PIANC

The World Association for Waterborne Transport Infrastructure

TECHNICAL-BIOLOGICAL BANK PROTECTIONS FOR INLAND WATERWAYS

PART 1: BASICS OF A BEST PRACTICE APPROACH

InCom Working Group Report N° 128 part 1 – 2025

PIANC REPORT N° 128 part 1

INLAND NAVIGATION COMMISSION

TECHNICAL-BIOLOGICAL BANK PROTECTIONS FOR INLAND WATERWAYS

PART 1: BASICS OF A BEST PRACTICE APPROACH

7 January 2025

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This report has been produced by an international Working Group convened by the Inland Navigation Commission (InCom). Members of the Working Group represent severalcountries and are acknowledged experts in their profession.

The objective of this report is to provide information and recommendations on good practice. Conformity is not obligatory and engineering judgement should be used in its application, especially in special circumstances. This report should be seen as an expert guidance and state-of-the-art on this particular subject. PIANC disclaims all responsibility in the event that this report should be presented as an official standard.

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VAT BE 408-287-945

ISBN 978-2-87223-045-7

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PREAMBLE

(Cited [with additions] and omissions (…) from the Foreword of the British Waterway Management Guide (called also shortly UK guide), prepared from the Cranfield University in 1999)

"For centuries man has been trying to control river erosion, in order to prevent damage to adjacent land, and especially, built property or infrastructure such as roads and railways. In many cases this objective was achieved – at least locally, and in the short term – by installing some form of protection so solid that the power of water could not move it. Typical examples are large stones or concrete, or steel sheet piling.

Recently, however, there has been a growing awareness among practitioners that it is far more effective to work with natural forces than to work against them. In river work this means it is necessary to gain a better understanding of how river processes work in practice, and the Agency's Series of geomorphology projects have certainly assisted practitioners in this understanding.

However, while understanding the processes is essential, in many cases actions are needed, as man can no longer allow a river to define its own course, with no regard for the damage it causes. We therefore need means of preventing bank erosion without causing further problems, and using a means which is environmentally acceptable.

This guide [and also the PIANC WG 128 report] *approaches the problem in a very logical way – by asking the reader if any protection is really needed, or whether a 'do-nothing' or a management solution could be acceptable in their situation. If the need for bank protection is confirmed, then a variety of ways of approaching the problem are given. … A large number of these solutions create habitat, and use living vegetation to strengthen the bank and reduce the risk of erosion. Many of these solutions have been used historically for bank protection, but often only in certain geographic areas – this guide widens the knowledge to a national basis."*

SHORT SUMMARY

The worldwide increasing number of national guidelines and growing experience with realised green bank protections (constructions using as far as possible living or at least wooden construction material) in navigable waters, led to install a PIANC InCom Working Group to collect and condense expert knowledge in this field of work and prepare it for practitioners for design purposes. The corresponding PIANC report, named *Technical-Biological Bank Protections* (TBPs) *for Inland Waterways*, is split into three parts:

The first part, *Basics of a Best Practice Approach* (BPA), provides basic information about the BPA for selecting and constructing TBPs.

The second part, *Part 2, Library of Measures*, provides detailed information on recommended TBPs that can be selected, combined, and adapted by using the BPA.

The third part, *Part 3, Decision-Support Advice*, guides practitioners through the whole design process with a focus on selecting appropriate measures. The latter will be complemented by an Excel spreadsheet, containing the majority of the TBP's preselection and decision-support tools, using inter alia modern decision-making tools as the Analytic Hierarchy Process (AHP).

The report also supports planners (as project engineers) and practitioners with numerous implementation best practices, especially in Chapter 3 (Part 1), but also in Part 2, where design features of recommended measures are presented, and of course in Part 3. But the report does not provide design guidance on every last detail (for example, concerning the necessary thickness and bonding depth of a palisade in muddy ground or the necessary extra surface weight to be placed on bank slopes in case of strong excess pore water pressure), because these features strongly depend on local conditions. Thus, the design approach should be understood as an *extended decision-support approach*, which provides excellent information for selecting appropriate measures and enough information for concrete design in many cases, but it may need additions especially in the case of critical subsoils and strong ship-induced impacts.

Generally speaking, the report tries to solve the usual design problems with TBPs, which needs knowledge and experience of civil engineers, eco-engineers and ecologists all together and the way how the success of bank stabilisation measures will be noticed and rated. The WG members had to notice that functionality assessment is not that simple, whereby partly huge differences between those who designed, realised and maintained measures and external parties as well as cultural differences occurred.

To overcome these challenges and thus, to objectivise the choice and layout of alternative solutions, (which may help to convince people responsible for waterway development and maintenance to use green measures instead of traditional bank protections as rip rap), an adapted BPA is developed, based on a catalogue of numerous realised measures (described in the Fact Files). The content of these descriptions (especially the local Boundary Conditions (BCs) and the balance between aims and achieved functionality issues), is used to assess the possible suitability of a chosen measure under generally different design conditions as those in the described realisations.

This is achieved by a scoring system:

- assessing *differences* between the Design Case (DC) and chosen Analysis Cases (AC), called *feasibility check* (answers the question whether experiences made with the AC-cases can be transferred to the Design Case (DC)).

- assessing differences between user-specified aims in the Design Case (DC) and expected performance issues of the ACs, called *suitability check* (answers the question, how far expected functionality issues may probably be achievable).

This scoring is done both for technical and ecological issues, whereby the scores are chosen and reviewed interdisciplinary and internationally.

In the end, the *Best Practice Approach* (BPA) provides ranking lists of generally appropriate measures. The latter may then be modified and adapted to DC conditions, leading to so-called *variants*. The latter will be checked by considering knockout criteria, e.g. concerning the stability against ice effects. Finally, the report and the corresponding Excel worksheets offer decision-making tools for selecting the best variants for the conditions and objectives at DC site.

EXECUTIVE SUMMARY

INTRODUCTION

The report of WG 128 offers a **Best Practice Approach** (**BPA**) to implement **Technical-Biological Bank Protections** (**TBPs**). These measures use, as far as possible, living plants or dead wood as construction elements. Conventional construction components such as sheet piling or rip rap (revetment made from heavy, loose stones) shall be avoided as far as possible, resulting in bank protections that are only as strong as technically necessary and as weak or green as biologically possible. Optimally, natural vegetation and succession shall take over the desired protection function short- and long-term.

