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German guidelines for designing alternative bank protection measures

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Prompted by the European Water Framework Directive, more environmental friendly bank protection measures will be demanded both for small waters and for inland waterways. These measures should contain as much living or at least dead plants as possible, combined with technical building materials if necessary, to avoid erosion from the natural and vessel-induced flow and wave field. In the following, they will be called technical-biological bank protections. To collect and condense the existing knowledge in this field, the German Association for Water, Wastewater and Waste (DWA) founded a corresponding working group whose main idea was to transfer existing experiences from waters without navigation to those with significant impact from navigation and to account for first results of an ongoing mutual research project of the German Institutes BAW (Federal Waterways Engineering and Research Institute) and BfG (Federal Institute of Hydrology) concerning the same subject but for waterways only. The results were published in a Code of Practice for planners of waterway infrastructure in 2016 (M519). The present paper outlines the basic ideas of M519, how it can be applied and shall encourage the readers to use it to find best-fitted environmental friendly bank protections for navigable waters.

Keywords: Bank protection; technical-biological; code of practice

1. Introduction

In order to protect the banks of inland waterways against erosion and other negative impacts from ship-induced hydraulic loads and/or floods, they are generally protected with technical constructions such as revetments consisting of riprap or sheet pile walls according to commonly accepted design codes of practice such as the German GBB (Grundlagen zur Bemessung von Böschungs- und Sohlensicherungen an Binnenwasserstraßen; BAW 2005, 2010; Gesing et al. 2016) or the MAR (Merkblatt zur Anwendung von Regelbauweisen; BAW 2008). Since the introduction of the EU-Water Framework Directive in 2000, ecological aspects have to be taken into consideration more diligently during building and maintenance measures. These aspects aim, for example, at preserving and enlarging habitats. Technical-biological bank protections (TBPs shortly in the following), which are regarded as close-to-nature bank protections that consist either of plants or of a combination of both plants and technical components (list of recommended measures in M519 see Figure 4, sketches see Figure 5), can be considered an environmentally friendly alternative to technical revetment. Since little experience on waterways has been gained so far and no framework has yet been established, a joint research project between the Federal Waterways Engineering and Research Institute

(BAW) as well as the Federal Institute of Hydrology (BfG) is concerned with the examination of the feasibility and resilience as well as the ecological efficiency of TBPs on inland waterways (Fleischer 2014, see also BAWs website 'http://ufersicherung.baw.de/de/index.html').

In this context, laboratory and model experiments, as well as on-site experiments as at the Rhine River near the town of Worms, were carried out. The objectives of the latter are the testing and monitoring of nine different bank protections (from vegetated riprap, over willow brush mattresses up to parts without any protection) under waterway conditions until 2016 (Schilling et al. 2013; Fleischer and Soyeaux 2013, 2014 and Behrendt et al. 2015). First results of the experiments, which are not yet finished, can be found on the above-mentioned BAWs website.

As the demand for consistent planning guidelines for TBPs has been increasing continuously, the working group WW1.5/ 2.5 of the German Association for Water, Wastewater and Waste (DWA), was founded in 2008, parallel to the above-mentioned research project. The aim of the working group was to gather up-to-date knowledge on the application of technical-biological bank protections on navigable waterways. Existing experiences with bioengineering constructions on watercourses without navigation, along with the present knowledge gained from waterways

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(among others from the aforesaid research project), formed the basis for a Code of Practice – despite the fact that there are neither sound insights nor long-term experiences with TBPs on waterways available, yet. The corresponding Code of Practice DWA-M519 ‘Technical-Biological Bank Protection Measures Applied on Large and Navigable Inland Waterways’ (DWA 2016) was established with the involvement of representatives of the BAW and BfG, the society of soil bioengineering (Gesellschaft für Ingenieurbioologie e.V.) as well as various other institutions, administrations and planning offices. In the following, some information will be given about the above-mentioned research project and the DWA-M519 Code of Practice (M519 shortly in the following).

