods (5–10% total coverage). In these periods of low water, the dominating plants were species typically found on the banks of nutrient-rich waters and annual shoreline species, such as gypsywort, beggarticks, fat-hen, many-seeded goosefoot, mugwort, common knotgrass, pale persicaria, hazel-leaved dewberry, etc.). These species do not tolerate flooding and temporarily disappear when water levels are high. By contrast, the herbaceous cover in the upper slope area attained a total coverage of up to 40% in a few years' time. Dominating plant species are hazel-leaved dewberry, field bindweed, mugwort, common knotgrass and grasses, such as common couch and cock's foot. In addition to these herbaceous species, common dogwood has gradually spread out towards the adjoining plane at the top of the slope. Common dogwood is a woody plant typical of alluvial hardwood forest and its development is considered to be a very positive sign. As the roots continue to grow, a stabilising effect on the slope can be expected, at least locally. Root excavation is planned for assessment purposes. The dynamic 'come and go' of the gradually establishing herbaceous plants meant that they have not yet been able to contribute to slope stability. No target vegetation was specified, as vegetation in the test field was intended to emerge by natural succession.

4.5 Summary rating of the stability of the measures

The objective of the field test on the Rhine was to examine from a technical point of view the effectiveness of technical–biological bank protection measures with vegetation components under the given boundary conditions and compare their performance to that of traditional riprap. Ship-induced loads vary between the test fields, as the distance between the fairway and the bank increases going downstream. Even within one single test field, hydraulic effects differ due to large water level fluctuations. For instance, the lower slope areas were flooded much more frequently and for longer times and were thus more exposed to loads from waves and flows than the upper areas. Consequently, a differentiated rating approach is necessary. Some measures are rated differently for the upper and lower slope areas.

If the vegetation component of a bank protection measure is a key requirement for ensuringe the stability of the bank (TF 2, 3, 5 and 7), the measure's success not only depends on the design and initial fixing of the protection, but is mainly determined by the plant species chosen, i.e. the plants' suitability under the given boundary conditions (e.g. flooding tolerance) and thus their vitality and long-term development. Annex 2 provides an overview of all plant species used and an evaluation, based on a colour code, of their development in the first six years after installation of the protection measures. It is also indicated for each vegetation component whether the plants are needed to ensure bank stability or whether their primary function is to enhance the structure ecologically.

A summary of the tested bank protection measures is given in Table 11. Based on all the findings obtained for the test stretch, the measures were compared and rated regarding their stability and effectiveness for ensuring local bank stability, on a scale from 1 (very poor) to 5 (very good). This assessment is also the basis for the summary rating of the measures in Chapter 7, taking account of the criteria of stability, ecology and cost.

Table 11: Rating of technical–biological bank protection measures on the test stretch in terms of their effectiveness in ensuring bank stability, on a scale from 1 to 5 (1 – very poor, 2 – poor, 3 – average, 4 – good, 5 – very good)

TF	Technical–biological bank protection measures/designs	Rating for bank stability
TF 1	Ecologically enhanced riprap with vegetation, without off-the-bank stone wall TF 1, upper and lower slope zones	5
TF 2	Removal of riprap; willow brush mattresses, at an angle to the flow direction TF 2, upper and lower slope zones	3
TF 3	Removal of riprap; willow brush mattresses, perpendicular to the flow direction TF 3, upper and lower slope zones	4
TF 4	Ecologically enhanced riprap with gravel and stone blocks, without dead wood fascines TF 4, upper and lower slope zones	5
TF 5	Removal of riprap; reed gabions TF 5a, lower slope zone	2
	Removal of riprap, stone mattresses TF 5a, top; TF 5b, upper and lower slope zones	5
TF 6	Ecologically enhanced riprap with alginate TF 6, upper and lower slope zones	5
TF 7	Removal of riprap; coir mat on hydroseeding TF 7a, upper slope zone	1
	Removal of riprap; plant mats TF 7a, b, c, lower slope zone	1
	Removal of riprap; plant mats TF 7b, c, upper slope zone	4
TF 8	Raising of existing stone wall; existing paving and riprap, reeds TF 8, lower slope zone	5
TF 9	Removal of riprap; without slope protection; willow branch cuttings on adjoining plane at the top of the slope[1)] TF 9, upper and lower slope zones	1
Ref.	Riprap as reference (already in place before redesign)	5

[1)] *In TF 9 bank stability was not a requirement; instead, the objective was for erosion to take place.*

Of the tested measures the ecologically enhanced riprap structures (TF 1, 4, 6 and 8) have proved most stable; they provided full bank stability independently of additionally introduced plants or structural elements. Stone mattresses (TF 5b) have also proven a reliable bank protection for the entire slope area under the prevailing conditions. Reed gabions (TF 5a) can only be regarded as suitable protection measures if the mix and arrangement of plants is optimised (see Annex 3). In the lower, frequently flooded slope area only the planted sedges have proven effective. They exhibited the highest flooding tolerance and the hightest level of vegetative regenerative capacity.

All measures without significant weight per unit area were less robust than those with sufficient weight. Some of them suffered damage already in the critical initial stage, so that local rehabilitation measures were required early on. Overall, willow brush mattresses (TF 2, 3) can generally be considered a suitable means for bank protection on waterways although their design and installation as well as their maintenance should be optimised (see Annex 3). Whether the willow roots and shoots develop well and sufficiently to cover the bank depends considerably on the properties of the installed branches and the fixings used.

The pre-cultivated plant mats were installed on the slope (TF 7) have found to be suitable as bank protection only for slope areas that are never or very rarely flooded. In these cases, the planted species that contributed towards bank stability were in particular slender-tufted sedge, greater pond sedge and tall fescue. In the upper slope areas, where hydraulic loads are lower, the bank protection potential of these species was strengthened by the combined effect of various grasses and herbs, some of which had been planted, while others had grown through natural succession. In the frequently flooded lower slope zones sufficient stabilisation and, consequently, regeneration of these plant species could only be achieved after covering the slope with a layer of armourstone. Coir mats on hydroseeding (TF 7a) is a weak design and failed to provide the necessary bank protection. It seems suitable only for areas above the maximum water level and/or wave run-up.

The unprotected slope in TF 9 clearly showed that the bank is instable without protection measures, even though it was exposed to the least ship-induced loads of all test fields. Although willows were installed in a few places between the maintenance path and the top edge of the slope, and developed very strongly, bank erosion progresses further with each flood event.

The table in Annex 3 provides an overview and explanations of the development of the measures, damages that occurred and the rehabilitation measures implemented. The necessary design and construction optimisations required for the individual measures (‘lessons learnt’) are described, and their general suitability as bank protection measures for inland waterways is assessed from a technical point of view. Application limits and recommendations are specified.

5 Ecological Results and Rating of Measures

5.1 Rating of ecological effectiveness

Ecological effectiveness is evaluated based on defined criteria, which are composed of sub-criteria describing vegetation (Chapter 5.2), terrestrial and aquatic fauna (Chapter 5.3) and the relations between these elements (Chapter 5.4). Further criteria are construction materials used (Chapter 5.5) and ecosystem services, with CO_2 fixation as an example (Chapter 5.6). Ecosystem performance is graded according to five rating values: very high value (5), high value (4), medium value (3), low value (2), very low value (1). An overall rating of ecological effectiveness can be found in Chapter 5.7

The technical–biological bank protection measures studied here are designs which take on the function of stabilising the bank. They are different from near-natural banks in that they do not develop dynamic morphological processes of their own, plants are brought in from outside and they are exposed to hydraulic loads from shipping, which is why measures below the mean water level line are only possible to a limited extent.

Because of these fundamental differences, the near-natural condition of a bank is not a suitable reference for evaluating ecological effectiveness. The ecological effectiveness of the technical–biological bank protection designs is therefore assessed in comparison with the condition of conventional revetments made of riprap, which are intended to be replaced with technical–biological bank protection on bank sections requiring stabilisation. The ecological enhancement achieved compared with conventional riprap is relevant to that extent.

5.2 Vegetation – results and rating

5.2.1 Methodology

The objects of research were the various designs and the two reference fields. They were differentiated into lower, middle and upper slope zones, i.e. areas between mean low water level (MNW) and mean water level (MW), between MW and approximately MW +1.70 m, and above MW +1.70 m. In the upstream reference the strip of vegetation between the shoulder of the slope and the maintenance path, i.e. the adjoining plane at the top of the slope, was also included (called 'floodplain' here). The condition before installation was recorded in summer 2009 and in spring 2010. After implementation of the measures, recordings took place on an annual basis in the years from 2012 to 2017. One spring and one summer field inspection were carried out in each of the years 2012 and 2014. Due to unfavourable water levels, there was only a spring recording in 2015; in the years 2013 and 2016 only summer recordings took place for the same reason. TF 6 is an exception: here, ecological enhancement failed as early as in the first two years due to hydraulic loads from the Rhine to which the bank was exposed, which is why the TF was no longer included in the recordings in the following years (Chapter 4.3.3). Rehabilitated portions of TF 5 and 7 were sampled in spring 2017.
On each of the recording dates, all plant species per slope zone and design were recorded and their vegetation coverage surveyed as a measure of species abundance according to the Braun-Blanquet scale (Dierschke 1994). A comprehensive presentation of the work, including particular

observations for every test field, is contained in (BAW, BfG, WSA-MA 2013). The monitoring resulted in 300 data records and more than 400 plant species found. For purposes of evaluation, parameters were established based on NMDS ordination (e.g. slope zone, design, species number), which explain the variance within the data. Mean Ellenberg indicator values were calculated from the plant species composition (Ellenberg et al. 1992). Biological–ecological plant traits were taken from the BiolFlor database (Klotz et al. 2002), the plant species distribution map (Netzwerk Phytodiversität Deutschland and BfN 2013) and www.floraweb.de. The threatened species status follows Germany's Red List (Metzing et al. 2018) and the Red List of the Land Hesse (HMULV 2008). The protection status is taken from the www.wisia.de database.

The data analysis did not distinguish between species brought in from outside and species that immigrated spontaneously, as it was often impossible to make this distinction beyond doubt at the time of recording.

The vegetation found in each design is assessed based on the following sub-criteria:

- Effect of special locations (shallow water zone, hedge layers)
- Species richness (accounting for species richness of flowers, see Chapter 5.4)
- Diversity and plant abundance in the lower zone of the slope
- Proportion of native and naturalised (invasive) neophytes
- Occurrence of riparian, endangered or rare plant species
- Slope zonation depending on hydrological conditions

The sub-criteria (except for 'special locations') are graded based on a 5-level scale and lead up to an overall rating of the 'vegetation' criterion at the end of this sub-chapter (Table 13 and Table 14) using verbal explanations.

5.2.2 Special locations: shallow water zone and hedge layers

A shallow water zone was created in front of TF 1 by installing a stone wall off the bank (armourstones with vegetation) protecting it against waves. Hedge layers were planted along the top edge of the slope in TF 2 and 5. These designs are suitable to be combined with any other measure implemented in the test fields. They were therefore considered separately as special locations. A separate evaluation was also necessary because their species composition is different from that of the slopes and a combined statistical evaluation is difficult as a result.

The dead wood structures installed (root plates in TF 1, dead wood fascines in TF 4 and a dead wood log groyne in TF 9) are considered special locations, too. However, they mainly fulfil fauna-related functions and are therefore not discussed in this section on vegetation.
A fine substrate layer of several centimetres of thickness deposited in the shallow water zone (TF 1). Plant species of river bank communities (e.g. cursed buttercup *Ranunculus sceleratus*) and reeds (e.g. flowering rush *Butomus umbellatus,* Figure 40) established here as initials, without forming stable populations, however. The shallow water zone promoted the growth of aquatic plants thanks to the protection against waves and the ingress of substrate. In 2017, five aquatic plants typical of the Rhine were found; in addition to the native species shown in Figure 40, Eurasian water milfoil (*Myriophyllum spicatum*) and the neophyte Nutall's pondweed (*Elodea nuttallii*) occurred. Some of the species are rather rare, such as loddon pondweed (*Potamogeton nodosus*), which is on Germany's watch list.

The planted shrubs in the hedge layers are species associated with the upper hardwood zone. Figure 41 shows examples of introduced species. The berry catchfly (*Cucubalus baccifer*), which has immigrated successively, is an endangered species (Chapter 5.2.7).

Shallow water zones and hedge layers are, from a vegetation point of view, an effective combination with the bank protection designs tested in the test fields. They add structure and increase the richness in riparian and floodplain species. They promote aquatic and frequently flooded semi-terrestrial or rarely flooded habitats and thus a broad range of location types on the bank slope. In addition, natural slope zonation is strengthened.

Figure 40: Shallow water zone with aquatic and reed plants (photos: Katja Behrendt, BfG)

Figure 41: Shrub species of the hedge layers (photos: Katja Behrendt, Andreas Sundermeier, BfG)

5.2.3 Species richness

The measures taken on the test stretch led to an increase in species richness of higher plants compared to the situation before the measures. In 2016 a total of 162 species were found on the test and reference stretches, while in 2009, before the test stretch was built, only 27 species were found.

Figure 42 shows an ordination of vegetation data records (excluding the special locations and TF 6) produced during the monitoring period. Text box 1 explains how to read such a plot. The situation on the slope is colour coded. We refrained from adding legends to the individual dots for better readability of the plot. With regard to species composition, the designs are characterised as being 'stony', 'woody' or 'grassy–herbaceous'. The stony designs are the two reference fields, the remaining riprap in TF 1 and the remaining riprap with gravel fill and stone blocks in the initial development years (TF 4). The woody designs are the planting trenches of TF 1, the willow brush mattresses (TF 2 and 3) and the berm zone protected by the stone wall with reed and woods found on site (TF 8) as well as the riprap vegetated by means of willow branch cuttings and fascines above the log groyne in TF 9. The grassy–herbaceous designs comprise TF 4 (existing riprap, gravel fill and stone blocks after a longer development time), TF 5 (reed gabions and stone mattresses), TF 7 (plant mats) and TF 9 (without slope protection). In addition to clustering by test fields, the overall data record and the data recorded in 2016 can also be categorised by slope zone because the slope zones in each test field displayed similarities regarding their species composition.

The spatial relationship of species numbers within the data records was modelled by means of regression analysis. The species numbers are mapped as contour lines. The model shows a clear gradient from the lower/middle slope level to the upper slope level both in the overall data set and the data recorded in 2016. The gradient is visualised by means of the direction of the arrows in the left portion of Figure 42.

Design, species number and slope zone are important factors allowing for a clustering of individual data records. The regression model explains almost 79% (overall data record) and 91% (year 2016) of the variance within the data record.

The species number rose from the lower/middle to the less often flooded upper slope zone. The stony designs showed the least species richness with a comparatively small variance between the upper and the lower slope zone (grey arrow or ellipsis in Figure 42). The composition of species differs considerably from that found in the other designs. With woody designs (arrow or ellipsis in magenta), lower to medium species numbers occurred. While the willow brush mattresses of TF 2 and 3 and the planting trenches with willow fascines and willow branch cuttings above the log groyne in TF 9 showed lower richness, the hedge layers in the upper slope zone of TF 1 showed medium species numbers. As these designs all use a large proportion of willows, they form a separate cluster with respect to species composition.

The grassy–herbaceous designs of TF 4 (gravel fill), TF 5 (reed gabions and stone mattresses), TF 7 (plant mats), TF 8 (stone wall in 2016) and TF 9 (without slope protection) achieved low to high values (red arrow or ellipsis). In the grassy–herbaceous designs the range in species numbers along the slope gradient was comparatively large. The fact that species numbers seem to increase in the upper zones of the slope is explained by the decrease in hydraulic loads (e.g. resulting from currents, waves, flooding) the higher the slope.

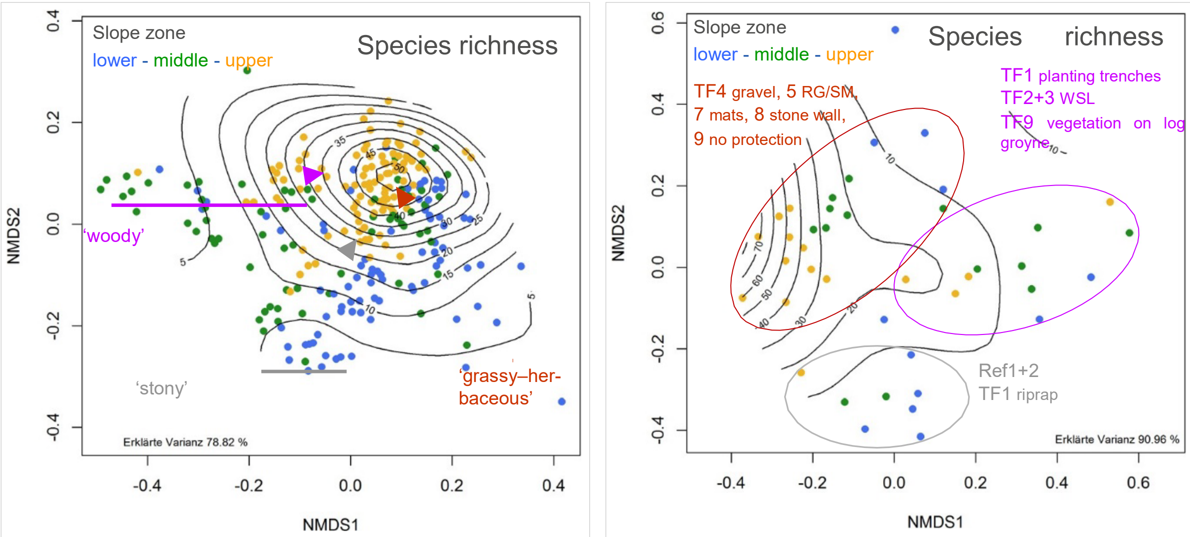


Figure 42: Similarities in species composition and richness throughout the monitoring period (left) and in 2016 (right). The location of stony, woody and grassy–herbaceous designs is symbolised by arrows in the picture on the left, they are pointing upwards from the lower to the higher slope zone.

> ***Text box 1: Interpretation of NMDS plots:*** *An NMDS plot is the illustration of the result of **n**on-metric **m**ulti**d**imensional **s**caling and provides an overview of large data volumes. Each data record captured as part of the monitoring (here the plant population in a specific slope zone of a design at a certain point in time) corresponds to a dot. The dot-to-dot distance is the smaller the more similar the information contained in the data record is between two points, i.e. dots located next to each other are very similar regarding their species composition. The plot has the grey isolines of a regression model superimposed. The isolines are to be interpreted like the contour lines of a map. Data records that hold highly similar data for a specific parameter (in this case the species number) are located on one of the isolines. The regression model shows that data records of the lower slope zone in the plot are located in the range of low species numbers, the records of the upper slope zone in the range of high species numbers.*

The development of species richness over time is illustrated in Figure 43 as a comparison between the monitoring years 2012 and 2016. Species numbers were highest immediately after completion of the installation work and declined in the following years. After completion, the construction activities caused growth of weed and ruderal species which, however, were suppressed in the course of succession by a growing and expanding vegetation cover. Moreover, some of the introduced plant species were lost, in particular in the reed gabions (TF 5a) and plant mats in the lower, frequently flooded slope area (TF 7) (Chapter 4).

For rating the species richness sub-criterion, and subsequently for rating further sub-criteria, the development state of the individual test fields or designs after completion of the first monitoring period (end of 2016) is relevant.

The rating of species richness is complemented by the rating of the species richness of flowers described in Chapter 5.4 to integrate a functional parameter (feed for flower visiting insects) in the vegetation rating. Both ratings are presented together.

Test field 7 (plant mats) was the field with the greatest richness of species and flowers and received a value rating of 5 (very high value). For the stone mattresses of TF 5, the value rating is 4 with respect to species richness and 5 with respect to species richness of flowers. TF 5a, which is poorer in species and flowers, was assigned a value rating of 3 according to both sub-criteria. The pronounced decline in species numbers in the lower, often flooded, slope areas of TF 7 and 5 (Figure 43, right) as a result of damages in this zone was striking. In monitoring year 2016, TF 7 had already been rehabilitated; TF 5a was rehabilitated later in the year. Considering the data from the lower slope zones captured in these two test fields in 2017, individual highly regenerating and flood-tolerant species from the original planting benefited from the stability of the surcharge load of the installed stone layer and have since grown through the gaps in the stone layer (Chapter 4.2.2 and Chapter 4.2.3). Ongoing monitoring will continue to observe and evaluate this development.

The vegetated riprap (TF 1) and the stone wall (TF 8) were assigned a medium rating with respect to species and flower species richness (value rating 3). Evaluation of TF 8 accounted for the fact that only data relating to the lower slope zone were considered. No measures had been carried out on the paving, which had displayed high species richness already before the implementation of the construction measures. TF 4 (gravel fill), TF 9 (without slope protection) and TF 2 and 3 (willow brush mattresses at an angle and perpendicular) showed relatively low species numbers (value rating 2). The willow brush mattresses and the gravel fill received value rating 3 due to their species richness of flowers, the TF without bank protection was assigned the value rating 2. The difference in species richness in the two willow brush mattress test fields in 2016 is due to higher losses of willows in TF 2 after intensive pruning (cf. Chapter 4.2.1). Since the stand is sparser, more species find it easier to develop, something which is negative from a stability perspective, but positive with respect to species richness. However, this did not result in an assignment of different value ratings with respect to species richness. The two reference stretches with the lowest species numbers and the least flower abundance received value rating 1 (very low value). An overview of the ratings for the sub-criteria ‘species richness’ and ‘species richness of flowers’ can be found in Table 13.

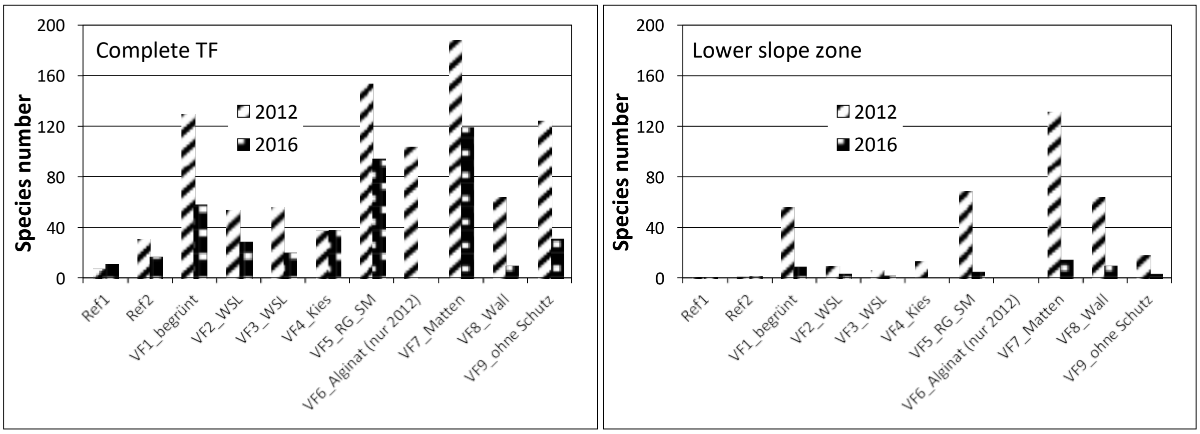


Figure 43: Total species numbers of the test fields (left diagram) and the lower slope zones (right) in the years 2012 and 2016. Only the lower slope zone was considered in TF 8

A high species number is not necessarily positive from the ecological point of view because it could also arise from ecologically undesirable species or indicators of disturbance. The sub-criterion 'species richness' is nevertheless used in the evaluation of the test stretch meaning 'species number', because the environment and surroundings of the test stretch are cleared and relatively species-poor. High species numbers per se (no matter what the ecological function of those species) can be regarded as positive in the context of the surrounding biotope. In addition, the very similar rating of species richness on the one hand and species richness of flowers on the other shows that the species number (as a measure of species richness) and a parameter of functional diversity (species richness of flowers) can be closely interrelated on the test stretch.

5.2.4 Diversity and plant abundance in the lower zone of the slope

The Shannon index, a dimensionless measure of diversity, was calculated based on the data relating to the year 2016 (Dierschke 1994) (Figure 44, left). In addition, the plant abundance in this slope zone is considered (total of vegetation coverage including all species, Figure 44, right).

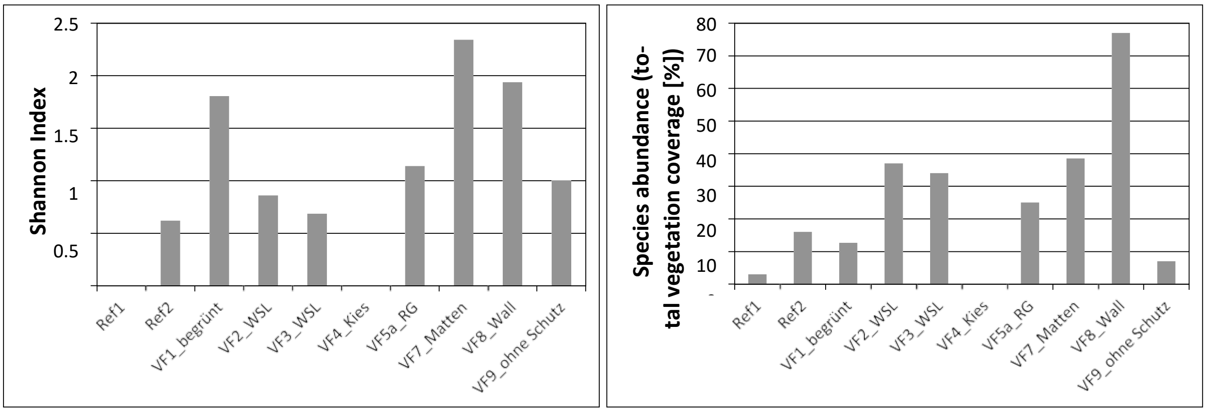


Figure 44: Left: Shannon diversity index (dimensionless); right: total vegetation coverage for the lower slope zone of the test fields

When combining diversity and plant abundance, the berm in the shelter of the stone wall (TF 8, Chapter 4.3.4, Figure 33 and Figure 34) performs best, followed by the plant mats (TF 7), which are relatively diverse although they show poorer plant abundance, but which had already been rehabilitated in the lower zone in 2016 (Chapter 4.2.3, Figure 22, centre). Both TFs received a value rating of 5.

The designs characterised by the use of willows in TF 1, 2 and 3 and the reed gabions (TF 5a) were assigned the value rating 4. The TFs either showed a relatively high plant abundance (willows in TF 2 and 3) or a high level of diversity, which was additionally favoured by the riverside stone wall (Chapter 4.3.1 Figure 30/Figure 31). The diversity in the reed gabions was attributable to existing plant species present already from before rehabilitation (Chapter 4.2.2, Figure 17, left and centre); however, plant abundance had already been low due to the loss of some species.

In TF 9 (without slope protection) individual representatives of annual riparian meadows occurred. This is a vegetation aspect associated with this slope zone and only occurred here of the entire test stretch. The still relatively high diversity justifies a value rating of 3, even if plant abundance is rather low. The reference (average of both stretches) showed poor values with respect to diversity and plant abundance and received value rating 2. No plants were found in the lower slope zone of the riprap with gravel fill and stone blocks (TF 4) (Chapter 4.3.2, Figure 32). In the lower zone of the stone mattresses (TF 5b), plant cover was sporadic and had not been sampled in 2016 (Chapter 4.2.2, Figure 20). Both designs received value rating 1. An improvement is expected on the stone mattresses in the course of the further development (Chapter 4.2.2, Figure 21). The reed gabions (TF 5a) and plant mats (TF 7) cannot be rated conclusively because of the initiated rehabilitation measures. Table 14 contains all ratings for the sub-criterion 'diversity in lower slope zone'.

5.2.5 Proportion of native and naturalised (invasive) neophytes

The ratios of species numbers and total vegetation coverage of both groups of species were used as a basis for the evaluation. Since both parameters returned similar results, Figure 45 shows the total vegetation coverage only for 2016. A high proportion of neophytes, in particular invasive neophytes, are regarded as negative.

Over the entire test stretch, the proportion of neophytes was regarded as relatively unproblematic from an ecological point of view and value rating 1 (very low value) was therefore not assigned. The proportion of naturalised neophytes and invasive naturalised neophytes was highest in the reference stretch (value rating 2). Due to the relatively high neophyte proportion in the ripraps between the planting trenches, the vegetated riprap (TF 1) was assigned a value rating of 3. TF 2 and 3 (willow brush mattresses), TF 4 (gravel fill), TF 5 (stone mattresses) and TF 7 (plant mats) received the value rating 4. The lowest neophyte proportion was recorded in TF 8 (stone wall), TF 9 (without slope protection) and in the reed gabions (TF 5a). These test fields were assigned a value rating of 5. Only the lower slope zone was considered in TF 8, which, due to long flooding periods, is not as intensely colonised by neophytes. Table 14 provides an overview of all the ratings for the sub-criterion 'neophytes'.

The fact that the neophyte proportion is regarded as unproblematic overall is also due to preventive maintenance work: false-acacia were pulled out of the willow brush mattresses at an early stage and ashleaf maple and plane in the stone mattress in TF 5 were pruned regularly. At the top edge of the slope in TF 7, Canadian poplar trees (*Populus x canadensis*) growing as shoots from the roots of felled poplar trees were controlled.

The relatively high proportion of neophytes on the reference stretches is due to Canadian poplar trees. The three most frequent invasive neophytes were ashleaf maple (mainly in TF 1, 4, 5 and reference), early and Canadian goldenrod (*Solidago gigantea* and *S. canadensis*) (mainly in TF 1, 5 and 7) and false-acacia (TF 3).

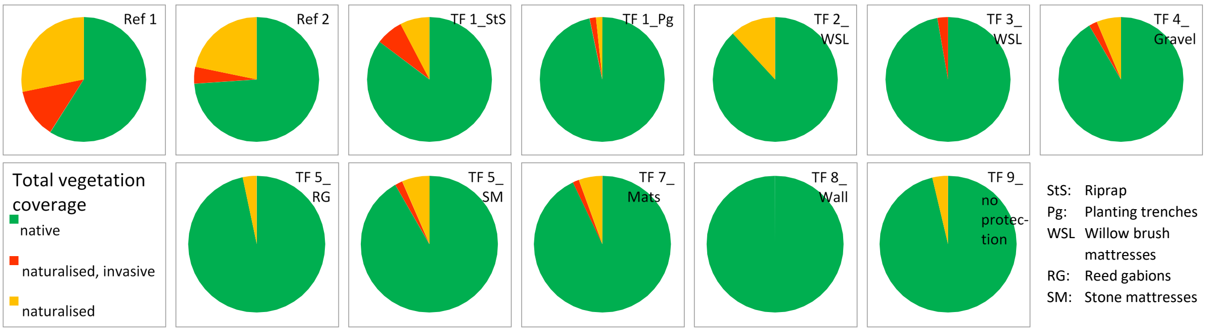


Figure 45: Total vegetation coverage: ratio of native to naturalised (neophyte) species in 2016. Total vegetation coverage normalised in relation to 100.

5.2.6 Riparian species

Both species numbers and species abundance (total vegetation coverage) were evaluated. Since both parameters returned similar results, Figure 46 shows the vegetation coverage ratio of riparian species to non-riparian species in 2016. The characterisations as '(non-)riparian' and/or 'dry' were based on indicator values and allocation to plant communities as in (Ellenberg et al. 1992).

Riparian species are distinguished into 'floodplain', i.e. moisture-loving species, and species indicating 'dry' conditions. On the test stretch with its steep, south-facing slopes, a number of dryness- and at the same time flooding-resistant species are found, above all in the upper, rarely flooded slope zone, whose occurrence is as typical of floodplains as that of species preferring moisture. There are dry spots in floodplains even under natural conditions. Species with indicator values for dryness were therefore also categorised as 'riparian'.

The proportion of riparian species was highest in the berm of TF 8 (value rating 5) and in the reference stretches (value rating 5). Only the lower slope zone was considered for TF 8, in which the proportion of riparian species is naturally high. The willow brush mattresses (TF 2 and 3) and the vegetated riprap (TF 1) were assigned value rating 4, the TF without protection (TF 9) received a medium value (value rating 3). TF 7 (plant mats) and TF 5 (reed gabions) were assigned value rating 2, TF 4 (gravel fill) and TF 5 (stone mattresses) value rating 1. Table 14 contains all the ratings for the sub-criterion 'riparian species'.

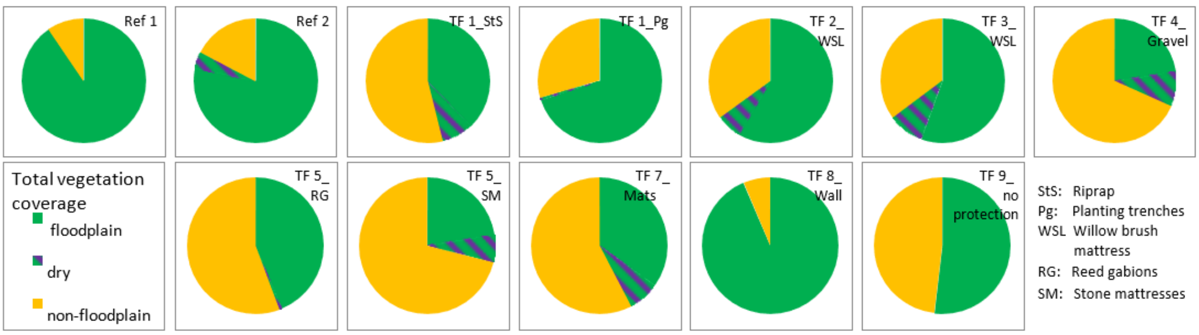


Figure 46: Total vegetation coverage: ratio of riparian species (floodplain species and species with indicator values for dryness) to non-floodplain species in 2016. Total vegetation coverage normalised in relation to 100.

5.2.7 Endangered and protected plant species, rarity

The highest number of endangered and protected species occurred in TF 7 (plant mats – 8 species, value rating 5) and TF 5 (stone mattresses – 5 species, value rating 4) (Table 12). As the difference between these two TFs and the other TFs was considerable, value rating 3 was not assigned in this category. The TFs with one or two species received value rating 2: willow brush mattresses (TF 2 and 3), reed gabions (TF 5a) and vegetated riprap (TF 1). TFs in which there is no evidence of any species or only of very low species abundance, i.e. TF 4 (gravel fill), TF 8 (stone wall), TF 9 (without slope protection) and the reference, received value rating 1. All the endangered species present are species that immigrated spontaneously; only the yellow iris was introduced deliberately in TF 7, but established spontaneously in TF 1, 5 and 9 at low individual numbers.

The 'reed gabions' (TF 5a) and 'protected by stone wall' (TF 8) designs are slightly disadvantaged in this rating criterion, as they were only installed in the lower or lower and middle zones of the slope, which are naturally species-poorer than the upper slope zone. Thus, it is less likely to encounter endangered or protected species in these designs. Table 13 contains all the ratings for the sub-criterion 'endangered species'.

The distribution maps shown in Figure 47 show meadow fleabane and berry catchfly as examples of the high representativeness of floodplain habitats along large German rivers. The berry catchfly also occurs in the hedge layers described earlier.

Table 12: Occurrence of endangered and protected plant species. StS: riprap, WSL: willow brush mattresses, RG: reed gabions, SM: stone mattresses. Test fields without occurrence of corresponding species are not shown.

Endangered and/or protected species		RL Federal level	RL Land Hesse	§	Occurrence in the test fields in 2016: TF 1 StS	TF 2+3: WSL	TF 4 Gravel	TF 5 RG	TF 5 SM	TF 7 Mats	TF 9 no protection
Allium scorodoprasum	Sand leek		V								
Aristolochia clematitis	Birthwort	V	V								
Carex otrubae	False fox-sedge		V								
Cucubalus baccifer	Berry catchfly	3	3								
Dianthus carthusianorum	Carthusian pink	V	V	§							
Inula britannica	Meadow fleabane	V	3								
Iris pseudacorus	Yellow iris			§							
Onobrychis viciifolia	Sainfoin	3									
Salvia pratensis	Meadow clary	V									
Thalictrum flavum	Common meadow-rue	V									
Ulmus minor	Small-leaved elm		3								

RL (Red List) 3: endangered
V: watch list
Protected by law: §: special protection

Basic colour green: spontaneous immigration
Basic colour brown: planted
The colour intensity symbolises total vegetation coverage

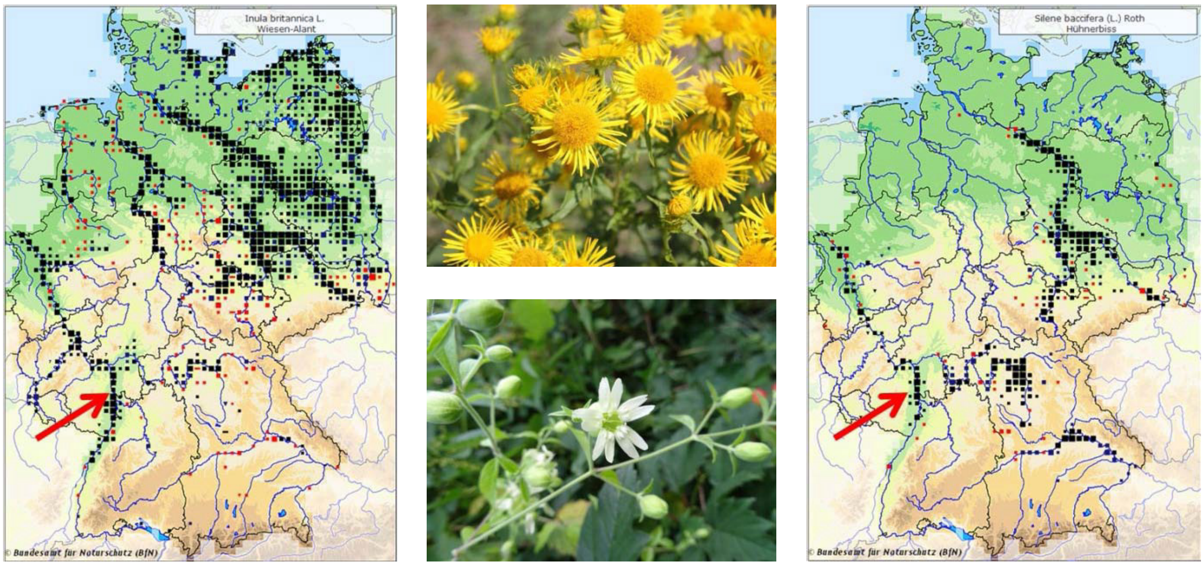


Figure 47: Distribution map and habitus of meadow fleabane (map on left, photo at top) and of the berry catchfly (map on right, photo at bottom). The red arrows show where the test stretch is situated. Map sources: Bundesamt für Naturschutz, Floraweb. (Photos top/bottom: Yasmin Wingender, Katja Behrendt, BfG)

The rarity of native species was assessed based on their occurrence on the ordnance survey map. This expresses in how many of the approximately 12,000 map sheet quadrants of the topographic map with a scale of 1 : 25,000 the species is found (www.floraweb.de). For example, the meadow fleabane (Figure 47, map on left) occurs in 1,837 quarter quadrants of the ordnance survey map, the berry catchfly in 575 of them (map on right). Planted stands of the moderately rare purple willow were not considered. Unlike in the previous chapter, in which the threatened and protected species are used as a basis to assess ecological effectiveness, this approach addresses the abundance or rarity of the entire species population.