Such green TBPs (see Figure 2 to Figure 4) cannot be designed in the same way as their conventional counterparts because the latter need much less design information than TBPs. Because conventional bank-protection designs only need, in principle, the magnitude of ship-induced impacts and some bank properties such as the slope inclination and friction angle, conventional designs allow greater standardization than green TBPs.

By contrast, the functionality of TBPs depends on a much greater number of influencing parameters in the local **Boundary Conditions** (**BCs**), such as the magnitude of water-level changes (ΔW), especially the duration of drought and flood periods, which influence the possible vegetation or the elevation difference between mean water (MW) and the highest shipping level (HSW), which in turn determines the efficiency of wave-breaking pre-embankment constructions. Other important local BCs determine the vitality of vegetation; for example, the precipitation, the slope (inclination), the width of the vegetation zone, and possible shading by buildings or large trees. Other relevant impacts – besides navigation – include frost heaving or ice drift.

Different planner's aims are also design relevant, such as the necessary stability; for example, against the dominant navigation-related loads or the fulfilment of ecological demands such as the enhancement of water-bound and terrestrial ecosystems, the creation of ecological stepping stones, or social or legal demands such as enabling recreational activities. The design of TBPs is therefore generally much more complex compared with conventional protections and led to the decision to develop a design approach based on practical experience gained from numerous implemented measures (collected in Part 2). These experiences were analysed and extended, by so-called **projections** using subject-matter expert knowledge from the members of PIANC WG 128. These projections include the assessment of worst-case BCs, where the measures may still function as intended according to expert assessment, and additional functionality, where the measures will offer extra functions if adaptions were implemented.

Transferring this expertise and experience represents the main challenge and purpose of this **Best Practice Approach** (BPA). That is, this guide seeks to make available the best practices for implementing TBPs concerning the achieved stability and sustainability, the potential ecological upgrade or other achieved planner's aims at the implementation site of an existing measure (called ***Analysis Case***, or ***AC***) to the BCs and planner's aims at sites where a new measure is planned (called ***Design Case***, or ***DC***) by gathering, organising, and presenting all relevant design criteria in a preferably quantitative way. In a PIANC report, this multicriteria approach should be facilitated as far as possible for practitioners.

LAYOUT AND CONTENT OF THE REPORT

This WG 128 report, *Technical-Biological Bank Protections (TBPs) for Inland Waterways*, is split into three parts. The first part, *Basics of a Best Practice Approach*, provides basic information about the BPA for selecting and constructing TBPs. The second part, *Part 2, Library of Measures*, provides detailed information on recommended TBPs that can be selected, combined, and adapted by using the BPA. The third part, *Part 3, Decision-Support Advice and an Excel spreadsheet*, guide practitioners through the whole design process with a focus on selecting appropriate measures.

The WG 128 report also supports planners and practitioners with numerous implementation best practices, especially in Chapter 3 (Part 1) but also in Part 2, where design features of recommended measures are presented, and of course in Part 3. The report does not provide design guidance on each detail (for example, concerning the necessary thickness and bonding depth of a palisade in muddy ground or the necessary extra surface weight to be placed on bank slopes in case of strong excess pore water pressure), because these features strongly depend on local conditions.

Thus, the AHP approach (**Analytic Hierarchy Process**), outlined in Part 3, should be understood as an *extended decision-support approach*, which provides excellent information for selecting appropriate measures and enough information for concrete design in many cases, but it may need additions especially in the case of critical subsoils and strong ship-induced impacts. Reference is made concerning this point to standard design tools such as the German GBBSoft+ (GBB 2010).

RELATIONSHIP BETWEEN THE DIFFERENT PARTS OF THE REPORT

The three parts of the report and their different chapters are variously linked together. Generally, the link is mentioned at the end of each chapter, and practitioners can follow these links mentioned in the texts to find the right path through the report. Of course, practitioners may also read the report in sequence, but the recommended jumping from one part to another as needed supports a selective reading and applying of the report, as different parts of the report are written for different readers and practitioners. Figure 1 shows how the three parts interact, and which chapter practitioners and planners should read or apply. The different colours in the text and frames of the tables highlight the relationship between different parts of the WG 128 report.

To further simplify the connections between Parts 1 and 3, Chapters 1-6 in Parts 1 and 3 correspond directly to each other. They are thus shown on the same level in Figure 1. The content of each chapter is similar but not the same. So, Parts 1 and 3 complement each other, whereby focuses on the basics of the recommended design approaches for readers who do not need details, and Part 3 focuses on the details of the approaches for readers who need more assistance for applying the WG 128 report to a real and implemented Design Case.

CONTENT OF THE REPORT WITH ADVICE ON READING ORDER

Readers should generally read Chapter 1 of the report first, using the three levels on the *left* in Figure 1 to guide the depth of their reading. The *dotted*, *coloured frames* on the *right* of Figure 1 show different readers how comprehensive each chapter is for their own application needs.

Readers interested in summaries of the report's main objectives only (for example, decision makers and contract makers), should read at least the abridged versions of Chapters 1-4 in Part 3 and the corresponding summaries in Chapters 5-8 in . These readers might also find useful a quick review of the collection of measures in Part 2.

First-time users of the report and experts should read chapters 1-4 in Part 1, chapters 5-7 in Part 3 and Appendixes A-C in Part 3, which offer several worksheets for applying the BPA. During subsequent reads, practitioners may concentrate on Part 3 only, which also serves as a tutorial document.

The following Part 1 provides comprehensive

- background information (Chapter 1); for example, about the members of Working Group (WG) 128, the Terms of Reference and other terminology, and the WG's specification and progress that led to the BPA as finally recommended and presented here;
- relevant literature (Chapter 2) collected and briefly summarised with a focus on the few existing guidelines currently available;
- relevant measure types and corresponding flanking measures (Chapter 3), which should be read especially by non-experts and decision makers, together with decisive selection criteria such as ΔW; and
- analyses of the collection of recommended measures in Part 2 (Chapter 4); for example, by the so-called *screening method* for preselection, which uses only a few characteristics of BCs and design features and which are collected in a large overview table.