2. Code of practice – content and procedure

M519 provides basic knowledge and specific help how natural, as well as ship-induced impacts on river banks and corresponding stability demands, should be considered (technical design aspects), how to work with nature (principles of bioengineering) and how to account for the demands of near water habitats (ecologic design and target vegetation). On this basis, an approach for selecting and designing TBPs for large and navigable waterways will be shown, including the detailed description of recommended measures. M519 contains also all relevant legal (for Germany only, but considering the European Water Framework Directive as well) and planning fundamentals.

For all recommended measures, a conservative procedure (ensuring that a slope failure may be avoided, but allowing local damage from erosion if applicable) is presented, based on the presently available set of design rules (BAW 2005, 2008, 2010; Söhngen et al. 2010; Gesing et al. 2016). Furthermore, measures to reduce the ship-induced impact on the riverbank are shown, but specific design rules will be given for measures on the bank slopes only, not for measures in front of it. Nevertheless, the reduction of impacts can be of particular importance in the initial period in which the plants that protect the banks need to grow and develop roots for stabilization purposes.

Further measures for the ecological appreciation of the banks are also explained. An annex to the described Code of Practice presents ten selected alternative construction measures, which today seem to be generally suitable for the application on large as well as navigable watercourses and which are expected to show an ecological appreciation of the banks, see Figures 4 and 5. These construction measures are for instance willow brush mattresses and pre-cultivated slope protection mats that provide long lasting bank protection through plants effects well as vegetated gabions and vegetated riprap where a combination of plants and technical components contribute to the stability of the slope (Figure 1).

Figure 2 demonstrates the general procedure for the planning of bank protections that consist mostly of plants.



Figure 1. Two examples of technical-biological bank protections on the Rhine (upper picture: willow brush mattresses, lower picture: vegetated gabions, both 7 months after installation).

After the recognition of all relevant boundary conditions (points 1 and 2 in Figure 2), it is mandatory to assess and determine the ecological requirements (point 3). It is also mandatory to examine whether a bank protection will, in fact, be necessary and/or to which extent erosion and bank deformation can be accepted since the unprotected bank that develops naturally resembles the natural state to a large degree (to support this decision according to technical aspects see also Figure 3).

In this context, M519 defines three design standards that can be chosen (point 4). If bank erosions or bank deformations can be accepted to a larger extent or are even wanted, design standard I is recommended. In this case, the dimension of the bank protection is either heavily reduced according to the requirements or even rejected. Design standard II allows erosion and bank deformation to a limited extent. Bank protections dimensioned according to this design standard do not have the adequate stability to withstand all kinds of exposure. Design standard III is recommended if the stability of the bank slope has to be guaranteed without any restrictions. The dimensioning is solely based on the assumptions of the ‘Principles