Figure 48 shows the distribution of species of different abundance categories in the test fields. For better orientation, mean values are indicated. The flora of the test stretch and the reference is mainly composed of commonplace species or species that are at least not rare in habitats around waterbodies. As no rare species occurred at all, value rating 5 was not assigned. The test fields 3 (willow brush mattresses), 4 (gravel fill), 5 (stone mattresses), 7 (plant mats) and 8 (stone wall) had the comparatively highest proportions of moderately abundant to moderately rare species (value rating 4). The reference stretches were heterogeneous with relatively sporadic occurrences of rare species (value rating 3 as an average for both stretches). TF 1 (combination of riprap and planting trenches), TF 2 (willow brush mattresses) and TF 5 (reed gabions) received value rating 2. TF 9 (without slope protection), which was assigned a value rating of 1, showed the largest proportion of nationwide very abundant species.

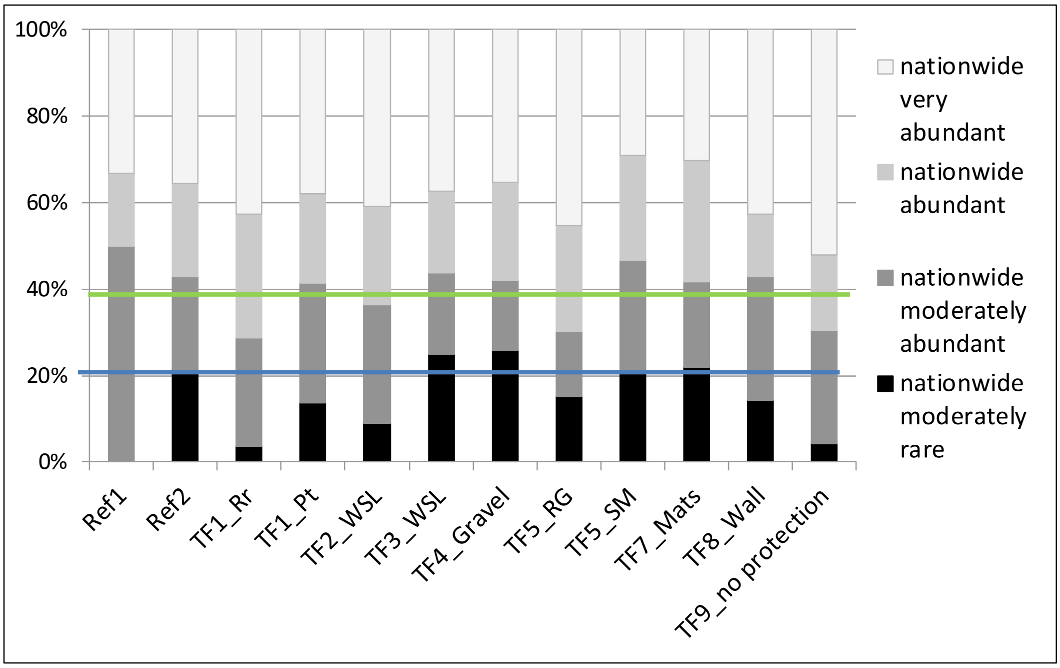


Figure 48: Relative distribution of species of nationwide abundance categories. Horizontal lines mark the average of all test fields for their proportion of moderately rare (blue) or moderately rare plus moderately abundant (green) species. For acronyms cf. Figure 46.

Comparatively rare nationwide were species that occur along large flowing waters such as common meadow-rue (*Thalictrum flavum*) (TF 5, stone mattresses), leafy spurge (*Euphorbia esula*) (stone mattresses in TF 5 and 7) and bulbous chervil (*Chaerophyllum bulbosum*) (reference stretch 2). Further examples are species associated with semi-arid grassland and nutrient-poor meadows, which flourish on the sunny, mostly 1 : 3 sloping bank in the more rarely flooded upper areas, e.g. cypress spurge (*Euphorbia cyparissias*) (TF 1, 4, 5, 7) and meadow clary (Salvia pratensis) (TF 7).

5.2.8 Slope zonation according to hydrological conditions

The average moisture values, weighted according to species abundance, were used for zonation purposes. These values were calculated using the data for 2016 (Figure 49). The extent to which the moisture gradient on the bank is reflected in the vegetation of the test fields was assessed, i.e. whether the combination of introduced and spontaneously immigrated plant species can be considered indicators of existing site conditions. As a reference, the moisture value of the vegetation between the shoulder of the slope and the maintenance path ('floodplain') and the moisture value of the vegetation at the downstream end of TF 9 (without slope protection) upstream of the log groyne were used. This is because of intense erosion which has resulted in the natural substrate (sand with alluvial loam) remaining here ('bank substrate').

A moisture zonation corresponding to the site conditions developed in the willow brush mattresses of TF 2, which received value rating 5. In TF 8, too, the lower, frequently flooded area of the slope achieved a value typical of this zone (value rating 5); the middle and upper zones were not evaluated. There were also clear differences in TF 9 (without slope protection) between the lower and the upper slope zones, which resulted in a value rating of 5. There were no data for the middle zone.

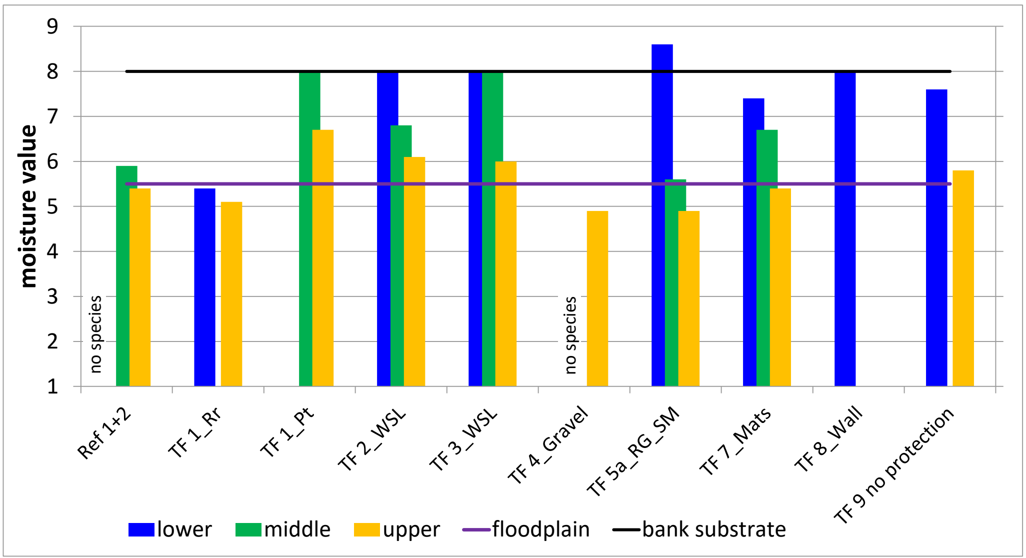


Figure 49: Weighted average moisture value of the three slope zones (lower – middle – upper) and reference moisture values 'floodplain' and 'bank substrate'. For acronyms cf. Figure 46.

Due to the limited spontaneous immigration of species, no differences have so far emerged between the lower and the middle slope zones of TF 3 (value rating 4); otherwise, conditions are similar to TF 2. TF 7 (plant mats) has somewhat drier conditions compared to the reference values with otherwise pronounced zonation (value rating 4). As conditions are distinctly drier in TF 1 (combination of riprap and planting trenches), value rating 3 was not assigned; because moisture was high in the planting trenches, TF 1 was assigned value rating 2. The reed gabions in TF 5 also received value rating 2. Zonation was particularly poor in TF 4 and TF 5 (SM) and in the reference stretches. This is due to the stony substrate and the associated dryness and heat.

5.2.9 Summary rating for vegetation

As the values for the three sub-criteria 'species richness', 'species richness of flowers' and 'endangered species' correlate (Table 13), these values were combined to produce the new criterion 'diversity and threatened species' for purposes of an overall vegetation rating. Refer to Table 14 for the overall rating.

The value ratings were aggregated into a single rating on the basis of the frequency distribution of the value ratings and a verbal explanation of the strengths and weaknesses of the designs with respect to the rated sub-criteria. Thus, the overall rating is not merely based on calculating mathematical averages from the value ratings of the sub-criteria but higher value ratings were interpreted as 'strengths' of the designs that received higher weight in the overall rating.

The designs were assigned to the individual value ratings in such a way that, pursuant to the sub-criteria, the design performing best achieved the highest value rating; the design performing worst received the lowest. Thus, wherever possible, the entire range of value ratings was used to compare the ratings with other ecological criteria (Chapters 5.3–5.6). The shallow water zone and the hedge layers, which were special designs, were only subjected to a comparatively rough value rating.

Table 13: Combination of the three correlating sub-criteria into a new criterion 'diversity and threatened species'
Value ratings for the special locations shallow water zone and hedge layers: good [+], neutral [ ], poor [-]
FWZ: shallow water zone, HL: hedge layer at top edge of slope
Value ratings: very high value (5), high value (4), medium value (3), low value (2), very low value (1)

Sub-criterion	FWZ	HL	TF 1	TF 2	TF 3	TF 4	TF 5 _RG	TF 5 _SM	TF 7	TF 8	TF 9	Ref
Species richness	+	+	3	2	2	2	3	4	5	3	2	1
Species richness of flowers (cf. Chapter 5.4)		+	3	3	3	3	3	5	5	3	2	1
Endangered species	+	+	2	2	2	1	2	4	5	1	1	1
New criterion: Diversity and threatened species	+	+	3	2	2	2	3	4	5	3	2	1

The summary rating can be derived from Table 14 and results in the following: The cluster with the best performance regarding vegetation development (overall rating 5) consisted of the plant mats including the rehabilitation measures (TF 7), the paved berm behind the stone wall (TF 8) and the wave-protected shallow water zone – a special location in TF 1. Almost all sub-criteria received a positive rating in TF 7 and 8. Deficiencies arose regarding riparian and/or endangered species.

Table 14: Summary rating for vegetation For abbreviations and signs cf. Table 13

Sub-criterion	FWZ	HL	TF 1	TF 2	TF 3	TF 4	TF 5 _RG	TF 5 _SM	TF 7	TF 8	TF 9	Ref
Diversity and threatened species	+	+	3	2	2	2	3	4	5	3	2	1
Diversity lower slope zone	+		4	4	4	1	4	1	5	5	3	2
Neophytes	-		3	4	4	4	5	4	4	5	5	2
Riparian species	+	+	4	4	4	1	2	1	2	5	3	5
Rare species	+		2	2	4	4	2	4	4	4	1	3
Zonation	+	+	2	5	4	1	2	1	4	5	5	1
Overall rating	5	4	3	4	4	2	3	3	5	5	3	2

The willow brush mattresses (TF 2 and 3) received an overall rating of 4 as did the hedge layers along the top edge of the slope. Most sub-criteria were assigned positive ratings here. The willow brush mattresses showed deficiencies in species richness, but not regarding species richness of flowers (particularly thanks to the intense spring blooming of the willows); there were few endangered or rare species. The willows quickly formed a dense woody plant stand on the bank slope resulting for the most part in a lack of herbaceous species due to competition and shade pressure.

TF 1 (vegetated riprap), the stone mattresses (TF 5_SM), TF 9 (without slope protection) and the reed gabions (TF 5_RG) were assigned value rating 3. Individual sub-criteria received a positive rating here. TF 1 had deficiencies in the poor occurrence of endangered and rare species and a less pronounced zonation of the plants along the moisture gradient of the slope. The remaining riprap between the planting trenches proved to be a negative element. The stone mattresses showed deficiencies regarding the sub-criteria ‘diversity lower slope zone’, ‘riparian species’ and the zonation. TF 9 showed deficiencies in species richness and species richness of flowers as well as in the incidence of endangered or rare species. The reed gabions of TF 5 were also assigned value rating 3. In late 2016 it was necessary to rehabilitate all of the reed gabions by installing a single layer of armourstone in response to widening gaps in vegetation cover and the instability of the gabions (Chapter 4.2.2). The vegetation cover has developed positively since then. This will be recorded and evaluated in the future course of the ongoing monitoring.

Far fewer positive effects were found in TF 4 (riprap with gravel fill and stone blocks) and the reference stretches, which were assigned an overall rating of 2. The gravel introduced in TF 4 was washed out, so that today the only differences between this test field and the reference stretches are the stationary stone blocks and the dead wood fascines, which have no effect on vegetation. Nevertheless, comparatively rare plant species such as a rather high proportion of riparian species (reference) are found here, so that the design definitely did not warrant a value rating of 1. Topsoil alginate (TF 6) has not proved effective and was assigned a value rating of 1 (not shown in Table 13 and Table 14). The effectiveness of rehabilitation measures and the type and intensity of maintenance work are decisive factors for further vegetation development. The ranking presented here is therefore subject to change.

5.3 Fauna – results and rating

5.3.1 Methodology

The ecological monitoring of the test stretch included studies on various groups of animal organisms (birds, ground beetles, spiders, reptiles, macrobenthos, fish) that function as indicators of the ecological effectiveness of the test stretch. The studies mainly focused on the potential of alternative bank protection designs to provide habitat structures for the organisms studied that are suitable in the long term. A highly differentiated analysis was made of the added ecological value that each type of measure offers the respective group of organisms compared to conventional riprap.

The studies of the above-mentioned groups of organisms were conducted at the time when the ACTUAL condition survey was performed in 2010, prior to the implementation of the test stretch, and during two success monitoring campaigns in the years 2013/14 and 2017. In both success monitoring campaigns the test fields of the test stretch were sampled for their fauna, with the exception of the fish fauna, which was recorded in 2010 and in the period from 2012 to 2017, usually twice a year (early spring, autumn).

The ecological effectiveness of each TF was evaluated based on the individual groups of organisms. In each case, specific criteria were applied, which were initially weighted for summary rating purposes on the basis of expert knowledge (Table 15).

Table 15: Main criteria, sub-criteria and weighting (Wt.) of the various groups of organisms used in the value rating of the test fields.

Group of organisms	Main criterion	Wt.	Sub-criterion	Wt.
Birds	*Reproduction*	1.0	(Assumed) breeding	0.6
			Breeding potential	0.4
Reptiles	*Species richness*	1.0	Number of species	0.5
			Sightings	0.5
Ground beetles	*Species richness*	0.6	Number of species	0.4
			Number of individuals	0.2
			Diversity	0.4
	Species composition	0.4	Proportion of riparian individuals	0.7
			Red List species	0.3
Spiders	*Species richness*	0.6	Number of species	0.4
			Number of individuals	0.2
			Diversity	0.4
	Species composition	0.4	Proportion of riparian individuals	0.7
			Red List species	0.3
Fish	*Species richness*	0.5	Total number of species	0.5
			Mean number of species per survey point	0.5
	Species composition	0.5	Mean proportion of invasive species	0.5
			Mean number of species in the reference field	0.5
Macrobenthos	*Species richness*	0.5	Total number of species	1.0
	Species composition	0.5	Mean proportion of invasive species	0.3
			Number of EPTCBO species*	0.7

* EPTCBO species are species of the orders Ephemeroptera (mayflies), Plecoptera (stoneflies), Trichoptera (caddisflies), Coleoptera (beetles), Bivalvia (bivalve shells) and Odonata (dragonflies and damselflies).

To this end, the parameters describing the criteria (sub-criteria, cf. Table 15) were translated into values from 1 (poor) to 5 (very good) and compared with the results obtained for the reference section (conventional riprap).

Similarly to the procedure applied in Chapter 5.2 (Vegetation), the weighted evaluation results were then translated into a 5-level scale with value ratings ranging from the poorest rating of 1 (very low value) to the best rating of 5 (very high value). The value ratings 2 (low value), 3 (medium value) and 4 (high value) were calculated (cf. Annex 6). The evaluations for each group of organisms were used to produce an overall 'terrestrial fauna' value rating for the terrestrial measures in test fields 1 to 9 and the terrestrial reference. An overall 'aquatic fauna' rating was produced for the aquatically effective measures in TF 1 and 4 (shallow water zone, dead wood fascines) and the aquatic reference. Only the test fields TF 1 and 4 were assumed to be ecologically effective for fish and aquatic invertebrates. However, since it is possible that the terrestrial measures have positive effects on the aquatic habitat, the other test fields were also studied. The findings are described below although these test fields were not included in the overall rating for aquatic fauna, because of their comparatively short development period of five years in combination with to some extent intensive maintenance work.

The overall 'terrestrial fauna' rating is based on a weighted mean value derived from the rating of the terrestrial groups of organisms in each TF. Evaluations of groups of organisms for which targets had been defined initially, and which were to be promoted by the specific measures, were double weighted (cf. Chapter 2, Table 1).

Weighting according to target with the willow brush mattress in TF 3 as an example

Target for the willow brush mattress in TF 3:
'Ecological enhancement through suitable woody plant population, structural diversity; improvement of habitat quality, esp. for woodland breeding *bird species, ground beetles, spiders*'

Rating of the ecological effectiveness of TF 3 for the following terrestrial groups of organisms: birds, reptiles, spiders, ground beetles (indicators listed in Chapter 5.3)

Group of organisms	*Birds*	*Reptiles*	*Spiders*	*Ground beetles*
Rating	5	3	3	4

Weighted mean value according to the above target:

$(2 * 5 + 3 + 2 * 3 + 2 * 4)/7 = 3.9$

Rating of terrestrial fauna in test field 3 (willow brush mattresses) = **4**

The mean value from the sub-ratings for fish and macrobenthos in TF 1 and 4 and the aquatic reference was used for the overall 'aquatic fauna' rating.

All the rating results (value ratings 1 to 5) for terrestrial groups of organisms (birds, ground beetles, spiders, reptiles) are summarised in Table 18, and the results for aquatic organisms (fish and macrobenthos) are summarised in Table 19. The overall 'terrestrial and aquatic fauna' rating contributes to the final overall ecological rating in Chapter 5.7.

5.3.2 Birds

The avifauna was recorded on 21 days in the period from September 2013 to June 2014 and on 20 days in the period from mid-March 2017 to October 2017 by means of field inspections of the transect, point observations and random observations. Bird species watched and heard, and nesting structures were documented. A method similar to the approach according to Flade (1994) was used to categorise the avifauna into indicator species, habitat-typical species and permanent companion species (based on a characterisation of bird communities associated with different habitats). It is not always possible to evaluate individual bank protection designs on the basis of the group of birds present because birds usually have larger habitats than those that could be provided by the test fields. The evaluation could therefore only be made using an expert assessment and five value rating levels. Initially, data collected each year for the complete test stretch (including a buffer zone in the adjoining 'floodplain' covering an area up to approximately 50–100 m on the landside of the maintenance path) were used to carry out a general evaluation of the development of the technical–biological designs over time. The total numbers of species counted in the ACTUAL condition survey in 2010 and in the survey years 2013/14 and 2017 were similar and comparable (Table 16). It was possible to show the presence of 67% of the indicator species and permanent companion species that have been described by Flade (1994) as associated with 'the riparian zones of large rivers', but only 17% of associated roosting birds. There was only a slight difference in the numbers of species listed either as endangered species on the Red List or listed on the watch list of Germany or Hesse (2013/14: 22; 2017: 16). Presumably, a period of five years was not a long enough period for conditions to improve significantly for breeding birds. Only minor changes were recorded for the period between the surveys of the two success monitoring campaigns (Table 16). The changes that had taken place were in the vegetated riprap (TF 1) and the willow brush mattresses (TF 2/3) and were probably due to the onset of natural succession of the willows. The secondary growth in thickness of the willow rods had a positive effect on breeding conditions of woodland nesting birds, but a negative impact for species breeding in reeds. The breeding potential for ground nesting birds, waders and species breeding on banks and in caves, which is assessed as good because of the installed structures and the more open design of the test fields with plant mats (TF 7) and without bank protection (TF 9), had to be partly reassessed as the intensity of disturbances caused by walkers, dogs and anglers increased.

Table 16: Total numbers of bird species observed on the test stretch and in the surrounding areas (buffer zone in the 'floodplain' and water) in 2010, 2013/14 and 2017; n.r.s. – 'not recorded separately'

Survey year	Total species number	Test stretch	'Flood plain', water farther off/passage
2010	52	n.r.s.	n.r.s.
2013/2014	55	37	18
2017	52	32	20

In 2017, four species of breeding birds were identified: nightingale (*Luscinia megarhynchos*) in the willow brush mattresses (TF 2/3), blackcap (*Sylvia atricapilla)* and garden warbler *(Sylvia borin)* in the old pollarded willows in the unchanged upper slope area of TF 8 (stone wall) and marsh warbler *(Acrocephalus palustris)* in the remaining reed area at the downstream end of the test field with plant mats (TF 7). During the 2013/14 season only the first two species were found to be philopatric to the test stretch.

The survey results show that, compared to the reference stretch, there was only a slight increase in the potential of the entire test stretch for providing habitat structures that are suitable for the seven habitat guilds (Table 17) (cf. Annex 6). While conditions for breeding birds or birds seeking a resting place or foraging are mostly unsuitable and only sometimes favourable in the reference areas, individual test fields show some potential for developing suitable habitat structures. In many cases this is due to the existing or growing woody plants in the test field. For example, the willow branches installed in the living brush mattresses (TF 2/3) and the vegetated riprap (TF 1) provide increasingly favourable habitat conditions for the nightingale (*Luscinia megarhynchos*) and various finch species. Moreover, the shallow water zone with low flow velocities in front of the vegetated riprap (TF 1, off-the-bank stone wall) and the well-developed herbaceous layer of the plant mats in combination with the remaining reeds (TF 7) create favourable foraging and roosting conditions for waterbirds (ducks, geese), ground nesters (e.g., white wagtail, *Motacilla alba*) and reed nesting birds. The best value rating was given to the designs with the highest potential for providing suitable habitat structures in the long term (based on an analysis of the data and on expert opinions). These are the test fields TF 2 and 3 (willow brush mattresses) and 7 (plant mats), which were assigned the value rating 5, followed by TF 8 (stone wall) with a value rating of 4 (high value). TF 1 (vegetated riprap) and TF 9 (without slope protection) received a rating of 2 (low value) and 3 (medium value) respectively, whereas TF 4 (gravel fill), TF 5 (reed gabions and stone mattresses) and the conventional riprap were assigned the lowest value rating of 1 (cf. Table 18).

Table 17: Distribution of bird guilds in the individual test fields compared to the reference in 2017 according to roosting/feeding potential (RaP), breeding potential (BrP) and development of breeding potential (BrE) (colour code: green = good; yellow = favourable; red = poor). Assessed improvements are marked with green frames, deteriorations with red frames; they are based on the data for 2013/2014.

Guild	Ex.	TF1			TF2/3			TF4			TF5			REF		
		RaP	BrP	BrE	RaP	BrP	BrE	RaP	BrP	BrE	RaP	BrP	BrE	RaP	BrP	BrE
Bank/cave breeders	*Kingfisher*															
Ground nesters excl. waders	*White wagtail*															
Waders	*Sandpiper*															
Woodland breeders (br. def.)	*Nightingale*															
Reed nesting birds	*Reed warbler*															
Waterbirds (narr. def.)	*Ducks*															
Other relevant species	*Grey heron*															

Guild	Ex.	TF6			TF7			TF8			TF9			REF		
		RaP	BrP	BrE	RaP	BrP	BrE	RaP	BrP	BrE	RaP	BrP	BrE	RaP	BrP	BrE
Bank/cave breeders	*Kingfisher*															
Ground nesters excl. waders	*White wagtail*															
Waders	*Sandpiper*															
Woodland breeders (br. def.)	*Nightingale*															
Reed nesting birds	*Reed warbler*															
Waterbirds (narr. def.)	*Ducks*															
Other relevant species	*Grey heron*															

5.3.3 Reptiles

Mapping work based on 'reptile boards' and visual search surveys was carried out in the first success monitoring campaign in 2013/14. In 2017, only visual searches were used as a survey method, because the reptile boards had not proved successful and were of negligible additional use. Subsequently to the reptile surveys, assessments were made of the presence and, if applicable, abundance and reproduction of the species found. The only reptile species found in the ACTUAL condition survey in 2010 and in the monitoring years 2013/14 was the sand lizard (*Lacerta agilis).* In 2017, however, individuals of a population of common wall lizards (*Podarcis muralis)* and single grass snakes *(Natrix natrix)* were counted as well (Figure 50).

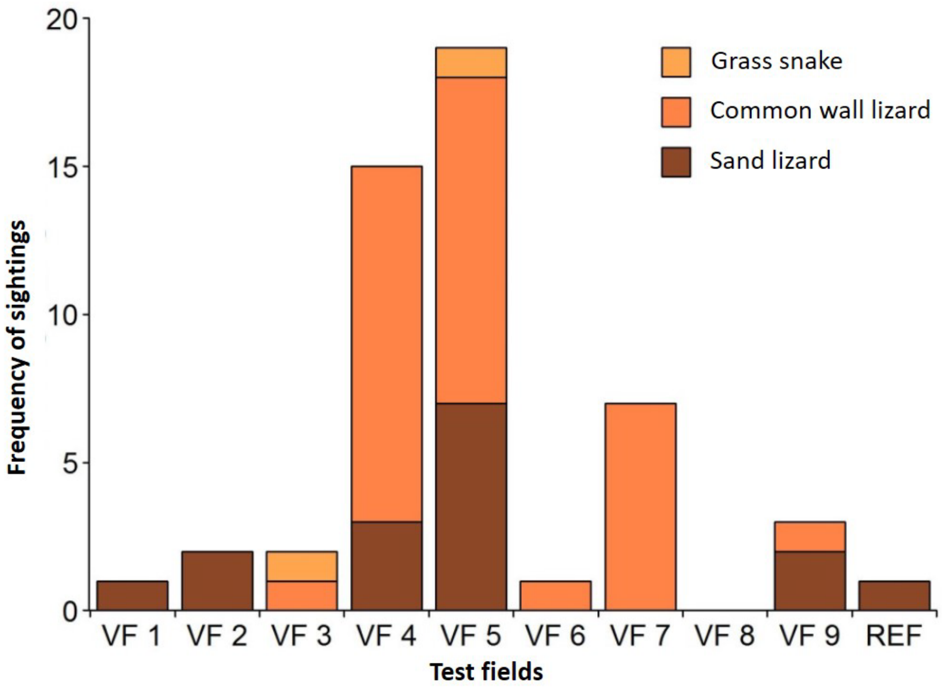


Figure 50: Sightings of reptile species in the individual test fields during the 2017 survey

It remains uncertain whether the common wall lizards migrated to these test fields because of the conversion of the bank protection or because of a general northward spread of the species in the natural space. Nevertheless, the significantly higher sighting rates in the largely open and sunny test fields with gravel fill and stone blocks (TF 4), stone mattresses (TF 5) and plant mats (TF 7) indicate that the measures taken in these test fields have created suitable habitats for reptiles. However, the recorded reptile populations probably extend across the entire surrounding 'floodplain' above the test fields and are not limited to individual test fields. Reptile surveys are therefore only of limited use for assessing the quality of any of the individual technical–biological bank protection measures. Despite this limitation, the findings (cf. Annex 6) indicate that the above-mentioned measures – if implemented across a wider area – may well be useful for establishing connectivity between reptile populations and creating large connected habitats. They were therefore included in the value rating.

The highest ecological effectiveness ratings of 4 and 5 (high and very high value) for the reptile groups of organisms were assigned to TF 4 (gravel fill) and TF 5 (reed gabions and stone mattresses). In addition, TF 7 (plant mats) and TF 9 (without slope protection) also show potential for providing suitable reptile habitats and were consequently assigned a rating value of 3 (medium value). The relatively densely vegetated lower slope area in the shelter of the stone wall of

TF 8 received the lowest rating (value rating 1), while TF 1 (vegetated riprap), 2 and 3 (willow brush mattresses) and the reference were assigned a rating of 2 (low value) (cf. Table 18).

5.3.4 Ground beetles

Ground beetles were recorded in the ACTUAL condition survey in 2010 and in the two subsequent success monitoring campaigns using pitfall traps and in some cases hand-catching. For the survey in 2010, three survey areas were determined, and five pitfall traps installed in each of them in such a way as to represent the zonation of the later test stretch and of the reference stretch. During the success monitoring campaigns (2013/14 and 2017) five pitfall traps per TF and also in the reference stretch were installed at different slope heights. In addition, five small cup traps were placed in the upper slope area of TF 8. Hand-catching was used additionally in TF 2, 5, 7 and partly in TF 8 and 9, as the construction measures carried out in these test fields limit the installation of pitfall traps.

The surveys of both success monitoring campaigns (2013/14 and 2017) showed the beetle (Carabidae) community to be developing very dynamically in general. The total numbers of species recorded in the surveys were quite similar with 77 species (1,425 individuals) recorded in 2013/14 and 69 species (1,102 individuals) in 2017; however, the species composition varied strongly and only around 60% of the species counted (44 identical species) were captured in both surveys. In the ACTUAL condition survey in 2010 only seven beetle species were found in the riparian zones of the future test stretch. However, account must be taken of the fact that the effort required for and the design of the preliminary study differ to some extent from the methods adopted in subsequent years; the findings must be interpreted accordingly. This underlines the high inter-annual variability in terrestrial invertebrate communities and shows why measurements other than the presence or absence of a specific species must be applied when rating the test fields. The assessment therefore relies on the numbers of species and individuals, the diversity index, the proportion of riparian individuals and the number of species listed on the Red List of Germany and/or Hesse (Schmidt et al. 2016, Malten 1998) (cf. Table 15). Eleven species recorded in 2017 (2013/14: 24 species) were listed in the Red List category of critically endangered or endangered species or on the watch list. The distribution in the test fields was similar, with the exception of the reference, so that in each TF at least one (willow brush mattress, TF 2) and a maximum of five of these species (without slope protection, TF 9) was found. Similar numbers of Red List species (4 respectively) were also found in the test fields with reed gabions and stone mattresses (TF 5), plant mats (TF 7) or the stone wall in the lower slope area (TF 8).

The number of ground beetle species and individuals was comparable between the two control surveys (2013/14 and 2017) in almost all of the test fields (Figure 51). This was true both for the ratio of the total number of species to the number of riparian species, and for the ratio of all individuals recorded to riparian individuals. However, the situation in the reed gabions and stone mattresses (TF 5) and the stone wall in the lower slope area (TF 8) was very different. In the monitoring period 2013/14, for example, very high numbers of individuals and species were counted in TF 5. By contrast, only 54% of these species and only 15% of the individuals were counted in 2017. On the other hand, the ratio of riparian to non-riparian species was relatively small: 4% in 2013/14 and 9% in 2017. These effects are very probably due to the large-scale loss of reed vegetation in the gabions in the second half of the monitoring phase and the subsequent rehabilitation measures carried out in October 2016 (installation of a layer of armourstones as cover, cf. Chapter 4.2.2). In contrast to this negative development in TF 5, the beetle community in TF 8 developed positively. Here, the number of species increased noticeably from 17 to 36, and diversity from 2.2 to 2.6; the proportion of riparian species grew strongly from 17% to 50%; the number of individuals rose from 1.3 to 7.9 individuals per 10 trap days and the proportion of riparian individuals increased from 17% to 69%. This means that very high to high values were achieved for nearly all parameters and the test field was assigned the best value rating (5 – 'very high value') for its beetle community. This successful development was primarily due to the good growth of the reed vegetation in the area of the berm, which is more sheltered because of the stone wall and which provides suitable habitats for a variety of riparian ground beetle species.

Compared to the reference, a more diverse beetle community with higher numbers of individuals has become established (Figure 51 below) in almost all test fields except for TF 6 (eroded alginate). The reference was therefore assigned a value rating of 2 (low value) and TF 6 was assigned the lowest value rating of 1 (very low value). The vegetated riprap in TF 1 exhibited similarly small ground beetle communities as in the reference. However, the very high proportion of riparian individuals had a positive effect on the overall rating, which was 3 (medium value). Apart from the above-mentioned TF 8, the test fields without slope protection (TF 9), with gravel fill and stone blocks (TF 4), with plant mats (TF 7) and the willow brush mattress (TF 3) were also assigned good value ratings, based on the parameters described above. The main reasons for the positive ratings were the higher numbers of species and individuals, the higher proportions of riparian individuals and/or the increase in the presence of Red List species (cf. Annex 6). All these test fields were assigned a value rating of 4 (high value). The willow brush mattress of TF 2, for which more intensive maintenance was carried out, and the reed gabions in TF 5 were rated at 3 (medium value). All the assigned value ratings are listed in Table 18.

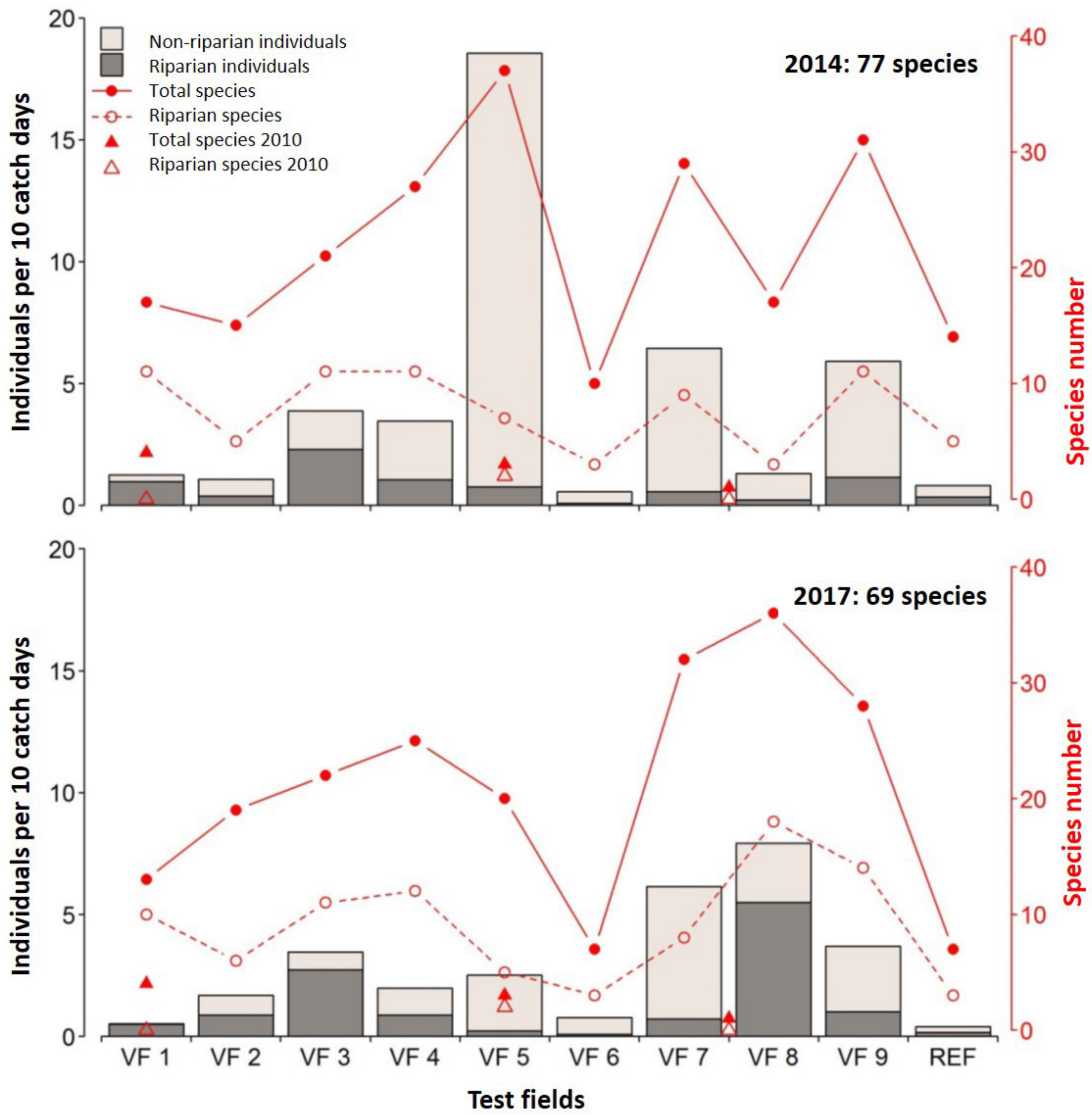


Figure 51: Numbers of species and individuals of ground beetle communities divided into riparian and non-riparian species for all TFs and the reference stretch in 2013/14 (top) and 2017 (bottom). It should be noted that both the methodology and the recording procedure were different in 2010 (triangle symbols).

