Bundesanstalt für Wasserbau
Kompetenz für die Wasserstraßen

BAW Letter No. 1 – January 2011

604 – G

Studies on Alternative Technical-Biological Bank Protection Measures Applied on Inland Waterways (Joint R&D Project of BAW and BfG)

Results from Test Stretch Stolzenau/ Weser km 241.550 – 242.300, Right Bank

1 Motivation

To ensure long-term bank protection of inland waterways from erosion and other negative effects of hydraulic loads generated by navigation, banks are usually retained by technical revetments such as riprap or sheet piling. In Germany, the application of those measures is based on comprehensive regulations provided by the German Waterways and Shipping Administration (WSV) (Guidelines and Codes of Practice such as [1], [2]). Since the EU Water Framework Directive (WFD) took effect in 2000 and the German Federal Water Act (Wasserhaushaltsgesetz, WHG) was modified accordingly, ecological aspects have been gaining more and more importance in the planning of construction measures along waterways. With regard to their maintenance, technical and ecological measures now are also to be considered as equal options. Thus, technical-biological measures are to be applied more often as an alternative to conventional methods such as riprap revetments. However, only little experience has been made with alternative methods, and guidelines have not yet been established. Therefore, in 2004, the German Federal Waterways Engineering and Research Institute (BAW) and the German Federal Institute of Hydrology (BfG) initiated a joint research project on the load-bearing capacity of technical-biological bank protection measures, taking into account the effects of navigation. The project aims at defining measurement guidelines and recommendations for the implementation of alternative bank protection measures on inland waterways.

In 2004 and 2005, a survey was conducted among WSV offices throughout the country. It concluded that in the past 20 years, WSV offices had independently initiated the implementation of different alternative bank protection measures at more than 150 short river stretches ([4], [5]). However, the documentation and evaluation of these experiences was either insufficient or non-existent. Therefore, since 2005, selected test stretches have been analysed in depth in the framework of the R&D project, involving the assessment of the current situation of the bank as well as the geotechnical and geometrical conditions, the documentation of existing fauna and vegetation and the measurement of hydraulic loads generated by navigation within a defined period of time. In addition, all available documents from the planning and implementation stage of the respective test stretch have been compiled, evaluated and compared with the new results. Thus, experiences can be quantified and used for general recommendations.

As the first object for in-depth analysis, a test stretch of the Weser River in the vicinity of Stolzenau (Niedersachsen/Lower Saxony) was selected. All measurements and documentations as well as the assessments and the results and recommendations that could be inferred therefrom are documented in a report [6]. This bulletin provides a summary of the most important results.

2 Area of study

The area of study at the Weser is situated in the reach of Landesbergen, km 241.55 - km 242.30, at the inner bank of a slight bend to the right (slip-off slope zone) in the vicinity of Stolzenau (Fig.1). The hydrostatic water level is at 26.5 m above sea level. Due to the adaptation of the Mittelweser (Middle Weser) in the early 1990s, this river section fulfils the requirements for a Class IV waterway according to the European classification system.

In terms of natural space, the area of the study forms part of the “Weseraue” (Weser meadows). The predominant soil types are various alluvial soils, gley-like brown earths with primarily sandy/gravelly/loamy texture as well as fen soils at the edge of the Geest (the North German coastal moorlands). The Weseraue region is now largely deforested and primarily used for agriculture. Along the banks of the Weser, which are mostly uniformly structured, reed beds, willow shrubbery and other riparian plants can only occasionally be found.

The water structure quality along the reach Landesbergen was accordingly categorised as Class 5 (significantly impaired) [7].

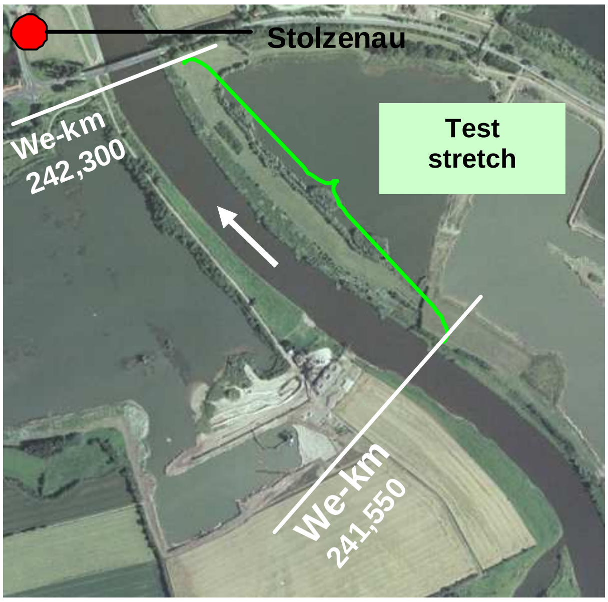

Fig. 1: Location of the test stretch, aerial photograph (c. 2007)

3 Bank protection measures in the test stretch

In the context of the adaptation of the Middle Weser, alternative technical-biological bank protection measures were installed along a stretch of approximately 750 m at the right bank on the initiative of the Local Waterways and Shipping Office (WSA) Verden and in cooperation with BfG and BAW.

3.1 Initial condition (before the installation of the test stretch)

The slope, having an inclination of approximately 1:3, was completely protected by loose armour stones. In the about 300 m long upstream section, the bank is divided up by single groynes. The adjoining terrain was used as grazing land (Fig. 2). In the groyne zone, animals had direct access to two watering places. The natural plant cover of the bank was restricted to small groups of shrubs, isolated colonies of reed canary grass and some tall forbs.

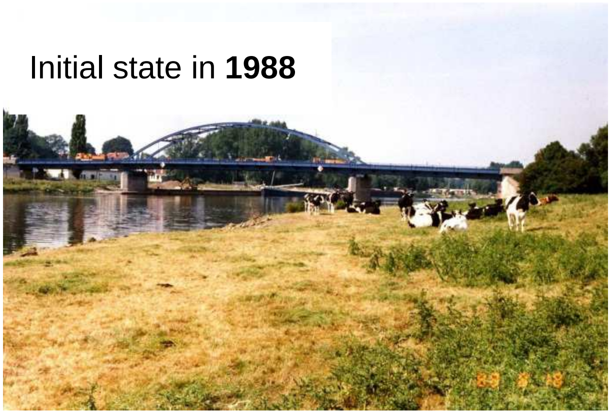

Fig 2: Initial condition of the test stretch: intensive use for grazing right up to the banks

3.2 Bank protection measures 1988/89

Fifteen different technical-biological bank protection measures were implemented above the hydrostatic water level along the 750 m long test stretch. The slope zone below the hydrostatic water level remained unchanged. There, the original riprap made of loose armour stones class III [2] was retained in its original thickness of 60 cm, or less if it had been reduced over the years. Construction measures were conducted in autumn/winter 1988/1989. Planting took place in spring/early summer 1989.