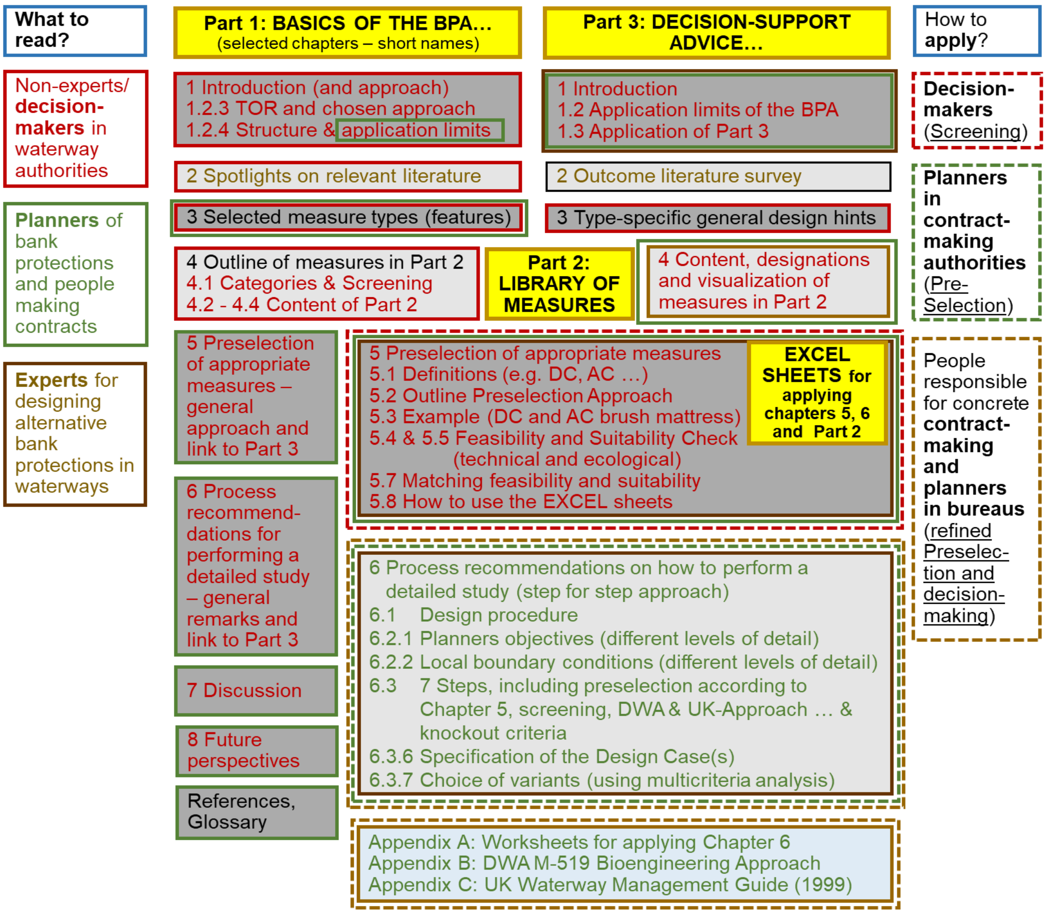


Figure 1: Structure and links between Parts 1-3 of the report and guidance for selective reading and applying

As mentioned above and with reference to Chapters 5 and 6 in Part 3, the *application* of the recommended preselection and detailed design approach is presented very briefly in the corresponding chapters. But this information may be sufficient to understand the main objective of the BPA and whether the BPA applies to the Design Case under consideration.

STRUCTURE AND CONTENT OF PART 2: LIBRARY OF MEASURES

The comprehensive collection of measures in Part 2 is categorised into three groups, which are explained in more detail in Chapter 4 of Part 1:

- The first category contains 23 *Basic Types* (BTs), which provide short summaries of common measures, such as standard bioengineering methods, without specific reference to implemented measures.
- The second category contains 34 *Fact Files* (FFs), which provide more comprehensive and standardized information than the Basic Types, especially on the motivations of the planners, the local BCs, and the achieved functionality.
- Finally, the third category contains 6 *Case Studies* (CSs), which include all the information of the FFs plus additional background information and other details on the implemented measures such as their achieved functionality.

All measures, which primarily concern waterways in a temperate climate, are further subdivided into applications at sites with low, average, and high ΔW (or corresponding channel types such as canals, impounded rivers, and free-flowing rivers) and applications at sites with low up to high ship-induced impacts because analysis showed that ΔW and ship-induced impacts are generally the most important criteria for choosing the appropriate measure. This categorisation allows to some extent preliminary selection of appropriate measures; see the following figures, which visualise all the measures considered in this report, including the standard example to understand the BPA – the DC at the impounded Weser close to Stolzenau town – and the AC, here willow-brush mattresses, which were implemented at the free-flowing Rhine section close to Worms, Germany. Part 2 also contains all the scores, which quantify several design criteria and which are used in the preselection tools.