The results of the monitoring show that the first target – ‘Promotion of species diversity’ – has been achieved for the ground beetle fauna in almost all test fields on the test stretch. The second target – ‘Promotion of site-adapted biocenoses’ – has only been successively attained in some of the test fields. This is explained by the strong fluctuation of species during the monitoring period and the clearly noticeable species turnover within the biocenoses. Higher proportions of riparian individuals and species were found to be present in the willow brush mattress (TF 3) and in the paving behind the stone wall in the lower slope area (TF 8) and, to a somewhat lesser extent, in the area with gravel fill and stone blocks (TF 4) and in the area without slope protection (TF 9). The successful development of site-adapted biocenoses depends to a large degree on the future maintenance and development of the test stretch.

5.3.5 Spiders

Spiders were recorded using the same methods as those employed for ground beetles. The same data on location, exposition and sampling interval of the pitfall traps apply. In the success monitoring campaigns, sweep nets were also used to detect the relatively stationary orb weavers and crab spiders in the vegetation that had grown in the reed gabions and stone mattresses (TF 5) and the plant mats (TF 7). The spider community developed very dynamically, similarly to the ground beetle community. Although with 77 and 87 species and higher taxa there was no significant difference between the total species numbers (Figure 52) counted in the two recording periods (2013/14, 2017), again only 48 taxa were recorded in the catches of both surveys (approximately 60%). As a result, the test field rating is based on the same parameters as those used for ground beetles (cf. Table 15 and Annex 6). While in the first recording period (2013/14) some test fields still had higher numbers of species and/or individuals (willow brush mattress (TF 3); reed gabions and stone mattresses (TF 5); plant mats (TF 7)), colonisation in the test fields was somewhat more evenly distributed in 2017, also compared to the reference (Figure 52). Slightly higher numbers of species and colonisation densities in comparison with the reference were only found in the plant mats (TF 7), the test field with paving behind the stone wall in the lower slope zone (TF 8) and the area without slope protection (TF 9). Higher colonisation densities, but with the same number of species, were found in TF 1. The relative proportions of riparian species and individuals were very similar. The relative proportions of moisture-loving (hygrophilic) individuals were slightly larger in the vegetated riprap (TF 1, 31%), the willow brush mattress (TF 3, 38%), the combination of gravel fill and stone blocks (TF 4, 41%) and the stone wall in the lower slope area (TF 8, 30%). The riprap reference (REF) showed a similar, only slightly lower proportion (31%). In the other test fields the proportions were smaller. The species in all test fields were overwhelmingly adapted to dry, sunny locations.

Compared to the success monitoring campaign of 2013/14, the total number of spider species had increased by 2017. However, the assumption that increasing vegetation in each TF provides more favourable habitat structures for a greater number of spider species compared to the ACTUAL condition (riprap) needs to be questioned in some respects. One aspect is whether the species are associated with the new vegetation structures. Thus, while during the ACTUAL condition survey in 2010 only one riparian species, i.e. a wolf spider (*Pirata latitans)* was found, another riparian wolf spider species (*Pirata hygrophilus)* was recorded in the monitoring periods in 2014 and 2017, at least in the willow brush mattresses (TF 2 and 3). In general, however, the number of species with specific riverine habitat requirements tended to be small (34%). The proportion of spider species that prefer dry habitats (xerophilic species) was found to be higher than in the case of ground beetles. This may be due to the fact that spiders frequently establish on vertical structures as well and are not exclusively dependent on the moisture conditions of the substrate. Finally, it can be stated that, at the present time and in contrast to the situation for ground beetles, the first target of ‘Promotion of species diversity’ has been partially achieved, at least in some of the test fields. The second target ‘Promotion of site-adapted biocenoses’ proved more difficult to attain; progress will be re-examined and evaluated in a long-term monitoring campaign.

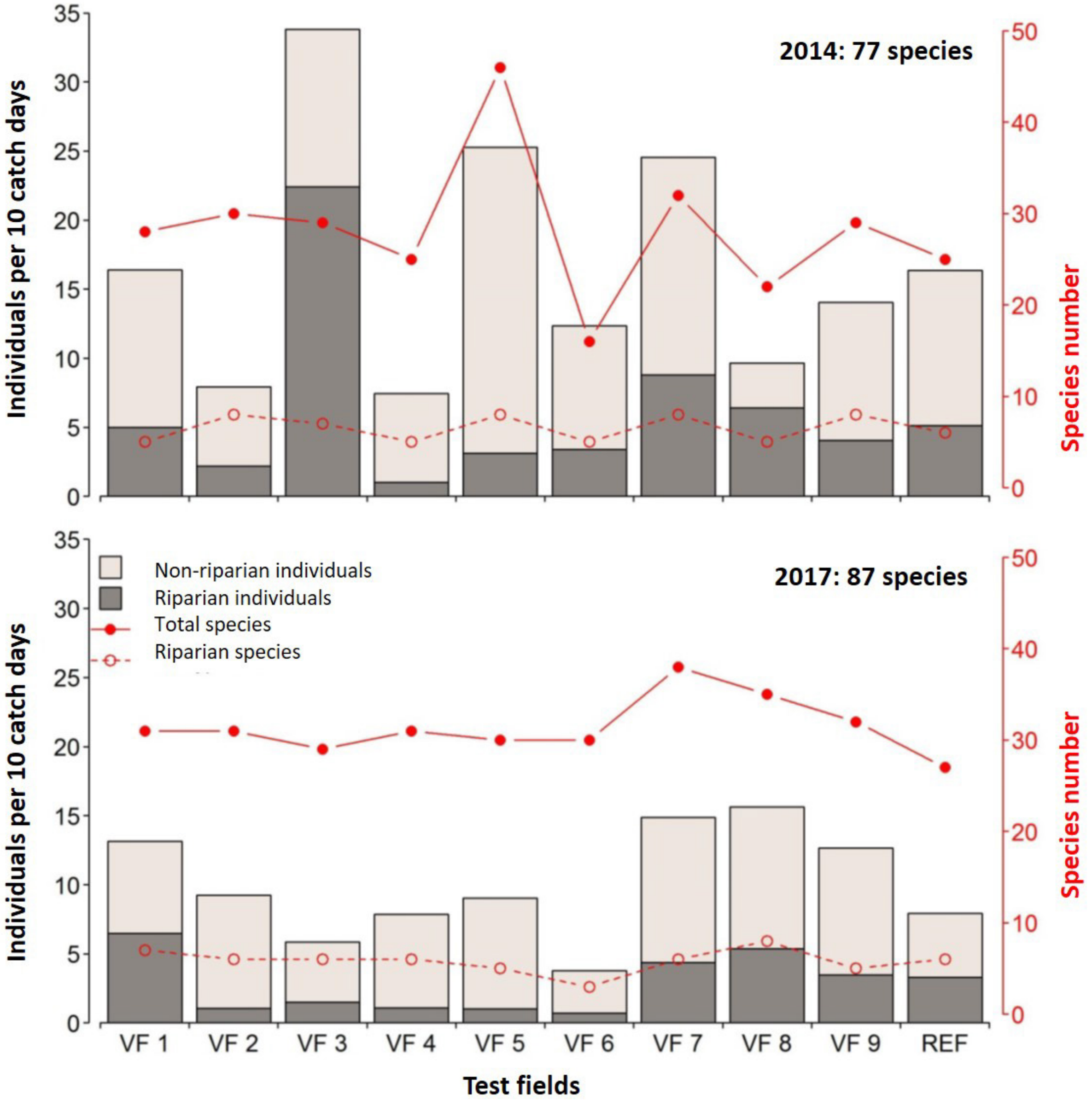


Figure 52: Numbers of species and individuals of spider communities divided into riparian and non-riparian species for all TFs and the reference stretch in 2013/14 (top) and 2017 (bottom).

Only very small numbers of the spider and harvestman species categorised as endangered on Germany's Red List were found in in both survey campaigns. In 2013/14 this was the endangered species *Clubiona germanica* (TF 1), and in 2017 the critically endangered species *Leptorchestes berolinensis* (TF 1). Both species were present at low densities only, because they are not strongly associated with riparian habitats. Additional species recorded were *Singa nitidula* (TF 7) and *Heliophanus auratus* (TF 1) in 2013/14 and *Heliophanus auratus* (REF) and *Thanatus striatus* (TF 5) in 2017, i.e. two species that are on the watch list and that are strongly associated with riparian habitats and their humid climate.

The measures shown to be most effective ecologically for spider communities were those in TF 7 (plant mats), TF 8 (stone wall in front of mean water level berm) and TF 9 (without slope protection). These measures were assigned the highest rankings (5 – very high value, or 4 – high value). A medium value (value rating 3) was assigned to the measures with vegetated riprap (TF 1), reed gabions and stone mattresses (TF 5) and alginate (TF 6). The willow brush mattress in TF 3 received the lowest value rating of 1 (very low value) because of the weighted rating results (cf. Annex 6). All other measures of TF 2 (willow brush mattress) and TF 4 (gravel fill) were rated as equivalent to the reference (value rating 2 – low value) (cf. Table 18).

5.3.6 Macrobenthos

Macrobenthos was sampled in both success monitoring campaigns using quantitative and qualitative recording methods. In all test fields, three samples for specific sampling areas were taken from soil substrates near the bank at a maximum water depth of 0.5 m, and evaluated subsequently. On the reference stretch, five samples were taken. In addition, interesting and unusual structures (e.g. root plate in TF 1, fascine in TF 4) were sampled qualitatively for 20 minutes. In the first success monitoring campaign, 18 unusual structures were sampled. In the second campaign only six of these could be examined, as the other structures were either lost or no longer wet.

The survey conducted in the 2017 monitoring year counted a total of only 26 taxa (species and higher taxonomic levels) within twelve invertebrate orders. The entire test stretch was characterised by colonisation of invasive species, in particular small crustaceans belonging to the order of *Crustacea.* Given the high hydraulic loads in the test stretch area, hydromorphological and/or structural enhancement measures in the aquatic zone were only implemented in two of the test fields, i.e. in the vegetated riprap (TF 1; stone wall, low flow velocities, root plate) and the combination of gravel fill and stone blocks (TF 4; dead wood fascines at mean water level). No effects on the composition of the aquatic fauna were therefore expected in any of the other test fields. The monitoring results and the rating on the basis of the selected criteria (see Table 15) provided indicators of the positive effects of these measures on the macrobenthos (cf. Annex 6). In general, colonisation density of the macrobenthos communities was found to have changed significantly between monitoring year 2013 and 2017. There were significantly fewer species in 2017 and, as a result, the biocenosis was poorer than in 2013. The general relative patterns in the test field remained largely the same, however (Figure 53). Compared to the reference and the test field in which the aquatic area had not been changed, it was especially the shallow water zone between the stone wall off the bank and the vegetated riprap (TF 1), which had been structurally diversified with dead wood elements (root plates), that showed a much higher species number (21) and a larger number of EPTCBO species (8) of the orders *Ephemeroptera* (mayflies), *Plecoptera* (stoneflies), *Trichoptera* (caddisflies), *Coleoptera* (beetles), *Bivalvia* (bivalve shells) and *Odonata* (dragonflies and damselflies) (Figure 53). The mean proportion of invasive individuals had not changed, however (68%, Figure 54), which shows that the numbers of individuals was small. Consequently, the rating for the macrobenthos in TF 1 was highest in relative terms, compared to the other test fields, but in absolute terms only a poor value was achieved. In the test field with gravel fill and dead wood fascines in the aquatic area (TF 4), the total species number and the number of EPTCBO species were slightly higher. Combined with the somewhat lower proportion of invasive species, the overall rating for this TF was better than that for the reference (cf. Annex 6). An analysis of mean species numbers and proportions of invasive species, differentiated by substrates (dead wood, stone or gravel), shows that the dead wood structures are very important for the positive trend in colonisation in these two TFs (Figure 54).

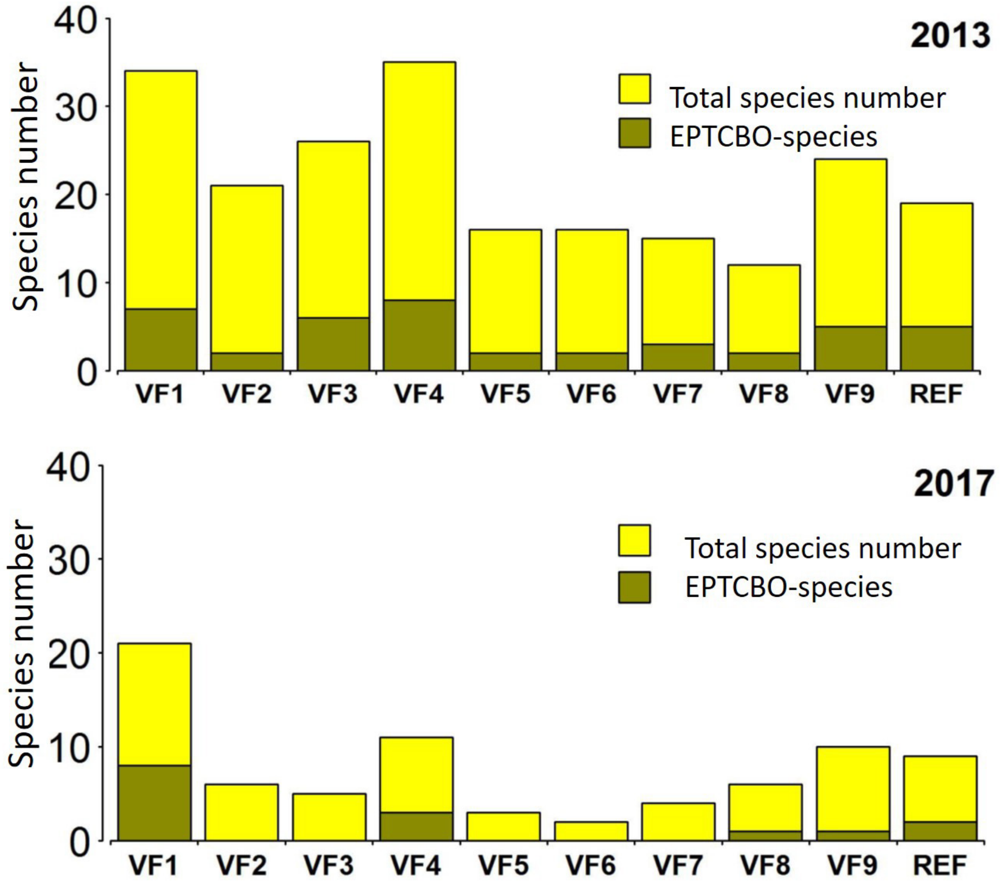


Figure 53: Total species numbers and numbers of EPTCBO species (of the orders Ephemeroptera, Plecoptera, Trichoptera, Coleoptera, Bivalvia and Odonata) in the test fields on the test stretch in the monitoring years 2013 (top) and 2017 (bottom).

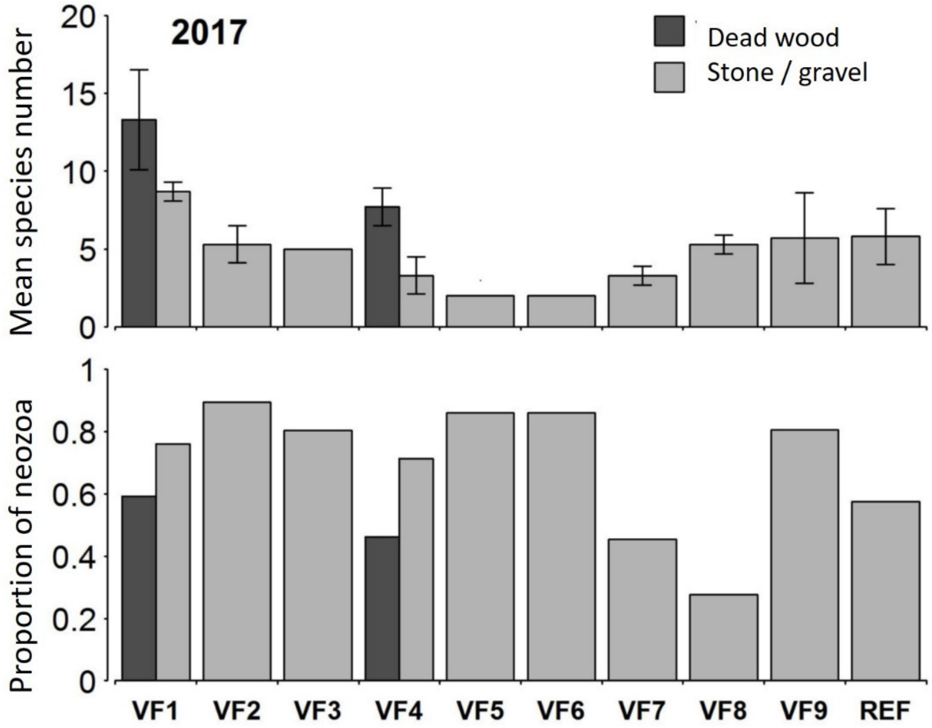


Figure 54: Mean species numbers (top, MW ± SD) and proportion of invasive individuals in the test fields on the test stretch in the monitoring year 2017. For the two test fields where dead wood elements were introduced in the aquatic area, the data are differentiated according to mineral substrates (light grey for stone and gravel) and dead wood (dark grey).

These findings suggest that dead wood elements may provide suitable habitats for autochthonous invertebrates typically found in water bodies. However, since species numbers are very small in some cases (especially in 2017) and indicate a biocenosis with little diversity, the results need to be assessed critically in general. It should be taken into consideration that various factors often make habitat conditions for aquatic organisms very unfavourable in the River Rhine. This could have an effect on the current results of the measures. Also, some of the aquatic measures are installed in the mean water level area and, consequently, can only be partly effective because they are not permanently wetted. This has a particularly negative effect on organisms with an annual life cycle that depends on the permanent availability of such habitats. Why the proportion of invasive species is significantly lower in the aquatic area of the unchanged test field with plant mats and on the stone wall in the lower slope area (TF 7 and 8) cannot be explained on the basis of the available data. The findings are therefore considered to be an artefact of the low-diversity biocenosis.

In TF 1 and 4 only the aquatically effective measures (shallow water zone, root plate in TF 1; gravel fill, dead wood fascines in TF 4) were assigned a value rating, which was derived from a comparison with the riprap (aquatic reference). In this comparison the shallow water zone was shown to be most ecologically effective for macrobenthos and was assigned the value rating 5 (very high value). The data also show that the dead wood fascines have a positive effect, but, in view of the results, only a value rating of 3 (medium value) was assigned. The poorest result, i.e. a value rating of 1 (very low value) was assigned to the riprap structure (cf. Table 19).

5.3.7 Fish

Fish sampling was conducted in 2010 (ACTUAL condition survey prior to construction measure) and between 2012 and 2017; the fish were sampled in June/July and in September/October. No sampling was possible in the spring of 2016 due to flooding. Moreover, persistent low water in the autumns of 2015 and 2016 prevented any fishing activities in TF 1 (low flow velocity zone behind stone wall). The method used was point abundance sampling by electric fishing (with direct current) aboard a boat moving against the current near the bank line. The fish were caught with a landing net at each survey point, identified, their length measured, before being immediately and carefully released to the water.

In total, 17,240 fish belonging to 29 species were identified in this way in the monitoring period. The most frequent species was the round goby (*Neogobius melanostomus)*, a species migrated from the Caspian Sea, with a proportion of individuals of 62.4%. Other, less abundant, species were roach (*Rutilus rutilus*) (17.7%), asp (*Leuciscus aspius*) (6.4%), chub (*Squalius cephalus*) (2.9%), perch (*Perca fluviatilis*) (2.5 %), bleek (*Alburnus alburnus*) (2.2%), common nase (*Chondrostoma nasus*) (1.6%), eel (*Anguilla anguilla*) (1.1%) and dace (*Leuciscus leuciscus*) (1%). All other fish species account for less than one per cent. Structural enhancement measures in the aquatic zone were only implemented in the vegetated riprap (TF 1; stone wall, low flow velocity, root plate) and in the test field with gravel fill and stone blocks (TF 4; dead wood fascines at mean water level), as described for macrobenthos (Chapter 5.3.6). Therefore, an impact on the composition of ichthyofauna was only to be expected in these two test fields. Here too, this has been confirmed by the monitoring results and the rating on the basis of the selected criteria (see Table 15, Chapter 5.3.1). There was no difference between the mean numbers of species per survey point or the species compositions recorded in these test fields and in the conventionally protected reference (riprap; Figure 55 and Figure 56).

However, compared to the reference stretch, the mean number of species per survey point tended to be noticeably higher (Figure 55) in the test fields TF 1 and TF 4 and there were also greater proportions of individuals of the reference species list according to the Water Framework Directive (Figure 56). The difference between the medium species numbers could not be corroborated statistically (rmANOVA, $p = 0.38$) because of the sometimes high variability and the resulting scattering of data. By contrast, the difference between the proportions of individuals of the reference species list is supported by statistics (rmANOVA, $p = 0.035$) although these data, too, were very variable. The reasons for this are not only population fluctuations due to biotic and abiotic environmental factors at a higher spatial scale than the TFs but also the in place limited effectiveness of the measures in both test fields. The fascines in TF 4, for instance, were installed in the mean water level area and were for this reason only ecologically effective on approximately 64% of the days in the monitoring period; they were not wetted on the other days. This also led to faster decomposition of the dead wood elements. They have gradually become less effective as a result, and will soon cease to have any effect. The aim is to replace the dead wood fascines. This requires an examination of rehabilitation options for achieving a lasting positive impact on the aquatic biocenosis at reasonable cost. Moreover, the new fascines will have to be installed below mean water level in order to ensure long-term effectiveness.

The total number of species found was also slightly higher in the vegetated riprap (TF 1) than in the reference (and all other test fields) (Figure 55). This is mainly due to the positive effect of the shallow water zone behind the stone wall: here, flow velocities are low and the installed root plates in particular provide diversified habitat structures for various fish species. Again, this was not a lasting positive effect: because of the relatively high height of the stone wall in relation to the slope and the resulting small water depth in the shallow water zone, the area behind the stone wall was not sufficiently connected to the main section of the river and sometimes even dried up. For this reason, this test field could not be sampled during two campaigns. These sampling dates were not included in the comparative analysis for statistical reasons, but on the other hand they did not significantly distort the data.

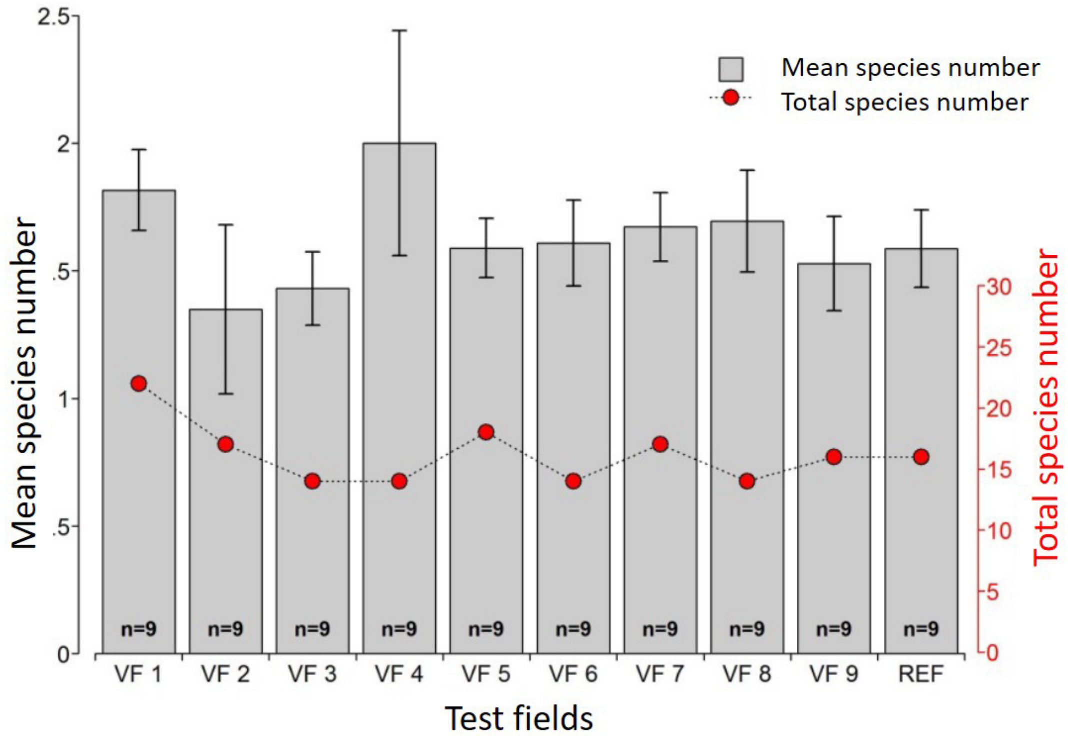


Figure 55: Mean number of species per survey point (±SE) and total numbers of species in the test fields of the test stretch over the entire monitoring period (2012–2017).

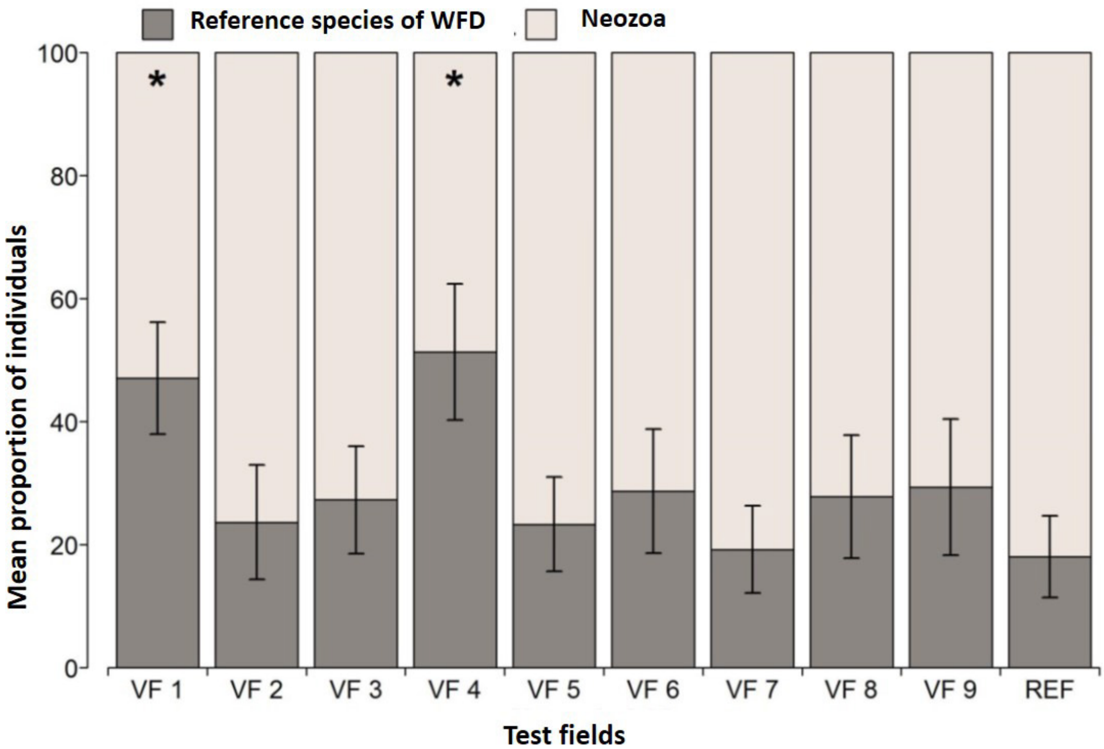


Figure 56: Mean proportions of individuals of the WFD reference species list compared to mean proportions of invasive individuals in the test fields of the test stretch over the entire monitoring period (2012-2017). The asterisks indicate significant differences.

The higher proportions of reference species individuals in TF 1 and 4 (Figure 56) suggest that the dead wood structures introduced in the test fields can create favourable habitat conditions for native fish fauna. The positive effects of such structures have been frequently observed in smaller flowing waters (Bavarian State Office for the Environment and Fisheries Association of the State of Bavaria, 2005). The sampling data also suggest that dead wood structures help to suppress dominant immigrated species (invasive species, in particular the invasive round goby) in German inland waterways. In summary, the monitoring results for two out of the nine test fields show improved habitat conditions for fish fauna (TF 1 and 4). However, this development is not entirely representative of the technical–biological bank protection measures installed in these test fields because of several determining factors (e.g. short wetting periods, small spatial scale). The positive effects of the measures could be promoted by optimising their design. At high water levels, fish colonisation was also positively influenced by small-scale structural elements (fascines and dead wood) and areas with low flow velocities (higher proportion of autochtonous fish species). By contrast, the reference stretch was dominated by the round goby, which prefers habitats with rocky rivers beds and higher wave wash.

The distribution of value ratings with respect to fish was the same as for macrobenthos. The shallow water zone (TF 1) was assigned the highest value rating, i.e. 5, followed by the dead wood fascines (TF 4) with a value rating of 3 (medium value). The conventional riprap, which was used as a reference, was assigned a rating of 1 and thus the lowest ecological value for fish (cf. Table 19).

5.3.8 Summary rating for fauna

Terrestrial fauna

The results of the five-year monitoring show that the bank protection designs used on the Rhine test stretch can provide increasingly suitable riparian habitats for some groups of organisms (cf. Table 18 and Table 19). The various designs promote different groups of organisms, which means that the decision which design to select strongly depends on the ecological objective and the surrounding natural environment. However, the insights gained to date need to be critically discussed, for several reasons. First, the small area of each TF is a critical parameter for highly mobile groups of fauna such as birds, as they normally colonise much larger territories. The type of measure installed (maximum length of 100 m) is therefore only of limited use in explaining the changes in the species inventory and population sizes. Second, the boundary conditions frequently prevailing on waterways, such as the proximity of maintenance paths, periodic maintenance and rehabilitation work and angling tourism, not only often disturbed fauna surveys but may also have adversely affected the colonisation potential. It cannot be ruled out that these disturbance factors have influenced the species inventory data and the measured population sizes. Therefore, it is likely that with fewer disturbances the tested designs would have greater potential for providing habitats for riparian fauna than has been the case so far.

Overall, one positive effect on the terrestrial fauna is that the species numbers of nearly all studied groups of organisms have increased across the entire test stretch compared to the reference stretch. Some test fields show initial signs of providing riparian habitat structures in the terrestrial areas, which meet the habit requirements of some of the species found. Depending on the execution and development of the various types of measures, different target organisms could thus be promoted. Overall, there was no one specific type of measure that was able to improve the habitat structures for all target organisms; rather, there were individual measures that were effective in promoting one or several specific target organisms (Table 18). The strongest indication of biodiversity in a riparian environment was found in the ground beetle community.

In the ranking of all bank protection measures or designs the overall ‘terrestrial fauna’ rating shows clearly that all test fields with the exception of the reference (and TF 6, which has been similar to the reference since the failure of the alginate) were able to achieve medium to high ecological effectiveness. TF 7 (plant mat), TF 8 (slope area in the shelter of the stone wall) and TF 9 (without slope protection) were assigned the value rating 4; they showed the best ecological effectiveness in the overall evaluation of all groups of terrestrial organisms investigated.

Finally, it should be emphasised that a suitable habitat for fauna can only establish if two key requirements are met: habitats need to develop over time, and a plan for the careful execution of maintenance work must be in place. Only when these two factors combine can riparian habitat structures evolve (e.g. woody plants for avifauna).

Table 18: Rating of the ecological effectiveness of the measures in the test fields for the groups of organisms studied (birds, reptiles, ground beetles, spiders), based on the value ratings 1 (very low value), 2 (low value), 3 (medium value), 4 (high value), 5 (very high value). The overall rating for 'terrestrial fauna' is derived from these ratings (value ratings are underlined where double weighting applies). The following colour code is used: orange = low value (value rating 2), yellow = medium value (value rating 3), green = high value (value rating 4)

Bank protection measure /design **Test field**	**Terrestrial area**				
	Birds	Reptiles	Ground beetles	Spiders	**Overall rating, terrestrial**
Ecologically enhanced riprap with vegetation TF 1	2	2	3	3	2.6
Removal of riprap; willow brush mattresses, at an angle to the flow direction TF 2	5	2	3	2	3.1
Removal of riprap; willow brush mattresses, perpendicular to the flow direction TF 3	5	2	4	1	3.1
Ecologically enhanced riprap with gravel and stone blocks TF 4	1	4	4	2	2.6
Removal of riprap; reed gabions and stone mattresses TF 5	1	5	3	3	3.0
Ecologically enhanced riprap with alginate TF 6	1	2	1	3	1.8
Removal of riprap; plant mats, coir mats on hydroseeding TF 7	5	3	4	5	4.3
Raising of the existing stone wall; existing riprap and paving with reed growth TF 8	4	1	5	4	3.5
Removal of riprap; without slope protection; willow branch cuttings on adjoining plane at the top of the slope TF 9	3	3	4	4	3.5
Riprap as reference (already in place before redesign)	1	2	2	2	1.8

Aquatic fauna

The installed structural elements in TF 1 (shallow water zone with low flow velocities, root plates) and TF 4 (gravel fill, dead wood fascines) proved to be ecologically effective for aquatic groups of organisms (fish and macrobenthos) compared to riprap in the aquatic area (reference) (cf. Table 19). In the overall 'aquatic fauna' rating, the shallow water zone has developed the highest ecological effectiveness (value rating 5). Nonetheless, these results must be interpreted with caution; at this point they are considered as corroborating first trends. One issue is that the validity of the results is inadequate owing to the height at which the measures were installed (mean water level). This means that their effectiveness for fish and macrobenthos communities is limited to certain periods, i.e. the ecological effectiveness is significantly reduced at decreasing water levels (below MW) and during short-term water level fluctuations. Also, the current data for the relatively short monitoring period of five years were influenced by frequent low water levels. Therefore, the effectiveness of the aquatic measures (especially for TF 1) should be verified in further surveys. The target organisms benefited from the aquatically effective structures although they were only used in a relatively small area on the test stretch.

Table 19: Rating of the ecological effectiveness of the aquatic measures in TF 1 and TF 4 for the groups of organisms studied (fish and macrobenthos), based on the value ratings 1 (very low value), 2 (low value), 3 (medium value), 4 (high value), 5 (very high value). The overall 'aquatic fauna' rating is derived from these ratings. The following colour code is used: red = very low value (value rating 1), yellow = medium value (value rating 3), dark green = very high value (value rating 5)

Design, structural element(s) **Test field**	**Aquatic area**		
	Macrobenthos	Fish	**Overall rating, aquatic**
Off-the-bank stone wall with shallow water zone, low flow velocities, root plates TF 1	5	5	5
Ecologically enhanced riprap with gravel; dead wood fascines MW -0.5m to MW TF 4	3	3	3
No measures in the aquatic area (reference)	1	1	1

On the other hand, ecological conditions for riparian fauna are still far from ideal as a result of the small area sizes of the test fields, the relatively short monitoring period, the insufficient diversity of structures and substrate below mean water level and the minimal connection between the aquatic and the terrestrial habitats (TF 1 and 4).

5.4 Vegetation and fauna – a synthesis

5.4.1 Background

Functional relationships between vegetation and fauna play an important role in ensuring the ecological effectiveness of measures taken. In terms of function the following questions arise: How does vegetation promote wildlife, what is it good for? Do the technical–biological bank protection measures provide suitable habitat structures for the animal groups studied and are these structures accepted by fauna? As there are numerous interconnections between vegetation and fauna, these questions can only be answered by examining a selection of interesting trends from the first five-year monitoring phase (Chapter 5.4.2 to 5.4.6). An attempt is made in section 5.4.7 to identify the potential of the individual test fields to provide suitable habitat structures and thus to improve habitat quality for groups of organisms other than the target organisms investigated in the monitoring applying the criterion 'heterogeneity of the test fields'.

5.4.2 Ground beetles and vegetation

The relationship between total vegetation coverage (as a measure of plant volume) and colonisation by riparian ground beetle species was particularly evident, and it was possible to map this relationship in a statistical model (Figure 57). The model shows that the proportion of riparian ground beetle species increased with increasing total vegetation coverage. This can be seen from the isolines, the direction of the black arrow and the concentration of riparian species at high isoline values. Plant cover was high in test fields 2, 3 (willow brush mattresses) and 8 (riprap and paving with stone wall) in particular with a high proportion of riparian ground beetles. TF 2 and 3 were planted with structure-forming woody plants, riparian reed vegetation was fostered in TF 8 and woody plants were already found to be growing on the adjacent bank in the ACTUAL condition survey. Similar patterns emerge if consideration is given only to the tree and shrub layer (not shown) rather than the total vegetation coverage, and this demonstrates the importance of woody plants for colonisation by riparian ground beetles. Reeds and dense woody structures showed high potential as suitable habitats for riparian ground beetle species. Although no pertinent data have been collected, this outcome may be assumed to be a function of more shadow and the moister soil which results.

Test fields 5 (reed gabions, stone mattresses) and 7 (plant mats) are located on the other side of the gradient and have a low proportion of riparian ground beetle species as well as comparatively low vegetation cover. Plant volume either decreased in the lower and middle slope zones during the monitoring period as a result of frequent flooding and simultaneous hydraulic load or – in the case of the stone mattresses – hardly any vegetation developed at all. This meant that there were no longer any favourable habitat structures for riparian ground beetles in 2017. The impact of rehabilitation (stone overlay) in TF 5 and 7 remains to be seen.

Test fields 1 (vegetated riprap), 6 (alginate) and the reference are on the very outside in Figure 57, as they are characterised by a low number of individuals. The combination of alginate and wet seeding (TF 6) very quickly failed and the slope is still covered by the original riprap. In the reference, unvegetated riprap covers a high proportion of the area in the middle and lower slope zones. There is also riprap between the planting trenches of the vegetated riprap (TF 1), but the planted woody plants are obviously a positive factor (as in TF 2, 3 and 8), as while there are fewer individuals overall, there is a high proportion of riparian species and individuals.

Finally, it should be noted that there are a number of riparian ground beetle species that prefer open, low-vegetation sites (Kleinwächter et al. 2017). These are gravel, sand and mud bank sites that dry out in summer on unsecured, near-natural banks between mean low and mean water (habitat type 3270 under the Habitats Directive). This type of site is characterised by highly specialised plant and animal species adapted to the hydromorphological dynamics of the flowing water. This type of site only exists on the test stretch on a very small scale in T 9 (without slope protection). It has not been possible so far to show that there is a positive trend promoting these species of ground beetle. The suitability of technical–biological bank protection for the promotion of this habitat is limited. However, in certain circumstances, technical–biological bank protection measures may be used as protective elements where secured and unsecured riparian zones lie in close proximity with each other.