The following bank protection measures including plants were implemented separately or in combination:

- common reed and sedge sods extracted by the WSA Verden (dug out spade-wide)
- cultivated common reed and sedge bales
- cultivated common reed and sedge bales in connection with a woven coir fabric
- cultivated common reed and sedge bales in connection with a coir straw mat
- vegetation fascines

- cultivated vegetation mats or pallets planted with common reed
- willow branch cuttings extracted by the WSA Verden
- willow brush mattresses
- cultivated willow plants
- cultivated alders

The following varieties of reed were planted: common reed, slender-tufted sedge, lesser pond sedge and cypress-like sedge.

Within existing groyne fields, the bank line was redesigned and given a less regular course through digging work.

The original riprap of armour stones was removed above the hydrostatic water level in most sections. In several sections, the bank was also flattened from 1:3 to 1:7 along an approx. 5-metre-wide strip (Fig. 3) to improve conditions for vegetation through the creation of flat bank zones. Some of these sections were further protected by fascines installed in front of the bank to determine their impact on vegetation development under these conditions.

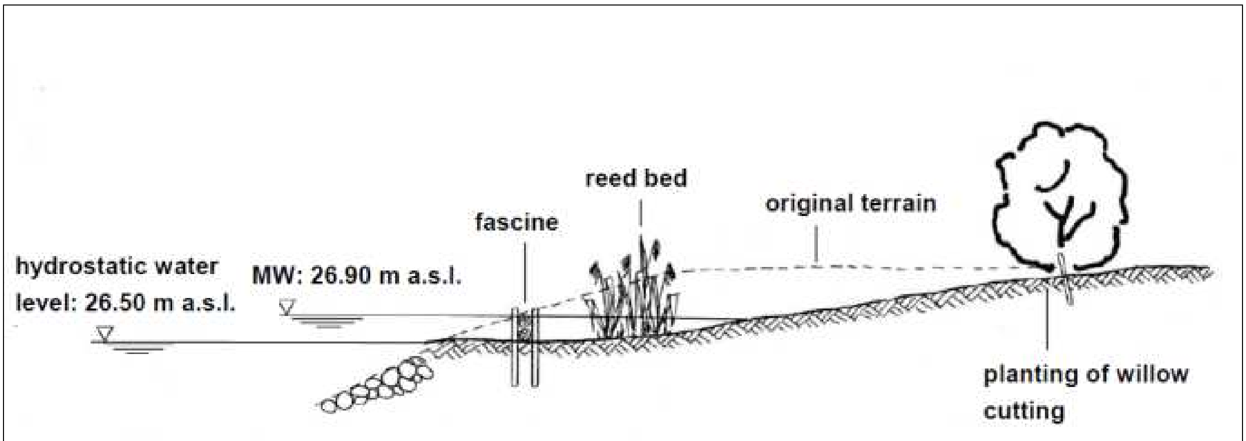

Fig 3: Schematic diagram of an alternative bank protection measure

To reduce hydraulic loads resulting from navigation and thus to protect the newly implemented bank protection measures including plants, two further measures were installed in some of the groyne fields at a distance of about 3.5 m parallel to the bank line: stone mounds made from armour stones or double rows of stakes with fascine bundles of different sizes (Fig. 3). The upper edges of the stone mounds and stakes were varied to allow a steady exchange of water on both sides. The gaps between the stone mounds and the bank were partially filled with gravel up to 10 cm below the hydrostatic water level, thus creating a shallow water zone to allow the proliferation of reed bed plants. The area was fenced in and signs were placed to prevent further use of the area for the grazing of cattle, or by anglers and those seeking recreation.

4 Technical boundary conditions

4.1 Ground and ground water

Ground assessment of the banks was based on a BAW ground expertise of the lock canal Schlüsselburg and on borings which were additionally performed in the test stretch area by the BAW in 2007. As an example, the results of the borings at km 242.00 are illustrated in Fig. 4. Under the topsoil, the bank consists primarily of sandy and clayey silts and of sands. Further below, at the MW and MLW level, medium to coarse sandy Weser gravel with a granularity from 0.2 mm to 60 mm can be found.

From the upper edge of the terrain to 26.5 m a.s.l., the ground corresponds roughly to soil type B4 according to [1]. The following simplified soil mechanical variables can be applied:

$\Phi' = 30°$, $c' = 0$ kPa, $\gamma' = 10$ kN/m^3, $k = 1 \cdot 10^{-6}$ m/s.

Below, up to a depth of 20.0 m a.s.l., the following soil mechanical parameters are applicable to verify bank stability:

$\Phi' = 35°$, $c' = 0$ kPa, $\gamma' = 11$ kN/m^3, $k = 5 \cdot 10^{-4}$ m/s.

This soil corresponds to soil type B1 according to [1].

Data compiled at four ground water measuring points near the test stretch between 1988 and 2002 was assessed. As expected, ground water levels correspond with water levels of the Weser. It was documented that ground water flows primarily into the Weser (77%). During high water, flow conditions, especially in case of a rapid rise in the water level, are reversed, and a flow of water from the Weser to the ground water takes place (19%). Equal water levels occur with an incidence of 4%. It should be noted that every time a ship passes, generating drawdown at the bank, the differential between the ground water and the Weser is increased for a short time and an additional amount of ground water flows into the river.