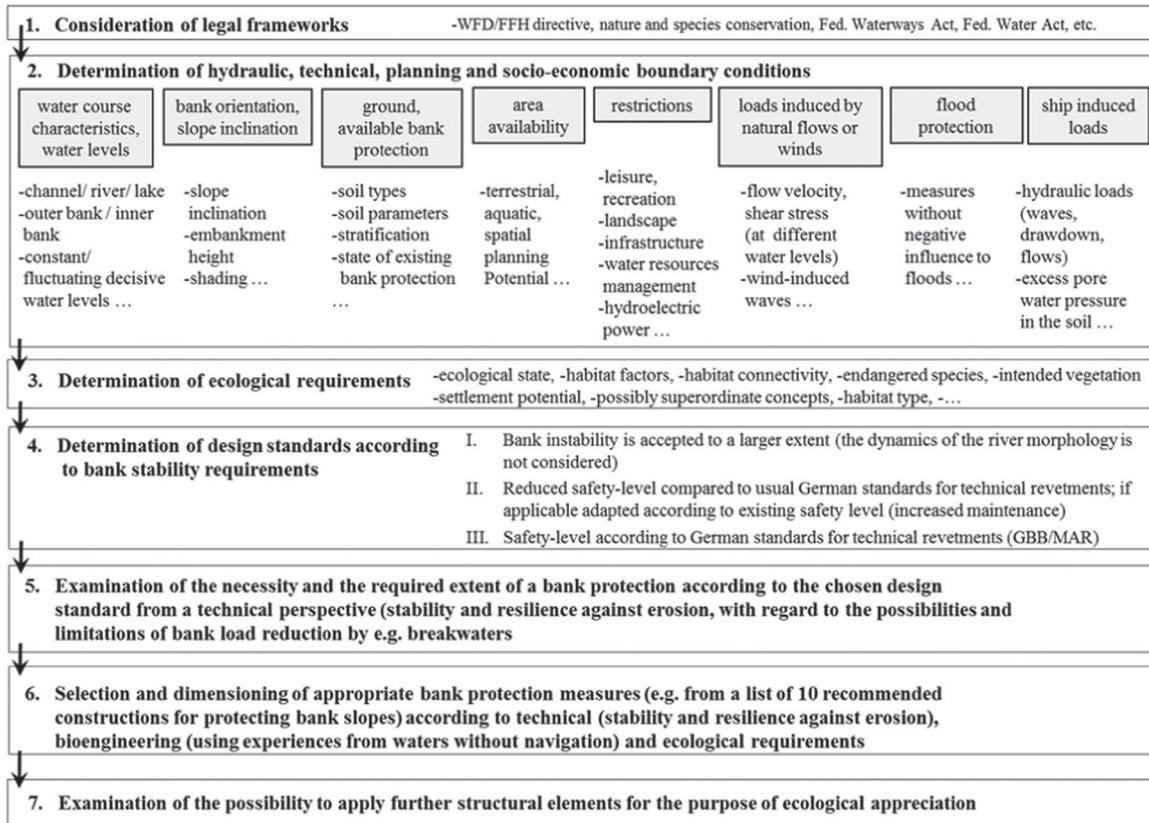


Figure 2. General procedure for planning technical-biological bank protections according to DWA-M519.

for the Design of Bank and Bottom Protection for Inland Waterways' (BAW 2010; Gesing et al. 2016).

Using this predefined selection of standards, an acceptable solution may be found both from technical as well as ecological aspects. It should be noted that the recommended three design standards, which reflect especially the possible impacts from navigation by providing hints on how fast (assuming, e.g. max. 90% of the critical ship speed in case of standard 2) and at which bank distances vessels sail (to mention just two important aspects, depending on technical aspects, e.g. powering, but also the 'human factor') needs to be adjusted from case to case if necessary, e.g. on basis of field data or existing experiences. Nevertheless, because of extensive experience and numerous data under manifold boundary conditions provided by the BAW, which support the assumptions (see, e.g. PIANC 2008; BAW 2010 or Söhngen & Kayser 2010), the design concept given in M519 seems to be very reasonable for local conditions without field data or local experiences.

In the next step, the necessity and the required extent of the bank protection have to be examined according to the technical criteria of the chosen design standard (point 5 in Figure 2). Details will be explained in particular in the following section.

Concerning the dimensioning of a specific bank protection measure (point 6 in Figure 2, selected measures

see Figures 4 and 5), further bioengineering criteria (optimal plant species, optimal type of measure et.), which were established based mainly on experiences from watercourses without navigation, as well as ecological criteria have to be taken into consideration. Those ecological criteria are currently based on assessments of experts since scientific evidence on the effectiveness of TBPs on large and navigable watercourses is not yet available. After the selection and the dimensioning of an appropriate construction, it is finally recommended to examine whether further structural elements such as dead wood for the purpose of an ecological appreciation can be integrated into the construction (point 7 in Figure 3).

3. Bank protection dimensioning according to technical criteria

Along with the bank soil and the slope inclination, ship-induced hydraulic loads on banks, which are explained in detail in M519, are of particular importance concerning the necessity and the extent of bank protections. Loads from ship-induced flows (displacement flows, return currents, flows induced by breaking waves as slope supply flows which is generally the most important source of erosion, if necessary also propeller wash) as well as waves (generally