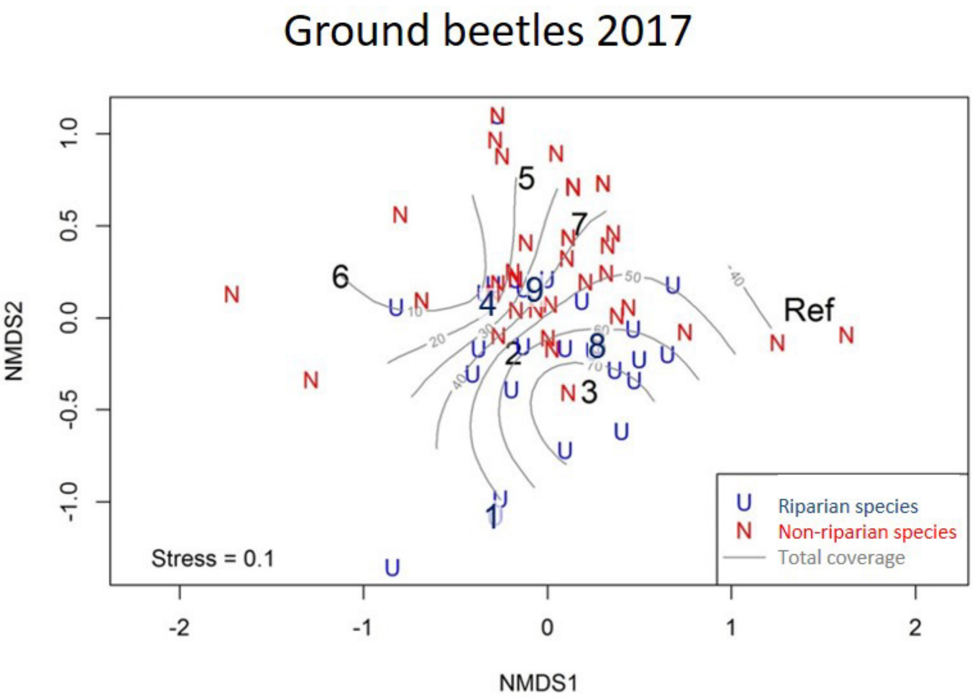


Figure 57: Non-metric multidimensional scaling (NMDS) of ground beetle communities in TF 1–9 (black numbers) and the reference (Ref) in 2017. Each letter represents a species, differentiated according to riparian (U = blue) and non-riparian (N = red). The isolines (grey lines) show total vegetation coverage (2016). The black arrow shows the gradient of test fields with low vegetation coverage to those with high coverage. See TextBox 1 in Chapter 5.2.3 for an interpretation of the NMDS diagrams.

5.4.3 Avifauna, reptiles and vegetation

Existing and developing woody structures that were already somewhat advanced in their growth had the highest potential as habitats for breeding birds (Chapter 5.3.2). Such dense, almost impenetrable structures as exist in TF 1, 2, 3 and 8 also kept recreationists, anglers and dogs away. This was not the case in the more sparsely wooded, easily accessible test fields, which were unable to develop their full potential for birds of the open countryside. The effect of vegetation structures that screen off open test fields from the path, such as the hedge layer at the top edge of the slope of TF 5 (reed gabions, stone mattresses), remains to be seen. However, after just 5 years of development, the layers of hedge have increased the diversity of species and structures and the flowers and fruits they produce have been important for birds and insects.

Marginal structures on the test stretch, such as a reed bed adjacent to TF 7, have had a positive effect. In this respect, the integration of technical–biological bank protection into the habitat structures of the surroundings is important for mobile fauna such as bird life.

It is important that woody plants of sufficient age and size are grown for woodland nesting birds, such as the nightingale. Willow brush mattresses only form young, flexible willow rods that fold over in a current to ensure erosion protection and, if necessary, do not obstruct flood discharge if they are regularly pruned (approximately every 5 years). This does not conform to the habitat requirements of woodland nesting birds. Test fields with woody plants are already and will continue to be maintained with the aim of promoting the growth of richly structured woody plant populations that meet both traffic and ecological requirements.

The sand lizard, as the most common species of reptile, requires an alternation of dense and absent vegetation, small structures, such as lying dead wood and stone surfaces exposed to the sun. These conditions were created in TF 5 (reed gabions, stone mattresses) and TF 4 (riprap with gravel fill and stone blocks) in particular. In the two willow brush mattress test fields, sand lizards were sighted in TF 2, which has a somewhat more open woody structure, but no evidence was found of sand lizards in the more densely wooded areas of TF 3.

5.4.4 Species richness of flowers

Species richness of flowers in the test fields was determined according to the vegetation data collected in 2016 by identifying the flower type (cf. TextBox 2), flower colour and flower phenology of each species from the BiolFlor database (Klotz et al. 2002). The quantity of a particular flower type over time was estimated from the cover of each species determined in the field and the presence of several types of flower at a given moment in time was then aggregated in the categories 'high – medium – low'. The flowering spectra determined in this way are shown in Figure 58. They show the potential flowering behaviour on the test stretch, as the actual number of plants of a species flowering over time was not directly observed. More precise data would require intensive field observations. However, the less accurate method adopted here allows for a comparison of the number of flowers fostered by different designs.

Conclusions can be drawn about the habitat quality for flower-seeking insects from the flowering spectra in Figure 58. All the test fields were found to have significantly higher flower diversity than the reference; this was particularly the case for TF 7 and 5. This suggests that the flowers there provide a favourable foraging habitat for flower-visiting insects. The greatest diversity of spiders was also found in TF 7 (Chapter 5.3.5), which may be due to the favourable spatial structure of the grassy-herbaceous vegetation, but also to the available food supply. Many plant species in TF 5 and 7 even flower late in the year. In contrast, the test fields in which willows dominate and where willow catkins flower early showed pronounced early peak flowering. This means that it is not only flowering behaviour within a test field but also the juxtaposition of different fields that produces a highly heterogeneous supply of rich flower diversity over space and time.

Species richness of flowers corresponds strongly with the species richness presented in Chapter 5.2.3 and ecological effectiveness is therefore assessed in that Chapter according to both rating criteria.

TextBox 2: Type of flower: *Figure 58 shows nine main groups of flower types and subtypes represented by numbers on the y-axis (Kugler 1970 in (Klotz et al. 2002)). In this classification, flower structure is categorised according to morphology, the reward (pollen, nectar) offered, type of presentation (e.g. nectar openly accessible or hidden in the flower), accessibility for insects, etc. Flower type 9, for example, includes brush flowers, such as those on willows (willow catkins in spring). Figure 58 shows willow-rich test fields (e.g. TF 2+3) in spring with pronounced peak flowering in yellow (white willow) and magenta (purple willow). Disc flowers with largely hidden nectar belong to flower type 1.2b. Hazel-leaved dewberry (Rubus corylifolius) grows on many test fields and can be seen here with white flowers and a clear flowering trait from May to July.*

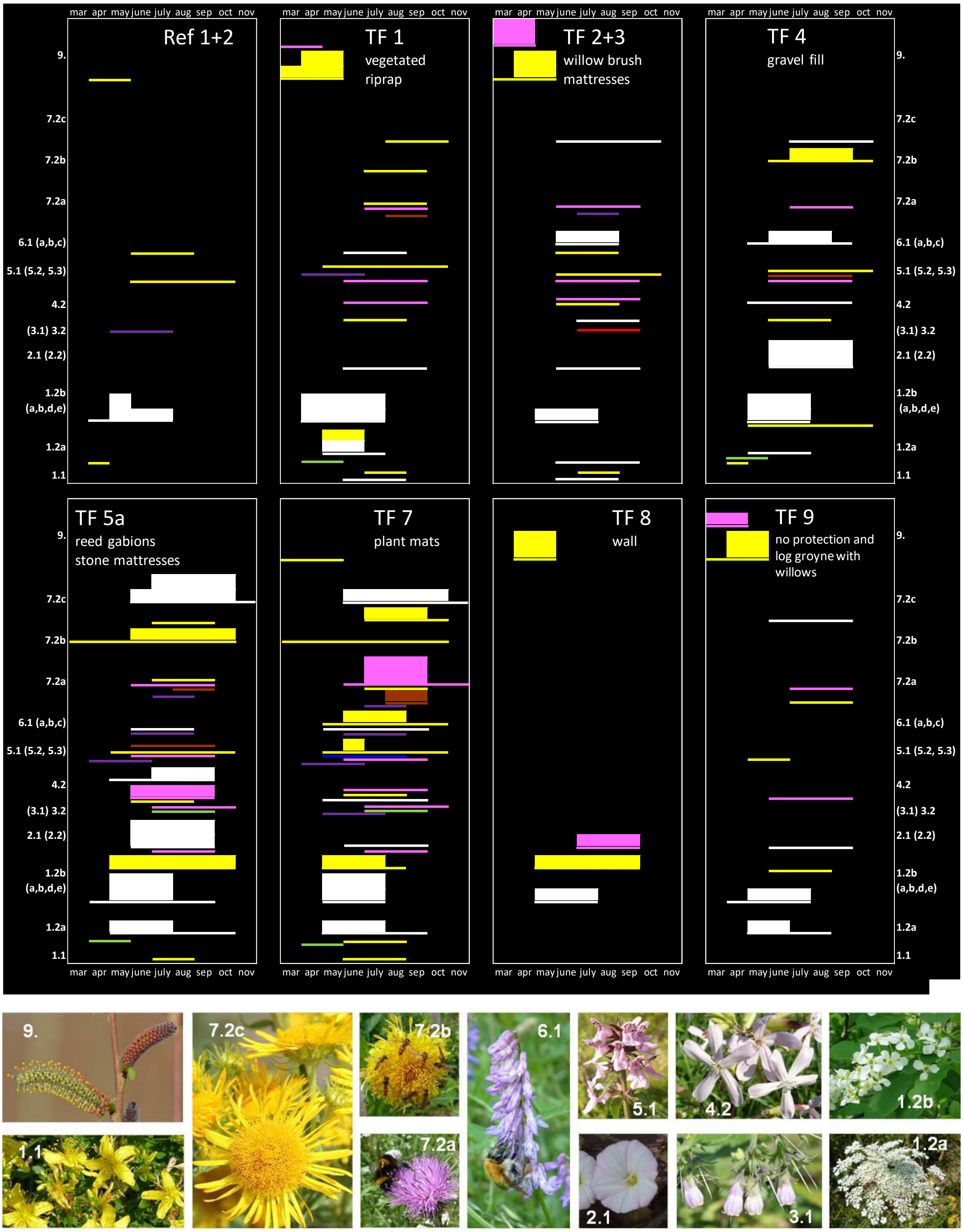


Figure 58: Species richness of flowers in the individual test fields and the reference stretch Numbers on the y-axis: flower types (cf. photos); x-axis: time (months); bar colour: flower colours. Height of the bars: flower volume; length of the bars: duration of flowering (photos: BfG: Katja Behrendt (5.1, 7.2a/b), Hans-Werner Herz (2.1, 9), Michael Schäffer (4.1), Krisztina Scholz (1.1, 1.2a, 6.1), Andreas Sundermeier (1.2b), Yasmin Wingender (3.1, 7.2c))

5.4.5 Dead wood

The influence on fish and macrobenthos of the installed dead wood was investigated during the monitoring, but not the influence of dead wood structures (including dead plant parts, accumulated debris) on terrestrial fauna. In particular, vegetated riprap and willow brush mattresses designed using woody plants (TF 1, 2 and 3) favour the spontaneous accumulation of dead wood, which is likely to have a correspondingly positive effect on species that use dead wood as their habitat. Wood-decay fungi, such as sulphur polypore fungus *(Laetiporus sulphureus*, Figure 59) were demonstrated in TF 1 and split gill fungus *(Schizophyllum commune*) in TF 2. These fungi break down wood for subsequent organisms. The dynamics of accumulated and washed out dead wood and its impact on structural enrichment and as a habitat for wood-decay organisms would require separate study.

5.4.6 Willows as host plants for specialised insects

The planted willows were colonised by a number of insect species that have a narrow host plant spectrum. Although only random observations are available on this topic, these showed that the planted stands are integrated into food webs and that the species presented reproduce in the test fields. The galls of the gall wasp *Pontania virilis*, which only occur on this willow species, were regularly found on the purple willows in the willow brush mattresses of TF 2 and 3 (Figure 60). The insects induce the growth on the plant, visible as gall, to provide their larvae protection and nutrition in the gall. Many gall-inducing organisms have complex life cycles (Bellmann 2017).

The willow spittle bug (*Aphrophora spec.*, Figure 61) lives exclusively on willows and was found on willow branch cuttings in TF 9. Caterpillars of the willow sawfly *(Nematis salicis*, Figure 62) were observed in TF 1 on willows in the vegetated riprap. The difference between these areas and the reference stretches is probably of a quantitative nature, as willows also occur there, albeit in smaller numbers and presumably therefore with a smaller quantity of colonising organisms.

Figure 59: Dead wood deposit in TF 1 (vegetated riprap) infested with sulphur polypore fungus (arrow) (photo: Katja Behrendt, BfG)

Figure 60: Gall of the gall wasp Pontania virilis on purple willow on willow brush mattresses in TF3 (photo: Andreas Sundermeier, BfG)

Figure 61: Willow spittle bug on willows that have emerged from willow branch cuttings (TF 9)

Figure 62: Caterpillars of the willow sawfly in TF 1 (both photos: Katja Behrendt, BfG)

5.4.7 Summary synthesis rating

The selected examples presented here strongly suggest that the technical–biological bank protection measures provide suitable habitat structures for the terrestrial animal groups studied and that these structures are also accepted by the fauna. The functional and structural diversity of all the still existing test fields is greater than that of the reference. The results and observations suggest that there is potential for the establishment of diverse food webs in the first years of development. This can be preserved and further promoted by maintenance measures of the kind taken so far that take biodiversity concerns into account.

Even though ground beetles were the only terrestrial insect group to be studied systematically, the considerations above nevertheless demonstrate the potential of technical–biological bank protection measures in promoting terrestrial insects, both qualitatively (species numbers) and quantitatively (insect abundance). Indeed, the Federal Government's Action Programme for Insect Conservation (BMU 2018) requires both these aspects to be taken into consideration.

The coexistence of different structures as well as the interconnectedness of the test stretch with the surrounding landscape is important for mobile groups of organisms. Some animal guilds (bird species that breed in woody plants, willow-feeding insects) can also be promoted by tolerating more and older native woody plants in conventional bank protection if such protection is required for safety purposes.

The aquatic fauna and species that are specialised in frequently flooded habitats below mean water benefit very little from the ecological effectiveness of the measures. The scope for measures below the mean water line must be significantly expanded in the future, particularly in order to contribute to the implementation of the European Water Framework Directive. This will require the use of other types of measures (off-the-bank wave protection measures, near-natural substrate with allowance for morphodynamics, use of dead wood, bank flattening).

For the purposes of a summary rating for all these aspects, the criterion ‘heterogeneity of the test fields’ is defined on the basis of the following descriptive parameters:

- Variety of forms of growth (woody/herbaceous)
- Variety of structural elements provided (dead wood, accumulated floating debris, different substrates)
- Mixing ratio of bare to planted areas

The assumption relevant to the rating is: the more heterogeneous the test field or the measure (shallow water zone/hedge layers) is with regard to the stated parameters, the more various groups of species benefit from the habitat quality provided (general, feeding and reproduction habitats). This approach goes beyond the groups of animal species studied and estimates the potential based on the heterogeneity of the test fields for a broader range of animal species. The rating of the heterogeneity of each TF is derived verbally and logically in the following and draws exclusively on expert knowledge.

Accordingly, TF 9 (without slope protection) has the highest rating value. At high water levels, displacement and deposition processes occur here that produce different substrate classes (large stones, sand, gravel). The measure itself involved installing willows on the adjoining plane at the top of the slope. Other woody plants established spontaneously. Species of annual ruderal vegetation appear when water levels are low.

TF 1 (vegetated riprap) and TF 8 (stone wall) were assigned a value rating of 4. In TF 1 the maintenance strategy produces various changing forms of woody plants (willow pollards, trees and shrubs). Woody plants of the hardwood floodplain then also grow. The measure transforms the field such that vegetated planting trenches alternate with predominantly unvegetated riprap areas that fill up with substantial quantities of dead wood and floating debris. The first reed bed initials have established in the protection provided by the stone wall. Annual riparian pioneer plants appear when water levels are low. In TF 8 the reed stand behind the stone wall is interspersed with previously existing willow pollards. Mud, dead wood and floating debris regularly accumulates in the protection of the stone wall. There are open paving areas around the willow pollards. The measure area is embedded in an alternation of dense to sparsely vegetated paved and stone slopes with a high proportion of woody plants in many places. However, the stone wall structure in TF 8 impairs the transition from aquatic to terrestrial habitats, i.e. lateral continuity. Value rating 5 was therefore not assigned.

Value rating 3 was assigned to TF 2 and 3 (willow brush mattresses) and TF 7 (plant mats). At high water levels, the dense growth of the willow brush mattresses retains a large volume of dead wood and floating debris that is then deposited between the willows. Maintenance alters the age and thus the height structure of the willows. However, these areas are too shady for herbaceous plants to establish. Open, sunny areas only form if the area is pruned enough. TF 7 is assigned value rating 3 on the basis of the uniformity of plant growth. A combination of successively migrated and planted species are dominant here, and the first woody initials are migrating into the TF. Structural diversity in the rehabilitated area is increased by installed wooden crossbars and the single-layer armourstones.

Armourstones (larger and smaller stone classes) predominate as the uniform substrate in TF 4 (gravel placement), TF 5 (reed gabions, stone mattresses) and in the reference, which means that the structure of the test fields is uniform. As the slope in TF 4 is additionally structured by dead wood fascines and stone blocks, this area is assigned a value rating of 2, while TF 5 and the reference are assigned a value rating of 1.

The shallow water zone is a special structure and is assigned a value rating of 5. The installed tree trunks with root plates act as dead wood structures. The first aquatic plants were able to settle in the protection of the stone wall, and there were positive effects on the aquatic fauna. The roots of the planted willow branch cuttings also reach into the water, where they form adventitious roots at high and long-lasting water levels. Floating debris frequently collects behind the stone wall, and over time a substrate deposit several centimetres thick has formed on the riprap. No assessment can be made of the hedge layers that have only been introduced in linear form. An overview of all ratings for the 'heterogeneity' criterion can be found in Table 20.

Table 20: Rating of the heterogeneity of the test fields.
FWZ: shallow water zone; HL: hedge layer at the top edge of slope.
Value ratings: very high value (5), high value (4), medium value (3), low value (2), very low value (1)

Criterion	FWZ	HL	TF 1	TF 2	TF 3	TF 4	TF 5 _RG	TF 5_ SM	TF 7	TF 8	TF 9	Ref
Heterogeneity	**5**	**-**	**4**	**3**	**3**	**2**	**1**	**1**	**3**	**4**	**5**	**1**

5.5 Use of artificial and non-natural materials

The construction materials used must also be included in the rating of the ecological effectiveness of the technical–biological bank protection measures (Table 21). The rating was based on the assumption that a design in which neither more nor less artificial or unnatural materials were used compared to the reference would be attributed the medium value rating of 3. The designs or test fields in which artificial or non-natural materials were not used were assigned the highest value rating of 5. These were the hedge layers (HL) and the test field without slope protection (TF 9). Willow brush mattresses (TF 2 and 3) fastened with wire were assigned the value rating of 4.

The volume of armourstone used in TF 1 (vegetated riprap) was identical with the amount used in the reference, no other materials were introduced and the test field was assigned the value rating of 3. More stones than were used in the actual state were installed for wave protection measures in the shallow water zone (FWZ), as single stones in TF 4 (gravel fill) and for the stone wall in TF 8. The value rating 2 was therefore assigned, as armourstones are natural stones although they do not occur naturally on the River Rhine.

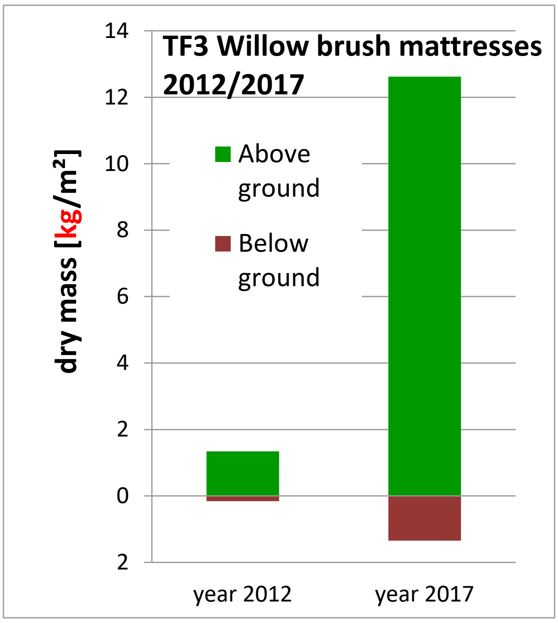
Polypropylene (thermoplastic) or galvanised wire was used to encase the stones in the stone mattresses (TF 5b) and reed gabions (TF 5a). Stones were also used, albeit smaller and fewer stones than in conventional riprap. A synthetic geotextile was used in part of TF 7 (plant mats) as well as a fine support frame made of synthetic material for the coir portion in the mats, which was installed to strengthen erosion resistance. Wire was used for fastening. Armourstone was also used as cover to rehabilitate the damaged reed gabions and plant mats. TF 5 and 7 were therefore assigned the lowest value rating of 1.

Table 21: Assessment of the use of synthetic and non-natural materials
FWZ: shallow water zone; HL: hedge layer at the top edge of slope.
Value ratings: very high value (5), high value (4), medium value (3), low value (2), very low value (1)

Criterion	FWZ	HL	TF 1	TF 2	TF 3	TF 4	TF 5 _RG	TF 5 _SM	TF 7	TF 8	TF 9	Ref
Materials	**2**	**5**	**3**	**4**	**4**	**2**	**1**	**1**	**1**	**2**	**5**	**3**

5.6 CO_2 storage of the construction methods

The root excavations in TF 3 (willow brush mattress) and TF 7 (plant mats) were presented in Chapter 4.2.1 and Chapter 4.2.3 and discussed in terms of stability. In addition to the root dry mass, the above-ground dry mass of the designs was also determined. Figure 62 (left) shows the dry mass in TF 3 by comparing the years 2012 (at the end of the first vegetation period after installation) and 2017, averaged over all samples examined. Figure 63 (right) shows the mean above- and below-ground dry mass of all sampling sites in TF 7 in 2017, differentiated according to different life forms.



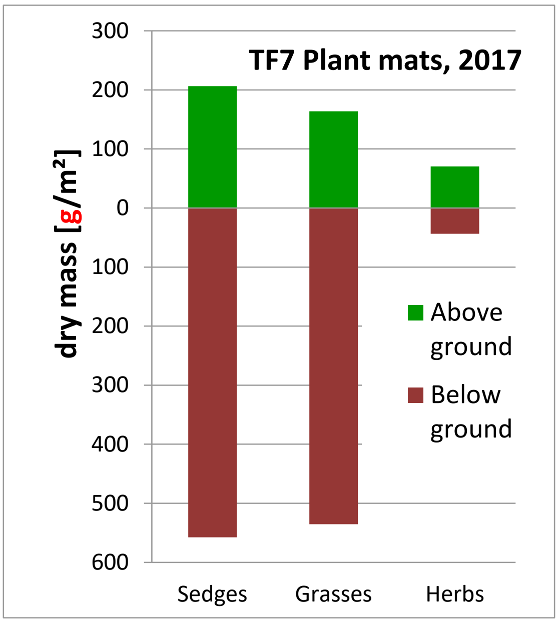


Figure 63: Above- and below-ground dry mass. Left: TF 3 (willow brush mattress, comparison of the years 2012 and 2017. Right: TF 7 (plant mats) in 2017, separated according to life forms. Note the different scaling of the y-axis. Graph based on data from (Schneider 2012), (Ziegenhorn 2017), (Heinzner 2017a, 2017b).

The CO_2 in the biomass was calculated from the dry weight via the carbon content. According to the (Millennium Ecosystem Assessment 2005), CO_2 storage capacity acts as a climate-regulating ecosystem service. Bearing in mind the size of the test field, 21,700 kg of CO_2 are stored in the woody TF 3 and 1,800 kg in the grassy–herbaceous TF 7, i.e. a total of around 23 tonnes of CO_2. A comparison is made with the climate model of (Notz & Stroeve 2016) to classify this value as a climate-regulating ecosystem service. According to their calculations, summer sea ice cover in the Arctic is being lost at a rate of 3 m^2 for every additional tonne of CO_2 released. If the amount of CO_2 bound is related to the emissions of cars in urban traffic, the CO_2 emissions of 100,000 car kilometres of urban traffic were bound in the above- and below-ground plant mass of TF 3 in 2017, and an equivalent of 8,500 kilometres in TF 7 *(calculated for a medium-sized car with an assumed consumption of 8.7 l petrol or 6.8 l diesel per 100 km city traffic, on average 21 kg CO_2 emissions per 100 km – calculated with the Dekra CO_2 consumption calculator www.CO2online.de*). Taking account of the development of the willow brush mattress in TF 3, the rule of thumb can be applied that the biomass growth of 1 m^2 of willow brush mattress per year binds the CO_2 emissions of 20 km of city driving by a medium-sized car.

The CO_2 storage per unit area can be assessed in relation to all the test fields on the basis of the biomass investigations for both test fields and the data on vegetation cover from 2016 (Table 22). The willow brush mattresses and vegetated riprap (TF 1–3) score best with value ratings of 4 and 5. TF 2 with the thinner willow stands was downgraded by one rating level compared to the more densely vegetated TF 3. The hedge layers and the reference were assigned value rating 3 as a result of the woody component. TF 7 (plant mats), which is most densely covered with grasses and herbs, was assigned the same value rating. Test fields that are more sparsely vegetated with grasses and herbs were assigned value ratings of 2 and 1. The shallow water zone with its aquatic plant cover, which has only a very low dry mass, was not evaluated.

Table 22: Rating of test fields in relation to the CO_2 storage ecosystem service
FWZ: shallow water zone; HL: hedge layer at the top edge of slope
Value ratings: very high value (5), high value (4), medium value (3), low value (2), very low value (1)

	FWZ	HL	TF 1	TF 2	TF 3	TF 4	TF 5 _RG	TF 5 _SM	TF 7	TF 8	TF 9	Ref
CO2 storage	**-**	**3**	**4**	**4**	**5**	**1**	**1**	**2**	**3**	**3**	**2**	**3**

5.7 Overall ecological rating

This Chapter brings together the findings from the ecological investigations along the test stretch from the previous Chapters (5.1–5.6) to arrive at an overall ecological rating. Account must be taken of the fact that assessments of outcomes were all undertaken relative to each other and must be considered under the existing boundary conditions applying to the test stretch on the Rhine. The technical–biological bank protection measures tested on the test stretch might develop otherwise if the boundary conditions were different.

5.7.1 Objectives

One aim of the overall ecological rating is to integrate all the ecological sub-assessments for the combined measures in test fields 1 to 9 of the test stretch. This enables the tested measures to be ranked according to their ecological effectiveness.

The overall ecological rating subsequently forms the basis for one of three criteria (ecology, stability of bank slopes, costs), which are included in an integrating overall rating of the test stretch in Chapter 7. Furthermore, it is used in Chapter 8 for the application of findings to other boundary conditions.

5.7.2 Methods

The methodological approach for determining the overall ecological rating is explained in the following. A basic distinction is made between two ratings:

- Overall rating of the terrestrial ecology
- Overall rating of the aquatic ecology

Criteria

The following abiotic and biotic criteria were used for the terrestrial and for the aquatic overall rating:

Overall rating of the terrestrial ecology (terrestrial area TF 1–9 and reference):

- ‘Vegetation’ (Chapter 5.2.9)
- ‘Terrestrial fauna’ (Chapter 5.3.8)
- ‘Heterogeneity’ (Chapter 5.4.7)

- 'Materials used' (Chapter 5.5)
- 'CO2 storage capacity' (Chapter 5.6)

Overall rating of the aquatic ecology (aquatic area TF 1 and 4 and reference):

- 'Aquatic fauna' (Chapter 5.3.8)
- 'Vegetation in the shallow water zone' (Table 14)

As aquatically effective structures were only implemented in TF 1 (stone wall with shallow water zone) and in TF 4 (dead wood fascines), the aquatic area in the other test fields was not expected to be ecologically effective. Potentially positive effects of terrestrial measures on the aquatic habitat are to be classified as very low due to the comparatively short development period of five years in combination with to some extent intensive maintenance work and they are therefore negligible for the overall ecological rating.

Overall ecological ratings

A weighted mean value was calculated for each test field and for the respective reference areas (terrestrial and aquatic), taking account of all the criteria referred to. The input criteria were weighted according to whether

a) an in-depth data evaluation based on an extensive data pool could be used as a basis for a criterion (double weighting), and

b) relevant information was derived from accompanying data (e.g. qualitative assessment of the dead wood in a test field during vegetation mapping) or from an expert assessment (simple weighting).

For the overall rating of the terrestrial ecology of the measures in test fields 1 to 9 and the reference, the two biotic criteria 'vegetation' and 'terrestrial fauna' were double weighted, as they are of central importance in the context of the five-year monitoring and the rating is based on an extensively collected pool of data. The biotic criterion 'heterogeneity' as well as the abiotic criteria 'materials used' and 'CO_2 storage capacity' are given single weighting in the overall rating of terrestrial ecology.

For the overall rating of aquatic ecology, the two criteria 'aquatic fauna' and 'vegetation in the shallow water zone' were each given a single weighting for TF 1 (stone wall with shallow water zone). The assessment of the criterion 'aquatic fauna' was included directly in the overall rating of aquatic ecology for the dead wood fascines as a special structure in TF 4, as no further sub-criteria were recorded and assessed in this case. This also applies to the overall rating of the aquatic reference area without special structures.

5.7.3 Assessment

The overall ecological rating is presented in Table 23. In terms of aquatic ecology, the shallow water zone in TF 1 (ecologically enhanced riprap) created by the off-the-bank stone wall is the most ecologically effective, followed by the medium ecological effectiveness of the dead wood fascines located below mean water level in TF 4. Both types of measures show clearly positive ecological effects compared to the reference area without special structures. Three groupings arise for the terrestrial ecology: TF 4 (ecologically enhanced riprap with gravel and stone blocks) and TF 5 (stone mattresses and reed gabions) as well as the reference area are assigned value rating 2 and are of only low ecological effectiveness. TF 1 (ecologically enhanced riprap with plants) is assigned an overall value rating of 3 and is of medium ecological effectiveness. Before these, there is a group of five test fields (TF 2, 3 – willow brush mattresses; TF 7 – plant mats; TF 8 – ecologically upgraded paving, TF 9 – without slope protection, willow branch cuttings at the adjoining plane at the top of the slope), each of which is highly effective ecologically and which are assigned a total value rating of 4 for all the criteria considered.

Table 23: Overall ecological rating for all measures in test fields 1 to 9 and in the reference areas (riprap). Value ratings 1-5, 1 = very low ecological effectiveness, 2 = low ecological effectiveness, 3 = medium ecological effectiveness, 4 = high ecological effectiveness, 5 = very high ecological effectiveness.

Measures assessed, test field (TF)	Vegetation	Terrestrial fauna	Heteroge-neity	CO_2 storage capacity	Materials used	Aquatic fauna	Vegetation FWZ	Overall rating of terrestrial ecology	Overall rating of aquatic ecol-ogy
Shallow water zone – TF 1						5	5		**5**
Dead wood fascines – TF 4						3			**3**
Riprap – Reference (aquatic)						1			**1**
Ecologically upgraded riprap with plants – TF 1	3	3	4	4	3			**3**	
Willow brush mattresses – TF 2	4	3	3	4	4			**4**	
Willow brush mattresses – TF 3	4	4	3	5	4			**4**	
Ecologically enhanced riprap with gravel and stone blocks – TF 4	2	3	2	1	2			**2**	
Reed gabions – TF 5a	3	3	1	1	1			**2**	
Stone mattresses – TF 5a, TF 5b	3	3	1	2	1			**2**	
Plant mats – TF 7	5	4	3	3	1			**4**	
Ecologically upgraded paving – TF 8	5	4	4	3	2			**4**	
Without slope protection, Willow branch cuttings on adjoining plane at the top of the slope – TF 9	3	4	5	2	5			**4**	
Riprap – Reference (terrestrial)	2	2	1	3	3			**2**	

5.7.4 Conclusion

Based on a large number of defined ecological criteria and sub-criteria, it was possible to produce an overall evaluation of ecological effectiveness for the aquatic as well as for the terrestrial area, by ranking the measures implemented on the test stretch. It is apparent that the majority of the measures provide added ecological value compared to the conventionally protected riprap (reference), especially where additional measures were implemented in the aquatic area. The trend in the terrestrial area is that measures that allow for the greatest possible structural diversity and heterogeneous development of vegetation near the bank, with correspondingly typical riparian zonation (TF 7, 8 and 9, to a lesser extent also TF 2, 3) are overall highly effective ecologically. Measures involving highly homogeneous structures that do not allow bank morphology and bank vegetation to develop dynamically, particularly robust designs with a weight per unit area in TF 4, 5a and 5b and the riprap of the reference bank are of low ecological effectiveness. As well as structural diversity, protection against ship waves and high flow loads is also relevant for the aquatic area. This is particularly evident in the aquatic area of test field 1, for example, as the off-the-bank stone wall and the introduction of dead wood enabled very high ecological effectiveness to be achieved.

It is important to note that, owing to various, potentially conflicting ecological objectives, none of the tested individual designs is capable of meeting all the necessary ecological objectives. It is, in contrast, extremely important to determine which organisms and which habitats are to be promoted before planning begins. It is then possible to select the most suitable type of measure or a combination of ecologically suitable measures.

Finally, the overall ecological rating shows that technical–biological bank protection measures can provide suitable riparian habitats for various groups of organisms.

6 CostsConstruction costs

The construction costs for the redesigned, around 800 m long bank section amounted to a total of EUR 924,000 in 2011. Table 24 lists these costs according to test field, m of bank length, and per m². Planning expenses charged by engineering firms and for services provided by the project parties BAW, BfG and WSA are not stated. The planning firm and the branch office Worms/Oppenheim supervised the construction works; these services have not been considered as expenses in the construction costs of the test fields, either.

The costs (as per 2011) are stated in gross amounts. Most of the cost items are subject to VAT at 19%, except for some expenses for planting material which is subject to a reduced VAT rate of 7%. The costs for construction site equipment were allocated to the test fields on a pro-rata basis. Further general costs that were incurred for the entire project but only affected individual test fields, such as ordnance disposal, were allocated only to the affected test fields (TF 1–5, TF 7, TF 9).

Prior to the redesign, the bank slope's inclination and height were almost the same along the entire stretch. For some test fields, the redesign resulted in a flattening, thus increasing the slope's surface area. Column 7 of Table 24 normalises the individual test fields to a uniform bank length. When comparing the values, it should be considered that some of the test fields featured several designs, not all of which were installed across the entire slope surface. This applies in particular to TF 8 where only the height of the stone wall was increased and the slope itself remained unaltered. The construction costs include the costs for removing the riprap because this was necessary to enable the installation of alternative bank protection structures.

Column 8 of Table 24 states the costs per square metre of slope surface area. The costs per test field are mostly for several different designs, and these are normalised to obtain a mixed price. TF 5, for example, is divided lengthwise (TF 5a and TF 5b) and, in addition, in slope direction. No square metre price is stated for TF 1 since the stone wall and the planting trenches are linear structures. This also applies to TF 8 (linear stone wall) and TF 9 (log branch cuttings do not cover the entire slope; construction of a log groyne).

The standard prices listed in the table cannot be used for calculation purposes as they are derived from an entrepreneurial calculation obtained from just one bidding consortium. Moreover, the work involved in creating several test fields cannot be compared with real bank protection construction projects.

Table 24: Construction costs per test field (TF)

TF	Km	Technical–biological bank protection measures	TF length	TF surface area	Costs per TF		
					per TF	per m of bank length	per m²
			m	m²	€	€/m	€/m²
1	2	3	4	5	6	7	8
1	440.630 to 440.800	Installation of willow branch cuttings, live fascines, brush and hedge layers in existing riprap; off-the-bank stone wall with shallow water zone, dead trunks with root plates	120.0	-	83,500	700	-
2	440.820 to 440.860	Removal of riprap; willow brush mattresses placed at an angle to the flow direction, fixed with crossbars, wooden stakes and wire; hedge layers on adjoining plane at the top of the slope	36.5	500	55,500	1520	111
3	440.880 to 440.950	Removal of riprap; willow brush mattresses placed perpendicular to flow direction, fixed with crossbars, wooden stakes and wire	67.0	885	99,000	1480	112
4	440.950 to 441.000	Existing riprap with gravel fill, groups of individual stones, dead wood fascines	45.0	383	65,000	1440	170
5	441.000 to 441.110	Removal of riprap; installation of reed gabions and stone mattresses on granular filters, pre-cultivated plant mats on stone mattresses, hedge layers	100.0	1100	203,500	2040	185
6	441.125 to 441.200	Existing riprap with filling of topsoil-alginate blend, hydroseeding, individual plants	67.5	624	59,500	880	95
7	441.200 to 441.375	Removal of riprap; installation of pre-cultivated plant mats on various filter mats (nonwoven sheep wool, geotextile, coir mat), dead wood fascines, plant rolls, woven coir fabric installed on hydroseeding; fixed with crossbars, wooden stakes and wire	157.0	1890	326,000	2080	172
8	441.375 to 441.475	Raising of existing stone wall; existing paving and riprap, reed growth	98.5	-	3,500	40	-
9	441.475 to 441.600	Removal of riprap; no new bank protection in the slope area; allowing for limited erosion and succession, log branch cuttings for protecting the maintenance path on the adjoining plane at the top of the slope; log groyne at the end of the test field	109.0	-	28,500	260	-
Σ	440.630 to 441.600		805.5		924,000		

The price range is 110–185 €/m² for the technical–biological designs (willow brush mattresses (TF 2 and 3), plant mats (TF 7) and reed gabions (TF 5)) which were mainly installed to cover the slope. Compared to this, the costs for installing loose riprap ($LMB_{10/60}$) are slightly lower at 100–120 €/m². These standard prices include general costs (e.g. construction site equipment, surveying services). Furthermore, prices strongly depend on the volume of a construction project so that deviations are possible. Since construction costs were only recorded per test field and not broken down by measure, the costs are stated additionally as a qualitative estimate for the different measures implemented in individual sections of some test fields (TF 5 and 7).