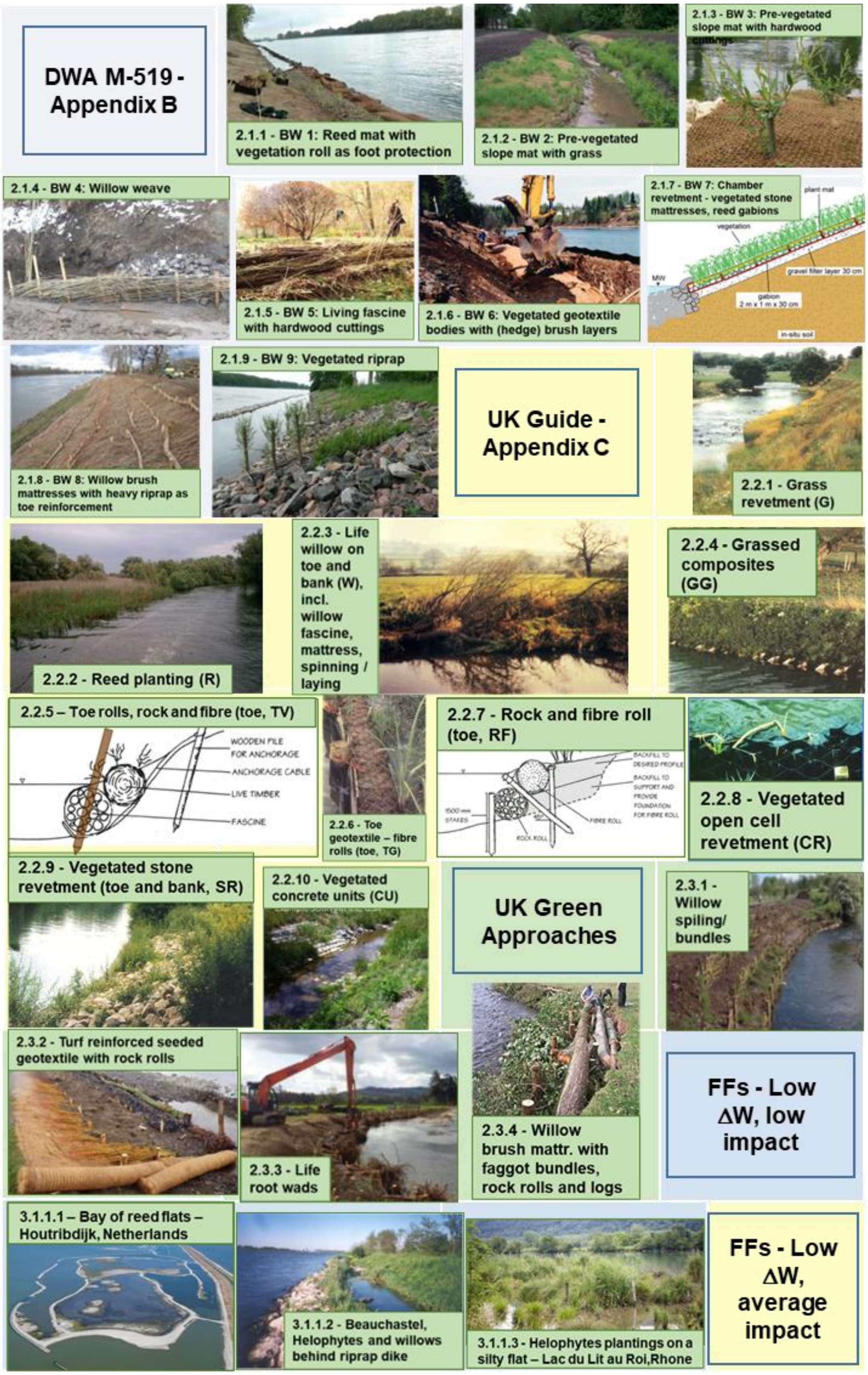


Figure 2: Visualisation of all measures described comprehensively in Part 2 of the WG 128 report: Basic Types (BTs) from DWA-M 519 and UK Waterway Management Guide and Fact Files (FFs) for low water-level changes (ΔW) and low ship-induced impact – the designations of the measures are abbreviated

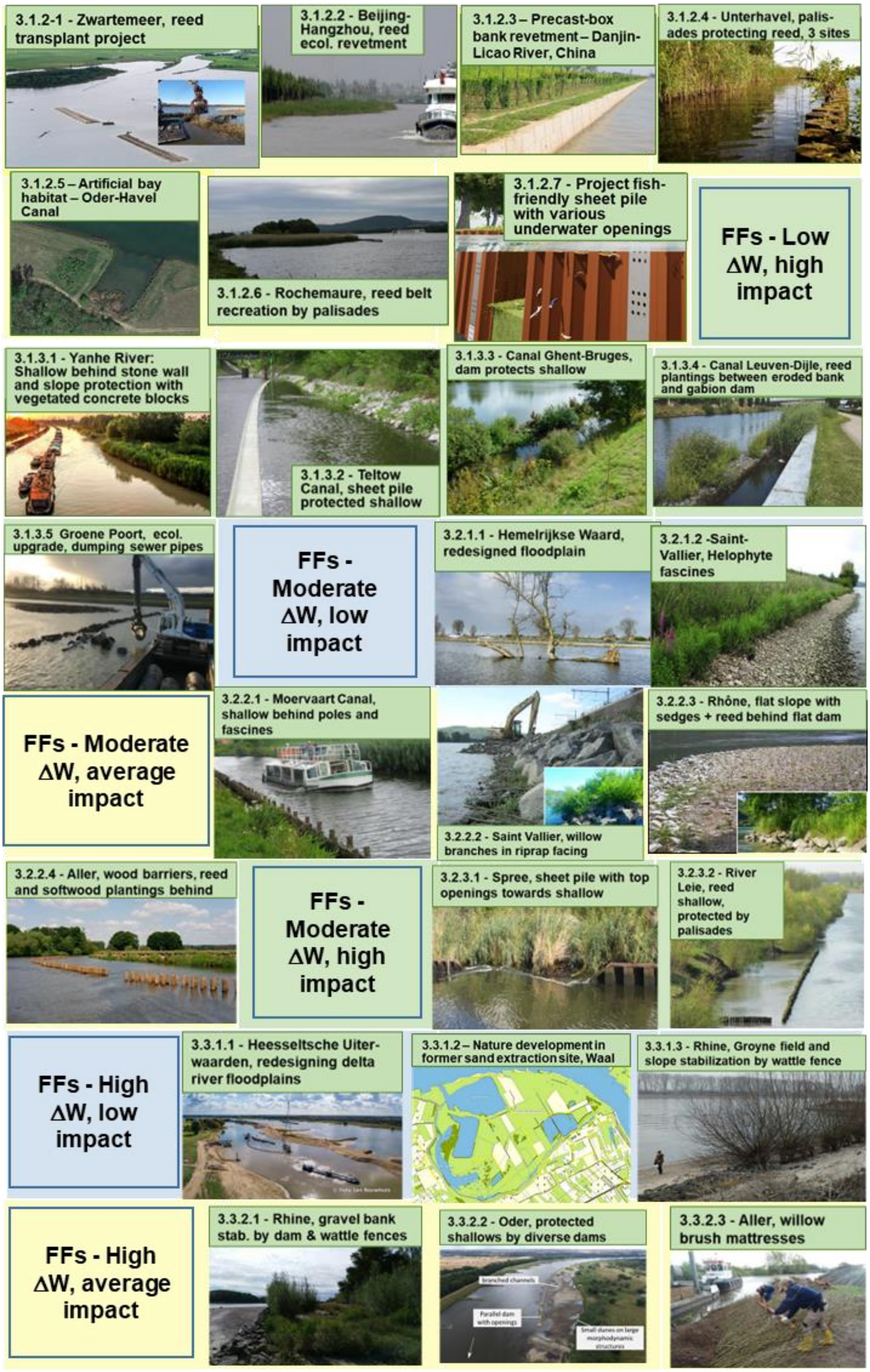


Figure 3: Visualisation of Fact Files (FFs) for low ΔW and average ship-induced impact up to high ΔW and average ship-induced impacts