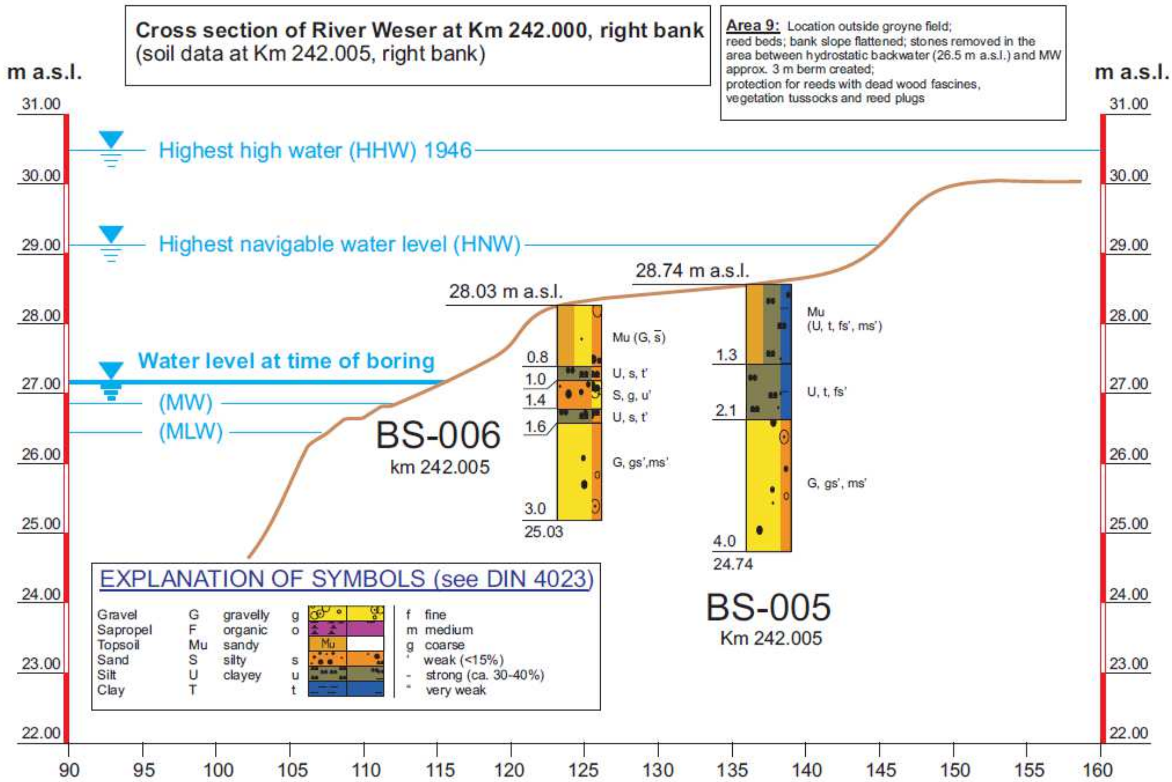

Fig 4: Results of exploratory borings at Weser km 242.000.

4.2 Bank geometry and water levels

Data of 13 cross sections, measured in 1996 and 2002, served as the basis for the assessment of the existing bank geometry. Data from the time when the construction of the test stretch was finished was not available for comparison purposes.

To allow assessment from the viewpoint of geotechnics, phytoecology and fauna, water levels for MLW, MW, HNW, and HHW, and hydrographs measured at the nearby Stolzenau gauge (km 243.400) from 1988 to 2006 – i.e. since the installation of the bank protection measures – were added to diagrams of the cross sections. Thus, times of flooding in the bank areas above MW which are stabilised by plantings can be illustrated and quantified. Fig. 5 exemplifies this for the cross section at km 241.800. It can be seen that middle water or low water levels have predominated since 1988; e.g. in 1997, MW and LW levels were observed for 237 days without interruption. Short-term flooding with maximum water levels of approx. 30 m a.s.l. – i.e. about one metre above the highest navigable water level – occurred at recurring intervals. During these events, high flow velocities increased the load on the slopes additionally (cf. 4.4). However, water levels above HNW (29.12 m a.s.l.) did not occur in ten out of the analysed 18 years. In the remainder of the time, those high levels usually occurred only during short periods – at a maximum of 12 days in a row in 1994.

Fig. 5 also illustrates the underwater slope zone with its inclination of 1:3, which is still secured by riprap, as well as the modified area above MW, which has remained unchanged at the inclination of 1:7 since its construction. The stone mound in front of the bank can be seen easily.

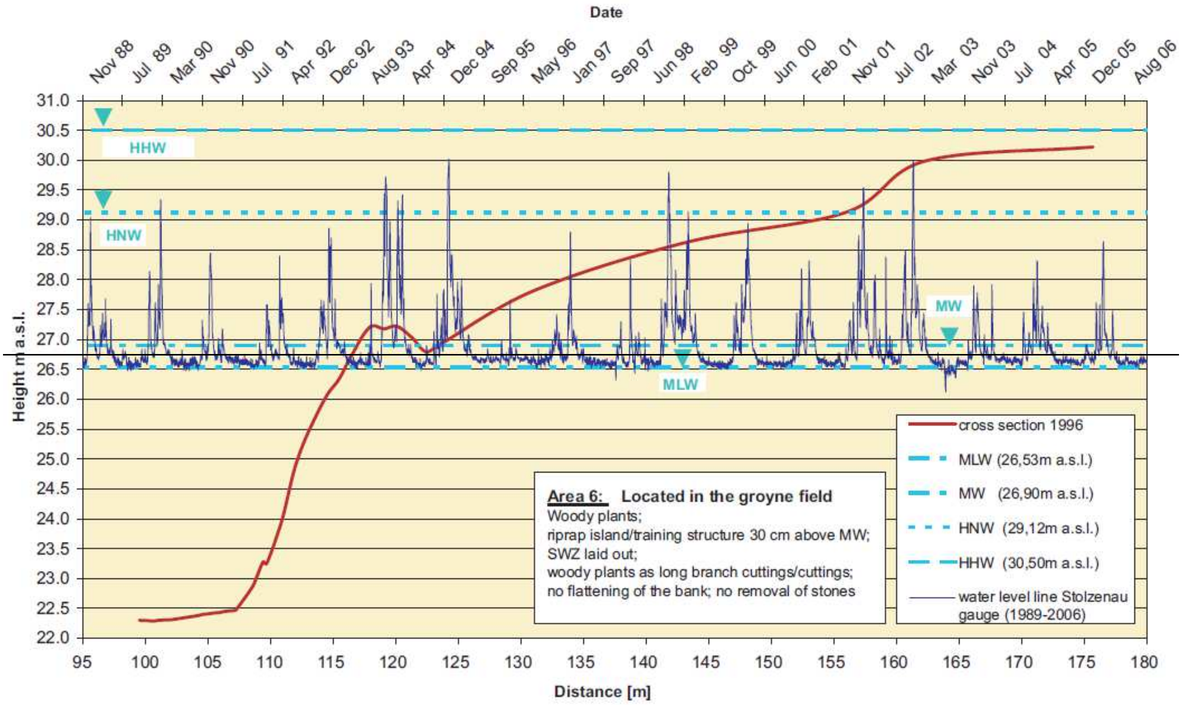

Fig. 5: Cross section at km 241.800, right bank (1996) with water levels of the Weser (Stolzenau gauge at km 243.400)