6.2 Maintenance expenses

In the initial years, maintenance work on the technical–biological protection structures, such as watering, neophyte control or controlling spontaneous vegetation around the structures, is indispensable. Pruning of the woody plants is, as a rule, not necessary until after several years.

Pruning and maintenance work has been carried out in test fields 1, 2, 3 and 9, all of which used woody plants (e.g. willow brunch cuttings, willow brush mattresses, brush and hedge layers), since their construction in 2011. Pruning work on the willow brush mattresses (TF 2 and 3) and in TF 1 took place for the first time after three years (Figure 64). This work will have to be repeated in the coming years to varying extents. A heterogeneous woody plant population developed in TF 1 thanks to pruning work during the initial years. The reed gabions (TF 5) did not require any sizeable maintenance work in the first four years. As described in detail in Chapter 4.2.2 and Annex 3, the measure that used reed gabions was unsuccessful. The reed gabions were rehabilitated by covering them with a layer of stones. In the designs that did not use any live material (plants) (TF 4, 6, 8) no maintenance was carried out except for neophyte control. However, the dead wood fascines placed immediately below mean water level in TF 4 will have to be replaced in the near future. Initially, the plant mats in TF 7 were mowed annually, and later, every other year at an early stage to eliminate unwanted plants and to foster denser plant growth (Figure 65). The establishing vegetation is usually rejuvenated every five to ten years or cut back to the trunk on conventional riprap such as that in the reference stretch. In the monitoring period until now, maintenance work took place in one of the reference stretches in February 2019.

Overall, the monitoring period until now is too short to make any robust statements regarding long-term maintenance expenses for individual designs. Moreover, detailed studies on maintenance strategies will be conducted in the context of continued monitoring (Chapter 9). Therefore, the expenses are rated in relative terms to each other with value ratings 1 to 5 (Table 25).

Figure 64: Partial pruning of the willow brush mattress in TF 3 (January 2015) (photo: WSA Upper Rhine)

Figure 65: Mowing of the plant mats in TF 7 (June 2015) (photo: WSA Upper Rhine)

Estimates of maintenance expenses are based on experience gained from the test stretch, combined with forward-looking estimates. The designs have different life spans, which is another aspect that is worth considering in the context of precise financial figures. Based on the research so far, the test fields can only be compared qualitatively among each other and to the reference stretch.

6.3 Rating

The costs (construction costs, maintenance expenses and total costs) are rated based on a 5-level scale:

- ‘5’ means low construction costs or low maintenance expenses
- ‘1’ means high construction costs or high maintenance expenses.

The results are shown in Table 25.

Construction costs

The plant mats and reed gabions were found to be the most cost-intensive designs and received the poorest rating of 1. The existing riprap of the reference stretch represents the initial situation. Since no costs are incurred here, the riprap is rated 5.

Maintenance expenses

There are no maintenance expenses indicated for TF 6 and TF 7 because the measures were not successful and no more work was carried out to maintain the originally installed designs. Almost no maintenance work occurred to maintain the slope area of TF 9. An additional row of willow branch cuttings was installed on the adjoining plane at the top of the slope to counteract the progressive erosion towards the maintenance path, and maintenance expenses increased as a result. In qualitative terms, technical–biological bank protection structures using live material such as woody plants or plant mats are estimated as more expensive to maintain than conventional riprap revetments.

Total costs

The overall rating for the costs is an aggregate of the sub-ratings for construction costs and maintenance expenses. Maintenance expenses were weighted higher than construction costs. The rehabilitation works carried out so far do not count towards the costs, because it is assumed that such works will no longer be necessary in the implementation of future projects if the designs are optimised based on the experience gained on the test stretch (cf. ‘lessons learnt’, Chapter 4.5 and Annex 3). Overall it can be assumed that the costs involved in constructing technical–biological bank protections are higher than for conventional revetments made of riprap.

Table 25: Rating of the costs per test field (TF)

Technical–biological bank protection measure/design	**Rating** (1: very poor, 2: poor, 3: average, 4: good, 5: very good)		
	Construction costs	**Maintenance expenses**	**Total costs**
Ecologically enhanced riprap with vegetation, without off-the-bank stone wall (stone wall not accounted for in the costs, but e.g. ordnance disposal) TF 1, upper and lower slope zones	3	4	4
Removal of riprap; willow brush mattresses, at an angle to the flow direction TF 2, upper and lower slope zones	2	2	2
Removal of riprap; willow brush mattresses, perpendicular to the flow direction TF 3, upper and lower slope zones	2	2	2
Ecologically enhanced riprap with gravel, stone blocks and dead wood fascines TF 4, upper and lower slope zones	2	5	4
Removal of riprap; reed gabions TF 5a, lower slope zone	1	5	3
Removal of riprap; stone mattresses TF 5a, upper slope zone; TF 5b, upper and lower slope zones	2	4	3
Ecologically enhanced riprap with topsoil alginate TF 6, upper and lower slope zones	3	-	-
Removal of riprap; coir mat on hydroseeding TF 7a, upper slope zone	3	3	3
Removal of riprap; plant mats TF 7a, b, c, lower slope zone	1	-	1
Removal of riprap; plant mats TF 7b, c, upper slope zone	1	4	3
Raising of existing stone wall; existing paving and riprap, reed growth TF 8, lower slope zone	5	5	5
Removal of riprap; without slope protection; willow branch cuttings on adjoining plane at the top of the slope TF 9, upper and lower slope zones	4	3	3
Riprap as reference (already in place before redesign)	5	5	5

7 Overall Rating of the Test Fields

The performance of the different technical–biological bank protection measures under the boundary conditions present along the Rhine River is being studied in the context of a long-term monitoring. The object is to establish whether they can be as effective in protecting the bank as riprap, and whether at the same time an ecological enhancement over riprap can be achieved. Ensuring the stability of the bank and increasing ecological effectiveness were therefore primary requirements. The costs of the measures were of secondary importance during the planning. Two reference stretches situated immediately upstream and downstream the test stretch and in which the existing riprap remained unchanged were used for comparison purposes.

The individual bank protection measures were assessed with regard to different aspects: ensuring bank stability (Chapter 4.5, Table 11, and Annex 3), terrestrial and aquatic ecology (Chapter 5.7, Table 23), and costs (total costs and broken down by construction costs and maintenance expenses (Chapter 6.3, Table 25)). Under the given boundary conditions of the field test, the existing riprap revetment is taken as the baseline situation for calculating the costs of constructing each of the measures. Comparative ratings were made for each of three categories (stability, ecology, costs) on a scale from 1 (very poor) to 5 (very good). To produce a rating for the costs, average values were derived from construction costs and maintenance expenses based on expert knowledge. Table 26 shows these ratings in columns 3–5 for the listed test fields 1 to 9 with their installed measures as well as for the reference (riprap). The table reveals the good or poor capability of each measure to protect the bank and to provide ecological enhancement, and it shows whether the costs for each measure were very high (very poor rating) or rather low (very good rating).

In addition, an overall rating is produced of the technical–biological bank protection measures arranged above mean water level, which show effects primarily on terrestrial ecology. For this purpose, the ratings for the three categories of bank stability, terrestrial ecology and total costs are weighted equally to calculate an average (shown in the last column of Table 26). An overall rating is possible for all measures except for ‘Ecologically enhanced riprap with alginate’ in TF 6. The alginate had already been washed away in the initial stage when water levels were high, so that this measure cannot be rated for its ecological performance. Stability continues to be ensured by the riprap, even if the alginate is gone.

Table 26: Comparative rating of technical–biological bank protection measures

Technical–biological bank protection measures/designs		**Rating** (1: very poor, 2: poor, 3: average, 4: good, 5: very good)			
		Terrestrial ecology	**Total costs**	**Bank stability**	**Overall rating (average)**
TF 1	Ecologically enhanced riprap with vegetation, <u>without</u> off-the-bank stone wall TF 1, upper and lower slope zones	3	4	5	4.0
TF 2	Removal of riprap; willow brush mattresses, at an angle to the flow direction TF 2, upper and lower slope zones	4	2	3	3.0
TF 3	Removal of riprap; willow brush mattresses, perpendicular to the flow direction TF 3, upper and lower slope zones	4	2	4	3.3
VF 4	Ecologically enhanced riprap with gravel and stone blocks, <u>without</u> dead wood fascines TF 4, upper and lower slope zones	2	4	5	3.7
TF 5	Removal of riprap; reed gabions TF 5a, lower slope zone	2	3	2	2.3
	Removal of riprap; stone mattresses TF 5a, upper slope zone TF 5b, upper and lower slope zones	2	3	5	3.3
TF 6	Ecologically enhanced riprap with topsoil alginate TF 6, upper and lower slope zones	-	-	5	-
TF 7	Removal of riprap; coir mat on hydroseeding TF 7a, upper slope zone	4	3	1	2.7
	Removal of riprap; plant mats TF 7a, b, c, lower slope zone	4	1	1	2.0
	Removal of riprap; plant mats TF 7b, c, upper slope zone	4	3	4	3.7
TF 8	Raising of existing stone wall; existing paving and riprap, reed growth TF 8, lower slope zone	4	5	5	4.7
TF 9	Removal of riprap, without slope protection; willow branch cuttings on adjoining plane at the top of the slope TF 9, upper and lower slope zones	4	3	1	2.7
Ref.	Riprap as reference (already in place before redesign)	2	5	5	4.0

Two structures that had no immediate bank protection effect – the off-the-bank stone wall in TF 1 and the dead wood fascine in TF 4 – were installed as additional measures for enhancing aquatic ecology. These measures could have been installed as additional structures in every other test field to contribute towards ecological effectiveness. The aquatic effectiveness of these two measures is rated separately (Table 27) to avoid a distorting influence on the results of the overall rating of the bank protection measures in the terrestrial areas of TF 1 to 9. Regarded in isolation, without the bank protection measures in the slope zone above mean water level, they show their basic potential to enhance aquatic ecology.

Table 27: Comparative rating of measures implemented in the aquatic area without immediate bank protection function

Measures – test field (TF)	Aquatic fauna	Vegetation FWZ	Overall rating of aquatic ecology
Off-the-bank stone wall with shallow water zone – TF 1	5	5	5.0
Dead wood fascines MW to MW – 0.5 m – TF 4	3		3.0
No measures in the aquatic area (reference)	1		1.0

A ranking of the tested bank protection measures 1–12 regarding their suitability under the boundary conditions of the test stretch (Table 28, 1st column) is derived from the overall rating shown in Table 26, graded 'very good (5)' through to 'very poor (1)'.
Measures with the same overall rating, i.e. for which the same average results from the individual categories, hold the same rank. This means that, if three measures are ranked 2nd, none of the measures are ranked 3rd or 4th and any following measure will be given a lower ranking of 5th and so on.

Overall, the results as shown in Table 28 can be explained as follows: the riprap and paving in the shelter of the raised stone wall in TF 8 perform best in the overall rating. This measure is cost-effective and, at the same time, ensures bank stability. Its terrestrial–ecological effectiveness is at least average. It should be considered, however, that this measure is only reasonable in cases where paved bank stretches that are stable and ecologically significant already exist and which it is therefore desirable to keep in place. Its ranking would be much lower if it was envisaged as new construction measure, because paving is expensive and alternatives with higher ecological effectiveness are available.

Table 28: Overall rating of the measures with equal weighting of all three criteria according to Table 26 (1st column: ranking of measures according to their suitability under the conditions of the test stretch)

Rank	Technical–biological bank protection measures	Test field	Overall rating
1	Raising of existing stone wall; existing paving and riprap, reed growth[1)]	TF 8	4.7
2	Ecologically enhanced riprap with vegetation, without off-the-bank stone wall	TF 1	4.0
2	Riprap as reference	Ref.	4.0
4	Ecologically enhanced riprap with gravel and stone blocks	TF 4	3.7
4	Plant mats (upper slope zone)	TF 7b,c, upper slope zone	3.7
6	Stone mattresses	TF 5	3.3
6	Willow brush mattresses, perpendicular to flow direction	TF 3	3.3
8	Willow brush mattresses, at an angle to flow direction	TF 2	3.0
9	Without slope protection[2)]	TF 9	2.7
9	Coir mat on hydroseeding[3)] (upper slope zone)	TF 7a, upper slope zone	2.7
11	Reed gabions[3)] (lower slope zone)	TF 5a, lower slope zone	2.3
12	Plant mat[3)] (lower slope zone)	TF 7, lower slope zone	2.0

1) *Measures in TF 8 only reasonable for upgrading existing paving, not as new construction.*
2) *In TF 9 bank stability was not a requirement; instead, erosion was allowed for ecological reasons.*
3) *These measures were ineffective for bank stability; riprap has already been placed as rehabilitation in some portions.*

The ecologically enhanced riprap in TF 1 (without the off-the-bank stone wall) and the riprap reference also performed rather well in the overall rating. This is also primarily attributable to the criteria of stability and costs. It must be considered, however, that no costs are accounted for in the rating for placing the riprap since riprap is taken to be the baseline situation for all measures. The enhanced riprap shows better ecological performance than the reference.

Next in the ranking, but still in the 'good' rating range, is the ecologically enhanced riprap with gravel and stone blocks, disregarding the dead wood fascines with aquatic effect (TF 4). The stability and costs are also good to very good, whereas the measure's performance regarding terrestrial ecology is poor. The plant mats in the upper, rarely flooded slope zone (TF 7) have the same overall performance as a result of their good rating with regard to terrestrial ecology. They performed slightly less well than TF 4 with regard to stability and costs.

Next level down are the stone mattresses (TF 5) and the willow brush mattresses (TF 2 and 3) with average ratings. Their ability to ensure the stability of the bank is rated good to very good, the ecological enhancement achieved is good, at least for the willow brush mattresses, while the costs are in the average to high range.

The test field without bank protection (TF 9) also receives an average rating overall because of its relatively low costs and good terrestrial–ecological enhancement, although it is not able to ensure stability.

Because of its good ecological effectiveness, the coir mat on hydroseeding (TF 7) in the upper slope zone only just receives an average rating, followed by the reed gabions (TF 5) and the plant mats in the lower, frequently flooded slope zone (TF 7), both of which receive a poor rating overall. None of these three measures were able to ensure bank stability and most of these areas were rehabilitated using riprap. The resulting poor rating for bank stability is the main reason for the poor overall rating. In addition, costs are very high, in particular for the plant mats, so that, despite their good rating for ecological effectiveness (except for the reed gabions), their overall rating is the poorest in comparison.

Table 29: Overall rating of the measures based on an equal weighting of stability and ecology, without accounting for costs (1st column: ranking of measures according to their suitability under the conditions of the test stretch)

Rank	Technical–biological bank protection measure	Test field	Overall rating
1	Raising of existing stone wall; existing paving and riprap, reed growth[1)]	TF 8	4.5
2	Ecologically enhanced riprap with vegetation, without off-the-bank stone wall	TF 1	4.0
2	Plant mats (upper slope zone)	TF 7b, c, upper slope zone	4.0
2	Willow brush mattresses, perpendicular to flow direction	TF 3	4.0
5	Willow brush mattresses, at an angle to flow direction	TF 2	3.5
5	Ecologically enhanced riprap with gravel and stone blocks	TF 4	3.5
5	Stone mattresses	TF 5	3.5
5	Riprap as reference	Ref.	3.5
9	Without slope protection[2)]	TF 9	2.5
9	Coir mat on hydroseeding[3)] (upper slope zone)	TF 7a, upper slope zone	2.5
9	Plant mat [3)] (lower slope zone)	TF 7, lower slope zone	2.5
12	Reed gabions[3)] (lower slope zone)	TF 5a, lower slope zone	2.0

1) Measures in TF 8 only reasonable for upgrading existing paving, not as new construction.
2) In TF 9 bank stability was not a requirement; instead, the objective was for erosion to take place.
3) These measures were ineffective for bank stability; riprap has already been placed as rehabilitation in some portions.

In addition to this overall rating, the bank protection measures were ranked for comparison purposes without taking account of costs as these were irrelevant for the planning of the test stretch. The average value was calculated solely on the basis of ratings for stability and terrestrial ecology. The results are shown in Table 29. The overall rating of the individual measures on a scale from 1 to 5 hardly changes at all under these boundary conditions. But in the ranking (1st column in Table 29) the more cost-intensive measures move up, as was expected – the plant mats in the upper slope zone come in 2nd instead of 4th and the willow brush mattresses move to 2nd and 5th from their original ranks 6 and 8. The very cost-effective riprap in the reference and the ecologically enhanced riprap with gravel and stone blocks drop from rank 2 to 5 and from 4 to 5. However, the ranking only changes for measures in the mid-field; the ranking of the two measures performing best and, in particular, of the three measures performing worst remain the same in this analysis, also when disregarding the element of costs.

Generally, the result shows that the ecological enhancement of existing riprap or paving is a good and ecologically successful and at the same time inexpensive way of making banks more natural even in cases where high hydraulic loads make riprap indispensable for bank protection. The placement of aquatically effective structures (e.g. creating shallow water zones by means of off-the-bank stone walls or dead wood fascines below mean water level) is always recommendable as they can bring about a considerable improvement in habitat conditions for fish, aquatic invertebrates and aquatic plants. Generally, the other technical–biological bank protection measures are also capable of ensuring bank protection and ecological enhancement. Which measures are feasible in each specific case depends largely on the hydraulic loads and the requirements for bank stability, but also on the relevance of costs in each case. Not all the measures are equally feasible and ecologically effective in every case. Chapter 8 discusses examples of the measures studied on the test stretch in terms of their ecological effectiveness under different boundary conditions and when pursuing more comprehensive objectives. Rankings of measures are established for different scenarios, which in the context of preliminary planning processes can help with the selection of suitable measures for bank protection.

8 Transfer of Findings

8.1 Background and requirements

The different technical–biological bank protection measures are assessed in Chapter 7 in an integrated rating based on the boundary conditions prevailing on the test stretch on the Rhine. The aim of the measures was to achieve ecological enhancement of existing terrestrial and aquatic riparian habitats while providing the same level of bank protection as would be ensured by a revetment made of riprap.

Moreover, to develop an integrated overall rating of the measures that is useful for a large number of decision makers, the findings obtained on the test stretch are transferred – where possible – to the riparian zones of free-flowing waterways with different boundary conditions. To this end, a multi-criteria analysis is used to enable a qualitative knowledge transfer. This analysis is performed for various scenarios, each of which is defined by a specific ecological objective and different boundary conditions.

The technical–biological measures are ranked according to their suitability for the specific scenarios. This provides a qualitative pre-selection of measures which can help with the preliminary planning for bank development projects. It is then possible to assess the suitability of technical–biological bank protection measures for specific waterway stretches and ecological objectives. It should be noted that this pre-selection is not sufficient to determine the technical applicability and assess the ecological potential of the measures in each specific case.

8.2 Methodology – multi-criteria decision analysis

The aim of multi-criteria decision analysis is to merge results from various disciplines that are organised on differing scales and based on differing evaluation methods, and to combine them to produce an integrative overall rating. Schröder und Kleinwächter (2017) show that the Analytic Hierarchy Process (AHP) is a good approach for the evaluation of ecological measures implemented on waterways.

The AHP was developed by the mathematician Thomas L. Saaty. Saaty applies fixed mathematical rules to make pairwise comparisons of criteria and, if required, sub-criteria that are relevant for the decision-making process. This allows for a transparent and in itself consistent evaluation of the tested technical–biological measures, which are referred to as ‘alternatives’ within the meaning of the AHP (Westphal 2016). The multi-criteria decision analysis described in this chapter follows the AHP method by Saaty.

8.2.1 Criteria

In the analysis three criteria are used to assess various scenarios. Unlike in Chapter 7, the ‘stability’ criterion is not considered in addition to the ‘ecology’ and ‘total costs’ criteria, because it is not possible to assess stability independently of the specific boundary conditions in each case (especially hydraulic load, in-situ soil, slope geometry). For purposes of the qualitative knowledge transfer, the ‘resilience’ of the measures is therefore used as a third analysis criterion.

Following the approach in BAW (2016), the term resilience refers to a measure's resistance to stress or failure, independently of the design and, consequently, of the boundary conditions. The measures are compared with each other and assessed as more or less resilient, based on the assessment of the sub-criteria 'weight per unit area', 'rate of defects during production', 'critical initial state' and 'self-healing or rehabilitation capability'. For each measure, resilience was also rated on a scale from 1 to 5 (1 – very poor, 5 – very good). Table 34, Table 35 and Table 37 show the ratings for ecology and total costs as well as resilience.

In addition, the transfer of the results was based on the assumption that the design of the measures will be technically optimised in future applications taking into account the experience gained on the test stretch (information on optimisations required can be found in Annex 3). The input data for the 'resilience' criterion were rated for an optimised condition.

8.2.2 Scenarios

Five different scenarios (A to E) are ranked, all of which are set on a free-flowing waterway navigated by motor vessels. In contrast to the situation on the test stretch, adequate surface area is available for flattening the river banks in all of the scenarios.

Scenario A assumes that it is possible to flatten the river banks to a high degree, which has a positive effect on bank stability. Total costs are of minimal relevance here. The ecological priority is to promote terrestrial riparian habitats. Unlike on the test stretch, ecological aspects are more important than the resilience of the measures.

Additionally, Scenarios B, C and D are analysed as marginal scenarios. These are used to determine the ranking that would result if one criterion was given absolute priority over the other two. Scenario B prioritises ecology, Scenario C resilience, and Scenario D total costs. In each case, the other two criteria are considered to be of minimal relevance. The ecological objective in each scenario is to promote terrestrial habitats.

The boundary conditions in Scenario E are assumed to be the same as in Scenario A. The two scenarios differ in that Scenario E is intended to promote aquatic rather than terrestrial habitats. By contrast, the measures introduced in Scenarios A to D are exclusively implemented in the terrestrial area of the riparian zone and therefore cannot ecologically enhance the aquatic habitat (below MW). However, they can be combined with various additional measures whose ecological effectiveness in the aquatic area has been demonstrated.

8.2.3 Scaling

The AHP according to Saaty (1990) uses matrices for pairwise comparison based on a 1–9 rating scale to determine different rankings for various alternatives (here: technical–biological measures). On this scale, value 1 means that in the pairwise comparison one criterion has the same importance as the other criterion. Value 9 on the scale means that in the pairwise comparison, one criterion has absolute dominance over the other criterion. The scale values are described in Table 30. The matrices for the paired comparisons are reciprocal, i.e. for the inverse comparison the reciprocal value must be used (cf. Table 30).

Table 30: Scale values and reciprocal values and their description for the pairwise comparison of (sub-)criteria according to Saaty (1990)

Scale values	Description	**Reciprocal values**	Description
1	Equal importance	1	Equal importance
3	Moderate importance of one over another	1/3	Moderately less importance
5	Essential or strong importance	1/5	Considerably less importance
7	Very strong importance	1/7	Very much less importance
9	Extreme importance	1/9	Absolutely unimportant
2, 4, 6, 8	Intermediate values	½, ¼, ⅙, ⅛	Intermediate values

8.2.4 Pairwise comparisons – creation of comparison matrices

Scenario A results in differences in importance between the three criteria ‘ecology’, ‘resilience’ and ‘total costs’. To show the relationships between these criteria regarding the different levels of importance, the criteria are arranged in paired comparisons in a matrix using the 9-level scale according to Saaty (1990). The ratio of one criterion to another is entered in the respective row and the reciprocal values are entered for reciprocals (cf. Table 31). It is not only necessary to judge whether one criterion is of greater, equal or less importance than another criterion. It is also necessary to determine the intensity of importance on the scale developed by Saaty (Saaty 1987).

Given the boundary conditions of Scenario A (more surface area available allowing for a flattening of the slope; minimal relevance of total costs), greater importance is assigned to the ‘ecology’ criterion than to the ‘resilience’ and ‘total costs’ criteria. More resilient measures tend to be more ecologically sustainable and the 'resilience' criterion is therefore assigned greater importance than the ‘total costs’ criterion. The following comparison matrix results:

Table 31: Comparison matrix for the criteria ‘ecology’, ‘resilience’ and ‘total costs’ for Scenario A using scale values and reciprocal values according to Saaty (1990)

Criteria	Ecology	Resilience	Total costs
Ecology	1	**3**	8
Resilience	**1/3**	1	3
Total costs	1/8	1/3	1

Table 31 shows a concrete example of pairwise comparisons for Scenario A where the ‘ecology’ criterion is ranked as moderately more important than ‘resilience’ (3 and 1/3, highlighted in bold). Compared to the criterion ‘total costs’, ‘ecology’ is ranked as of almost extreme importance (pairwise comparison: 8 and 1/8). The ‘resilience’ criterion is ranked as moderately more important than ‘total costs’ (pairwise comparison: 3 and 1/3) (cf. also Table 30).

For each of the three marginal scenarios, one of the three criteria is assigned extreme importance over the other two criteria (pairwise comparison: 9 and 1/9): ‘ecology’ in Scenario B, ‘resilience’ in Scenario C and 'total costs' in Scenario D. The two other criteria are ranked as equally important (pairwise comparison: 1 to 1). Table 32 provides an example of a matrix for Scenario B ('Large variety of alternatives for promoting ecology; resilience and costs are of minimal relevance').

Table 32: Comparison table for the criteria 'ecology', 'resilience' and 'total costs' for Scenario B (extreme importance of ecology; resilience and costs are of minimal relevance); scale value 1 = equal importance, scale value 9 = extreme importance

Criteria	Ecology	Resilience	Total costs
Ecology	1	9	9
Resilience	1/9	1	1
Total costs	1/9	1	1

8.2.5 Determination of weightings

Based on the comparison matrices, the weighting for each criterion is calculated in the AHP according to Saaty (1990). The AHP requires that the consistency of the pairwise comparisons is verified. A consistency ratio C.R. is calculated for this purpose, which should be < 0.1. Detailed information on the calculations is provided in Annex 7 (section 4, Calculation of the weightings and section 5, Consistency check). Table 33 shows the results of the calculations of the weightings for Scenarios A to E:

Table 33: Weightings in % for the criteria 'ecology', 'resilience' and 'total costs' for Scenarios A–E (Scenario A: terrestrial ecology, Scenario E: aquatic ecology, Scenarios B C, D: marginal scenarios); consistency ratio (C.R.).

Criteria	**Ecology**	**Resilience**	**Total costs**	**Consistency Ratio (C.R.)**
Scenarios A and E	68%	24%	8%	0.001
Scenario B	82%	9%	9%	0
Scenario C	9%	82%	9%	0
Scenario D	9%	9%	82%	0

8.2.6 Ranking

The total overall weight for each measure has to be calculated before a rank order of suitable technical–biological measures for Scenario A can be established. For this purpose, the technical evaluations of the measures initially made according to the three criteria 'ecology', 'resilience' and 'total costs' (value ratings 1–5, cf. Table 34) were multiplied with their corresponding computed weightings (cf. Table 33) and then added up. Ranks are assigned to the technical–biological measures based on the computed total overall weights ('ranking' function in MS Excel).

Similarly to Chapter 7, a distinction is made between the rank order established for technical–biological bank protection measures and the ranking of the additional measures without direct bank protection function (cf. Table 34, Table 35, Table 36, Table 37). However, unlike in Chapter 7, for purposes of the knowledge transfer the measures themselves, and not the different test fields, are rated, independently of how they are situated on the test stretch. As a result, the willow brush mattresses and plant mats, for example, are only listed once as a measure. Differently from Chapter 7, the measures installed in TF 8 ('Raising of existing stone wall; existing paving and riprap, reed growth') are here considered to be additional measures without any direct bank protection function ('Stone wall in front of mean water level berm'), as this section only looks into the stone wall's ecological effectiveness. The stone wall can be generally assessed as a measure with high ecological effectiveness because it has the function of a sediment trap and reduces the wave impact.

8.3 Results – suitability of measures for Scenarios A to E

8.3.1 Scenario A

Table 34 shows the ranking of suitable measures for Scenario A: 'The measure should promote terrestrial riparian habitats on a free-flowing waterway with navigation by motor vessels. Surface area is available for flattening the river bank. Total costs are of minimal relevance' (cf. 8.2.2 and 8.2.4).

*Table 34: Ranking of technical–biological bank protection measures for Scenario A; *ratings for the 'ecology' criterion refer exclusively to terrestrial riparian habitats in line with the definition of Scenario A; rating scale for criteria: 1 = very poor, 2 = poor, 3 = average, 4 = good, 5 = very good; ranks 1–8; 1= first rank (green), 8 = last rank (red)*

		Ecology*	Resilience	Total costs	Total weights	**Rank order Scenario A**
	Weighting	**68%**	**24%**	**8%**		
Bank protection measures[1)]	Ecologically enhanced riprap with plants	3	5	4	3.56	**2**
	Ecologically enhanced riprap with structural elements (gravel, stone blocks)	2	5	4	2.88	**7**
	Willow brush mattresses	4	3	2	3.60	**1**
	Reed gabions	2	4	3	2.56	**8**
	Stone mattresses	2	4	3	2.56	**8**
	Coir mat on hydroseeding[2)]	4	1	3	3.20	**4**
	Plant mats	4	2	3	3.44	**3**
	Without bank protection; natural succession of vegetation	4	1	3	3.20	**4**
	Riprap as reference	2	5	5	2.96	**6**

[1)] *Design of bank protection measures optimised according to Annex 3*

[2)] *Coir mat on hydroseeding only suitable for installation above highest level of wave run-up according to Annex 3*

It is clear from the rank order determined for Scenario A that willow brush mattresses are the most suitable design for promoting terrestrial ecology. This measure is followed in rank by the ecologically enhanced riprap with plants and the plant mats. The coir mat on hydroseeding, the slope without bank protection and natural succession of vegetation, and the conventional riprap rank in the middle. The lowest ranks are assigned to the ecologically enhanced riprap with structural elements, the reed gabions and the stone mattresses. The determined rank order is a generalised preliminary ranking. Further technical and ecological assessment is necessary for its application in concrete cases.

The rank order is the same for the additional measures without direct bank protection function in the terrestrial riparian area (cf. Table 35). The measures with hedge layers on the adjoining plane at the top of the slope and a stone wall in front of the mean water berm (of the paved bank) are equally suitable with an overall rating of 4.31 and also have a similar ecological rating, albeit for different target organisms.

*Table 35: Rank order of the additional measures without direct bank protection function for Scenario A; weightings for the criteria analogous to Table 34; *ratings for the 'ecology' criterion in Scenario A exclusively refer to terrestrial riparian habitats*

		Ecology*	Resilience	Total costs	Total weights	**Rank order Scenario A**
	Weighting	**68%**	**24%**	**8%**		
Additional measures	Hedge layer on the adjoining plane at the top of the slope	4	5	5	4.32	1
Additional measures	Stone wall in front of mean water level berm (of paved bank)	4	5	5	4.32	1

8.3.2 Scenarios B, C and D (marginal scenarios)

Table 36 shows the ranking of suitable measures for the marginal scenarios B, C and D in comparison to Scenario A.

Table 36: Rank orders of the technical–biological bank protection measures for scenarios A to D, C.R. = 0; ranks 1–8 or 1–9; 1 = first rank (green), 8 or 9 = last rank (red); weightings of the criteria: cf. Table 33

	Rank order for scenarios	A	B – Main weight ecology	C – Main weight resilience	D – Main weight total costs
Bank protection measures [1)]	Ecologically enhanced riprap with plants	2	5	1	2
	Ecologically enhanced riprap with structural elements (gravel, stone blocks)	7	7	3	3
	Willow brush mattresses	1	1	6	9
	Reed gabions	8	8	4	4
	Stone mattresses	8	8	4	4
	Coir mat on hydroseeding[2)]	4	3	8	7
	Plant mats	3	1	7	4
	Without bank protection; natural succession of vegetation	4	3	8	7
	Riprap as reference	6	6	1	1

[1)] *Design of bank protection measures optimised according to Annex 3*
[2)] *Coir mat on hydroseeding only suitable for installation above highest level of wave run-up according to Annex 3*

Scenario B shows a similar ranking of the technical–biological bank protection measures as Scenario A. In addition, plant mats and willow brush mattresses are assessed as very suitable measures. The lowest ranks are assigned to the measures using reed gabions and stone mattresses. If the resilience criterion has the main weight, bank protection measures with technical components are clearly ranked higher than measures without weight per unit area. If the main weight is allocated to total costs, such as in Scenario D, the measure with willow brush mattresses is ranked lowest regarding suitability, while the riprap reference and the vegetated riprap are assigned the highest ranks.

Both additional measures without direct bank protection function in the terrestrial riparian zone, i.e. hedge layers on the adjoining plane at the top of the slope and stone wall in front the mean water berm, received the same rating for Scenarios B, C and D as for Scenario A.

8.3.3 Scenario E

Table 37 shows the results for Scenario E: 'The measure should promote aquatic habitats on a free-flowing waterway navigated by motor vessels. Surface area is available for flattening the river bank. Total costs are of minimal relevance' (cf. 8.2.2 and 8.2.4).

*Table 37: Rank order of the additional measures without direct bank protection function for Scenario E; weightings for the criteria analogous to Table 8; C.R. = 0.001; *ratings for the 'ecology' criterion in Scenario E refer exclusively to measures in the aquatic habitat and in the zone with fluctuating water levels (MW and below)*

		Ecology*	Resilience	Total costs	Total weights	**Rank order Scenario E**
	Weighting	**68%**	**24%**	**8%**		
Additional measures in the aquatic area	Stone wall with shallow water zone	3	5	4	3.56	2
	Dead wood fascines below MW	3	3	3	3.00	3
	Stone wall with shallow water zone and root plate/dead wood fascines	5	3	2	4.28	1
	Dead wood and root plate below MW	3	3	3	3.00	3
	Riprap as reference (aquatic)	1	5	5	2.28	5

The rank order shows that the best approach for Scenario E (rank 1) is to combine additional measures for protection against the impacts of waves and flows (stone wall with shallow water zone) with measures for creating greater structural diversity (root plates, dead wood fascines). Protecting the bank against waves and flows without introducing additional measures for enhancing structural diversity is somewhat less effective (rank 2). This can be explained by the lower input rating assigned to the 'ecology' criterion.

Even with lower flow velocities, fish refuges and feeding grounds for macrobenthic organisms cannot be provided to the same degree as when the measure is combined with a more diversified structure. Likewise, if structural enhancement is not combined with a measure to protect the bank against the impact of waves and flows (rank 3), it is also somewhat less suitable than the alternative with combined measures. From an ecological point of view this is due to the fact that especially on free-flowing waterways fish and macrobenthos are affected in their feeding and reproduction activities by the strong impact of flows and ship-induced waves. These boundary conditions also prevent aquatic macrophytes from establishing. On impounded waterways the impact of flows is usually lower, so that measures to enhance structural diversity may be more effective in certain circumstances. However, impounded waterways are also subject to sometimes high loads due to waves caused by commercial and recreational navigation. This limiting factor for aquatic organisms has to be taken into account. Moreover, the installation of dead wood or root plate structures and dead wood fascines is associated with higher total costs.

8.4 Conclusion

The multi-criteria analysis of different scenarios on a free-flowing waterway demonstrates that, depending on objectives and boundary conditions, a variety of technical–biological bank protection measures can be suitable for bank development purposes on Germany's federal waterways. Where sufficient surface area is available on the land-side and bank slopes can be flattened, for instance, measures without technical components and with high ecological effectiveness, such as willow brush mattresses, are ranked first in a pre-selection.

An analysis of the marginal Scenarios B, C and D shows that the rank order of suitable measures is very much influenced by the weightings determined in the AHP, which were derived from the initially defined ecological objectives ('What is to be promoted?'), the technical requirements and the financial framework. Where resilience, and thus the stability of the bank protection measures, is of particular relevance, the measures of first choice for free-flowing waterways are those that include technical components, such as vegetated riprap, but also reed gabions and stone mattresses. Less resilient protection measures are ranked lower. On the other hand, if costs are the most important decision criterion, the reference and the vegetated riprap appear in the top ranks – not least because the existing riprap is used as a basis for costing. High-cost measures such as willow brush mattresses are ranked lowest in these cases.

If absolute priority is attached to the 'ecology' criterion, with very low relevance of costs and resilience, measures that do not include technical components but which are highly effective ecologically, e.g. plant mats and willow brush mattresses, are ranked highest. This is the case in Scenario A. The lowest ranks are assigned to reed gabions and stone mattresses, which showed a poorer ecological effectiveness.

The results also show that where hydraulic loads act on a free-flowing waterway, various alternative additional measures, which do not fulfil any direct bank protection function, can be implemented to enhance the aquatic habitat ecologically (Scenario E). The particular advantage of all these additional measures, especially those in the aquatic area, is that they can be flexibly combined with bank protection measures. This allows for a great number of alternative designs to promote more natural bank protection on inland waterways. Such creatively combined solutions will make a significant contribution to the ecological enhancement of river banks and the ecologically sustainable development of water bodies.

9 Continued Monitoring

This report presents and assesses the results of the first monitoring phase from 2012 to 2017. On this basis, important insights were obtained regarding the suitability of the tested technical–biological bank protection measures for guaranteeing bank protection and ecological effectiveness. It is not yet possible to draw adequate conclusions regarding certain issues – such as long-term stability, ongoing ecological development and optimal maintenance of the various plant-based measures – after such a comparatively short observation period. The monitoring will therefore be continued accordingly. Annex 5 provides an overview of the content and scope of the activities initially planned for the period 2021 through to 2030. A further report with interim results is planned for 2026.