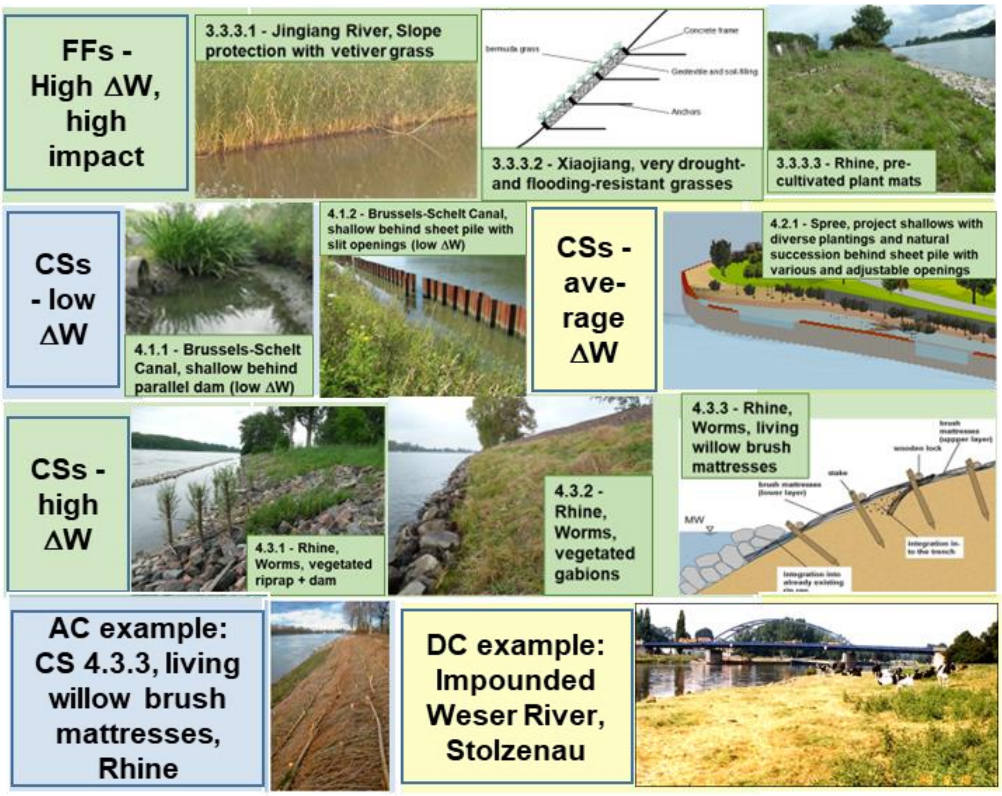


Figure 4: Visualisation of Fact Files (FFs) and Case Studies (CSs) for high ΔW and high ship-induced impacts

STRUCTURE AND CONTENT OF PART 3

To facilitate selective reading of the report and to support tutorials, Part 3 can stand, as Part 1, on its own. Therefore, it includes (as visualised in Figure 1) the same Chapters 1-4. As the reading of these chapters is generally recommended for almost all users of the report (from interested laypeople up to experts, from decision-makers up to planning bureaus, see Figure 1**Error! Reference source not found.**), Part 3 reminds only a few facts from Part 1, which are basically necessary to understand and apply the BPA.

To support end users of our approach, Chapter 5 of Part 3 provides, together with Appendixes B (DWA approach) and C (UK approach), very comprehensive information about all the preselection schemes used here, explained using specific examples of real-world implementation. Building on this, Chapter 6 provides process recommendations on how to perform a detailed design study, including the BPA's *7 Steps* and a final tool for comparing selected variants (generally TBPs from the ACs collected in Part 2, but adapted to conditions at DC site and corresponding planner's aims). In addition, an Excel worksheet is attached to the report, including examples. The following section outlines these design steps in more detail.

PRINCIPLES OF THE BEST PRACTICE APPROACH (BPA)

As mentioned above, the BPA developed by the PIANC WG requires considering of a large number of design criteria. These criteria are documented, together with selected measures, in various ways in Part 2 of the report about design-relevant BCs and functionalities.

The basic idea of the BPA is to compare relevant BCs and requirements at the site of the planned bank protection (Design or Planning Case). The result is, among other things, a ranked list of measures for the special planning case, whereby the following principles are applied (see also Figure 5, which visualises the BPA):

Quantification: All relevant design criteria are substantiated (concretised, quantified) by specific technical statements (attributes) – for example, on the size of ship-induced loads or on the growth conditions for plants – whereby two limiting attributes will always be offered; for example, low hydraulic loads such as in large water bodies without significant navigational impact and very large shipping loads such as in a canal with a small fairway–bank distance. The degree of fulfilment of the attributes must be assigned a score (*degree of fulfilment score*) between one (1) (in the example with low loads) and zero (0). A large number of tools are made available for this purpose, such as correlations to the waterway class or the fairway–bank distance, which make it possible to estimate the number of points without measured values (for example, the wave height); see, for example, Chapter 5 and Appendix B. The significance of the criterion (weight between 0 and 1) for the DC is also quantified to summarise and quantify the individual criteria in the sense of weighted averages.

Comparative analysis: To quantify the suitability of an AC from the catalogue of measures, the degree of fulfilment scores for the DC and AC (criterion by criterion) are always compared with one another. The smaller the difference between the two scores, the greater the associated comparison score. The weighted mean of all comparison scores is a measure of the suitability of the selected AC measure at the planning location.

Categorization: For methodological reasons, the individual criteria are grouped into technical and economical, ecological, and social as well as legal issues; see the following figures. Technical and economic criteria are, for example, the durability and the effort involved in building and maintaining the measures in relation to site-typical conventional bank protections, such as loose rip rap. Among the social and legal aspects, access for leisure activities is assessed. Ecological concerns include the promotion of selected target species and typical bank habitats. For the preselection of measures, only technical and ecological issues and the BCs and functionalities will be considered.