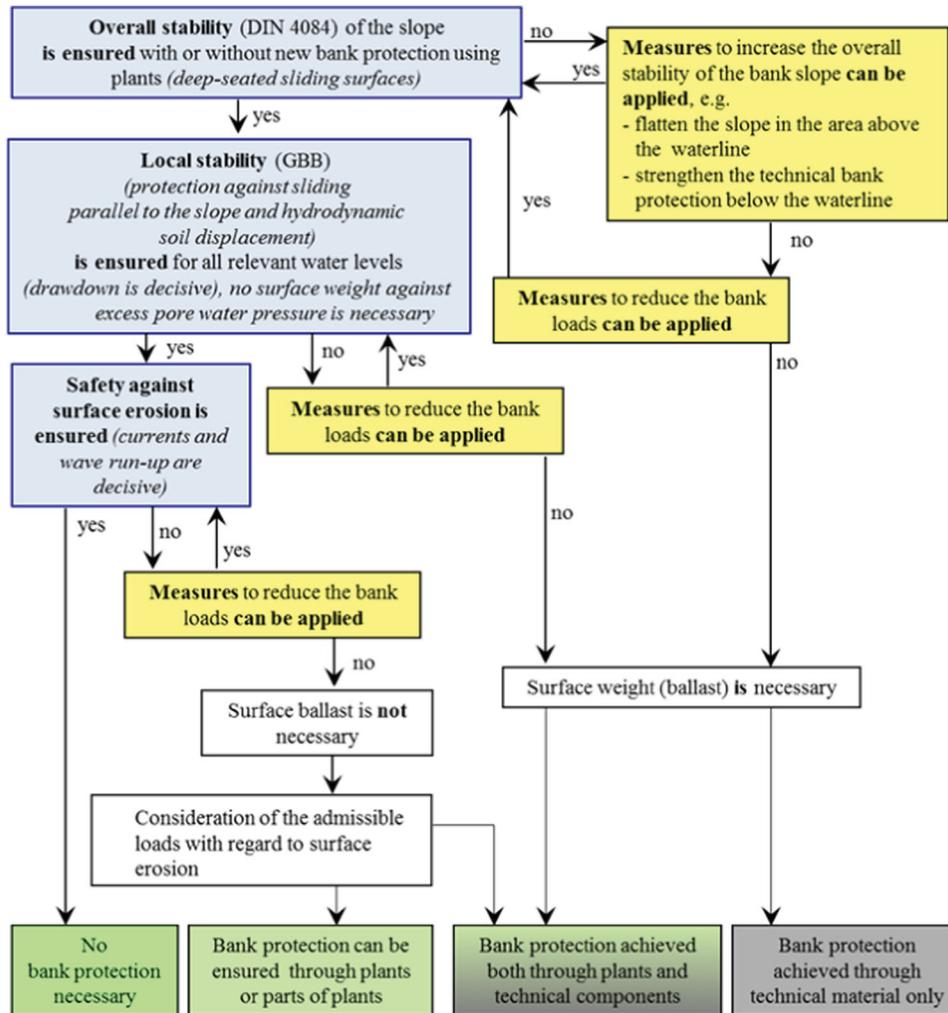


Figure 3. Procedure in DWA-M519 to check the necessity and the extent of technical-biological bank protections.

stern and secondary waves) can lead to soil erosion on the banks (see paragraph 4).

Rapid water level drawdown caused by a passing vessel can induce excess pore water pressure, which reduces the effective soil tension to such an extent that sliding of the slope and hydrodynamic soil displacements as a result of local hydraulic failure (liquefaction) and thus increased surface erosion of the subsoil (also between plant roots) may occur (Holfelder and Kayser 2006). The last mentioned impact seems to be the most important in case of measures with minor technical components as willow bushes). In order to pre-empt these occurrences, technical revetments consisting of loose riprap have to be dimensioned with a particular minimum thickness ensuring a specific weight per unit area (surface weight) to counteract excess pore water pressures according to the ‘Principles for the Design of Bank and Bottom Protection for Inland Waterways’ (GBB shortly in the following, see BAW 2005, 2010; Gesing et al. 2016).

This necessary surface weight on the bank slope may restrict the use of several types of alternative bank

protections. However, plant sprouts and roots, especially willow roots, are able to stabilize the bank slope by increasing the erosion resistance and by producing a tension force similarly to a soil with cohesion (‘root cohesion’). Thus, a sufficiently dense and deep reaching network of roots is able to prevent slope sliding due to excess pore water pressure and the stability may be achieved without a surface weight on the slope.