10 Summary and Outlook

The applicability of technical–biological bank protection measures for areas along inland waterways where stable banks are essential is currently being investigated between km 440.6 and km 441.6 on the right bank of the Rhine. The measures are intended to protect the bank above mean water in the same way and as a replacement for conventional riprap revetments and at the same time to enhance its ecological value. The section on the Rhine with its high hydraulic loads as a result of shipping and high water, large fluctuations in water level, steep slopes and technical riprap revetments was selected specifically in order to investigate the application possibilities and limits of these bank protection measures.

The technical–biological bank protection measures to be tested were installed in nine test fields (TF). Riprap was retained in four fields. However, design and planting measures were implemented for ecological enhancement purposes. In four other fields, the riprap above mean water level was removed and replaced by bank protection measures with plants. One field remained without any slope protection after the riprap above mean water had been removed. In certain fields, additional local measures that had no immediate bank protection function were implemented below mean water. Banks adjacent to the stretch that were protected using conventional riprap served as a reference.

Vegetation and fauna groups along the test stretch were recorded before construction work began. The measures have been extensively monitored since their completion in 2011. This involved regularly recording and assessing the condition of the measures, the technical boundary conditions (bank geometry, hydraulic loads, water levels, weather data) and ecological parameters (vegetation, terrestrial and aquatic fauna groups and their interactions, CO_2 storage capacity, construction materials used) as well as construction and maintenance effort (costs).

The monitoring results were used to assess the technical–biological bank protection measures with regard to the three criteria − ensuring bank stability, ecology (terrestrial/aquatic) and costs − in comparison to riprap as a reference. Comparative assessments of the measures were made for each criterion on a scale from ‘1’ (very poor) to ‘5’ (very good). These were combined to produce an integrative overall rating.

The test fields along the Rhine were exposed to various impacts. In addition to ship-induced loads, the particularly large fluctuations in water level of up to 6 m and the resulting long periods of flooding, long dry periods with low water and hot summers all proved to be decisive stresses for the plants used in the technical–biological bank protection measures. Under these conditions, the different measures and the construction and design selected for them – with and without technical components – were not equally suitable to ensure bank protection. However, after optimising the measures (‘lessons learnt’) and taking into account the limits that were determined for each application, it may be concluded that all the technical–biological bank protection measures tested can in principle be applied on inland waterways. Which measures are technically feasible in each specific case depends largely on the hydraulic loads and the requirements for bank stability.

At the same time, the measures were shown to result in ecological enhancement compared to riprap − particularly with regard to species and structural diversity, the presence of rare, riparian and endangered species, the proportion of native species compared to neobiota and the formation of riparian zonation. It is apparent with regard to ecological objectives, which may differ significantly (e.g. promoting sunny reptile habitats or developing riparian reed beds), that none of the individual designs tested are capable of promoting all the necessary ecological objectives. It is therefore of central importance to determine in advance of planning which organisms and habitats are to be promoted. It may be more effective to implement a combination of different measures rather than a single measure.

Ecologically enhanced riprap and paving (TF 1, 4, 6 and 8) proved most suitable in the context of high demands on bank stability, high hydraulic loads and steep slopes, as is the case on the Rhine. These measures provide full bank stability regardless of the additional plants or structural elements introduced. As existing riprap has remained in place, these measures are also relatively inexpensive. Compared to the reference, medium to good ecological effectiveness is achievable in the terrestrial area; only the ecologically enhanced riprap with gravel and stone blocks (TF 4) shows little difference in comparison with the reference. The ecologically enhanced riprap is thus an ecologically successful and at the same time relatively inexpensive way of making banks more natural even in those cases in which large hydraulic loads make riprap indispensable for bank protection.

Construction methods which replace riprap revetment, such as plant mats (TF 7b and c) in the upper, rarely flooded slope areas, stone mattresses (TF 5) and willow brush mattresses (TF 2, 3), can also be applied under these boundary conditions and achieve good results when all three criteria are taken into account. Willow brush mattresses and plant mats also show comparatively high ecological effectiveness, while the ecological effectiveness of stone mattresses has not been much higher than the reference so far. In contrast, coir mats on hydroseeding (TF 7a), reed gabions (TF 5a) and plant mats (TF 7) did not provide sufficient bank protection in the lower, frequently flooded area. These were also more expensive, so that despite good ecological results they are assigned the lowest overall rating on the test stretch. TF 9, which had no slope protection after the riprap had been removed, shows good ecological enhancement but also increasing bank erosion and thereby demonstrates that bank protection is required here for stable banks.

The overall measures installed above mean water only have an ecological effect in the terrestrial area, where the greatest possible structural diversity and heterogeneous vegetation development are particularly effective. Measures involving highly homogeneous structures that do not allow bank morphology and bank vegetation to develop dynamically, particularly resilient designs with a weight per unit area, are of low ecological effectiveness.

Significant added ecological value compared to conventional riprap was achieved in particular where additional measures were implemented in the aquatic area, such as the dead wood fascines (TF 4) and root plates below the mean water level and the shallow water zone created by an off-the-bank wall (TF 1). Compared to the reference, the effectiveness of these measures was shown to be very good for aquatic plants, fish and macrobenthos. In addition to structural diversity and the presence of dead wood, an important role was also played in this context by protection against ship waves and high flow loads.

Recommendations for the optimisation of individual measures for future applications, especially with regard to structural design and fastenings, are provided based on the lessons learnt during installation and during the critical initial state. Bearing these optimisations in mind, the possible technical applications and limits of all the measures for inland waterways are indicated (Annex 3).

The evaluations of the test stretch were also used in a multi-criteria decision analysis to apply the findings to other boundary conditions. If the requirements for bank stability are not as great as on the test stretch or if the hydraulic load is lower, purely plant-based measures, such as willow brush mattresses and plant mats, will perhaps be the preferred option. These may be more effective in achieving ecological enhancement in the terrestrial area than vegetated riprap. In any case, additional enhancement through aquatically effective structures is necessary to bring about the best possible ecological development of the water.

Monitoring will be continued on the test stretch. The primary technical and ecological objective is to investigate the long-term development of the measures and possible maintenance strategies. Since 2020, biodegradable nonwoven geotextiles have also been investigated in test field 6 for use as filters in technical–biological bank protection measures. The aim is for these to contribute temporarily to bank stability in the critical initial state until the roots can take over the filter function.

In general, the investigations have shown that when planning and carrying out bank protection measures with plants on inland waterways a number of special features that differ from those for conventional riprap must be taken into account during the planning and implementation:

- Restricted installation times (construction only during dormancy)
- Required lead times (pre-cultivation of plant mats, obtaining willow branches during dormancy, etc.)
- Higher requirements for construction tendering and construction supervision
- Potentially higher construction costs
- Potentially higher maintenance expenses in the critical initial state (watering, reworking)

What is more, the flood neutrality of bank protection measures on rivers must be taken into account. Appropriate maintenance (pruning) must be carried out to avoid unacceptable constriction of the discharge cross section and obstruction of flood discharge.

The results obtained so far already provide a good basis for future applications of technical–biological bank protection measures in areas along inland waterways which, due to the boundary conditions, should not be allowed to develop completely freely but which must be protected. A dimensioning procedure (DWA 2016) and corresponding software (GBBSoft+), which also incorporate the lessons learnt from the test stretch (Söhngen et al. 2017), have been developed for the technical planning of measures. This makes it possible to check for each bank whether bank protection is fundamentally necessary, and if so, which technical–biological measures are applicable. A concrete design can be made. In addition, knowledge of the ecological potential of the bank protection measures should be used to assess their contribution to remedying the known ecological deficits of specific bank sections.

Specifications have also been prepared as an additional planning basis for various measures (vegetated riprap, willow brush mattresses, reed gabions and plant mats) (https://ufersicherung-baw-bfg.baw.de/binnenbereich/en/arbeitshilfen/kennblaetter). These will be supplemented in the follow-up to this report with new findings on the ecological effectiveness and technical optimisation of the measures as well as on specific application limits. This provides the first sound basis for the planning, design, implementation and ecological assessment of technical–biological bank protection measures.

Further results, reports and information on the test stretch and all other activities within the framework of the research project are currently being made available on the joint BAW and BfG internal portal (https://ufersicherung-baw-bfg.baw.de/binnenbereich/en).

Technical–biological bank protection measures provide designs that can ecologically enhance waterway areas where bank protection is indispensable. In these cases they offer a sensible alternative to riprap. However, they should not and cannot replace unprotected banks with the natural hydromorphological dynamics typically occurring in water bodies, wherever these are feasible on inland waterways. Even though technical–biological designs may have ecological deficits in terms of the artificial introduction of plants and technical components, they can nonetheless support sustainable bank management taking account of the wide range of interests that apply to inland waterways. In this way, they contribute to the implementation of legal, environmental policy and water management requirements. The objective is to use the ecological potentials in a significantly expanded and more opportunity-oriented manner in the future in order to actively promote sustainable watercourse development. In addition to the promotion of terrestrial ecology, the focus should in particular be on the permanent ecological enhancement of the aquatic area and the lateral and longitudinal networking of riparian habitats.

Annex 1

Overview: Boundary Conditions in the Area of the Rhine Test Stretch, Km 440.6 to Km 441.6, Right Bank (BAW, BfG 2010)

Annex 1: Overview – Boundary conditions in the area of the Rhine test stretch, km 440.6 to km 441.6, right bank (BAW, BfG 2010)

Location	Rhine-km 440.6 to km 441.6, right bank (1 km length) Hessian bank of the Rhine below the confluence of the Lampertheim oxbow lake in the 'Rhine-Hessian Rhine Area' landscape protection area
Initial state of the bank protection	Technical revetment – loose riprap without additional filter layer Armourstones LMB5/40 in a layer thickness of 60 to 90 cm, local old paving, many stones in the subsoil
Bank geometry	Slope inclinations: 1:2 to 1:3 Slope height: 10 m (km 440.6) …. 7 m (km 441.6), top edge of the adjacent ground (GOK = ground surface): approximately MSL + 91.0 m …MSL + 89.5 m
River geometry	In the direction of flow, transition from the undercut bank area to the slip-off zone Km 440.6: Undercut bank area, fairway close to the bank (approximately 25 m) Km 441.6: Slip-off zone, fairway further from the bank (approximately 140 m)
Ground	From GOK to approximately MSL + 89.0 m alluvial loam; below this to approximately 3 m below Rhine bed: gravelly sands, low to medium strength, silt lenses
Hydrology/Loads on banks due to natural flows	Large water level fluctuations – difference between GlW and HSW (HW): approximately 6 m (> 7 m) Flow velocities and shear stresses close to the bank (from HN models): HWMI: vStr = 0.99 *(km 440.6)* … 0.95 m/s *(km 441.6),* τ = 3.6 *(km 440.6)* … 3.4 N/m² *(km 441.6)* HWMII: vStr = 1.50 *(km 440.6)* … 1.30 m/s *(km 441.6),* τ = 7.0 *(km 440.6)* … 5.7 N/m² *(km 441.6)* Flow velocities close to the bank (from measurements taken at a distance of approximately 5 m from the bank): maximum 1.5 m/s
Hydraulic loads due to shipping	From measurements: Maximum stern wave height at the bank: 0.81 m (km 440.9), maximum secondary wave height: 0.57 m (km 440.9) Remark: The measurements only record a fraction of the approximately 40,000 inland vessels that pass through here every year. Calculation (BAW 2011): Maximum wave height: 0.40 (km 441.5) … 0.88 m (km 440.9); maximum water level drawdown: 0.19 m (km 441.5) … 0.73 m (km 440.9); maximum flow velocity: 1.10 m/s (km 441.5) … 1.99 m/s (km 440.9)
Initial state of the vegetation	Low species diversity (no species protected by law, predominantly European dewberry scrub, mainly widespread common species, alien (neophytic) woody plants such as box elders and Canadian poplars), low vegetation zonation, very little structural diversity, low colonisation potential
Initial state of the fauna	Low species diversity; no riparian specialists among terrestrial groups of fauna, mostly dominated by species without specific environmental requirements; aquatic fauna is dominated by invasive species

Annex 2

Overview of Designs Using Live Material and Plant Elements Introduced in Each of the Test Fields, Their Primary Function and Species Planted

Annex 2: Overview of designs using live material and plant elements introduced in each of the test fields, their primary function and species planted

Explanations to the table:

Plant species with colour-coded ratings of their development in the first 6 years following installation (plant species in brackets: introduced in comparatively small quantities):

- Green: Plant species have developed very well in this design/zone (could potentially spread!).
- Orange: Plant species have been consistently found in this design/zone, but relatively low quantity and/or sparse cover. May potentially spread with optimised design (see Annex 3).
- Red: Plant species have mostly failed with this design/zone.
- Black: This design with live material/plant element failed from the very beginning and it is therefore not possible to rate the development of the plant species introduced.

Identification of the primary function of the plants in the test fields:

- **U**: Plants primarily installed and necessary for bank protection – without plants there would be no bank protection!
- **Ö**: Plants installed primarily for ecological enhancement, not required for bank protection. However, if they develop well, the plants can also contribute to bank protection in the long term – bank protection guaranteed even without plants!

Test field 1 M8 Digging of planting trenches perpendicular to the bank; M9 Planting of log branch cuttings; M12 Building of a stone wall parallel to the bank line; M13 Installation of dead wood structures		
Design with live material/plant elements	**Function**	**Plant species**
Willow branch cuttings (M8, 9)	Ö	White willow, osier, ('Hutchinsons Yellow')
Live fascines (M8)	Ö	White willow, (purple willow, 'Hutchinsons Yellow', osier)
Brush layers (M8)	Ö	White willow, (purple willow, 'Hutchinsons Yellow', osier)
Hedge layers (M8) (bare-rooted seedlings)	Ö	Field maple, hazel, common dogwood, common ash, European spindle, guelder rose, bird cherry
Test fields 2 and 3 M1 Willow brush mattresses, hedge layer		
Design with live material/plant elements	**Function**	**Plant species**
Willow branches (M1)	U	White willow, purple willow, ('Hutchinsons Yellow', osier)
Crossbar timbers (M1)	U	White willow
Hedge layer (TF 2) (bare-rooted seedlings)	Ö	Common hawthorn, field maple, hazel, common dogwood, European spindle, guelder rose

Test field 4 Test M13 Installation of dead wood structures, M14 Placing of gravelly substrate and stone blocks		
Design with live material/plant elements	**Function**	**Plant species**
---		---
Test field 5 M2 Reed gabions, M3 and M4 Stone mattresses without or with pre-cultivated plant mats, hedge layer		
Design with live material/plant elements	Function	Plant species
Pre-cultivated reed gabions (TF 5a, M2) in the area from MW – 0.5 m to MW + 1.70m →with a different mix of dominant species for two planting zones!	U	**Planting zone 1: between MW - 0.5 m and MW + 0.5 m** Main species: Slender-tufted sedge, greater pond sedge (60–75 %) + mixture of species from the reed or softwood zone, e.g.: creeping bent, common club-rush, yellow iris, reed canary grass, gypsywort, purple loosestrife (25–40%) **Planting zone 2: between MW + 0.5 m and MW + 1.70 m** Main species: Tall fescue and reed canary grass (60–75%) + mixture of species from the reed or softwood zone, e.g.: slender-tufted sedge, greater-pond sedge and see above; grasses, e.g.: common couch, meadow foxtail, tufted hair-grass Yorkshire fog (25–40%) →fully vegetated and rooted on delivery
Pre-cultivated plant mats on stone mattresses (TF 5b, M4) in the area from MW – 0.5 m to MW + 1.70 m →with a different mix of dominant species for two planting zones!	Ö	**Planting zone 1: between MW – 0.5 m and MW + 0.5 m** See reed gabions planting zone 1 →fully vegetated and rooted All species failed in the monitoring period! **Planting zone 2: between MW + 0.5 m and MW + 1.70 m** See reed gabions planting zone 2 →vegetated and rooted on delivery, in some areas little vegetation due to the failure of dominant species All species failed in the monitoring period!
Hedge layer (TF 5a and b) (bare rooted seedlings)	Ö	Common hawthorn, field maple, hazel, common dogwood, European spindle, guelder rose

Test field 6 Test M10 Introduction of topsoil alginate and subsequent hydroseeding; M11 Planting of reed bales into the riprap		
Design with live material/plant elements	**Function**	**Plant species**
Hydroseeding (M10) (30 g/m² seed)	Ö	False oatgrass, perennial rye-grass, cock's foot, tall fescue, common couch, meadow foxtail, Yorkshire fog, smooth bedstraw, common yarrow, creeping bent, reed canary grass Most of the seeds were flushed away!
Single plants (M11) (4 reed bales/m²) in the area from MW – 0.5 m to MW	Ö	Yellow iris, lesser bullrush, reed, common club-rush, water mint, gypsywort, purple loosestrife All the reed bales were flushed away!
Test field 7 M5 Pre-cultivated plant mats on geotextiles, M6 Woven coir fabric on hydroseeding, M7 Reed rolls		
Design with live material/plant elements	**Function**	**Plant species**
Pre-cultivated plant mats*¹ (M5) (20 plants/m²) in the area of TF 7a1/a2 from MW – 0.5 m to MW + 0.5 m in the area of TF 7a1/a2 from MW + 0.5 m to MW + 1.70 m (integration in fascine trench) and TF 7b/c from MW + 0.5 m to top edge of the slope	U	Main species: Reed, reed canary grass, slender-tufted and greater pond sedge (60–75%) + mixture of species of the reed zone, e.g.: creeping bent, common comfrey, common figwort, purple loosestrife, common club-rush, gypsywort (25–40%) →already without vegetation in some areas on delivery because of failure of individual species due to difficult cultivation conditions! Main species: Slender-tufted*² and greater pond sedge*², reed canary grass*², tall fescue*² (60–75%) + mixture of species of the reed zone, e.g.: creeping bent, common comfrey, common figwort, purple loosestrife, common club-rush, gypsywort (25–40%) →already without vegetation in some areas on delivery because of failure of individual species due to difficult cultivation conditions; some areas therefore have a different combination of species (replacement):
		Reed canary grass*² (30%), slender-tufted sedge*² (20%), yellow iris (20%), lesser pond-sedge (10%), purple loosestrife (5%), meadowsweet (5%), water mint (5%), brooklime (5%) →fully vegetated and rooted on delivery
Hydro-seeding (M6) (approximately 20 g/m²) in the area from MW + 1.70 m to top edge of the slope	Ö	False oat grass, perennial rye-grass, cock's foot, tall fescue, common couch, meadow foxtail, Yorkshire fog, smooth bedstraw, common yarrow, creeping bent, reed canary grass

Reed rolls (M7) in the area of TF 7b/c from MW to MW + 0.5 m (4 reed bales/m^2)	Ö	Yellow iris, reed, common club-rush, purple loosestrife, gypsywort, water mint →the reed roll did not withstand loads from the Rhine. All the reed bales were flushed away!
Test field 8 M12 Building of a stone wall running parallel to the bank line		
Design with live material/plant elements	**Function**	**Plant species**
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Test field 9 M15 No bank protection above MW, log willow branch cuttings on the slope crest, log groyne with willow branch cuttings and fascines		
Design with live material/plant elements	**Function**	**Plant species**
Willow branch cuttings and fascines (M15)	U	White willow, (osier, ‘Hutchinsons Yellow’, purple willow)

*1 See also (BAW/BfG/WSA-MA 2012) for additional information on the plant mats used (mat types with different combinations of species, cultivation conditions, quality characteristics)

*2 The orange colour coding for the species refers to the lower slope area; in the upper slope zone, the species have developed well among all the other species (= green!).

Annex 3

Summary Rating of the Performance of Technical-Biological Bank Protection Measures Regarding Their Stability and Effectiveness in Ensuring Bank Protection; Design Optimisation and Technical Application Recommendations

Annex 3: Summary rating of the performance of technical-biological bank protection measures regarding their stability and effectiveness in ensuring bank protection; design optimisation and technical application recommendations

Bank protection measure/ design	**Stability of the measures** **Ensuring local stability of the bank slope**	**Completed rehabilitation works**	**Technical feasibility of the design for waterways** **Required design optimisation ('lessons learnt')**	**Technical application recommendations**
Ecologically enhanced riprap (1:3) **TF 1, 4, 6, 8,** upper and lower slope zones	Local stability ensured by riprap from the beginning	No rehabilitation required	Generally feasible design *(Topsoil alginate not suitable for establishing vegetation! (TF 6))*	Can be applied without technical limitation (riprap design required)
Willow brush mattresses **TF 2 and 3**, upper and lower slope zones **(1:3)**	Insufficient local stability! Local erosion of the soil under the willow brush mattresses at the beginning; erosion is progressing (fewer roots and shoots between the crossbars); worsened as a result of maintenance activities, most intense erosion in TF 2 following large-area pruning (cavities of up to 70 cm depth overall), in TF 3 with limited pruning: erosion up to 40 cm depth	Local rehabilitation in the middle area of TF 2 in 2018: Willow branch cuttings, common dogwood (unsuccessful), local willow brush mattress (effect to be confirmed in the longer term); ongoing observation.	Feasible design Optimised installation/ maintenance: Install willow branches completely covering the bank, possibly placed on degradable geotextile; reduce spacing of crossbars (< 50 cm) and use wooden stakes to improve soil contact; avoid large-area pruning to 10 cm above ground during maintenance	Can be applied with optimised design where conditions* are similar as or more favourable than on the test stretch

Italics: Results that are not relevant to stability

** Conditions similar as or more favourable than on the test stretch means that the slope's inclination, the in-situ soil and the hydraulic loads result in similar or more favourable conditions with respect to bank stability (to be verified by corresponding calculations)*

Bank protection measure/ design	**Stability of the measures** **Ensuring local stability of the bank slope**	**Completed rehabilitation works**	**Technical feasibility of the design for waterways** **Required design optimisation ('lessons learnt')**	**Technical application recommendations**
Reed gabions **TF 5a,** lower slope zone **(1:2.5)**	Insufficient local stability! After five years almost all plant species had been lost (except for slender-tufted and greater pond sedge); coir fabric cover destroyed early; loss of soil from the gabions; stones in the gabions displaced down the slope; local loss of granular filter	Rehabilitation 2017: Area was covered with gravel and a layer of armourstones; slender-tufted and greater pond sedge grow through gaps in stone layer; local stability sufficient after rehabilitation with armourstones	Feasible design Optimised installation: Suitable plants (here: slender and greater pond sedge); use of a geotextile as cover which is stable in the initial years, if possible biodegradable in the longer term	Can be applied with optimised design where conditions* are similar as or more favourable than on the test stretch
Stone mattresses **TF 5a**, upper slope zone **TF 5b**, upper and lower slope zones **(1:2.5)**	Local stability ensured from the beginning	No rehabilitation required *(TF 5b, lower slope zone: establishing vegetation with pre-cultivated plant mats unsuccessful.)*	Generally feasible design *(suitable for natural succession of vegetation)* *(plant mats on stone mattresses not suitable for establishing vegetation)*	Can be applied where conditions* are similar as or more favourable than on the test stretch
Plant mats **TF 7b, c,** upper slope zone **(1:3)**	Insufficient local stability in the initial state Local erosion of soil under the plant mats (no filter stability; stakes, crossbars instable due to buoyancy, buoyancy caused plant and filter mats to rise and fall)	Local rehabilitations 2012: Installation of sod secured with crossbars, subsequent hydroseeding; local stability sufficiently ensured following rehabilitation	Feasible design for rarely flooded slope areas Optimised installation: Use filter-stable geotextile, preferably biodegradable; tightly spaced crossbars and sufficiently deep-reaching stakes	Can be applied with optimised design for rarely flooded areas where conditions* are otherwise similar as or more favourable than on the test stretch

Italics: Results that are not relevant to stability

** Conditions similar as or more favourable than on the test stretch means that the slope's inclination, the in-situ soil and the hydraulic loads result in similar or more favourable conditions with respect to bank stability (to be verified by corresponding calculations)*

Bank protection measure/ design	**Stability of the measures** **Ensuring local stability of the bank slope**	**Completed rehabilitation works**	**Technical feasibility of the design for waterways** **Required design optimisation ('lessons learnt')**	**Technical application recommendations**
Plant mats TF 7a, b, c, lower slope zone **(1:3)**	Insufficient local stability from the beginning! Rising and falling of plant and filter mats caused by frequent flooding prevents root growth into the subsoil; plants fail to take root and establish; stakes and crossbars become loose; erosion of soil under the plant and filter mats; plants die back, sheep wool dissolves very quickly	Rehabilitation 2012/2013: Plant mats covered completely with a layer of armourstones; plants grow through gaps in stone layer; local stability sufficiently ensured after rehabilitation with armourstones	Not feasible with the tested fixings in frequently flooded areas Optimised installation: Secured in place by means of a layer of armourstones	Can be applied with optimised design where conditions* are similar as or more favourable than on the test stretch
Coir mat on hydroseeding TF 7a, upper slope zone **(1:3)**	Insufficient local stability from the beginning! Loosening of stakes; significant erosion of soil below and through the coir mat (lack of filter stability); comprehensive soil displacement below the coir mat (lack of crossbars to check erosion); increasing deformation of the slope	Rehabilitation 2012: Filling of cavities; covering with sods, secured with stakes and crossbars; subsequent hydroseeding (largely unsuccessful) Rehabilitation 2017: Large area covered by a layer of armourstones; local stability sufficiently ensured following rehabilitation with armourstones	Not feasible for mostly or temporarily flooded slopes	Can be applied only for areas above the highest wave run-up

Italics: Results that are not relevant to stability

** Conditions similar as or more favourable than on the test stretch means that the slope's inclination, the in-situ soil and the hydraulic loads result in similar or more favourable conditions with respect to bank stability (to be verified by corresponding calculations)*

Bank protection measure/ design	**Stability of the measures/ Ensuring local stability of the bank slope**	**Completed rehabilitation works**	**Technical feasibility of the design for waterways/ Required design optimisation ('lessons learnt')**	**Technical application recommendations**
Without slope protection, willow branch cuttings on adjoining plane at the top of the slope TF 9, upper and lower slope zones **(1:3)**	Insufficient local stability from the beginning, as expected! Lasting, progressive erosion in the slope area; soil around willow branch cuttings exposed by water erosion, they loosen and get lost (Only measure which was not designed to ensure bank stability)	Local rehabilitation 2016: Securing the 500 m-sign with armourstones Ongoing observation! Far-reaching rehabilitation required in case of need to stabilise the bank	Not feasible if stable banks are required Scattered willow branch cuttings on the adjoining plane at the top of the slope are not able to prevent bank erosion	Can be applied where banks are erosion-stable or where unlimited erosion is tolerable

Italics: Results that are not relevant to stability

* *Conditions similar as or more favourable than on the test stretch means that the slope's inclination, the in-situ soil and the hydraulic loads result in similar or more favourable conditions with respect to bank stability (to be verified by corresponding calculations)*

Annex 4

Specifications (Documentation of Individual Measures)

Annex 4: Specifications (Documentation of Individual Measures)

The object of this report is to set out the technical–biological bank protection measures implemented in the individual test fields and to produce a rating. In addition, the development of all the individual measures since their installation in 2011 is documented considering technical and ecological aspects. Table A1 provides a list of all single measures which either form part of the planned technical–biological bank protection measures or were implemented as complementary measures without an actual bank protection function. The table also shows the test fields in which the measures were installed.

Table A1: Test field and installed measures

Technical-biological bank protection measures as replacement for technical riprap revetments above MW or MW – 0.5 m		
M1	Willow brush mattresses at an angle and perpendicular to flow direction	TF 2 and 3
M2	Reed gabions on granular filter	TF 5a, lower slope zone
M3	Stone mattresses on granular filter without plant mats	TF 5a and 5b, upper slope zone
M4	Stone mattresses on granular filter with plant mats	TF 5b, lower slope zone
M5	Plant mats on various geotextiles as filters	TF 7a, 7b and 7c
M6	Coir mats on hydroseeding	TF 7a, upper slope zone
M7	Reed rolls	TF 7b and 7c (at AZW)
Measures to achieve ecological enhancement of the existing riprap		
M8	Preparation of planting trenches perpendicular to the bank in a riprap planted with a choice of shoot-forming willow fascines, brush and hedge layers	TF 1
M9	Planting of willow branch cuttings	TF 1, TF 9
M10	Introduction of topsoil alginate into the riprap and subsequent hydroseeding	TF 6
M11	Planting of reed bales into the riprap	TF 6
M12	Building of a stone wall running parallel to the bank line to reduce ship-induced loads	TF 1, TF 8
M13	Installation of dead wood structures (dead trunks with root plates, dead wood fascines, log groyne) in the riprap	TF 1, TF 4, TF 9
M14	Placing of gravelly substrate and groups of stones or rocks on existing riprap	TF 4
No bank protection after removal of riprap above MW, allowing for a limited degree of natural development		
M15	Removal of technical bank protection, no bank protection above MW, allowing for a limited degree of natural development	TF 9

Measure M1: Willow brush mattresses at an angle (TF 2) and perpendicular (TF 3) to flow direction

<table>
<tr><th colspan="2">Willow brush mattresses (WSL) at an angle or perpendicular to flow direction
(slope inclination 1:3)</th></tr>
<tr><td>Bank stability</td><td>– Initial stage (2012): At higher water levels, gravel layer eroded progressively to complete loss; willow branches and fixings largely stable; individual stakes pulled out due to buoyancy during flooding, limited erosion and soil displacement under the willow branches; additional covering with brushwood in the lower slope zone unable to prevent erosion; erosion intensified where surface coverage of branches was not complete; subsequent placing of another layer of gravel for better soil contact of willow branches; good root development, relatively densely branched root system with lengths of up to 60 cm confirmed by means of root excavation
2013/14:
– Good, largely surface-covering development of willows despite frequent flooding, temporarily reaching past GOK and lasting for ten weeks up to approximately MW + 1.5 m; overall good integration with in-situ soil achieved; checking of ongoing sediment erosion and soil displacement under the willow branches with some scattered willows still lacking firm soil contact, in particular between the crossbars; this does not compromise overall stability
– Area of strongest growth between MW + 0.5/1.0 m and MW + 1.7 m
– In the lower slope areas that are most intensely exposed to shipping and long periods of flooding (MW to MW + 1 m), comparatively sparse vegetation coverage, fewer and less vital willow shoots, in 2014 with roots forming from shoots
2015:
– Further excavation reveals well-developed root system with lengths of up to 1.70 m, root development as found locally sufficient for ensuring bank stability if present throughout the slope
– Testing of initial maintenance concepts: pruning of the willows up to approximately 10 cm above the slope surface, larger areas in TF 2, smaller portions in TF 3; subsequent damage of pruned willows in the larger areas owing to extreme weather (first longer lasting flooding, then dryness), slopes mainly affected in the middle zone resulting in intensified soil erosion
– Good development of the unpruned or only locally pruned willows
– In TF 2 in particular, local bank stability was no longer ensured sufficiently throughout the slope after pruning of the willows, increasing soil erosion occurred during HW
2018:
– Strongest growth zone in the lower slope area, willow dieback in the upper slope zone owing to a very dry summer
– Ongoing observation because local bank stability critical as erosion progresses</td></tr>
<tr><td>Ecology</td><td>Vegetation:
– Surface-covering development of site-typical alluvial softwood plants; willow shrubs (purple willow) were planted in combination with taller-growing willow trees (white willow), the latter being clearly discernible (layering of the plant stand as structural feature)
– Initially dominant development of purple willow in all slope zones, progressive development of zonation in later years (white willow dominant in the lower, wetter zone)</td></tr>
</table>

	– Spontaneous development of initial herbaceous species and false-acacia (neophyte) in the shelter of the willows (2012); spontaneous vegetation declining more and more due to increasing shading by the willows in subsequent years (largely woody design with lower species richness); in dry years weakening of the willows in some areas due to infestation with dodder (Cuscuta lupuliformis), minor infestations of purple willows with rust fungus – Since 2015 (first maintenance): Richly structured, layered vegetation development, in particular in TF 3 where maintenance was less intensive; loss rates higher among willows that were subjected to intensive pruning (TF 2), but temporary increase in herbaceous species (higher species richness and moisture zonation discernible); successive immigration of berry catchfly, an endangered species Aquatic fauna (2012–2018): – The measure has not been shown to have had any influence on fish and macrobenthos colonisation compared to the reference. Terrestrial fauna (2013–2017): – Birds: The willow brush mattresses show first tendencies of developing suitable habitat structures for woodland breeding birds – Ground beetles: Emergence over time of a more diverse beetle community with higher numbers of individuals and a proportion of riparian species – Reptiles: Willow stand not suitable as habitat for reptiles – Spiders: So far, no clear indication regarding spider communities – Other groups of organisms: Willow brush mattresses favour the spontaneous accumulation of dead wood, which is likely to have a positive effect on species that use dead wood as their habitat; extensive flowery bee pasture for nectar- and pollen-collecting insects, many insect species with narrow host plant spectrum observed on willows (galls of the gall wasp, willow spittle bug, caterpillars of the willow sawfly) Other: – The design consists almost exclusively of live and natural material – High CO_2 storage capacity of the willows as climate-regulating ecosystem service
Maintenance	– Initially: Monitoring of plant-feeding pests, parasitic species, rust fungus infestation (weakening the willows); removal of emerging neophyte individuals (false-acacia) – 2015: Pruning of the willows; TF 2: large-area pruning on 95% of the test field, fostering individual willow trees as target vegetation; TF 3: pruning in smaller portions of the stand (3 sections, no pruning between them); fostering individual willow trees as target vegetation
Rehabilitation measures	– 2012: Subsequent placing of gravel layer – 2018/19: Attempt to foster denser willow growth in the middle slope zone of TF 2 by planting branch cuttings and placing one willow brush mattress locally – monitoring of further development; subsequent introduction of common dogwood in the upper slope area unsuccessful

Measure M2: Reed gabions on granular filter (TF 5a)

Reed gabions on granular filter (slope inclination 1:2.5)	
Bank stability	– Initial stage (2012): Relatively uncritical, as stable position on the slope from the very beginning due to self-weight, no additional fixings required; initially insufficient toe integration in the riprap resulted in reed gabions sliding slightly after first floods (steep slope inclination); good positional stability after reinforcement of toe integration with armourstones 2013: – Bank stability continues to be ensured by the self-weight of the gabions and their positional stability across the entire slope as well as by the filter-stable structure within the gabions and in relation to the subsoil (granular filter) – Further flooding, in particular the 10-week continuous flooding of the entire gabions, with simultaneous hydraulic loading led to major losses of certain plant species (planting zone 1 (MW to MW + 1 m): reed canary grass, creeping bent, common club-rush, gypsywort, purple loosestrife, yellow iris; planting zone 2 (MW + 1 m to MW + 1.7 m): reed canary grass); after HW, discrete local damage to the gabions, caused by plant failure and damage to the woven coir fabric, leading to flushing out of small amounts of local internal substrate 2014: – Loss of vegetation intensified; in planting zone 1 (see above), the gabion squares that had ‘no’ or ‘hardly any’ vegetation were predominant; only the planted tall sedges still provided coverage of 30% at 35% total vegetation coverage; in planting zone 2 (see above), the planted species tall fescue and reed canary grass only reached total coverage of 25%, and gabion squares with ‘no’ or ‘hardly any’ vegetation again predominated; damage to the gabions intensified due to a lack of plants and missing woven coir fabric as well as progressive loss of substrate from the gabions 2015: – Continued strong decline in vegetation development (further decrease in total vegetation coverage to 15–20% in planting zone 1 and 5–35% in planting zone 2); remaining species in each of the planting zones analogous to 2014; progressive displacement of stones down the slope within the substrate- and vegetation-free gabions 2016: – Partially ‘empty’ wire mesh lining in the upper area as a result of the stone displacements within the gabions, the underlying granular filter can be increasingly washed out. This means that long-term bank stability is endangered; therefore, stabilisation in 2016 by covering the gabions with a layer of armourstone 2017–2020: – Bank stability sufficiently ensured following rehabilitation with armourstones
Ecology	Vegetation: – Initial stage (2012): Initiation of suitable bank vegetation by means of reed gabions vegetated according to different zonation and onset of colonisation with spontaneous plant growth, thus increasing the habitat function compared to the largely vegetation-free original state

<table>
<tr><td></td><td>
– 2013: Reed zone (lower slope area) only pronounced in partial areas with major losses of individual species (see above); decline in initial species diversity; sedges so far tolerant of flooding and spreading; higher vegetation coverage in higher planting zone 2 (flooded for a shorter period than planting zone 1); decline in spontaneous plant growth
– 2014: Further loss of vegetation, decline in species numbers and coverage (planting and spontaneous plant growth), planting zone 1 more affected than planting zone 2
– 2015: Continuing strong decline in vegetation development and species numbers in both planting zones; vegetation-free gabion areas with exposed wire body predominate and pose an increasing risk to fish during flooding events
– 2016 (before rehabilitation): Scattered patches of vegetation with only sedges remaining from original planting in planting zone 1; low species and flower diversity in both planting zones (almost exclusively native, but predominantly ‘spontaneous’ non-riparian species), low plant volume, with occurrence of successively migrated RL-species meadow fleabane
– 2017 (after rehabilitation) – 2019: Especially sedges, but also other species of the original planting and native spontaneous plant growth benefit from the stability of the surcharge load and grow through gaps in the stone layer; subsequently, renewed positive development of plant species diversity
Aquatic fauna (2012–2018):
– The measure has not been shown to have had any influence on fish and macrobenthos colonisation compared to the reference.
Terrestrial fauna (2013–2017):
– Birds: An expert assessment shows that the measure has not so far developed in a way that provides suitable habitat structures for birds.
– Ground beetles: Higher numbers of individuals and species in the 2013/14 monitoring period compared to 2017; however, comparably low proportion of individuals of riparian species (effects possibly due to loss of reed vegetation and rehabilitation measures), overall emergence of a more diverse beetle community with higher numbers of individuals compared to the reference
– Reptiles: It is not possible to obtain a clear rating of the impact of the measures
– Spiders: In the 2013/14 monitoring period, the measure resulted in higher numbers of species and individuals compared to the reference. However, by 2017 these numbers had fallen back to the reference level; overall high proportion of non-riparian individuals, no clear effect of the measure can be determined
Other:
– Design with a high proportion of artificial and non-natural materials (galvanised wire, stones, polypropylene as a fine support framework for the plant body)
</td></tr>
<tr><td>Maintenance</td><td>
– Watered a few times after completion, but no other maintenance
– Monitoring of neophytic species and plant-feeding pests
– Intensive monitoring of the gabions with regard to vegetation development and the washing away of material
</td></tr>
<tr><td>Rehabilitation measures</td><td>
– 2012: Reinforcement of toe integration with additional armourstones shortly after installation
– 2016: Coverage of all the reed gabions with a layer of armourstones (LMB5/40)
– 2017–2020: No further rehabilitation measures required
</td></tr>
</table>