4.3 Navigation

According to the German Regulations for Navigation on Inland Waterways (Binnenschifffahrtsstraßenordnung, BinSchStrO) of 2005, ships and push-tow units with maximum dimensions of 85 m x 11.45 m and 91 m x 8.25 m respectively are currently permitted at a given channel depth of a maximum of 2.5 m. According to BinSchStrO, there are no speed restrictions for freight shipping in the test stretch. For pleasure craft, the maximum speed is 35 km/h.

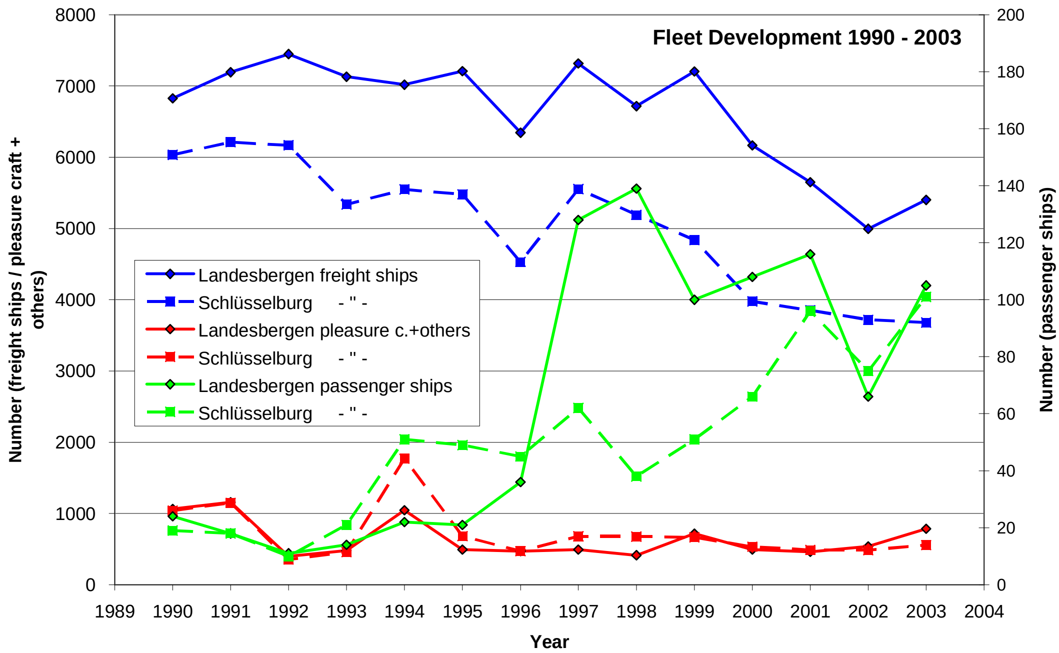

Fig 6: Fleet development in the years 1990 - 2003, shown separately for freight ships (right ordinate), pleasure craft + others (left ordinate) and passenger ships (right ordinate!).

After the construction of the test stretch, the statistics for the years 1990 to 2003 from the locks at Landesbergen and Schlüsselburg were analysed. In Fig. 6, the development of the fleet in this period is shown separately for freight ships, passenger ships and pleasure craft and others (e.g. workboats and patrol boats).

With regard to freight traffic, an overall decrease in the number of ships can be observed; since 1989, ships are fewer in number, but larger. The number of pleasure craft has decreased by about one half compared to the early 1990s; since 1996 the figures have remained nearly constant. In passenger shipping, a constant upward trend has been observed.

4.4 River hydraulics

A one-dimensional, unsteady hydraulic-numerical model of the Landesbergen reach, kept at Section W1 of the BAW, helped to determine hydraulic variables in the test stretch. It makes calculations between the hydrostatic water level and the highest navigable discharge HNQ = 735 m^3/s possible. Values that are higher than HNQ need to be extrapolated. Variables such as flow velocity and shear stress in the direct vicinity of the bank are vital to the bank stability as well as to the living conditions of fauna and vegetation. These variables were determined in a 5-metre-wide segment close to the bank. Fig. 7 illustrates the values documented for the right bank up to a discharge corresponding to HNW.

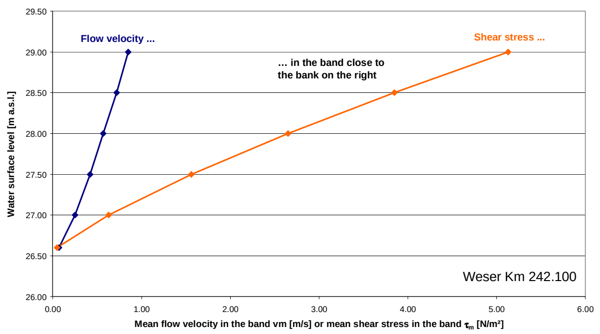

Fig. 7: Mean flow velocity and mean shear stress at water levels up to HNW in the 5-metre-wide segment close to the right bank

5 Measurement of the hydraulic load generated by navigation

5.1 Phenomenon

When a ship travels through a body of water, the reciprocal hydraulic action causes in situ and temporary alterations to the water surface and to the flow of water around the ship. During this process, waves, water level drawdown and return flow are generated, which all influence the banks in the form of hydraulic load. The following effects result:

- Depending on factors such as drawdown speed or the soil type in situ, the rapid drawdown at the bank can lead to excess pore water pressure in the subsoil. The excess pore water pressure can cause the sliding of a soil layer close to the surface (including the bank protection measure on top of it) in a direction parallel to the slope. This must be taken into account in the geotechnical dimensioning of the bank protection measures.
- The waves cause short-period water level changes; i.e. loads on the bank are generated. As wave run-up, they can have an impact on, amongst others, the flora and fauna in the bank area.
- The return flow causes shear stress at the river bed and at the banks. This influences the capacity of the soil and the bank protection measures to resist erosion.