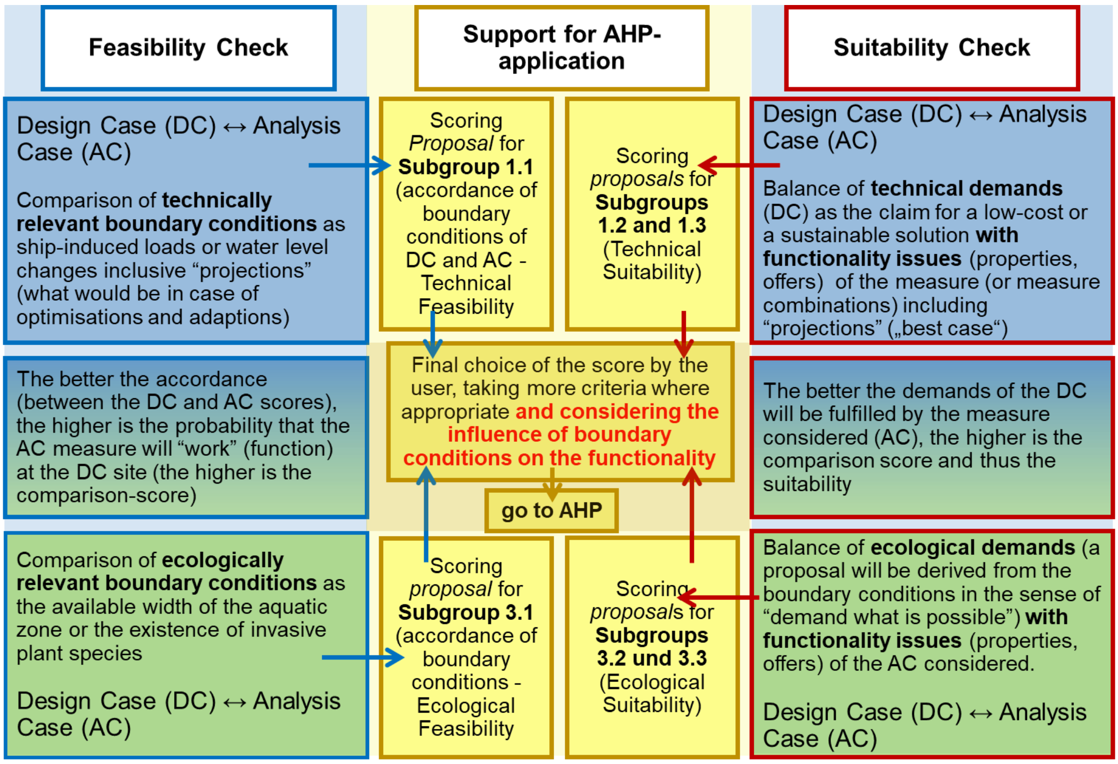


Figure 5: Structure of the preselection scheme with its links to the analytical hierarchy process (AHP) approach

Methodological separation between feasibility and suitability: Weighting the comparative scores of the BCs from DC and AC leads to a summary score, which can be assigned to the feasibility of a measure (*feasibility check*), because the more similar the BCs, the greater the probability that the AC measure will also work at the planning site. At the same time, the suitability of the measure (*suitability check*) is evaluated by comparing the functionalities formulated as requirements (demands) for the DC with the functionalities actually achieved. The better the AC measure meets the requirements, the higher the measure's suitability for the site. During the final assessment, of course, the two design aspects of feasibility and suitability are linked. For example, the stability of a measure can be better guaranteed if the water-level fluctuations in canals or impounded rivers are smaller than in free-flowing waters. To avoid an overly complex criteria matrix, the BPA did not directly link these two aspects.

Comparison of feasibility and suitability: Both aspects are subsequently linked numerically for the preselection of measures; for example, with a so-called (arithmetical) logical matching method. The latter ensures that both feasibility and suitability must be fulfilled equally to receive a high score, but that measures, whose boundary conditions fit not optimally with those at DC site, are nevertheless not sorted out too early. The results are summarizing scores for technical and ecological aspects, which are processed with Excel support into ranking lists of suitable measures. Because even the best matching procedure cannot account for the aforementioned strong link between BCs and the achieved functionality, the scoring method applies the analytical hierarchy process (AHP) approach, shown in Figure 6; see also the last point of the *7 Steps* in Figure 7.

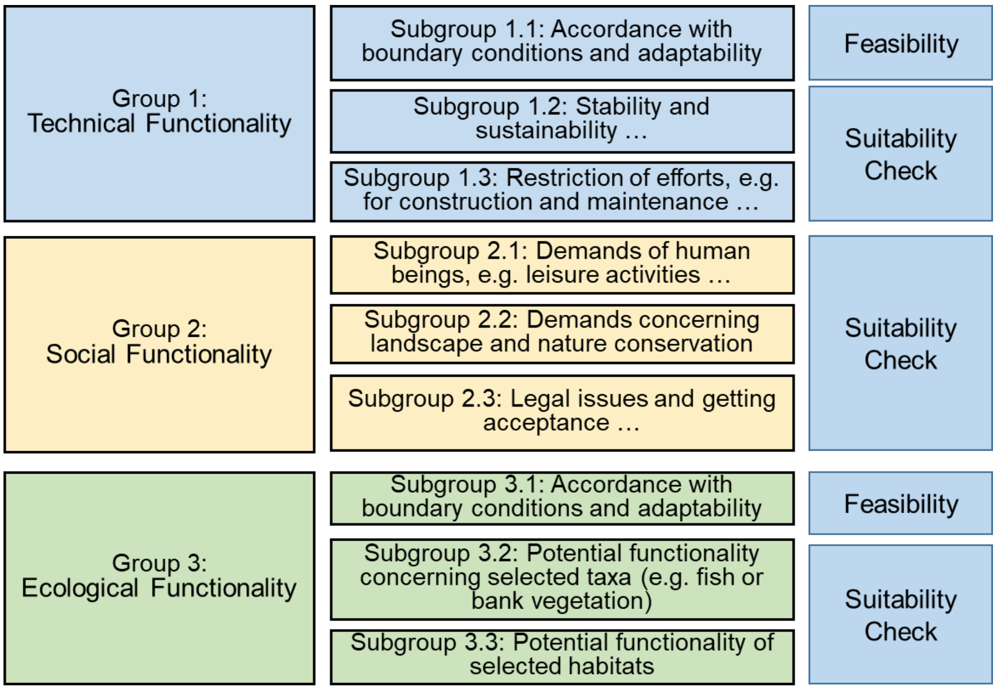


Figure 6: Groups and subgroups of the AHP approach

Projections: To make the subject-matter-expert knowledge in the WG available to practitioners and planners, two main states were considered for the technical aspects. All measures were evaluated first with regard to the implemented state and then also an ideal state if, for example, adaptions to account for the local BCs and optimisations were made. These assessments, called *projections*, significantly increase the informative value of the selection methods and lead to further rankings. In the ecological analysis, only the state that can potentially be achieved with regard of the boundary conditions is evaluated, among other things because usually no long-term experience or concrete monitoring results exist for the measures under consideration.

Comparison of technical and ecological (and social) aspects: The application of the preselection tools described above has shown that ranking lists of technical and ecological aspects usually have only a few things in common, so that a comparison makes sense here too, which, for example, can be done again in a 'logical way'. Various different averaging options are offered here. One of those options, which is recommended here, is basing on a geometrical mean (or a weighted geometrical mean) of the technical and ecological scores. The latter is different to the one combining feasibility and suitability issues ('arithmetical logical matching'), because both aspects have to be fulfilled strictly to achieve a good score. Nevertheless, the same designation ('logical matching') for this matching procedure is used.