Measure M3: Stone mattresses on granular filter without plant mats, with topsoil application (TF 5a and TF 5b above)

Stone mattresses (SM) on granular filter, without plant mats, with topsoil application (slope inclination 1:2.5)	
Bank stability	– Initial stage (2012): Uncritical, as stable position on the slope from the beginning owing to self-weight; no additional fixings required; topsoil application in flooded areas eroded as expected, but without relevance for bank stability – 2013: Bank protection ensured by the area-wide stable position of the stone mattresses on the slope and by the filter-stable structure through granular filters even after further flooding and hydraulic loads; damage to the plastic net in a few places – 2014–2020: Statements remain valid; no further damage to the plastic net, bank protection sufficiently guaranteed by stone mattresses
Ecology	Vegetation: – Initial stage (2012): Rapid and extensive colonisation of the stone mattresses with spontaneous herbaceous vegetation; denser and more vigorous growth in areas near the shoulder of the slope, which are still covered with soil, compared to the stone mattresses in the lower slope areas, which have been exposed by flooding; development of species- and structurally-rich vegetation due to the different substrate coverage – 2013: Higher total coverage of vegetation in areas still covered with soil compared to areas exposed by water (approximately 90% vs. 50%); nitrogen-loving species, especially mugwort, dominate – 2014: Higher total coverage of vegetation, but lower number of species in areas that are still covered with soil compared to areas that have been exposed by flooding (approximately 75% vs. 55% coverage/Ø 34 species vs. Ø 60 species); nitrogen-loving species, especially mugwort and greater burdock dominate – 2016: Higher total coverage and number of species in areas that are still covered with soil compared to areas that have been exposed by water (approximately 60% vs. 20% coverage/57 species vs. 51 species); strong grassy-herbaceous vegetation of predominantly native, but non-riparian species (due to the location of the SM in the middle and upper slope areas), occurrence of 5 RL species and one protected species, furthermore occurrence of some rare nationwide species with occurrences along large flowing waters or species of semi-arid grassland and nutrient-poor meadows, overall high level of both species richness and species richness of flowers compared to the reference Aquatic fauna (2012–2018): – The measure is ineffective for fish and macrobenthos due to its location in the middle and upper slope areas. Terrestrial fauna (2013–2017): – Birds: No corroborated effect – Ground beetles: Overall emergence of a more diverse beetle community with higher numbers of individuals compared to the reference; occurrence of 4 RL species – Reptiles: Significantly higher number of sightings compared to the reference indicate that open and sunny areas can provide suitable reptile habitats – Spiders: In the 2013/14 monitoring period, the measure resulted in higher numbers of species and individuals compared to the reference. However, by 2017 these numbers had fallen back to the reference level;

	overall high proportion of non-riparian individuals, no clear effect of the measure can be determined – Other groups of organisms: High and diverse species richness of flowers compared to the reference indicates increased habitat quality for flower-visiting insects Other: – Design with a high proportion of artificial and non-natural materials (polypropylene net, small armourstones)
Maintenance	– Low maintenance: Regular removal of individually occurring neophytes (ashleaf maple, goldenrod, false-acacia, London plane, hybrid poplar, Jerusalem artichoke)
Rehabilitation measures	– 2012/2013: Minor repair work on the plastic net; no further subsequent measures required

Measure M4: Stone mattresses on granular filter with plant mats (TF 5b, lower slope zone)

After removal of the plant mats in 2013 no further observation of the original design, further monitoring in the future as for M3

Stone mattresses (SM) on granular filter, with plant mats (slope inclination 1:2.5)	
Bank stability	1. Stone mattresses: – Initial stage (2012): Uncritical, as stable position on the slope from the beginning owing to self-weight; no additional fixings required on the slope – 2013: Bank protection ensured by the surface-covering stable position of the stone mattresses on the slope as well as filter-stable structure through granular filters even after further flooding and hydraulic loads; damage to the plastic net in a few places – 2014–2020: Statements from 2013 still hold true, no further damage occurred to the plastic net 2. Plant mats, fixed on stone mattresses: – Initial stage (2012): The plant mats were not in an optimal condition when they were installed; the mats have hardly any self-weight; buoyancy and wave loads during flooding lead to changes in pressure (‘pumping effects’), corresponding up and down movement of the mats prevents them establishing close contact with the soil to enable roots to grow into the stone mattresses; dry periods with low water levels and frost have damaged plants; complete loss of the pre-cultivated species on plant mats in a relatively short period of time as well as damage and local destruction to pre-cultivated supporting fabric (coir) – 2013: Further heavy loads, especially due to 10-week uninterrupted flooding and simultaneous ship-induced loads; no plant development, supporting coir fabric completely eroded; only 3-dimensional polyethylene netting still present – Under the given boundary conditions (slope inclination 1:2.5, repeated flooding combined with ship-induced hydraulic loads, dry and frost periods, poor initial condition of the mats, resulting in lack of rooting in the stone mattresses) plant mats are not suitable on stone mattresses (the remains of the plant mats were therefore removed) – Banks sufficiently protected by stone mattresses
Ecology	Vegetation: – ‘Plant mats’ sub-measure not successful due to the complete loss of pre-cultivated and few spontaneously immigrated species; the ecological objective of developing more natural riparian vegetation could not be achieved by using plant mats on stone mattresses; ecological development by natural succession anticipated after removal of the plant mats – 2013: Natural succession produces approximately 5% total vegetation coverage on stone mattresses after removal of the plant mats – 2014/2015: Natural succession has not progressed further (still low coverage of approximately 5%) – 2016–2018: Overall only sparsely colonised with predominantly temporarily occurring non-riparian species (not flood-tolerant) Aquatic fauna (2012–2018): – The measure has not been shown to have had any influence on fish and macrobenthos colonisation compared to the reference.

	Terrestrial fauna (2013–2017): – No differentiated monitoring took place between M3 and M4; therefore, no corroborated effect on the groups of terrestrial animal species Other: – Design with a high proportion of artificial and non-natural materials (polypropylene net, small armourstones)
Maintenance	– Watering of plant mats in the initial period – Removal of individually occurring neophytes (ashleaf maple, goldenrod)
Rehabilitation measures	– 2012: Plant mats subsequently weighted down with individual armourstones – August 2013: Removal of the remains of plant mats after complete plant loss, including the fixings; stone mattresses are left to succession – as in the upper area – see measure M3 – No further measures required

Measure M5: Plant mats on various geotextiles as filters (TF 7)

Plant mats on various geotextiles as filters (slope inclination 1:3)	
Bank stability	– Initial stage (2012): Plant mats in very poor condition when installed; very critical, especially in the lower slope area that is frequently flooded and consequently subject to greater loads; buoyancy and wave loads during flooding lead to changes in pressure (‘pumping effects’), corresponding up and down movements of the mats, which have virtually no self-weight, between linear fixings and point fixings; movements of the mats prevent them establishing close contact with the soil; roots consequently not always able to grow into the subsoil; some stakes and crossbars loosened by buoyancy and pulled out in some cases; as a result, some of the mats are no longer sufficiently fixed in flooding area; some downward soil displacement under the mats (limited only by crossbars); overall, there is a lot of damage, especially in the area with nonwoven sheep wool; rapid biodegrading in contrast to the installed synthetic nonwoven; bank protection in the lower, frequently flooded slope area is no longer sufficient; – better condition in the upper, less flooded slope area, limited loss of soil due to non-filter-stable coir mats – 2013: Further increase in damage in the lower slope area due to 10-week uninterrupted flooding combined with simultaneous ship-induced loads, loss of all plants, supporting coir fabric destroyed; bank protection no longer ensured here by plant mats and filter mats, rehabilitation of the entire lower slope area (below MW + 1.7 m) by coverage with a layer of armourstones; in contrast, stabilisation of the condition in the upper, rarely flooded slope areas (above MW + 1.70 m) after local rehabilitation measures with sods, crossbars and hydroseeding, good development of the plants here – 2014/2015: Bank sufficiently protected in the lower slope area by a layer of armourstones (LMB5/40), plants grow through the gaps in the armourstones; further stabilisation in the upper slope area due to predominantly low water levels; ‘undisturbed’ further development and spreading of the plants; TF area extensively and densely vegetated except for a few small damaged areas – 2016–2019: Bank sufficiently protected in the upper slope area (above MW + 1.70 m) by plant mats; – plant mats on filter mats in the slope areas that are frequently flooded for long periods are not suitable under the given boundary conditions; the permanent close contact with the soil required for roots to develop and for interlocking with the subsoil could not be guaranteed here by linear or point fixings; nonwoven sheep wool (too rapid biodegrading) and coir fabric (not filter-stable) are unsuitable in these areas
Ecology	Vegetation: – Initial stage (2012): Despite large amount of vegetation lost and initial difficulties (predominantly in the lower slope area), positive development from a vegetation point of view: large number and diversity of flowering tall forbs, reeds, grasses and herbs; initiation of site-typical vegetation zonation; increase in structure on the bank slope; noticeable differences between contents and plant growth of different geotextiles: sheep wool with fertilising effect → stronger growth, promotion of nitrogen-loving species; synthetic nonwoven → good and vital plant growth, but not recommended from an ecological point of view, as it does not decompose

	– 2013: Large loss of plants in the lower slope area due to flooding at higher water levels combined with ship-induced loads; ecological statements initially only possible for the upper slope area, here positive development of the plant mats; planted species become competitive and build up site-typical vegetation with a good mix of species – 2014: After rehabilitation of the lower slope area (up to MW + 1.70 m), growth of individual highly regenerating and flood-tolerant species (from original planting) growing through gaps in the stone layer, plants benefit from stability of the surcharge load of the installed stones; most of the upper slope area extensively and densely vegetated, high level of species diversity in the area of TF7 b and 7c; progressive development of the TF apparent as species are increasingly distributed according to their natural habitat requirements (natural bank zonation) – 2015: Predominantly occurrence of sedges and reed canary grass from the original planting in the gap system of the riprap (rehabilitation area); upper slope area still extensively and densely vegetated with plants typical of dry-warm sites as well as species from the original planting; species are increasingly distributed according to their natural habitat requirements (natural riparian zonation) – 2016/2017: Sparse initial vegetation with isolated reed beds and wet tall forbs in the lower rehabilitated slope area; grassy-herbaceous vegetation in the upper area, predominantly native species, but high proportion of non-riparian ‘spontaneous species’, occurrence of 6 endangered and 2 protected species; of all the measures investigated (M1–M15) this measure provides the greatest species richness of plants and flowers, pronounced zonation – 2018/2019: Progressive development of a reed zone in the lower rehabilitated slope area Aquatic fauna (2012–2018): – The measure has not been shown to have had any influence on fish and macrobenthos colonisation compared to the reference. Terrestrial fauna (2013–2017): – Birds: Positive effect of the well-developed herbaceous layer in combination with adjacent reed beds on conditions for foraging and resting for waterbirds, ground nesters and reed nesting birds; measure with high potential for providing suitable habitat structures in the long term – Ground beetles: Compared to the reference, higher numbers of species and individuals, higher proportions of riparian individuals and increased occurrence of RL species – Reptiles: Significantly higher sighting rates compared to the reference (indication of suitable reptile habitats) – Spiders: Slightly higher species numbers and colonisation densities compared to the reference (favourable spatial structure of grassy-herbaceous vegetation); occurrence of a species that is listed on the watch list and that is strongly associated with humid habitats – Other groups of organisms: High flower diversity indicates favourable foraging habitat for flower-visiting insects Other: – Design with predominantly live material, nevertheless some synthetic and non-natural materials (fine support framework made of plastic for coir share in mats, synthetic geotextile, wire for stake/crossbar fixing) – Average CO_2 storage capacity compared to all measures (climate-regulating ecosystem service)

Maintenance	– Watered a few times after completion – September 2012, May and July 2013: Mowed with trimmers between the slope and the maintenance path, no mowing in the slope area – 2014: Mowed with trimmers on and at the top of the slope – 2015: Completely mowed in the slope area (June), partially mowed again in TF 7b and c (autumn); removal of the mown material in each case – Since 2016: Alternating partial mowing in each test field section – Monitoring and removal of neophytic species (young growth of hybrid poplar)
Rehabili-tation measures	– 2012: Stakes and crossbars driven back into the ground after each flooding; subsequent extensive hydroseeding for stabilisation and local rehabilitation with sod in the upper slope area; lower slope area covered with a layer of large armourstones to ensure sufficient bank protection, higher in the areas with nonwoven sheep wool (up to MW + 1.70 m), less high in areas with synthetic nonwovens (up to approximately MW + 1.00 m) – 2013: Rehabilitation of the entire lower slope up to the height of MW + 1.7 m – covered with a layer of large armourstones – 2014: Marking of a small, local scouring area in the upper slope of TF 7c; no rehabilitation measures, further monitoring of the marked area

Measure M6: Coir mats on hydroseeding (TF 7a, upper slope zone)

Coir mats on hydroseeding (slope inclination 1:3)	
Bank stability	– Only applied in the upper, less frequently flooded slope area – Initial stage (2012): Very critical, coir mats that have hardly any self-weight and that are only fixed at certain points with stakes (no crossbars) are not sufficient if subject to flooding and simultaneous ship-induced loads; large-scale downward soil displacement under the mats, limited only by dead wood fascines at the lower end of the measure; coir mats are not filter-stable so that soil is also lost through the mats; formation of larger cavities under the coir mats; rehabilitation measures required – 2013: Stabilisation of the condition after rehabilitation measures with sods and crossbars, good development of the plants, as only infrequent waterlogging occurs – 2014: Due to low water levels, overall plant development remains good with vegetation over most of the area; manifestation of six smaller, local scour areas that continue to be monitored further – 2015: Enlargement of the locally damaged areas in the lower part of the upper half of the slope as more and more material is washed away at high water levels; remaining area almost fully vegetated – 2016: Rehabilitation of the large damaged areas with a layer of armourstones, plants are growing through gaps in the stone layer – Coir mat on hydroseeding not suitable under the prevailing conditions – Bank sufficiently protected after various rehabilitations with armourstones and plant development
Ecology	Vegetation: – Initial stage (2012): Initial seeding (scheduled planting) failed to establish due to the problems described above (extensive soil displacement, hollows, washed-out seed); incipient development of grass/herbaceous cover only after rehabilitation and predominantly low water levels – 2013: Progressive development towards site-typical vegetation with a good mix of species; increased structural diversity compared to the reference – 2014: Predominantly extensive and dense vegetation with site-typical grasses and herbs, sporadic occurrence of site-typical woody plants; highest species diversity with 88 species (compare reference areas with Ø 11.5 species in the upper slope area); advanced development of the TF indicated by the increasing distribution of species according to their natural habitat requirements (natural riparian zonation) – 2015: With the exception of the locally damaged areas, the upper slope zone continues to be densely vegetated over a large area with originally seeded and reseeded species typical for dry-warm sites; species are increasingly distributed according to their natural habitat requirements (natural riparian zonation) – 2016: Following rehabilitation, renewed growth of highly regenerating plants through gaps in the stone layer, rejuvenation of individual willows at the border of the softwood/hardwood floodplains, individual elms and hawthorns in the area of the hardwood floodplain; otherwise statements comparable to M5

	– 2018/2019: Progressive development of a softwood zone in the rehabilitated area; stable, species- and flower-rich grass and herb cover in the upper unrehabilitated area Aquatic fauna (2012–2018): – The measure is ineffective for fish and macrobenthos due to its location in the middle and upper slope areas. Terrestrial fauna (2013–2017): – Compare with statements on M5 (no differentiated monitoring between M5 and M6) Other: – Increasing heterogeneity of vegetation (woody initials, grasses/herbs) that are positive from an ecological point of view – Live and near-natural material mainly used (exception: wire for stake/crossbar fixing) – CO_2 storage capacity (see M5)
Maintenance	– September 2012, May and July 2013: Mowed with trimmers between the slope and the maintenance path; no mowing in the slope area – 2014/2015: Mowed with trimmers on and at the top of the slope; removal of the mown material – 2016–2018: Partial mowing, alternating between here and M5, in the unrehabilitated upper slope area – Monitoring and removal of neophytic species (young growth of hybrid poplar)
Rehabilitation measures	– 2012: Cavities filled with soil and sod after cutting open the coir mat, covered with coir mat and adequately fixed (with stakes and crossbars); subsequently extensive hydroseeding – 2014: Marking and monitoring of local damaged areas – 2016: Rehabilitation of the damaged areas by filling them with gravel and covering them with a layer of large armourstones – Since 2017: No further rehabilitation measures required

Measure M7: Reed rolls (TF 7b, TF 7c, lower slope zone)

Covered with armourstones when the lower slope area was rehabilitated in 2012/13; no further monitoring required for this measure

Reed rolls	
Bank stability	– Reed rolls were installed parallel to the bank line in the area near MW as toe protection for the plant mats on the slope above (cf. M5) – Initial stage (2012): Very critical; very rapid biodegradation of nonwoven sheep wool mats resulting in rapid loss of strength; local damage due to hydraulic load, discharge of the gravel fill; coir mats not sufficiently stable either; no development of plant tussocks through the nonwoven sheep wool and coir fabric lining – Reed rolls are not suitable in the tested form under the given boundary conditions; covered with armourstones in the course of rehabilitating the lower slope area in 2012/13 – Bank protection ensured by restored riprap
Ecology	– Establishment/initiation of a reed zone with individual plants in the area around MW failed – Measures not effective for target animal organisms
Maintenance	– No maintenance required
Rehabilitation measures	– 2012: Covered with armourstones to ensure stable toe protection for the plant mats; no further rehabilitation measures required subsequently

Measure M8: Preparation of planting trenches perpendicular to the bank in a riprap planted with a choice of shoot-forming willow fascines, brush and hedge layers

Preparation of planting trenches perpendicular to the bank in a riprap planted with a choice of shoot-forming willow fascines, brush and hedge layers	
Bank stability	– Initial stage (2012): Not critical regarding bank protection; only slight settlement in the area of filled trenches after first flooding; restoration of a uniform riprap surface by additional installation of stones in the trenches; stable state as a result – 2013–2020: Potentially better bank protection through increasing growth of plant roots into the revetment and the subsoil. – Bank protection ensured by existing riprap
Ecology	Vegetation: – Initial stage (2012): Overall good and vital growth of introduced woody plants with a few exceptions; only minor differences in shoot development between the log branch cuttings installed at different heights; no plants lost despite sometimes very long flooding periods – 2013–2015: Development of site-typical alluvial softwood plants (purple and white willow, to a minor degree osier and 'Hutchinsons Yellow') in the MW to MW + 1.70 m slope zone and of alluvial hardwood plants (ash, guelder rose, common hazel, bird cherry and field maple) in the slope zone above MW + 1.70 m, good mix of species; in 2015, richly structured, layered growth of willows owing to the different maintenance strategies adopted for the development of willow trees and pollards. – 2016: Increase in species numbers along the slope gradient from the lower zone (willow plantings) to the upper area (hedge layer); significantly higher share of riparian species in planting trenches than in the intermediate riprap areas with a relatively high proportion of neophytes; herbaceous plant growth mainly consists of commonplace species without any riparian zonation. – 2017–2019: Richly structured, heterogeneous woody plant population owing to the defined maintenance strategies Aquatic fauna (2012–2018): – The measure has not been shown to have had any influence on fish and macrobenthos colonisation compared to the reference. Terrestrial fauna (2013–2017): – Birds: Increasingly favourable habitat conditions as a result of habitat structures provided for woodland breeding birds – Ground beetles: Species-poor beetle community similar to the reference, but a higher proportion of riparian individuals – Reptiles: Low effectiveness for reptiles – Spiders: Higher colonisation density at similar species number as in reference, slightly increased proportions of moisture-loving individuals in comparison to other measures – Other groups of organisms: Plantings of woody plants favour the spontaneous accumulation of dead wood, which is likely to have a positive effect on species that use dead wood as their habitat; flowering of woody plants (esp. willows) as bee pasture for nectar- and pollen-collecting insects, many insect species with narrow host plant spectrum (cf. M1) observed on willows, large offer of fruits for birds and insects

	Other: – Greater richness of structures due to deposition of dead wood and floating debris after flood events – Dense, hard-to-penetrate woody plant population keeps anglers and walkers away – High CO_2 storage performance of the woody plants as climate-regulating ecosystem service
Maintenance	– 2012–2014: Minor maintenance; monitoring of invasive species, plant-feeding pests and plant parasites (e.g. dodder (Cuscuta lupuliformis)); cutting back of fresh growth in hedge layers – 2015–2019: Alternating manual pruning techniques carried out on willow branch cuttings and fascines; objective: richly structured, multi-layered woody plant population – No maintenance pruning of hedge layers required
Rehabilitation measures	– 2012: After settlement, additional installation of armourstones in the planting trenches; no more rehabilitation measures required subsequently

Measure M9: Planting of willow branch cuttings (TF 1, TF 9)

Planting of log branch cuttings	
Bank stability	TF 1: – Planting of log branch cuttings in the existing riprap in the lower slope zone (no bank protection function) – Initial stage (2012): Not critical regarding bank protection – 2013–2019: Good development, in the long term potentially increased bank protection through growth of plant roots into the revetment and the subsoil – Bank protection ensured by existing riprap TF 9: – Planting of log branch cuttings on top edge of the slope; branch cuttings to check bank erosion above the unsecured slope area to protect the adjoining maintenance path – Initial stage (2012): Not critical regarding protection of maintenance path because water levels remained sufficiently below the top edge of the slope – 2013: Flooding exceeds the ground surface for the first time causing some of the log branch cuttings in the row of willows close to the bank to be partly exposed by water – 2014: Further progression of erosion, single log branch cuttings exposed in 2013 still anchored in the ground, and vital – 2015: Since removal of riprap in 2011, the slope shoulder has moved further inland by up to 5 m due to erosion; several log branch cuttings exposed by water; some branch cuttings fell over and died off; root excavation on a log branch cutting showed that root growth was not able to halt erosion on the slope shoulder; further erosion between the willows to be expected – 2016: Km-sign (441.500) newly secured, foundation exposed due to erosion of slope shoulder – Until 2020: Increasing erosion, which will continue to progress in the years to come; single log branch cuttings are not suitable as erosion protection under the boundary conditions of the test stretch – Continued monitoring of erosion with a view to the protection of the maintenance path
Ecology	Vegetation (TF 1 and 9): – Initial stage (2012): Individual willows weakened because of plant parasites (infestation with dodder (Cuscuta lupuliformis)) – 2013–2019: Especially in dry years increased occurrence of parasitic or winding plants (dodder, field and hedge bindweed), minor losses of vitality; progressive growth of woody plant population consisting of site-typical willows native to the area; willow branch cuttings provide additional habitat function to the adjoining plane at the top of the slope, which is dominated by spontaneous herbaceous growth (TF 9), and to the riprap, which was vegetation-free in its original state (TF 1), thus increasing structural richness; layered vegetation development after application of different types of pruning and depositing of dead wood and floating debris on log branch cuttings after flood events (TF 1) Aquatic fauna (2012–2018): – The measure (TF 1 and 9) has not been shown to have had any influence on fish and macrobenthos colonisation compared to the reference.

	Terrestrial fauna (2013–2017): – No differentiated analysis for M9; cf. information provided in M8 Other: – Only live material used for the measure – Willows with high CO_2 storage performance as climate-regulating ecosystem service – Flowering of willows as bee pasture for nectar- and pollen-collecting insects
Maintenance	TF 1: – 2015–2020: Carrying out of different types of maintenance pruning (cf. M8) TF 9: – September 2012, May and July 2013: Mowing in the area of the log branch cuttings between the slope and the maintenance path to counteract competition pressure of tall-growing spontaneous vegetation which hinders growth of young willows' shoots – 2014–2020: Monitoring of bank erosion; in 2014 preventive planting of an additional row of log branch cuttings next to the maintenance path as a precaution for future bank erosion, alternating pruning of single willow branch cuttings in the older planting; in 2015 repeated mowing in the area of the newly planted log branch cuttings to counteract competition pressure of herbaceous spontaneous vegetation – Monitoring of plant-feeding pests and plant parasites (e.g. dodder, field bindweed, black bindweed, hedge bindweed) – Monitoring and removal of invasive species (e.g. Jerusalem artichoke).
Rehabilitation measures	– TF 1: No rehabilitation measures required to date – TF 9: In 2014 planting of a third row of willow branch cuttings (the row had to be renewed several times because of shade pressure from the log branch cuttings in the riverside row; pruning of the latter was required to enable growth of the branch cuttings in the third row) – TF 9: In 2016 rehabilitation/securing of the km-sign (km 441.500)

Measure M10: Introduction of topsoil alginate into the riprap and subsequent hydroseeding

M10 Introduction of topsoil alginate into the riprap and subsequent hydroseeding	
Bank stability	– Initial stage (2012): Near-surface erosion of topsoil-alginate blend up to the highest recorded water level due to flooding and ship-induced loads; after first erosion occurrences in the topsoil-alginate blend additional introduction of gravel in the lower slope zone (up to approximately MW + 1 m) – 2013: Further erosion of topsoil-alginate blend due to repeated flooding with higher water levels than in 2012, leaving only some alginate residues in stone spandrels – no impact on stability – 2014/2015: Only small portions of alginate remained in the upper slope zone (transition to adjoining plane at the top of the slope) – Bank protection ensured by existing riprap; alginate not suitable for establishing vegetation under the prevailing conditions
Ecology	Vegetation: – 2012: Initiation of grass cover with site-typical grasses and herbs only successful in the slope zone above highest recorded water level (transition to adjoining plane at the top of the slope); alginate residues in the gaps in the riprap promote the development of a limited amount of spontaneous vegetation – 2013: Decrease in size of grass cover due to further erosion, almost no alginate left – 2014/2015: Sparse grass cover, unchanged compared to 2013 (only left in a few places on topsoil alginate with total coverage of 15%) – 2016–2019: Plant colonisation showed only minor difference between TF and reference stretch; objective regarding plant ecology not attained Aquatic and terrestrial fauna (2012–2018): Measure ineffective for animal organisms
Maintenance	– No maintenance required to date – Monitoring of invasive species
Rehabilitation measures	– No rehabilitation measures required to date

Measure M11: Planting of reed bales into the riprap (TF 6)

Reed bales were eroded under the prevailing conditions; the measure is therefore no longer considered for the test stretch

Planting of reed bales into the riprap	
Bank stability	– Initial stage (2012): Exposure of reed bales due to water erosion in the zone with fluctuating water levels, caused by ship-induced loads and temporary flooding; no sufficient anchoring in the riprap; however, no impact on bank protection as reed bales do not fulfil any bank protection function – Bank protection ensured by existing riprap; reed bales in the existing riprap are not suitable for establishing vegetation under the prevailing conditions
Ecology	– Failure to establish or initiate a reed zone with scattered plants in the area of wave run-up around MW – Measure ineffective for animal organisms
Maintenance	– No maintenance required
Rehabilitation measures	– No rehabilitation measures required

Measure M12: Building of a stone wall running parallel to the bank line to reduce ship-induced loads (TF 1 and TF 8)

Building of a stone wall running parallel to the bank line to reduce the exposure of the bank to wash (TF 1 and TF 8)	
Bank stability	– Hydraulic loads (wash, flow velocities) acting on the actual bank slope when water levels reach the upper edge of the stone wall (MW + 0.5 m) can be reduced by building (TF 1) a stone wall running parallel to the bank line or by increasing its height (TF 8) – 2012–2020: Stone walls in TF 1 and 8 stable and technically effective, bank protection ensured by remaining riprap on the slope
Ecology	Vegetation: – Initial stage (2012): Positive effect of the stone wall on the development of riparian vegetation in TF 1 and 8, muddy deposits on armourstones in the protection of the stone wall provide a substrate and nutrients for colonisation with spontaneous vegetation – Colonisation with initials of the pondweed and reed zone (TF 1) – Expansion of small reed beds and tall forbs typical of moist sites, which were already present before the building measure (TF 8) – 2013: Intensified deposition of mud in the shallow water zones created by the wall and on the armourstones in the lowest slope area (TF 1) and on the berm between the paving and the stone wall (TF 8); single occurrences of the endangered flowering rush (red list of Hesse) in TF 1; further positive development of reed growth in TF 8 – 2014/2015: Increasing number of site-typical riparian plant individuals (reed canary grass, purple loosestrife, flowering rush, beggarticks, pale persicaria, gypsywort) on mud deposits in TF 1; in 2015 distinctive development of a herbaceous shoreline with annual species on this layer; in TF 8 reed zone with tall forbs typical of moist sites and short-lived pioneer plants typical of muddy soils with a total coverage of 40–50% – 2016/2017: Initials of reeds and plant species of river bank communities present (no stable population); in 2017 evidence of 5 aquatic plants typical of the Rhine and 2 non-native species in the shallow water zone (TF 1); highest diversity and plant abundance in the area of the berm in the protection of the stone wall (TF 8) in the lower slope zone, highest proportion of riparian species and lowest neophyte proportion compared to all measures (lower slope zone) Aquatic fauna (2012–2018): – Measure in TF 8 ineffective for fish; no evidence of effectiveness for macrobenthos (clearly lower proportion of invasive species in 2017) – Regarding TF 1 cf. information provided in M13 (effectiveness described refers to combination of measures M12/M13; however, decreasing effectiveness of the actual stone wall when water levels are high or very low and during short-term water level fluctuations) Terrestrial fauna (2013–2017): – Birds: High potential for providing suitable habitat structures for woodland and reed nesting birds (TF 1 and 8) – Ground beetles: Positive development of beetle community in TF 8 between 2013/14 and 2017; noticeable increase in species number, diversity, proportions of riparian species and individuals (best rating compared to the other measures); no differentiated analysis in TF 1

	– Reptiles: No positive effect due to relatively dense vegetation cover in the shelter of the stone wall (TF 8) – Spiders: Species numbers and colonisation densities slightly higher in TF 8 than in the reference; slightly higher proportions of moisture-loving species compared to the other measures Other: – Strikingly high animal activity (insects, birds) in TF 1 – Stone wall as an effective combination with bank protection designs in the slope area (reduction in hydraulic loads, promotion of growth)
Maintenance	– No maintenance required to date
Rehabilitation measures	– No rehabilitation measures required to date

Measure M13: Installation of dead wood structures (dead trunks with root plates, dead wood fascines, log groyne) in the riprap (TF 1, TF 4, TF 9)

Installation of dead wood structures (dead trunks with root plates, dead wood fascines, log groyne) in the riprap (approximately MW –0.5 m to MW)	
Bank stability	– Initial stage (2012) and 2013: Dead wood elements firmly anchored in riprap on the slope, despite several flood events – 2014/2015: Dead wood fascines in TF 4 more loosely structured (shrinking, weathering, loss of individual branches) but still firmly in place – 2017: Increasing dissolution of the birch dead wood fascines installed just below MW in TF 4, replacement required – Until 2020: Dead wood elements of TF 9 (beech trunks of the log groyne) and TF 1 (beech trunks with root plates) largely intact and functioning – Bank protection ensured by existing riprap
Ecology	– 2012–2015: Deposition and displacement of eroded gravel and fine substrate in the area of the dead wood fascines (TF 4); formation of small flat gravelly areas on the bank between the fascines; increased substrate diversity – 2016–2020: Gravel deposits around the largely weathered dead wood fascines (TF 4) partly eroded Aquatic fauna (2012–2018): – Compared to the reference, clear trend towards increased mean numbers of fish species and higher proportions of individuals of the reference species list according to the WFD, both around the dead trunks with root plates (TF 1 – findings need to be interpreted in conjunction with the measure in M12: dead wood in the flow-reduced zone, which is protected against the wash from waves) and around the dead wood fascines (TF 4); dominance of round goby (invasive species) less pronounced than in other test fields and the reference, regular observation of schools of juvenile fish; log groyne (TF 9) as yet without noticeable effect on the fish – Compared to the reference, significantly higher number of species of macrobenthos and increased number of EPTCBO species on dead wood elements in shallow water zone (TF 1); however, persistently higher mean number of individuals of invasive species; slight increase in total number of macrobenthos species and in number of EPTCBO species on dead wood fascines (TF 4) compared to reference, slightly decreased proportion of invasive species Terrestrial fauna (2013–2017): – No differentiated analysis of the measure’s effectiveness for terrestrial fauna Other: – More frequent occurrence of demoiselles observed, especially on root plates in shallow water zone (TF 1)
Maintenance	– No maintenance required to date
Rehabilitation measures	– No rehabilitation measures required to date – TF 4: Replacement of dead wood fascines planned

Measure M14: Placing of gravelly substrate and groups of stones or rocks on existing riprap (TF 4)

Placing of gravelly substrate and groups of stones or rocks on existing riprap	
Bank stability	– Initial stage (2012) and subsequent years: Depending on loads due to shipping and flood levels and duration, erosion of gravel on the slope, partly with deposition in the area of the dead wood fascines; stable position of the large single granite stones – Bank protection ensured by existing riprap
Ecology	Vegetation: – 2012/2013: To a little extent colonisation with spontaneous vegetation, predominantly in the flow-reduced area next behind the single granite stones – 2014/2015: Colonisation with spontaneous vegetation mainly limited to the upper slope zone (only a few species in the lower and middle zones); highest substrate diversity in the upper slope area – 2016: No plants in the lower and middle slope zones; relatively small species numbers in the upper slope zone; medium species-richness of flowers (lack of slope zonation); non-riparian species dominating (in a nation-wide comparison, highest proportion of moderately abundant to moderately rare species); low proportion of neophytes – 2017–2019: Upper (and/or middle) slope zone overgrown with dewberry scrub; lower slope zone vegetation-free Aquatic fauna (2012–2018): – Gravel deposition on dead wood fascines may have additionally enhanced the positive effect on the fish biocenosis and macrobenthos colonisation described in M13 (combination of measures M13/M14) Terrestrial fauna (2013–2017): – Birds: No positive effect verifiable – Ground beetles: Higher numbers of species and individuals; higher proportions of riparian species and individuals; more frequent occurrence of RL species compared to reference – Reptiles: Significantly higher number of sightings compared to the reference indicate that open and sunny areas can provide suitable reptile habitats – Spiders: No positive effect verifiable Other: – Increased substrate diversity of the originally uniform riprap (class $LMB_{5/40}$ armourstones) – No use of artificial materials – Increased frequency of visitors (single granite stones provide seats, use as angling site because of combination with M13)
Maintenance	Little maintenance required: Removal of emerging neophyte individuals (ashleaf maple, false-acacia)
Rehabilitation measures	– No rehabilitation measures required to date

Measure M15: Removal of technical bank protection, no bank protection above MW, allowing for a limited degree of natural development (TF 9)

Removal of technical bank protection above MW, allowing for a limited degree of natural development	
Bank stability	– According to planning, no measures for ensuring bank stability after removal of the riprap from the slope above MW (only willow branch cuttings on adjoining plane at the top of the slope, cf. M9); below MW, bank protection through remaining riprap – Initial stage (2012): Erosion occurred in the flooded area (as expected and desired) – 2013: More floods; for the first time, flooding of the entire slope and the adjoining terrain, water levels of around 1 m above the top edge of the slope; progressive erosion in particular of the finer-grained material; as a result, larger stones with edge lengths > 5 cm, which became exposed as water washed away the subsoil, now dominate in the slope area; increasing scarps on slope shoulder, single willow branch cuttings exposed by water – M9 (but still with root–soil contact); internal erosion also due to flood water flowing back from adjoining terrain – 2014: Only limited progression of erosion up to the maximum water level (approximately flood level mark HWMI ≙ MSL + 88.56 m); some of the willow branch cuttings exposed in 2013 were still relatively stable and vital; planting of a third row of willow branch cuttings on the landward side – 2015: Since removal of the riprap in 2011, the slope surface had more and more moved further inland due to erosion; largest erosion at the end of the TF (movement of slope shoulder by up to 5 m); root excavation on a log branch cutting planted on the adjoining plane at the top of the slope showed that root growth had not been able so far to halt erosion on the slope shoulder; log branch cuttings exposed by water fell over and died off; further erosion between the willows to be expected – 2016: Km-sign (km 441.500) newly secured on the adjoining plane at the top of the slope as erosion had exposed the foundation and thus jeopardised the stability of the sign – 2017–2019 and future: Monitoring of erosion processes with respect to maintenance path; state not critical as yet – Bank stability still not ensured; however, stones exposed by water help to stabilise the bank; further progression of erosion especially in the upper area with alluvial loam – Monitoring continued – Single log branch cuttings not suitable as erosion protection
Ecology	Vegetation: – 2012/2013: Introduction of spontaneous vegetation to initiate colonisation of the upper slope zone where hydraulic loads are lower, especially alluvial hardwood forest (common dogwood) – 2014/2015: Further expansion of alluvial hardwood forest by natural succession; natural establishment of willows in a sandy scour area downstream of the measure – 2016: Relatively low species numbers compared to the other measures; occurrence of individual representatives of annual riparian meadows in the lower, more frequently flooded slope zone (with relatively high diversity but low plant abundance); quite similar proportions of floodplain and non-floodplain species