Single roots can increase the stability comparable to ‘soil nailing’. As the examination and quantification of the efficiency of various types of plant roots at different development and growth stages have not yet been finished within the scope of the above-mentioned research project, the M519 recommends at this point the conservative application of bank protection measures with a minimum necessary ballast per unit area, calculated without considering the root tension (safe side design, Gesing et al. 2016).

In this context, the necessity and the extent of a bank protection have to be examined in the first instance based on technical aspects only by using the GBB (BAW 2010). It delivers design-relevant hydraulic loads, which can be

Construction method	Flow velocity close to protected bank: flow without navigation, return current, slope supply flow or superposition of different velocities. $v > \text{m/s}$	Shear stress w $> \text{N/m}^2$	Height of waves, running predominantly parallel to the slope – generally transversal stern waves and secondary waves, roughly valid also for wind waves. $H > \text{m}$
Vegetated roll with pre-cultivated reed mat	1.3 – 2.3 1.9, 2.3	25 – 65 45, 65	0.15 – 0.55 0.30, 0.45
Pre-cultivated slope protection mat with lawn	1.1 – 1.4 1.3	10 – 40 30	0.10 – 0.20 0.20
Pre-cultivated slope protection mat with cuttings	1.5 – 1.9 1.6	40 – 60 50	0.20 – 0.35 0.25
Wattle fence	1.6 – 2.2 1.9, 1.6 (1.9 without, 1.6 with possible scouring)	15 – 60 30, 15	0.10 – 0.50 0.25, 0.15 (up to 0.5 without, 0.15 in case of possible scouring)
Living fascine and brush layers	1.3 – 2.5 2.1, 2.3	50 – 120 80, 80	0.15 – 0.60 0.45, 0.45
Vegetated geotextile bodies with brush layers	1.9 – 2.3 2.3, 2.1	60 – 65 65, 65	0.4 – 0.6 > 0.55, 0.50
Vegetated gabions	2.6 – 3.2	–	1.0
Living brush mattresses with riprap as toe reinforcement	2.0 – 2.5 2.3, 2.4	50 – 240 120, 100	0.40 – 1.1 0.65, 0.55
Vegetated riprap	2.1 – 2.6 (Calculations with GBBSoft for $LMB_{5/40}$)	70 – 110 90	0.9 – 1 1.0 (Calculations with GBBSoft for $LMB_{5/40}$)
Subsequently vegetated riprap	See above	See above	See above

Figure 4. Thresholds defining the erosion resistance of recommended TBPs (sketches of the measures see Figure 5).