Consistent methodological procedure: Because of the large number of influencing parameters and the locally very different BCs and requirements, the selection and design of a planned measure will always require individual case studies, even if the preselection process in particular is supported by the Excel-based tools described above. It is therefore all the more important to formulate process recommendations for how the complex design task can best and most efficiently be handled methodologically. These recommendations comprise the following steps (see also Figure 1).

PROCESS RECOMMENDATIONS FOR READING AND APPLYING PART 3

The recommendations focus on decision-makers, who may only need the screening method to find out whether any feasible alternatives to conventional bank protection exist. Employees in contract-making authorities, which are responsible, for example, for functional tendering of construction works, may need all the preselection tools to specify TBPs to assess possible expenses or people responsible for the concrete design of the measure, such as planners in waterway authorities and engineering bureaus. These practitioners should at least read Chapter 1.2 in Part 3 for the implementation limits of the BPA and Chapters 3 in Parts 1 and 3, which offer short descriptions and common design features of TBPs, general design rules, and implementation ranges. Contract-making authorities should then review Part 2. Because Part 2 contains all the various construction details and implementation ranges, it is very important for practitioners to consult it to learn about possible solutions for a site's BCs.

To apply the preselection tools, practitioners should consult Chapter 5 in Part 3, which presents the most important and very comprehensive preselection tools. They tackle both technical and ecological issues. Social and legal aims are not considered in the preselection tools because the focus is on answering the questions: What is feasible? and What really works? But these aims are still accounted for when comparing selected measures by using the multicriteria tool AHP.

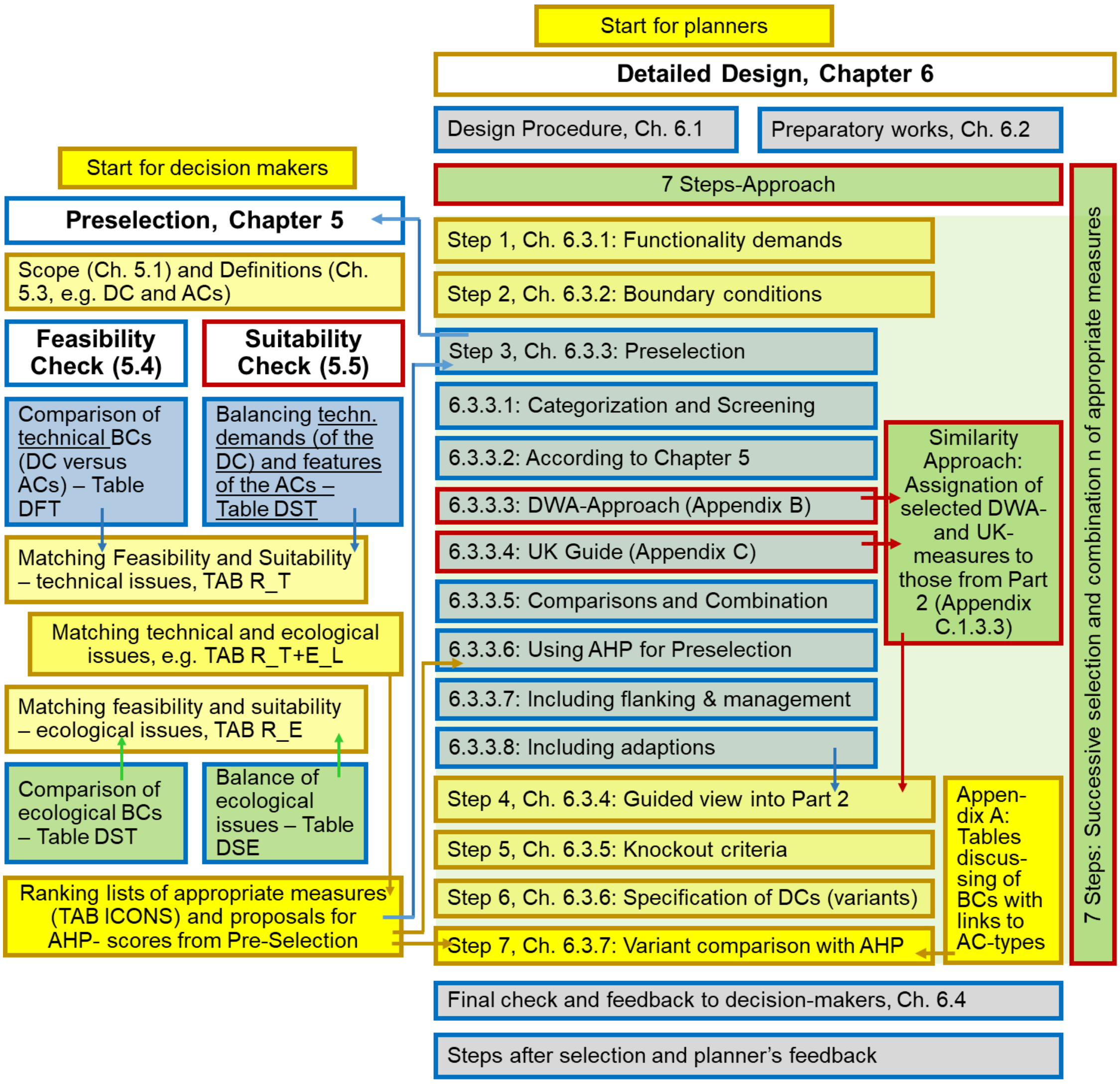
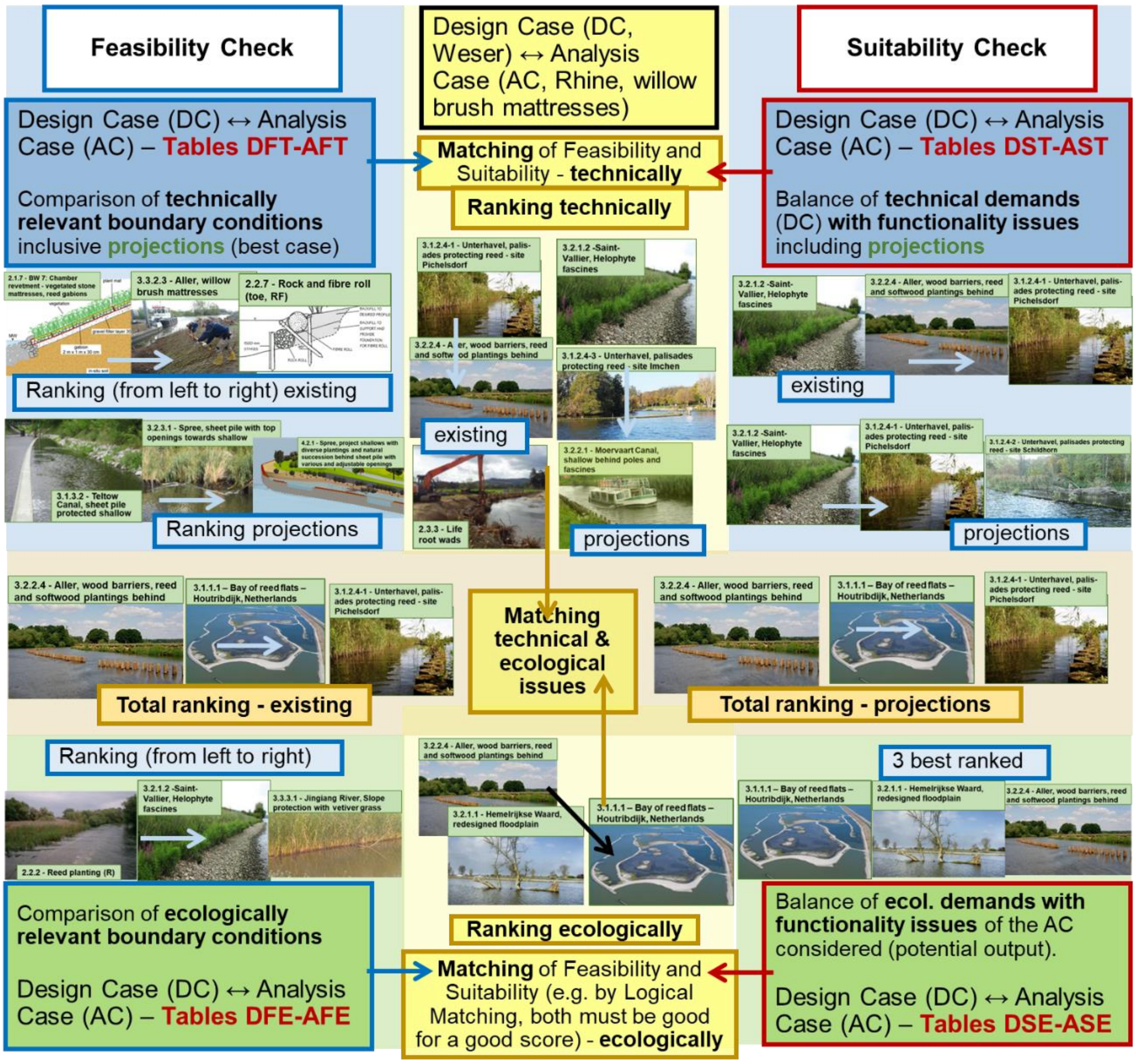