5.2 Measurements

Hydraulic loads in the direct vicinity of the banks were measured in the course of a traffic monitoring campaign on seven days in August 2005, the month with the highest traffic volume. A radar device was used to document ship positions and speeds. At the same time, water level changes were recorded by pressure measuring devices installed at the bank, which allowed deductions on waves, drawdown and drawdown velocity. Specific sensors were deployed to measure simultaneously the flow velocities generated close to the banks. Information on ship dimensions and draught could be gathered through observation or based on lock records.

5.3 Results

A total of 156 ships was observed: 72 were motor cargo/motor tank vessels (46%), 8 push-tow units (5%) – i.e. a total of 80 cargo vessels, 68 pleasure craft (44%), 6 passenger ships (4%) and 2 WSA patrol boats (1%).

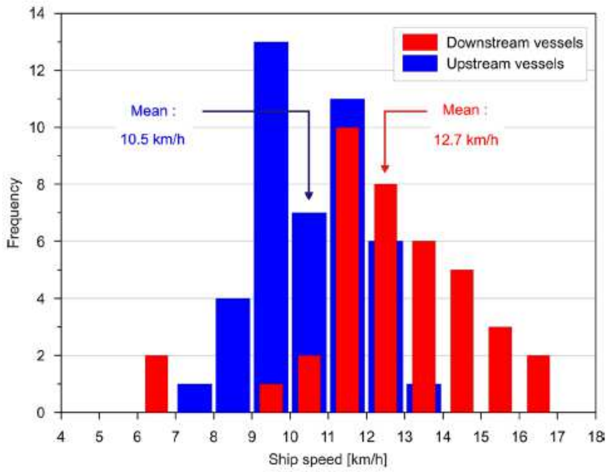

Fig 8: Distribution of the speeds of all 80 cargo vessels; upstream and downstream vessels shown separately.

As expected, speeds (above ground) recorded for cargo vessels travelling downstream were higher than for those travelling upstream (Fig. 8). The fastest upstream vessel travelled at 13.1 km/h; the fastest downstream vessel at 16.5 km/h. The most frequently occurring speeds, however, all lay below the respective mean values. The analysis of the speeds of pleasure craft showed a marked cluster at around 13 - 14 km/h, which was considerably below the mean value.

As loads increase when ships travel closer to the bank, the distances of the ships from the bank were also measured. All cargo vessels – with one exception – passed the test bank at a distance of 40 - 65 m. Pleasure craft travelled much closer to the test bank than freight traffic (35 - 65 m), in individual cases, as close as 25 m.

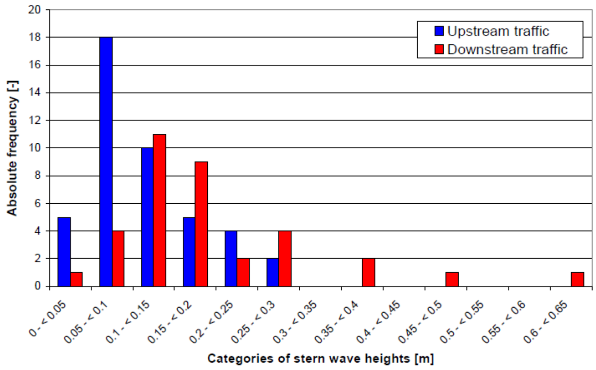

Fig. 9: Stern wave heights of all cargo vessels; upstream and downstream vessels shown separately.

The bow wave heights of all cargo vessels observed were on average 15 cm; the highest value of 39 cm was generated by a downstream vessel. The stern wave heights (Fig. 9) were on average 11 cm for upstream traffic and 19 cm for downstream traffic; maximum values differed significantly with 30 cm for upstream and 64 cm for downstream traffic. In only two incidents, extreme values between 45 cm and 65 cm were observed among the vessels travelling downstream; usually values of 40 cm were reached. Wave heights of pleasure craft were on average 8 cm; the maximum value was 41 cm.

All important hydraulic load variables are listed in the specification of this test stretch, which can be found in the annex.

6 Assessment of the measures including plants

6.1 Development of the vegetation

In order to document and compare the development of the different bank sections, variously structured with respect to technical-biological measures, from the phytosociological point of view, mapping of the vegetation was carried out in the years 1989 (the year of construction), 1992, 1999, 2005 and 2006.

By September 1989, the reed beds had become well established in all planting sections. Only some single plants had died. Willow cuttings, willow branch cuttings, and willow brush mattresses had developed positively as well.

The mapping of 1992 showed that, by that year, the reed beds planted had developed well almost everywhere, in particular the common reed. Only the common reed of the pre-cultivated vegetation mats initially demonstrated poor growth and little vitality. Stone mounds and fascines, locally installed in front of the plantings, provided protection against waves and thus helped reed beds to spread extensively.

As the non-planted bank zone and all adjacent areas no longer were used for grazing, the vegetation zoning typical for banks could develop, consisting of reed canary grass and common reed as well as of quack grass flood meadows and belts of tall forbs and stinging nettles.

Among the woody plants, the best growth was documented for the live brush mattresses and individual willows that had developed from fascines.

By 1999, the reed beds had spread along the entire test stretch up to the bank line, even in the sections of the test stretch that were not protected by stone mounds or fascines. The vegetation zonation typical for banks developed further in the following years in all test sections.

As for the woody plants, in the slope zones which had remained unmodified (inclination: 1:3) and are located outside the groyne fields, only the planting of live brush mattresses was successful. By contrast, the woody plants planted inside the groyne fields on the flattened slope zones had developed well. In addition, along the entire test stretch there had been a spontaneous succession of woody plants.

About 15 years after the completion of the test stretch (2005 and 2006), a repeat mapping indicated that the zoning of non-woody plants still corresponded to the 1999 mapping. However, the succession of woody plants had led to a reduction in area of non-woody plants. The advanced succession of woody plants featured hedge maple as a new species.