	– (almost exclusively commonplace species) but very low proportion of neophytes; well-developed slope zonation as a function of hydrological conditions – 2017–2019: Mainly dynamic vegetation development (come and go of species); stable and vital alluvial hardwood forest (common dogwood) expanding further; dewberry increasingly growing over the upper (and/or middle) slope area; development of scattered willows in the lower slope zone Aquatic fauna (2012–2018): – Bank flattening due to erosion without any positive effect so far on fish and macrobenthos communities Terrestrial fauna (2013–2017): – Birds: As yet, medium potential for providing suitable habitat structures – Ground beetles: Higher numbers of species and individuals; higher proportions of riparian species and individuals compared to reference; highest occurrence of RL species in comparison to the other measures – Reptiles: Measure tends to be able to provide suitable habitats for reptiles – Spiders: Species numbers and colonisation densities slightly higher than in the reference; as yet, no positive effect on proportion of riparian species Other: – Increased substrate diversity and structural richness due to erosion and/or sedimentation and deposition of dead wood and floating debris after water level fluctuations and flooding; highest level of heterogeneity compared to the other measures – Hydromorphologically dynamic (to some degree) – No use of artificial or non-natural materials
Maintenance	– Little maintenance required; increased requirement to make adjoining plane at the top of the slope safe for traffic – Removal of emerging neophyte individuals (Jerusalem artichoke, ashleaf maple)
Rehabilitation measures	– 2014: Planting of a third row of willow branch cuttings on the landward side (the row had to be renewed several times because of intense shade pressure from the log branch cuttings in the riverside row; pruning of the latter was required to enable growth of the branch cuttings in the third row) – 2016: Km-sign (km 441.500) newly installed – 2017–2020: No further rehabilitation measures

Annex 5

Continued Monitoring Activities from 2021 to 2030

Annex 5: Continued Monitoring Activities from 2021 to 2030

		Activities/examinations
Bank stability	**Bank inspection**	2 x per year (winter, summer); if required, additional inspections after extreme events (e.g. flooding, heavy rain, dry periods)
	Photographic documentation	For all bank inspections
	Panorama images	2 x per year (winter, summer); if required, additional photos after extreme events (e.g. flooding, heavy rain, dry periods)
	Surveying	In 2022 and 2027 surveying of selected cross sections; if required, additional surveying after extreme events (e.g. flooding, heavy rain, dry periods)
	Pore water pressure measurements	In total, 3 measurements (with water levels above MW); if required, additional measurements when measuring hydraulic load
Hydraulic loads	**Ship-induced loads**	In total, 3 measurements (with water levels above MW)
	Natural loads	In total, 3 measurements (with water levels above MW)
Climate data, water levels		Continuous recording and analysis (as before)
Special studies		Testing of biodegradable geotextiles (TF 6), installation in 01/2020 with subsequent regular sampling after 2, 3, 5, 10 and 20 years; examination of the samples at the BAW to determine their technical properties and biodegradation behaviour
Vegetation: root excavation		Root examination in different test fields (willows in TF 3; sedges in TF 5; plant mats in TF 7; common dogwood in TF 9; ...)
Vegetation: recording		In 2022 and 2027, comprehensive recording of vegetation Additional specific vegetation recording if required (e.g. capturing specific data for brambles, ...)
Fauna		In 2022 and 2027, recording of fauna (all groups of animals, e.g. fish – comparison of TF 1 and 4 with reference)
Maintenance		Recording and documentation of all maintenance and development measures that are/need to be carried out in the monitoring year
Damage		Continuous documentation if required
Rehabilitation work		Continuous documentation if required

Annex 6

Rating Tables for Fauna

Annex 6: Rating tables for fauna Rating table for birds

The overall rating of the measures for their effectiveness for birds is based on the main criterion *reproduction* with the sub-criteria *(assumed) breeding* and *breeding potential.*

Birds	**Main criterion**	**Reproduction**		**Overall rating birds**	**Ranking**
	Sub-criterion	*(Assumed) breeding*	*Breeding potential*	Weighting (0.6/0.4)	
Type of measure	Test field	Value rating	Value rating		
Vegetated riprap	TF 1	1	3	1.80	**2**
Willow brush mattress	TF 2	3	4	3.40	**5**
Willow brush mattress	TF 3	3	4	3.40	**5**
Gravel covering with stone blocks	TF 4	1	1	1.00	**1**
Reed gabions and stone mattresses	TF 5	1	1	1.00	**1**
Topsoil alginate (eroded)	TF 6	1	1	1.00	**1**
Plant mats	TF 7	3	4	3.40	**5**
Stone wall in lower slope zone	TF 8	3	3	3.00	**4**
Removal of riprap, without bank protection	TF 9	1	4	2.20	**3**
Conventional revetment	REF	1	1	1.00	**1**

Rating	**Ranking**
1.00–1.30	1
1.31–1.90	2
1.91–2.50	3
2.51–3.10	4
3.11–3.40	5

Rating table for reptiles

The overall rating of the measures for their effectiveness for reptiles is based on the main criterion *species richness* with the sub-criteria *species number* and *sightings.*

Reptiles	**Main criterion**	**Species richness**		**Overall rating reptiles**	**Ranking**
	Sub-criterion	*Species number*	*Sightings*	Weighting (0.5/0.5)	
Type of measure	Test field	Value rating	Value rating		
Vegetated riprap	TF 1	2	1	1.50	**2**
Willow brush mattress	TF 2	2	1	1.50	**2**
Willow brush mattress	TF 3	3	1	2.00	**2**
Gravel covering with stone blocks	TF 4	3	4	3.50	**4**
Reed gabions and stone mattresses	TF 5	4	4	4.00	**5**
Topsoil alginate (eroded)	TF 6	2	1	1.50	**2**
Plant mats	TF 7	2	3	2.50	**3**
Stone wall in lower slope zone	TF 8	1	1	1.00	**1**
Removal of riprap, without bank protection	TF 9	3	2	2.50	**3**
Conventional revetment	REF	2	1	1.50	**2**

Rating	**Ranking**
1.00–1.38	1
1.39–2.13	2
2.14–2.88	3
2.89–3.63	4
3.64–4.00	5

Rating table for spiders

The overall rating of the measures for their effectiveness for spiders is based on the main criteria *species richness* and *species composition.* The main criterion of species richness is divided into the sub-criteria *species number, number of individuals* and *diversity.* The main criterion of species composition is divided into the sub-criteria *proportion of riparian individuals* and *Red List species.*

Spiders	**Main criterion**	**Species richness**			**Total**	**Species composition**		**Total**	**Overall rating spiders**	**Ranking**
	Sub-criterion	*Species number*	*Number of individuals*	*Diversity*	Weighting (0.4/0.2/0.4)	*Proportion of riparian individ.*	*Red list*	Weighting (0.7/0.3)	Weighting (0.6/0.4)	
Type of measure	Test field	Value rating	Value rating	Value rating		Value rating	Value rating			
Vegetated riprap	TF 1	4	4	1	2.8	3	1	2.4	2.64	**3**
Willow brush mattress	TF 2	4	2	3	3.2	1	1	1.0	2.32	**2**
Willow brush mattress	TF 3	3	1	2	2.2	2	1	1.7	2.00	**1**
Gravel covering with stone blocks	TF 4	4	2	3	3.2	1	1	1.0	2.32	**2**
Reed gabions and stone mattresses	TF 5	4	2	5	4.0	1	1	1.0	2.80	**3**
Topsoil alginate (eroded)	TF 6	4	1	5	3.8	1	1	1.0	2.68	**3**
Plant mats	TF 7	5	5	5	5.0	2	1	1.7	3.68	**5**
Stone wall in lower slope zone	TF 8	5	5	3	4.2	2	1	1.7	3.20	**4**
Removal of riprap, without bank protection	TF 9	4	4	5	4.4	2	1	1.7	3.32	**4**
Conventional revetment	REF	3	2	2	2.4	3	1	2.4	2.40	**2**

Rating	**Ranking**
2.00–2.21	1
2.22–2.63	2
2.64–3.05	3
3.06–3.48	4
3.49–3.68	5

Rating table for ground beetles

The overall rating of the measures for their effectiveness for ground beetles is based on the main criteria *species richness* and *species composition.* The main criterion of species richness is divided into the sub-criteria *species number, number of individuals* and *diversity.* The main criterion of species composition is divided into the sub-criteria *proportion of riparian individuals* and *Red List species.*

Ground beetles	**Main criterion**	**Species richness**			**Total**	**Species composition**		**Total**	**Overall rating ground beetles**	**Ranking**
	Sub-criterion	*Species number*	*Number of individuals*	*Diversity*	*Weighting (0.4/0.2/0.4)*	*Proportion of riparian individ.*	*Red List*	Weighting (0.7/0.3)	Weighting (0.6/0.4)	
Type of measure	Test field	Value rating				Value rating				
Vegetated riprap	TF 1	2	1	2	1.8	5	1	3.8	2.60	**3**
Willow brush mattress	TF 2	2	2	3	2.4	3	1	2.4	2.40	**3**
Willow brush mattress	TF 3	3	3	3	3.0	4	2	3.4	3.16	**4**
Gravel covering with stone blocks	TF 4	4	2	5	4.0	3	2	2.7	3.48	**4**
Reed gabions and stone mattresses	TF 5	3	2	3	2.8	1	3	1.6	2.32	**3**
Topsoil alginate (eroded)	TF 6	1	1	1	1.0	1	1	1.0	1.00	**1**
Plant mats	TF 7	5	4	4	4.4	1	3	1.6	3.28	**4**
Stone wall in lower slope zone	TF 8	5	4	5	4.8	4	3	3.7	4.36	**5**
Removal of riprap, without bank protection	TF 9	4	3	5	4.2	2	3	2.3	3.44	**4**
Conventional revetment	REF	1	1	1	1.0	3	1	2.4	1.56	**2**

Rating	**Ranking**
1.00–1.42	1
1.43–2.26	2
2.27–3.10	3
3.11–3.94	4
3.95–4.36	5

Rating table for fish

The overall rating of the measures for their effectiveness for fish is based on the main criteria *species richness* and *species composition.* The main criterion of species richness is divided into the sub-criteria *total species number* and *mean numbers of species* per survey point. The main criterion of species composition is divided into the sub-criteria *mean proportion of invasive species* and *mean number of species* in the reference.

Fish	**Main criterion**	**Species richness**		Total	**Species composition**		Total	**Overall rating fish**	**Ranking**
	Sub-criterion	*Total number of species*	*Mean number of species*	Weighting (0.5/0.5)	*Mean proport. of invasive species*	*Mean number of reference species*	Weighting (0.5/0.5)	Weighting (0.5/0.5)	
Type of measure	Test field	Value rating	Value rating		Value rating	Value rating			
Off-the-bank stone wall with shallow water zone, root plate	TF 1	3	3	3.0	3	4	3.5	3.25	**5**
Willow brush mattress	TF 2	1	1	1.0	1	1	1.0	1.00	**1**
Willow brush mattress	TF 3	1	1	1.0	2	1	1.5	1.25	**1**
Ecologically enhanced riprap with gravel and dead wood fascines	TF 4	1	3	2.0	3	2	2.5	2.25	**3**
Reed gabions and stone mattresses	TF 5	2	1	1.5	1	3	2.0	1.75	**2**
Topsoil alginate (eroded)	TF 6	1	2	1.5	2	2	2.0	1.75	**2**
Plant mats	TF 7	1	2	1.5	1	3	2.0	1.75	**2**
Stone wall in lower slope zone	TF 8	1	2	1.5	2	2	2.0	1.75	**2**
Removal of riprap, without bank protection	TF 9	1	1	1.0	2	3	2.5	1.75	**2**
Conventional revetment	REF	1	1	1.0	1	2	1.5	1.25	**1**

Rating	**Ranking**
1.00–1.28	1
1.29–1.85	2
1.86–2.41	3
2.42–2.97	4
2.98–3.25	5

Rating table for macrobenthic organisms

The overall rating of the measures for their effectiveness for macrobenthic organisms is based on the main criteria *species richness* and *species composition.* The main criterion of species composition is divided into the sub-criteria *mean proportion of invasive species* and *number of EPTCBO species**.

Macrobenthic organisms	**Main criterion**	**Species richness**	**Species composition**		Total	**Overall rating macrobenthic organisms**	**Ranking**
	Sub-criterion	*Species number*	Proportion *of invasive species*	*EPTCBO species**	Weighting (0.3/0.7)	Weighting (0.5/0.5)	
Type of measure	Test field	Value rating	Value rating	Value rating			
Off-the-bank stone wall with shallow water zone, root plate	TF 1	4	2	3	2.7	3.35	**5**
Willow brush mattress	TF 2	1	1	1	1.0	1.00	**1**
Willow brush mattress	TF 3	1	1	1	1.0	1.00	**1**
Ecologically enhanced riprap with gravel and dead wood fascines	TF 4	2	3	2	2.3	2.15	**3**
Reed gabions and stone mattresses	TF 5	1	1	1	1.0	1.00	**1**
Topsoil alginate (eroded)	TF 6	1	1	1	1.0	1.00	**1**
Plant mats	TF 7	1	3	1	1.6	1.30	**2**
Stone wall in lower slope zone	TF 8	1	4	1	1.9	1.45	**2**
Removal of riprap, without bank protection	TF 9	2	1	1	1.0	1.50	**2**
Conventional revetment	REF	1	2	1	1.3	1.15	**1**

* EPTCBO species are species of the orders Ephemeroptera (mayflies), Plecoptera (stoneflies), Trichoptera (caddisflies), Coleoptera (beetles), Bivalvia (bivalve shells) and Odonata (dragonflies and damselflies).

Rating	**Ranking**
1.00–1.29	1
1.30–1.88	2
1.89–2.47	3
2.48–3.06	4
3.07–3.35	5

Summary rating

The overall 'terrestrial fauna' rating is based on a weighted mean value derived from the rating of the terrestrial groups of organisms in each test field. An overall ‘aquatic fauna’ rating was produced for the aquatically effective measures in TF 1 and 4 (shallow water zone, dead wood fascines) and the aquatic reference.

								Ecological effectiveness	
Type of measure		**Birds**	**Reptiles**	**Spiders**	**Ground beetles**	**Fish**	**MB**	**Terrestrial fauna**	**Aquatic fauna**
Vegetated riprap	TF 1	2	2	3	3	5	5	**2.6**	**5**
Willow brush mattress	TF 2	5	2	2	3	(1)	(1)	**3.1**	**-**
Willow brush mattress	TF 3	5	2	1	4	(1)	(1)	**3.1**	**-**
Gravel covering with stone blocks	TF 4	1	4	2	4	3	3	**2.6**	**3**
Reed gabions and stone mattresses	TF 5	1	5	3	3	(2)	(1)	**3.0**	**-**
Topsoil alginate (eroded)	TF 6	1	2	3	1	(2)	(1)	**1.8**	**-**
Plant mats	TF 7	5	3	5	4	(2)	(2)	**4.3**	**-**
Stone wall in lower slope zone	TF 8	4	1	4	5	(2)	(2)	**3.5**	**-**
Removal of riprap, without bank protection	TF 9	3	3	4	4	(2)	(2)	**3.5**	**-**
Conventional revetment	REF	1	2	2	2	1	1	**1.8**	**1**

The underlined values were double weighted in line with the initially defined ecological objective (cf. Table 1 in the report).

Values in brackets are not taken into account, as the ecological effectiveness for the aquatic fauna was only rated for TF 1, TF 4 and the reference. Only test fields TF 1 and 4 were assumed to be ecologically effective for fish and aquatic invertebrates. However, since it is possible that the terrestrial measures have positive effects on the aquatic habitat, the other test fields were also studied and rated, but they were not taken into account for the overall rating of the aquatic fauna.

Annex 7

Multi-Criteria Decision Analysis Following the Analytic Hierarchy Process (AHP) According to Saaty (1990)

Explanatory Notes to Chapter 8

Annex 7: Multi-Criteria Decision Analysis Following the Analytic Hierarchy Process (AHP) According to Saaty (1990) – Explanatory Notes to Chapter 8

1 Introduction

The Analytic Hierarchy Process was developed by Thomas L. Saaty. The basic idea of the AHP is to break down complex decision making to separate individual decisions that are manageable. The simplest individual decision is a pairwise comparison of two components. If a decision has to be made on more than two components, it is therefore broken down into several pairwise comparisons. These can be solved successively, independently from each other, and then offset against each other. The strength of the AHP is the computation method, which is structured in a mathematically logical way. This method not only enables individual pairwise comparisons, it is also suitable for verifying the consistency of decisions, i.e. analysing whether the individual pairwise comparisons are consistent or whether there are inconsistencies. The outcome is a structured, transparent and, in itself, consistent decision (Westphal 2016).

The AHP involves the following steps:

1. Defining specific objectives (scenarios)
2. Creating a structure for the decision problem (objectives, criteria, alternatives)
3. Pairwise comparison of the criteria – creation of a comparison matrix (scaling)
4. Calculation of the weightings
5. Consistency check
6. Ranking

2 Defining specific objectives (scenarios)

The objective is to transfer the insights gained on the Rhine test stretch to river bank sections where different boundary conditions prevail. To this end, scenarios are defined, and the suitability of the different technical–biological measures for these scenarios is determined based on the AHP. Five different scenarios (A to E) are used for the evaluation, all of which are set on a free-flowing waterway with navigation by motor vessels. The scenarios are evaluated against three criteria (cf. section 3.1). In contrast to the situation on the test stretch, adequate surface area is available for flattening the river banks in all of the scenarios.

Scenario A assumes that it is possible to flatten the river banks to a high degree, which has a positive effect on bank stability. Total costs are of minimal relevance here. The ecological priority is to promote terrestrial riparian habitats. Unlike on the test stretch, ecological aspects are more important than the resilience of the measures.

Additionally, Scenarios B, C and D are analysed as marginal scenarios. These are used to determine the ranking that would result if one criterion was given absolute priority over the other two. Scenario B prioritises ecology, Scenario C resilience and Scenario D total costs. In each case, the other two criteria are considered to be of minimal relevance. The ecological objective in each scenario is to promote terrestrial habitats.

Scenario E corresponds to Scenario A with regard to boundary conditions, except for the fact that aquatic instead of terrestrial habitats are to be fostered. The measures introduced in scenarios A–D were exclusively implemented in the terrestrial area of the riparian zone and therefore have no beneficial ecological impact on the aquatic habitat (below MW). However, they can be combined with various additional measures whose ecological effectiveness in aquatic habitats has been demonstrated.

3 Creating a structure for the decision problem

3.1 Criteria

Similarly to Chapter 7, three criteria for selecting suitable measures are used to transfer the findings. Besides the criteria ‘ecology’ and ‘total costs’, the third criterion considered is ‘resilience’ instead of stability. The measures' effectiveness for the ecology is distinguished into effectiveness for the terrestrial and for the aquatic ecology, as in Chapter 7. Similarly, the criterion ‘total costs’ is composed of construction costs and maintenance expenses.

3.2 Alternatives

The various technical–biological bank protection measures represent alternatives for purposes of the AHP. These were initially rated on a uniform 1–5 scale for the criteria. In addition, measures without any bank protection function in the terrestrial and aquatic zones were analysed. The results were analysed separately for measures with and without bank protection function, and for measures in the terrestrial and the aquatic riparian zones.

Figure 1 illustrates the structure of the AHP. The structure maps the relations between the objective, i.e. identification of an optimum bank protection measure for a specific scenario, the criteria and the alternatives.

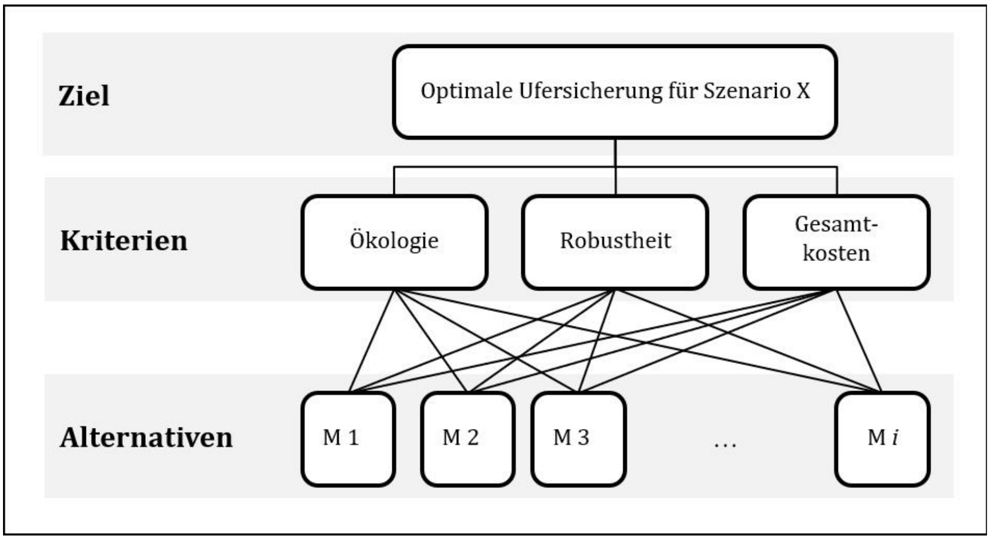

Figure 1: Structure of the decision-making process, adapted based on Saaty (1990); M = measures (technical–biological bank protection measures or additional measures)

Table 1: Rating of the alternatives for the three criteria analogously to Chapter 7

Alternatives	**Criteria** (5: very good to 1: very poor)		
Technical–biological bank protection measures (only terrestrial)	Terrestrial ecology	Resilience	Total costs
Ecologically enhanced riprap with vegetation	3	5	4
Ecologically enhanced riprap with structural elements (gravel, stone blocks)	2	5	4
Willow brush mattresses	4	3	2
Reed gabions	2	4	3
Stone mattresses	2	4	3
Coir mat on hydroseeding	4	1	3
Plant mats	4	2	3
Without bank protection (natural succession of vegetation)	4	1	3
Riprap as reference	2	5	5
Additional measures without bank protection that have an effect on terrestrial ecology	Terrestrial ecology	Resilience	Total costs
Hedge layer on adjoining plane at the top of the slope	4	5	5
Stone wall in front of mean water level berm	4	5	5
Additional measures without bank protection that have an effect on aquatic ecology	Aquatic ecology	Resilience	Total costs
Stone wall with shallow water zone	3	5	4
Dead wood fascines below MW	3	3	3
Stone wall with shallow water zone and root plate/dead wood fascines	5	3	2
Dead wood/root plate below MW	3	3	3
Riprap as reference (aquatic)	1	5	5

1) *Design optimisation of bank protection measures according to Annex 3*

2) *Coir mat on hydroseeding only suitable for installation above highest level of wave run-up according to Annex 3*

Table 1 shows the initial ratings of the alternatives with regard to the three criteria. These ratings are based on a scale from 1 to 5 as proposed in Chapter 7 of this report, with the value 1 meaning 'very poor' and value 5 meaning 'very good'. The same value scale is used for all the criteria, so that the same value has the same meaning for each criterion. Table 1 also illustrates that the different alternatives have an impact either on the terrestrial or on the aquatic ecology, but that they do not affect both ecological domains.

4 Pairwise comparison of the criteria – creation of a comparison matrix (scaling)

The first step is to compare each criterion with each of the other criteria. It is not only necessary to judge whether a criterion is of greater, equal or less importance than another criterion. It is also necessary to determine the intensity of importance on the scale developed by Saaty (Saaty 1987). The meaning of the individual numerical values is explained in Table 2.

Table 2: Scale values and reciprocal values and their description for pairwise comparison of (sub-)criteria according to Saaty (1990)

Scale values	Description	Reciprocal values	Description
1	Equal importance	1	Equal importance
3	Moderate importance of one over another	1/3	Moderately less importance
5	Essential or strong importance	1/5	Considerably less importance
7	Very strong importance	1/7	Very much less importance
9	Extreme importance	1/9	Absolutely unimportant
2, 4, 6, 8	Intermediate values	½, ¼, ⅙, ⅛	Intermediate values

Given the boundary conditions of Scenario A (more surface area available for a flattening of the slope; minimal relevance of total costs), greater importance is assigned to the 'ecology' criterion than to the 'resilience' and 'total costs' criteria. Resilient measures tend to be more ecologically sustainable; the 'resilience' criterion is therefore assigned greater importance than the 'total costs' criterion. The following comparison matrix results (cf. Table 3):

Table 3: Comparison matrix for the criteria 'ecology', 'resilience' and 'total costs' for Scenario A using scale values and reciprocal values according to Saaty (1990)

Criteria	Ecology	Resilience	Total costs
Ecology	1	3	8
Resilience	1/3	1	3
Total costs	1/8	1/3	1

5 Calculation of the weightings

The weighting is derived from the comparison matrix. According to mathematical considerations, the weighting corresponds to the eigenvector of the largest eigenvalue (Saaty 2004).

This eigenvector can be calculated analytically. However, as this is very complex, Saaty recommends an alternative method: to calculate the eigenvector, the comparison matrix has to be squared a sufficient number of times. Then the values of an eigenvector are calculated by summing over the rows of the newly calculated matrix. These values can be normalised by dividing each of them by the total sum of all values (Saaty 1990). 'This theory is operationalised [...] by squaring the start matrix and calculating the normalised sums of the rows as many times as is required to arrive at a change in the derived priorities between two squaring operations that is smaller than a predefined value [...].' (Westphal 2016).

First, the comparison matrix is squared.

$$A_A^{\,2} = \begin{pmatrix} 1 & 3 & 8 \\ 1/3 & 1 & 3 \\ 1/8 & 1/3 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 3 & 8 \\ 1/3 & 1 & 3 \\ 1/8 & 1/3 & 1 \end{pmatrix} = \begin{pmatrix} 3 & 8{,}67 & 25 \\ 1{,}04 & 3 & 8{,}67 \\ 0{,}36 & 1{,}04 & 3 \end{pmatrix}$$

In the multiplication, the result is calculated by forming the inner product from the respective row vector of the first matrix and the respective column vector of the next matrix (Bronstejn 1991). The result 25, for example, is the inner product of the vector of the first row and that of the third column:

$$\begin{pmatrix} 1 & 3 & 8 \end{pmatrix} \cdot \begin{pmatrix} 8 \\ 3 \\ 1 \end{pmatrix} = 1 \cdot 8 + 3 \cdot 3 + 8 \cdot 1 = 25$$

To calculate the normalised row sums, the sum of the respective rows of the result matrix is divided by the total sum of all values (Table 4).

Table 4: Calculation of the weighting vector for the squared comparison matrix

Values of the squared comparison matrix Scenario A			Row sum	Weighting
3	8.67	25	36.67	68.2%
1.04	3	8.67	12.71	23.6%
0.36	1.04	3	4.40	8.2%
		∑	53.78	100%

This procedure has to be repeated until the result has the desired accuracy. In the following example the result matrix is squared again:

$$A_A^{\,4} = \begin{pmatrix} 3 & 8{,}67 & 25 \\ 1{,}04 & 3 & 8{,}67 \\ 0{,}36 & 1{,}04 & 3 \end{pmatrix}^2 = \begin{pmatrix} 27{,}1 & 78{,}0 & 225{,}1 \\ 9{,}4 & 27{,}1 & 78{,}0 \\ 3{,}3 & 9{,}4 & 27{,}1 \end{pmatrix}$$

It is now possible to calculate the weighting with the new matrix (Table 5). A comparison with the previously calculated values (Table 4) shows that the changes are no longer visible within the accuracy used here. It is therefore not necessary to perform another squaring operation.

Table 5: Calculation of the weighting vector for the double squared comparison matrix

Values of the squared comparison matrix Scenario A			Row sum	Weighting
27.1	78.0	225.1	330.2	68.2%
9.4	27.1	78.0	114.5	23.6%
3.3	9.4	27.1	39.8	8.2%
		∑	484.5	100%

6 Consistency check

Saaty has developed a method to determine the weighting of the criteria in cases where the comparison matrix is not fully consistent. Nevertheless, the ratings must be logical in themselves. For this purpose, the consistency check is performed. Here, the consistency ratio *C.R.* is decisive; it should not exceed the value of 0.1 (Saaty 1990). It is determined by comparing the consistency index *C.I.* with a fixed random consistency (*R.I.*). The random index *R.I.* is an averaged consistency index. It was calculated from 50,000 different reciprocal matrices where the comparison values were randomly chosen. For three-dimensional matrices created for 3 criteria, this random index is R.I. = 0.52 (Saaty and Tran 2007).

C.I. is calculated using the maximum eigenvalue λ_{max}. This is calculated as follows:

The general formula for the eigenvalue calculation $A \cdot v = \lambda\, v$ must be solved (Bronstejn 1991). Since the eigenvector v occurs on both sides of the equation, it can be multiplied by any real number, i.e. it can be scaled. It is therefore also possible, for example, to use the percentage weighting vector w from Table 4. This results in an equation system for Scenario A that can be solved as follows:
$A_A \cdot w_A = \lambda_{\max} \cdot w_A$

If the equation is represented in matrix notation, the left side can be multiplied out:

$$\Leftrightarrow \begin{pmatrix} 1 & 3 & 8 \\ ⅓ & 1 & 3 \\ ⅛ & ⅓ & 1 \end{pmatrix} \begin{pmatrix} 0{,}682 \\ 0{,}236 \\ 0{,}082 \end{pmatrix} = \lambda_{max} \begin{pmatrix} 0{,}682 \\ 0{,}236 \\ 0{,}082 \end{pmatrix}$$

This is equivalent to the equation system:

$$\begin{aligned} & {}^{1}/_{0{,}682}\,(1 \cdot 0{,}682 + 3 \cdot 0{,}236 + 8 \cdot 0{,}082) = 3{,}0000 = \lambda_{max} \\ \Leftrightarrow\ & {}^{1}/_{0{,}236}\,(⅓ \cdot 0{,}682 + 1 \cdot 0{,}236 + 3 \cdot 0{,}082) = 3{,}0056 = \lambda_{max} \\ & {}^{1}/_{0{,}082}\,(⅛ \cdot 0{,}682 + ⅓ \cdot 0{,}236 + 1 \cdot 0{,}082) = 2{,}9990 = \lambda_{max} \end{aligned}$$

Averaging the three values for Scenario A results in: $\boldsymbol{\lambda_{max}}$ **= 3.00154.**

The difference $\lambda_{max} - n$ can thus be used to evaluate the consistency. However, this has the following disadvantage: the difference of the value *n* from the maximum eigenvalue is as large as the sum of the deviations of all other eigenvalues from zero. $\lambda_{max} - n$ is thus not only dependent on consistency, the difference also becomes larger and larger as the number of criteria increases. Therefore, the average values of all other eigenvalues are taken as the consistency index (*C.I.*) following Saaty's approach (Saaty and Tran 2007):

$$C.I. = \frac{\lambda_{max} - n}{n - 1}$$ Thus, the following applies for Scenario A: $$C.I. = \frac{3{,}00154 - 3}{3 - 1} = 0{,}0077$$

The consistency ration C.R. is derived as follows:

$$C.R. = \frac{C.I.}{R.I.}.$$ Thus, the following applies for Scenario A: $$C.R. = \frac{0{,}0077}{0{,}52} = 0{,}00148$$

The comparison matrix of Scenario A thus complies with this condition and is nearly consistent (cf. Table 6).

Table 6: Consistency check for the priorities and eigenvectors (total weights) determined for the 'ecology', 'resilience', and 'total costs' criteria for Scenario A.

Parameter	**Definition**	**Value**
Maximum eigenvalue	λmax	3.00154
Consistency Index	*C.I.* = (λ_{max} - *n*) / (*n* - 1)	0.00148
Random consistency with 3 criteria	*R.I.* (Saaty and Tran 2007)	0.52
Consistency Ratio	C.R. = C.I./R.I.	0.00148

7 Ranking

7.1 Calculation of the rank orders for Scenario A

According to the AHP, the ratings of the technical–biological bank protection measures have to be normalised in relation to the different criteria. This is necessary to integrate all ratings into one uniform scale (Saaty 1990). Since in this case the ratings are already present in a uniform scale, it was not necessary to perform this computational step. The rankings can therefore be determined directly.

The total overall weight for each measure has to be calculated before a rank order of suitable technical–biological measures for Scenario A can be established. For this purpose, the technical evaluations of the measures initially made according to the three criteria 'ecology', 'resilience' and 'total costs' (value ratings 1–5, cf. Table 1) were multiplied with their corresponding computed weightings (cf. Table 4) and then added up. Ranks are assigned to the technical–biological measures based on the computed total overall weights ('ranking' function in MS Excel).

*Table 7: Ranking of technical–biological bank protection measures for Scenario A; *ratings for the 'ecology' criterion refer exclusively to terrestrial riparian habitats in line with the definition of Scenario A; rating scale for criteria: 1 = very poor, 2 = poor, 3 = average, 4 = good, 5 = very good; ranks 1-8; 1= first rank (green), 8 = last rank (red)*

		Ecology*	Resilience	Total costs	Overall rating	Rank order Scenario A
Weighting		**68%**	**24%**	**8%**		
Bank protection measures[1)]	Ecologically enhanced riprap with vegetation	3	5	4	3.56	2
	Ecologically enhanced riprap with structural elements (gravel, stone blocks)	2	5	4	2.88	7
	Willow brush mattresses	4	3	2	3.60	1
	Reed gabions	2	4	3	2.56	8
	Stone mattresses	2	4	3	2.56	8
	Coir mat on hydroseeding[2)]	4	1	3	3.20	4
	Plant mats	4	2	3	3.44	3
	Without bank protection, natural succession of vegetation	4	1	3	3.20	4
	Riprap as reference	2	5	5	2.96	6

[1)] *Design of bank protection measures optimised according to Annex 3*

[2)] *Coir mat on hydroseeding only suitable for installation above highest level of wave run-up according to Annex 3*

Table 8: Calculation of the rank order for additional terrestrial measures without bank protection function

Additional measures without direct bank protection function	**Weighting**			**Overall rating**	**Rank order Scenario A**
	Terrestrial ecology	Resili-ence	Total costs		
	68%	24%	8%		
Hedge layer on the adjoining plane at the top of the slope	4	5	5	4.32	1
Stone wall in front of mean water level berm	4	5	5	4.32	1

7.2 Calculation of the rank orders for Scenarios B, C and D

Scenarios B, C and D are considered to be marginal scenarios. They are used to establish how the result changes when one criterion is assigned absolute priority over the other two criteria.

The first step is to specify the importance of the criteria in relation to each other and enter these data in the comparison tables. Based on the pairwise comparisons, the comparison tables are generated (Table 9).

Table 9: Comparison matrices of Scenarios B, C and D

	Scenario B			Scenario C			Scenario D		
	Ecology	Resilience	Total costs	Ecology	Resilience	Total costs	Ecology	Resilience	Total costs
Ecology	1	9	9	1	1/9	1	1	1	1/9
Resilience	1/9	1	1	9	1	9	1	1	1/9
Total costs	1/9	1	1	1	1/9	1	9	9	1

The maximum eigenvalue is λ_{max} = 3 for all three scenarios, because the comparison matrices are consistent (Saaty 1990). The weighting can be derived directly from the column vectors of the comparison matrix (Saaty 1990; cf. Table 10)

Table 10: Weightings of Scenarios B, C and D

	Scenario B		Scenario C		Scenario D	
Ecology	9/11	82%	1/11	9%	1/11	9%
Resilience	1/11	9%	9/11	82%	1/11	9%
Total costs	1/11	9%	1/11	9%	9/11	82%

The three matrices are consistent. Hence, the consistency ratio is 0 (cf. Table 11).

Table 11: Consistency check for Scenarios B, C and D

Parameter	Definition	Value
Maximum eigenvalue	λmax	3
Consistency Index	*C.I.* = (λ_{max}-*n*) / (*n* - 1)	0
Random consistency with 3 criteria	*R.I.* (Saaty and Tran 2007)	0.52
Consistency Ratio	C.R. = C.I./R.I.	0

To determine the rank order, the scale values are again offset with the weightings (cf. Table 12).

Table 12: Calculation of the rank orders of technical–biological bank protection measures for Scenarios B, C and D; evaluation of criteria and rank order as in Table 7

Technical-biological bank protection measures[1]				**Scenario B**		**Scenario C**		**Scenario D**	
	Weighting	Ecology		82%		9%		9%	
		Resilience		9%		82%		9%	
		Total costs		9%		9%		82%	
	Scale value (scale 1–5)								
	Ecology	Resilience	Total costs	Overall rating	Rank	Overall rating	Rank	Overall rating	Rank
Ecologically enhanced riprap with vegetation	3	5	4	3.27	5	4.73	1	4	2
Ecologically enhanced riprap with structural elements (gravel, stone blocks)	2	5	4	2.45	7	4.64	3	3.91	3
Willow brush mattresses	4	3	2	3.73	1	3	6	2.27	9
Reed gabions	2	4	3	2.27	8	3.73	4	3	4
Stone mattresses	2	4	3	2.27	8	3.73	4	3	4
Coir mat on hydroseeding[2]	4	1	3	3.64	3	1.45	8	2.91	7
Plant mats	4	2	3	3.73	1	2.27	7	3	4
Without bank protection, natural succession of vegetation	4	1	3	3.64	3	1.45	8	2.91	7
Riprap as reference	2	5	5	2.54	6	4.73	1	4.73	1

1) *Design of bank protection measures optimised according to Annex 3*

2) *Coir mat on hydroseeding only suitable for installation above highest level of wave run-up according to Annex 3*

7.3 Calculation of the rank order for Scenario E

Scenario E differs from Scenario A only in that its objective is to improve the aquatic ecology, and not the terrestrial ecology. Hence, the aquatically effective measures rather than the terrestrial measures are relevant here. All other input variables correspond to those of Scenario A. The calculation can be seen in Table 13.

Table 13: Calculation of the rank order of additional measures without bank protection function in the aquatic area without direct bank protection for Scenario E; rating of criteria and rank order as in Table 7

Additional measures in the aquatic zone without direct bank protection function	**Weighting**			**Overall rating**	**Rank order Scenario E**
	Aquatic ecology	Resilience	Total costs		
	68%	24%	8%		
Stone wall with shallow water zone	3	5	4	3.56	2
Dead wood fascines below MW	3	3	3	3.00	3
Stone wall with shallow water zone and root plate/dead wood fascines	5	3	2	4.28	1
Dead wood/root plate below MW	3	3	3	3.00	3
Riprap as reference (aquatic)	1	5	5	2.28	5