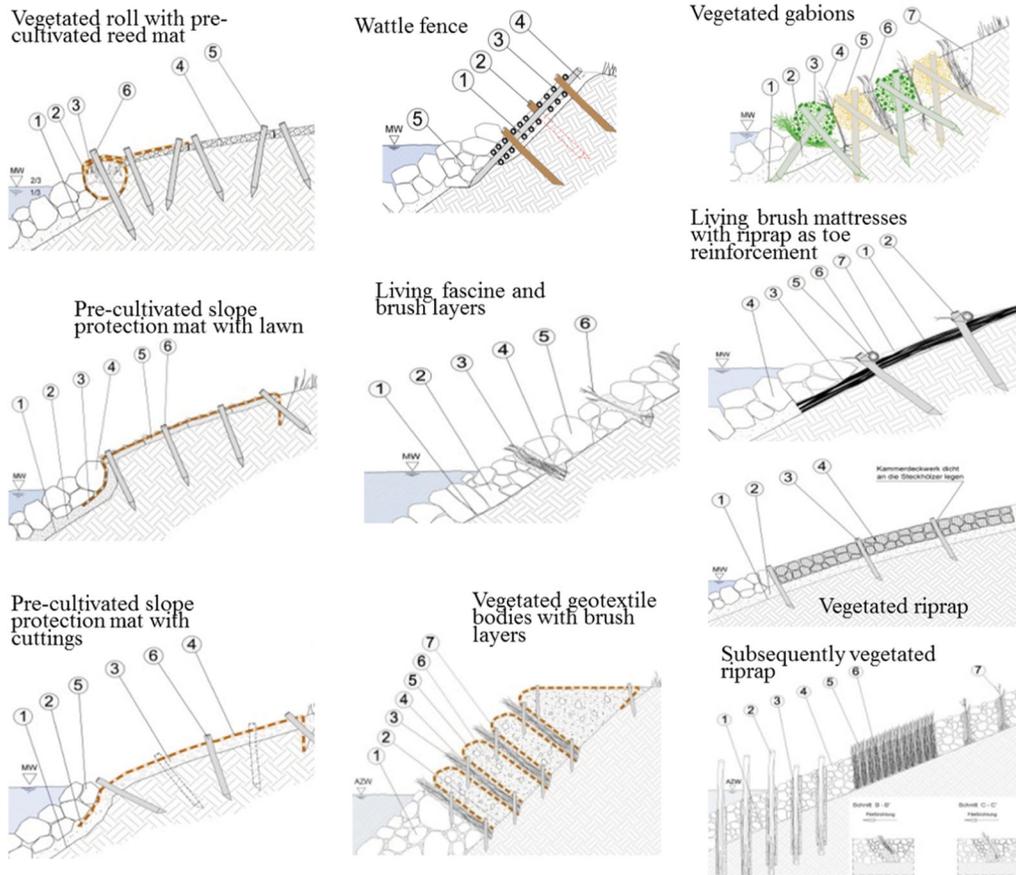


Figure 5. Recommended types of TBPs.

compared to corresponding thresholds of the erosion resistance of the ten recommended technical-biological constructions, see Chapter 4 for details and the required thickness of a hypothetical riprap revetment to counteract the excess pore water pressures as explained before.

The calculated surface weight has to be provided by the chosen alternative construction measure such as vegetated gabions with a corresponding layer thickness. A construction measure consisting entirely of plants, willow brush mattresses, for instance, can solely be chosen if a surface weight is mathematically not necessary.

This design step can be performed very efficiently by using the GBBSOft software, which will be explained in detail in Gesing et al. (2016). It was extended recently to meet the demands of M519 (GBBSOft+). It should be noted that GBBSOft and GBBSOft+ are generally restricted to nearly prismatic channels as those in canals or strongly trained rivers. In case of strongly varying cross sections or irregular banks, the loads from the natural flow field may be obtained alternatively using, e.g. 2D flow modelling or (better) by making field measurements. This holds especially true for ship-induced loads in such cases.

It is also recommended in M519 to examine whether ship-induced bank loads can be reduced by constructive measures, e.g. wave protection constructions parallel to the slope, administrative measures as reducing the permitted ship speed or by displacing the fairway further away from the bank protection, especially in the regrowth period of plants or by flattening the bank slopes if applicable.

The result of the above-mentioned ‘technical design’ shows whether a bank protection is generally necessary, i.e. whether the ship-induced loads or loads from the natural flow field, which may be superimposed to impacts from navigation, lead to significant erosion or not or whether excess pore water pressure occurs. The technical design furthermore shows whether an appropriate bank protection can be achieved by using the wooden material, including living plants only, or just in combination with additional technical components, especially in case of design-relevant pore water pressure. This may lead to the decision that an entirely technical solution is necessary. The corresponding procedure is illustrated in Figure 3.

It starts with the check, whether the overall stability of the bank slope is ensured or not. If ‘not’, the bank slope may, e.g. be flattened. If ‘yes’, the local stability according to effects from excess pore water pressure must be checked next. If the stability is not ensured, only measures with some ballast may be applicable (e.g. in case of possible hydrodynamic soil displacement). If no ballast is necessary, the safety against surface erosion must be checked by using, e.g. Figure 4, leading to possible solutions from technical arguments only. Bioengineering and ecological criteria may follow to find the best-fitted solution.

For 10 selected protection measures, M519 provides comprehensive information including set-point values for

hydraulic loads with regard to soil erosion. Due to the limited experience on inland waterways, these values have initially been defined on the basis of experiences from smaller watercourses without navigation, as shown in the following chapter.

4. Thresholds of erosion resistance

With reference to DWA (2016), which provides detailed information on how the thresholds of erosion resistance were derived and which literature was used, only few information will be given concerning this topic. Reference is made also to the methods of the GBB how to assess ship-induced loads as described, e.g. in Gesing et al. (2016) and BAW (2005, 2010).