6.2 Evaluation of planting success and achievement of objectives

The analysed time period showed a positive development of the reed and willow plantings (Fig. 10). Thus, the redesign of the river bank with technical-biological measures could be qualified as successful.

Among the species of the reed beds, common reed has become predominant. By 1999, it had spread so much that its area had reached a size ten times as big as in 1989, both in length and width, especially around the mean water level (26.90 m a.s.l.) ± 50 cm.

Overall, reed beds could develop better in the flattened than in the steeper, unmodified slope zones. Moreover, they benefited from the stone mounds and fascines placed in front of them. In these areas wider belts of reed beds have developed, which, in turn, is advantageous for bank protection, the appearance of the landscape and for the fauna.

The main stands of common reed and reed canary grass were completely submerged for an average of 3 (max. 15) and 14 (max. 52) days respectively, considering the average size of 2 m for the common reed and 1 m for the reed canary grass. These measured periods of submergence lie substantially below the critical values for the two species (common reed: 50-250 days/year; reed canary grass: 50-150 days/year). This explains why reed beds have to compete with woody plants, because areas where reed beds are located feature, at least partially, desirable conditions for woody plants.

Fig. 10: Development of the vegetation in one section of the test stretch between 1989 and 2006

Common reed occurs within the test stretch mainly in the bank sections parallel to the river, where the current is relatively gentle, whereas reed canary grass also frequently colonizes the groyne heads which are exposed to current and wave action. Compared with common reed, the tolerance of reed canary grass towards flow velocity and wave action is higher.

Willows, which had been planted in the form of cuttings and log branch cuttings, have developed well not only in the flattened but also in unmodified (inclination: 1:3) slope zone as long as they had been planted close to the hydrostatic water level. They have spread continuously and, as described above, started competing with the reed beds and the reed canary grass. The stands of the woody plants require maintenance; see [6].

Planting woody plants in the unmodified (inclination: 1:3) slope zone with a larger distance to the zone of fluctuating water level has not proven successful. A major reason for this might be the lower accessibility of water to the plants.

The studied bank section was originally shaped by its function as a grazing area for cattle, only interrupted by small groups of bushes and scattered areas of reed beds as well as some tall forbs. After the redesign of the bank area, diverse habitats have developed and the number of species has increased. Considering these two aspects, the studied bank section has become far more valuable than any of the adjacent areas.

7 Evaluation of the fauna

No documentation of the existing fauna prior to the redesign of the bank was available. When an inventory of the fauna was made in 2006, the opposite bank, protected by a conventional riprap revetment, was used for comparison. Bird, fish and macrobenthos (benthic invertebrates) populations were analysed (Table 3).

7.1 Birds

During the breeding season, a great diversity of bird species could be observed in the test stretch area (Table 1). Typical species for the habitat included Eurasian reed warbler, willow warbler, reed bunting, common blackbird, chaffinch, common whitethroat, common chiffchaff and marsh warbler; for each of these species several breeding pairs were observed. Nightingale and common grasshopper warbler were found with one pair each. Of the threatened or strictly protected species, only one pair of common buzzards bred in one of the few older trees. Typical feeding guests observed included Eurasian penduline tit, sand martin and common tern.

As far as both breeding birds and feeding guests are concerned, the number of species was higher in the test stretch than at the reference bank. Sixteen years after the implementation of the alternative bank protection measures, birds could find a habitat in the shrubs, grass and reed beds of the flattened slope area. Anthropogenic impairment could moreover be qualified as low. The 30-50-metre-wide bank stretch was demarcated by electric fence and has therefore not been accessible to grazing cattle; people could access it only with difficulty. In spring, paths to the groynes were observed, which resulted from the use by anglers.

7.2 Fish

In 2006, seven species of fish could be found in the tested section of the Weser. However, the occurrence of different species at the test bank and the opposite reference bank with the conventional riprap revetment varied only slightly. Common dace and common roach dominated at both banks. The European chub (14% of the total catch) was observed more frequently at the reference bank. Single eels and carp breams occurred in both bank areas occasionally. Two juvenile specimens of the gravel-spawning ide were caught in the test stretch with the alternative bank protection, where gravel was one of the substrata. One juvenile specimen of the common perch, who favours riprap revetments, could be observed at the reference bank only.

	Test stretch		Riprap
Birds			
Breeding bird species	30		18
Guest bird species	22		8
Fish			
Species	6		6
Juvenile fish (Ind /m^2)	6.8		4.3
	I	**II**	
Macrozoobenthos			
Total no. of taxa	44	43	30
Red List species	2	2	1
No. of invasive species	11	12	8
Diversity of species α*	4.2	4.7	2.7
Potamon Typie Index**	3.4	3.4	3.6

Table 1: Evaluation of the fauna along the test stretch and along the opposite bank secured with conventional riprap revetment.
Explanations:
** acc. [8],*
*** acc. [9],*
I – reed canary grass, II – common reed

The density of juvenile fish is a good indicator for diversity in a river section because larvae and juvenile fish have high demands towards their habitat. When examining the river stretch, structural diversity and the diversity of the substrata were higher in the alternative bank area than along the conventional bank protection. The sections where vegetation had developed represent an important habitat for juvenile fish, as all of them were settled by juvenile fish to an equal extent. However, the juvenile fish density of the alternative bank and the density of the opposite reference bank differed only slightly (Table 1). This might be due to methodological reasons because it is harder to take samples in areas covered with reed. Furthermore, the test stretch might be too small to generate significant effects on the fish fauna.

7.3 Macrobenthos

When analysing the macrobenthos, sections with reed canary grass cover and gravel as the main substratum and sections with common reed cover and silt as the main substratum were examined separately. Both of them were later compared to the opposite reference bank protected with riprap (Table 1). In both sections of the bank with technical-biological protection measures, significantly more taxa could be found than at the reference bank. Species with higher demands towards their habitat, such as mayflies, dragonflies and bugs, could only be observed in the sections of the test stretch covered by common reed. The humpbacked pea clam *(Pisidium supinum),* a highly threatened species in Germany, could be found in both above-mentioned sections of the test bank. Within the test stretch, the reed beds functioned as habitat for both rheophilic species (running water specialists) and limnophilic species (standing water specialists), while the riprap at the reference bank was dominated by rheophilic species. High densities of invasive species, such as *Dikerogammarus villosus* (killer shrimp), *Jaera istri* (*German*: Donauassel), and *Chelicorophium curvispinum* (Caspian mud shrimp), were repeatedly observed in all bank sections.