It is essential to note first that the threshold values given in the following Figure 4 hold true for near-bank loads, not averages over, e.g. the entire channel, as it is often the case in the literature (data from waters without navigation). Thus, loads should be determined in the area of the TBPs or, even better, at the toe of the alternative bank protections to stay on the safe side, because the relevant water depth reaches its maximum there and thus the loads from the flow field without navigation as well as the ship-induced loads with the exception of breaking waves. If the GBB+ software will be used for assessing these loads, the maxima of all relevant impacts and scenarios (relevant water stages, vessel types and loading conditions, driving directions, ship positions in the fairway etc.) will be used, especially those from breaking waves. Also, possible superimpositions with components of the natural flow field will be accounted for.

It should be noted additionally that the toe of TBPs should be chosen generally not lower than at mean water level (MW) because plants are not able to survive over long time periods below this level as the flooding probability is too high. Additionally, it will be assumed in M519 that the bank slopes will stay protected with adequate technical measures underneath the toe of the TBPs. Thus, it can be assumed that the toe will be protected sufficiently from erosion. This is important since especially protections without strong technical components, using predominantly living plants, need strong toe reinforcements to avoid undercurrent and to meet peak loads caused by abrupt roughness changes between technical revetment and the TBP.

As mentioned earlier, the origin of the thresholds of erosion resistance (in terms of flow velocities, shear stresses and wave heights) of selected measures in Figure 4 is from waters without relevant navigation. It should be noted that only values from positive long-term experiences with TBPs were used. Additionally, the literature data had to be interpreted according to the fact that given permissible velocities or shear stresses are generally averages over the entire cross section and do not concern the bank area. Consequently, they had to be reduced using some

unavoidable assumptions about the shape of the cross sections and the water depth above mean water at design-relevant water levels in relation to average depths. Finally, field experiments of Gerstgraser (1998) were interpreted according to the same principles of local loads, not averages. These numbers of permissible flow velocities v and shear stresses τ were then used to assess corresponding wave heights H , which are not given in the literature for the selected measures in M519. This was achieved by calculating stone sizes of a fictitious riprap revetment by using v and τ and compared with formulae delivering stone sizes for H (similarity between design formulae for technical revetments concerning flow and wave impact), using several applicable approaches from relevant literature. These wave heights were then compared with the few existing experiences from realized measures.

According to M519, it should be recognized that more exact thresholds for erosion resistance cannot be given at the present state of knowledge. This may apply for the future as well because thresholds depend not only on the type of the TBP and the time after installation (state of maturation), but even more on the know-how about the optimal time of installation, the hydrologic conditions especially during the first months after planting, possible peak ship-induced loads during that time, the method and know-how of performing the construction, the frequency and intensity of maintenance measures and the local site conditions, especially the probability and duration of flooding and the exposure to sun-light. Therefore, it is recommended to use rather the lower given numbers in case of probably unfavourable conditions. The highest numbers should be used only if there are positive experiences from existing measures, which are comparable according to local boundary conditions and ship-induced loads (design according to experience).

The threshold values given in the first line of each row in Figure 4 denote the range of existing data (e.g. Johannsen 1996; Gerstgraser 1998; Fischenich 2001; Florineth 2004; LfU 2013) from a lower bound to an upper bound. The lowest value may be used for the initial state just after the construction; the highest number may be used for a mature bank protection after several years of plant growth under good boundary conditions. The values provided in the next line in bold print indicate averages and may be used after some month of growing. The last given values printed in italics refer to the new interpretation of Gerstgraser's field investigations. They are the most probable values in case of good boundary conditions.

5. Conclusions and outlook

The Code of Practice DWA-M519 'Technical-Biological Bank Protection Measures Applied on Large and Navigable Inland Waterways', which were published as a standard in the beginning of 2016, is considered to be a first consistent basis for the planning of alternative bank

protections using plants on inland waterways. As a result of the ongoing research, dimensioning and application restrictions are still necessary, especially concerning the quantification of the bank stabilizing effect of plant roots. After evaluation of the final results, especially from the on-site experiment at the river Rhine, and considering the increasing experience on waterways, it will be possible to revise already existing design standards of the Code of Practice to adapt the set-point values of particular measures with regards to soil erosion and to precise ecological criteria. The update of the Code of Practice is thus planned for the following years. Nevertheless, it makes sense to publish a design code as it was done as soon as possible in order to promote the usage of alternative bank protections for waterways and therefore to be able to have more experiences with such measures in the upcoming years.