The diversity of species in the bank area where technical-biological protection measures had been applied could be qualified as merely modest. Yet, it was significantly higher than in the area of the riprap at the opposite bank (Table 1), where diversity was quite low. However, the Potamon Typie indices, which describe the ecological condition of the river according to the WFD of the EU [9], differed only slightly (Table 1). The determined values at the two banks with technical-biological and conventional protection measures were qualified as being in a modest ecological condition.

The results need to be seen in a wider context. Considering that the overall ecological condition of the macrobenthos in the Middle Weser has been qualified as being unsatisfactory or even poor by the river basin community (*German*: Flussgebietsgemeinschaft) of the Weser [10], even small changes can be seen as a significant improvement. Thus, it is exactly what could be expected.

8 Assessment of the technical condition

The technical condition of the bank stretch where alternative protection measures had been applied was assessed based on the results of inspections of the test stretch, on the current cross section data as well as on the amount of money spent for the maintenance. According to the WSA Verden [11], no maintenance measures have been required within the test stretch since 1989. This means that there has not been any significant erosion or severe sliding at the banks; they have proven overall to be stable. Therefore, it can be assumed that under the hydraulic conditions that have been observed so far, the combination of the “old” riprap revetment in the underwater zone and the alternative technical-biological protection measures above the hydrostatic water level can be considered effective.

After the removal of the riprap and the subsequent redesign and planting of the banks, the slope zones above the hydrostatic water level may have initially been deformed slightly by water current and wave action. Yet, they presumably stabilised after the vegetation had been established and spread. The slope areas that had been flattened to 1:7 in the course of the redesign have slightly been further flattened up to a maximum of 1:8. The artificially created shallow water zones have all silted up to this day. This means that sedimentation has taken place within the dead zones behind the groynes. Even the bank sections where the original inclination of 1:3 had been kept while the riprap had been removed are stable overall thanks to the various alternative protection measures. A difference between the sections with and without groynes was not been observed.

For comparison purposes, calculations were made for revetments that would have theoretically been required under the given hydraulic conditions at MW and HNW. These confirmed that the dimensioning of the loose riprap (armour stones class III; thickness of revetment: 60 cm) is sufficient under mean water and high water conditions.

During mean water conditions, the applied technical-biological bank protection measures are subject only to relatively small loads, primarily due to wave run-up (cf. 4.3). When considering the rare higher levels of high water, the alternative measures theoretically have to be able to provide a level of protection equivalent to a 35 cm thick revetment made of loose class $CP_{45/125}$ armour stones acc. to [3] with a density of 2.6 t/m^3. This is a class of small armour stones with stone sizes between 45 and 125 mm (granularity), roughly corresponding to the former class 0 acc. to [2].

Due to the very good condition of the bank, it can be assumed that the applied technical-biological bank protection measures provide a level of protection equivalent to the riprap which would have normally been required under the given conditions.

9 Conclusion

The current condition of the alternative technical-biological protection measures applied at the banks of the Weser in the test stretch near Stolzenau can be assessed as being very good overall. Apart from a few exceptions, all applied planting measures have developed well, thus providing a good level of slope protection from surface erosion and possible instabilities under the given hydraulic conditions.

Favourable conditions in the test stretch – relatively low hydraulic loads due to navigation, location within the slip-off zone of the river and therefore low shear stress and low flow velocities – have promoted a positive development of the planted vegetation, especially of the sensitive reeds. The development of the vegetation was further promoted by waterwards implementing stone walls and fascines.

From the perspective of nature conservation, contrary to the initial condition of the bank, the test stretch today features a highly valuable complex of bank-specific habitats. Valuable, in some cases protected types of biotopes such as reed beds of common reed, riparian willow communities and beds of reed canary grass have been able to develop. Moreover, in the succession areas, a series of shrub species has settled which represent a valuable element from a biocenological perspective and complement the willow species due to different times of flowering and fruit bearing. The diversity of species has overall increased.

The increased structural diversity at the test stretch is also reflected by the locally increased number of bird species. Breeding birds as well as guest birds have benefited from the wide bank stretch with its diverse vegetation. However, results relating to the aquatic fauna suggest that small-scale measures cannot produce major effects in the analysed impounded test stretch. Yet, the installation of alternative bank protection measures can help to locally increase the diversity of habitats. They have lead to a wider diversity of macrobenthos species and created habitats for juvenile fish in the test stretch. If alternative protection measures were applied more frequently, biotopes could interconnect and the various habitats could form a network of biotopes on a larger geographic scale.

In conclusion, the alternative technical-biological protection measures have not only provided a stable bank protection; at the same time, they have promoted the ecological improvement of vegetation and fauna at the bank.

The specification, which is to be found in the Annex, gives a summary of the most important parameters relevant to the test stretch. All results are described in detail in a comprehensive report [6]. This report can be downloaded as PDF file on the homepage of the joint research group of BAW and BfG on the issue of applying technical-biological bank protection measures on inland waterways:

www.baw.de/ufersicherung/ergebnisberichte.php.

10 Literature

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Abbreviations

BAW	(German) Federal Waterways Engineering and Research Institute
BfG	(German) Federal Institute for Hydrology
BinSchStrO	Binnenschifffahrtsstraßenordnung, engl. (German) Regulations for Navigation on Inland Waterways
HHW	highest high water
HNQ	highest navigable discharge
HNW	highest navigable water
LW	low water
MLW	mean low water
MW	mean water
R&D	research and development
WFD	Water Framework Directive
WSV	(German) Waterways and Shipping Administration
WHG	Wasserhaushaltsgesetz, engl. German Federal Water Act

Annex

Bundesanstalt für Gewässerkunde / Bundesanstalt für Wasserbau

Studies on Alternative Technical-Biological Bank Protection Measures Applied on Inland Waterways