In order to facilitate the application of the Code of Practice M519, the software GBBSOft for technical revetments was developed further. The updated software GBBSOft+ enables a comprehensive dimensioning of technical-biological bank protections based on the recommended procedures of M519. It is already available (Gesing et al. 2016) and will enlarge the planning and application possibilities of close-to-nature technical-biological bank protections on larger and navigable watercourses remarkably which amongst others will be of considerable importance with regard to the bank reshaping on inland waterways which are envisaged in the German federal programme 'Blaues Band Deutschland' ('blue belt Germany').

Parallel to the above-mentioned DWA working group, the DWA founded another working group named 'Bio-engineering Measures in Water Construction' (more information of DWA website). This working group focusses on the planning, the construction, tendering, and the realization as well as result-monitoring of these measures. A more general design code, considering, e.g. a possible reduction of flow and wave impact with measures in front of the bank, basing on international experiences of implemented measures, shall be worked out in the next years in a renewed PIANC (World Association for Waterborne Transport Infrastructure) INCOM (Inland Commission) working group No. 128 on 'Alternative Technical-Biological Bank Protection Methods for Inland Waterways'. The readers of this paper will be encouraged to take part in this working group, especially if they are able to support the group with experiences from implemented measures on large waters with navigation.

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Notes on contributors

Bernhard Söhngen was born in Wiesbaden, Germany in 1950. He studied civil engineering at the University of Darmstadt and worked then as a scientific assistant at the Institute of Hydraulic Engineering. He finished with a doctoral thesis on roughness and shape effects in open channel flow. After working as a hydrologist in an engineering bureau, he started working for the Federal Waterways Engineering and Research Institute (BAW), leading the Danube Project Group at first and then – up to his retirement last year – the section Ship-Waterway-Interaction and Field Investigations. His research field was and still remains sediment transport, vessel behaviour in shallow and confined waters as well as ship-induced loads with its links to ecologic questions. He led several national and international working groups for the German Association of Water and Wastewater (DWA) and The World Association for Waterborne Transport Infrastructure (PIANC), the last on ‘Design Guidelines for Inland Waterways’ and ‘Technical-biological Bank Protections’. He is still consulting BAW and delivering lectures at the University of Darmstadt on Inland Waterway Engineering (professorship of honour).

Petra Fleischer was born in Königs Wusterhausen, Germany in 1958. She studied civil engineering at the Technical University Dresden, where she graduated in 1981. Since 1990 she has been working in the earthworks and bank protection section within the department Geotechnical Engineering at the Federal Waterways Engineering and Research Institute (BAW) in Berlin and since 1999 in Karlsruhe. Her main works and research are focused on the construction and stability of technical and technical-biological bank protection as well as on calculation methods for the design of bank protection measures. Since 2004 she has been leading the joint research project between BAW and BfG, in which engineers and biologists investigate the feasibility and resilience as well as the ecological efficiency of close-to-nature bank protections on inland waterways. She was a member of the working group for the German Association of Water and Wastewater (DWA) ‘Technical-biological Bank Protections’, led by Bernhard Söhngen.

Hubert Liebenstein was born in Würzburg, Germany in 1953. He studied landscape planning at the University of Hannover, the main focus on ecology, landscape planning and nature conservation. After working for a private landscape planning office at first, he then started working for the German Federal Institute of Hydrology (BfG). During the employment at BfG, he was a project manager of various studies, e. g. ‘Floristic monitoring in the context of compensation projects at the Lower and Outer Elbe River’ or ‘Examination of the ecological development potential of the Lower and Outer Elbe River’. Since 2006 he is a member of the R&D-project group ‘Studies on alternative biological-technical bank stabilization on Federal waterways’. Since 2007 he is the head of the department ‘Vegetation Studies, Landscape Management’ at BfG.

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