Research project

SPECIFICATION

Test section Stolzenau, River Weser Km 241.55 – 242.30, right bank

Technical-Biological Bank Protection Measures and Boundary Conditions

(1) Bank protection methods and their evaluation	**Planting methods**	**Success of planting**	**Value regarding nature protection**[7]
	Planting common reed and sedges		
	a) Planting plugs and sods of common reed on flattened bank slopes protected by stone mounds or berms, in some stretches additionally with fascines or vegetation fabric	**Very good**	Very high value[5]
	b) Planting plugs and sods of common reed on steep bank slopes where stones have been removed, protected by vegetation fabric	Good	Medium to high value[6]
	c) Planting plugs and sods of common reed on unmodified bank slopes (i.e. steep and protected with armour stones) with or without protection from training structures or fascines	Good	Medium to high value[6]
	d) Planting plugs and sods of sedges; varying topography and protection as in a) to c)	Good[1]	Of medium value
	e) Reed mats on flattened bank slope	Moderate[2]	-
	Planting woody plants		
	f) Willow cuttings and long branch cuttings on flattened bank slopes protected by training structure or stone mound	Very good	Medium to high value
	g) Willow cuttings and long branch cuttings on unmodified bank slope, if placed close to the water line and protected by stone mound	Very good	Medium to high value
	h) Brush mattresses of willows on flattened as well as on steep bank slopes, if armour stones have previously been removed	Very good	Medium to high value
	i) Alder plantings in the upper part of unmodified bank slopes	Failed[3]	-
	j) Willow cuttings and long branch cuttings if placed in the upper part of the (flattened or unmodified) bank slope	Failed[4]	-

1) In 2005 often still in places where originally planted, without any tendencies to spread
2) In the first years, the common reed plants of the mats showed poor growth and low vitality. The later development cannot clearly be retraced.
3) Probably dried up (due to lack of precipitation and irrigation) or affected by the lethal alder disease (phytophthora)
4) Presumably dried up (due to lack of precipitation and irrigation)
5) In 2005 wide common reed stands, i.e. also of benefit to fauna
6) In 2005 relatively narrow, though vital common reed stands
7) By 2005, the test section achieved, as a whole, a high value in terms of nature protection; this was due to its habitat diversity i.e. the way in which the planted and unplanted sections had developed.

Note: Below the water level (mean low water) the slopes – with a continuous inclination of 1 : 3 – are protected with class III armour stones in accordance with TLW 1993 (*TLW – Technical supply conditions for armorstones*).

(2) Body responsible for project	WSA Verden, in cooperation with BfG and BAW
(3) Start year	1988/89
(4) Monitoring	Examined and documented between 1989 and 2007: waterway geometry, ground, ground water and river water levels, hydraulic bank load resulting from navigation and natural river flow, vegetation, birds, fish, macrozoobenthos

(5) **Bank geometry**	- slip-off slope - slope inclinations 1 : 3.5 to 1 : 7 (1 : 8) - partly with stone mound in front of alternative protection measures, shallow water zone, training structure or berm In the test section only minor changes in the slope geometry had occurred by 2007. Even relatively steep slope sections, where riprap had been replaced by live brush mattresses or reed beds, had remained stable to a very large extent.
(6) **Ground**	In the immediate bank area, up to approx. 3 m below the upper edge of the terrain (corresponding roughly to the mean low water level) the native soil mainly consists of silts bearing sandy or clayey constituents and partly also of silty or gravelly sands. Below this, the Weser Gravel begins (intermittently to widely graded medium to coarse sandy gravel, 0.2 mm to 60 mm) with a depth of 6 to 8 m.
(7) **Navigation**	**Number of vessels** (calculated from number of lockings) Freighters: approx. 500 / year; approx. 20 / working day Recreational, passenger, other vessels: approx. 100 / year (journeys within the reach are not recorded!) **Dimensions** (mean/maximum from down- and upstream travel taken from traffic observation) Freighters (motor cargo and motor tank vessels, push-tow units) Length: 76 m (max. 114 m) Width: 8.5 m (max. 9.5 m) Draught: 1.8 m (max. 2.5 m) Recreational craft Length: 9.1 m (max. 15 m) Width: 3.4 m (max. 4 m) Draught: 1 m (max. 1.6 m) **Data on journeys** (minimum/mean/maximum from down- and upstream travel taken from traffic monitoring) Freight ships (motor cargo and motor tank vessels, push-tow units) Distance from the bank: 52 m (min. 38 m / max. 67 m) Vessel speed: 11.5 km/h (min. 7.0 km/h / max. 16.5 km/h) Recreational craft Distance from the bank: 47 m (min. 15 m / max. 75 m) Vessel speed: 16.4 km/h (min. 7.7 km/h / max. 58 km/h)
(8) **Hydraulic loads**	Shear stress (τ): ≤ 6 N/m² Flow velocity (v): ≤ 1 m/s Wave heights: Drawdown: 0.14 m (max. 0.39 m) Stern waves: 0.15 m (max. 0.64 m) Secondary waves: 0.06 – 0.08 m (max. 0.41 m) All values given here refer to the loads in the bank area by 2007. Shear stress and flow velocity values are noticeably below the load-bearing capacity limits – known from the literature – of the technical-biological bank protection measures applied here. The ship-induced waves mentioned here can be absorbed by the bank protection measures without damage. As limiting values for the capacity of bearing load resulting from ship waves are not yet known from the literature, further experience must be gained within this research project in order to make valid statements as to whether waves higher than those measured here can be absorbed without damage.
(9) **Evaluation of fauna**	In spring and summer 2006 the area with alternative bank protection and, as a reference, an area of traditional bank protection were examined regarding animal ecology. For this purpose, inventories were taken of birds, fish (especially juvenile fish) and macrozoobenthos. This revealed an increased density of juvenile fish as well as a higher diversity of birds and macrozoobenthos in the alternatively protected bank section, including some Red List species. Therefore the evaluation of the alternative bank protection applied in the Stolzenau stretch has a positive result regarding animal ecology. Continued monitoring in a 5 to 10 year rhythm would be desirable.
(10) **Overall result**	After 20 years of operation, the current state of the technical-biological bank protection measures can be estimated as being very good – with the exception of the issues stated under (1). Under the given boundary conditions, almost all planting measures could develop in a positive manner. The bank protection provides good protection from erosion. The banks are in a stable condition. From the perspective of the WSA, so far no maintenance measures have been necessary. (Future maintenance needs are referred to in the report.)