Figure 7: Simplified application steps of the preselection scheme (left) and the detailed design (right)

Practitioners should next read Appendix B, which describes an important part of a German Code of Practice – the DWA-M 519 Bioengineering Approach, tackling a very restricted number of design criteria that are all related to local BCs and may be used as alternatives to other preselection tools – and Appendix C, which describes a reviewed and extended British Waterway Management Guide (1999) – using a larger number of criteria than the DWA approach but still mostly related to BCs. The UK Guide offers a very stringent, technological approach compared with the one in the DWA Guideline; see also Figure 9. Decision makers may prefer to also read Chapter 5 and the aforementioned appendixes to apply the preselection tools, but planners especially should read all of Chapter 6, which explains all the ideas behind the AHP and its implementation using the Excel tools.

The application of both preselection and the detailed design is shown in Figure 7 (with Chapter names from Part 3). On the *left*, the steps, outlined above are shown again according to their correlations with each other; for example, how the results from the feasibility and suitability checks and the technical and ecological results are matched. Also, the designations of the corresponding TABs in the Excel file are mentioned. The *arrows* between the boxes indicate the workflow; for example, how the scores from preselection are linked to the issues for the detailed design, which is shown on the *right* in Figure 7.



Abbreviations: DFT = Design Case, feasibility check, technical aspects), DFE = Design Case, feasibility, check, ecological aspects, DST = Design Case, suitability check, technical aspects, DSE = Design Case, suitability check, ecological aspects. AFT, AFE, AST, ASE = the same as above, but concerning the Analysis Case

Figure 8: Visualisation of ranking lists (first-named three measures each) of the four categories (left and right columns) and corresponding matched results (middle column) for the standard DC (Weser, Stolzenau)

Finally, practitioners should read and apply the approach outlined in Chapter 6, which guides the user through the whole design process with recommendations for each step. Its kernel forms the procedure called *7 Steps for Design* (according to Chapters 6.1-6.7), which includes the preselection tools (Chapter 6.3). Practitioners should read and apply each section in Chapter 6 in succession, as indicated on the *right* in Figure 7.

The 7 Steps comprise the following:

Step 1: Discuss and specify the planner's aims.

Step 2: Discuss relevant local BCs, whereby the practitioner must specify the BCs and demands to reduce the number of relevant design criteria as far as possible. This report offers numerous tables with advice on how the criteria will affect the design (also in Appendix A).

Step 3: Apply the preselection tools (screening and comprehensive preselection according to Chapter 5, the DWA-M 519 and UK Guide to develop ranked lists of appropriate measures that match the BCs, especially accounting for both technical and ecological issues.

Results from applying the preselection tools to the standard DC on the impounded Weser River at Stolzenau, Germany, according to Chapter 5 are shown in Figure 8. Comparisons to the results of the application of the other recommended tools, such as using the UK guide (called also *UK approach*), are shown in Figure 10. Figure 9 shows one of the numerous design charts of the UK approach, whose results were used in Figure 10. The figures also include those for the standard AC, willow-brush mattresses (measures 2.1.8 from the DWA-Gide and similar measures 2.2.3 and "W" from the UK-guide are mentioned in both figures, not the one from the Rhine River, measure 4.3.3, because it was not selected by the approach in Chapter 5).

During Step 3 practitioners should also discuss measure combinations, combination with flanking methods, and management strategies. By the end of Step 3, a large number of potential solutions may fit the BCs and demands for the site, depending on the focus of the practitioner – and these potential solutions might satisfy decision-makers, who will then support the use of alternatives to conventional bank protections. But to find the optimal measure, these potential solutions must be sorted using the next steps.

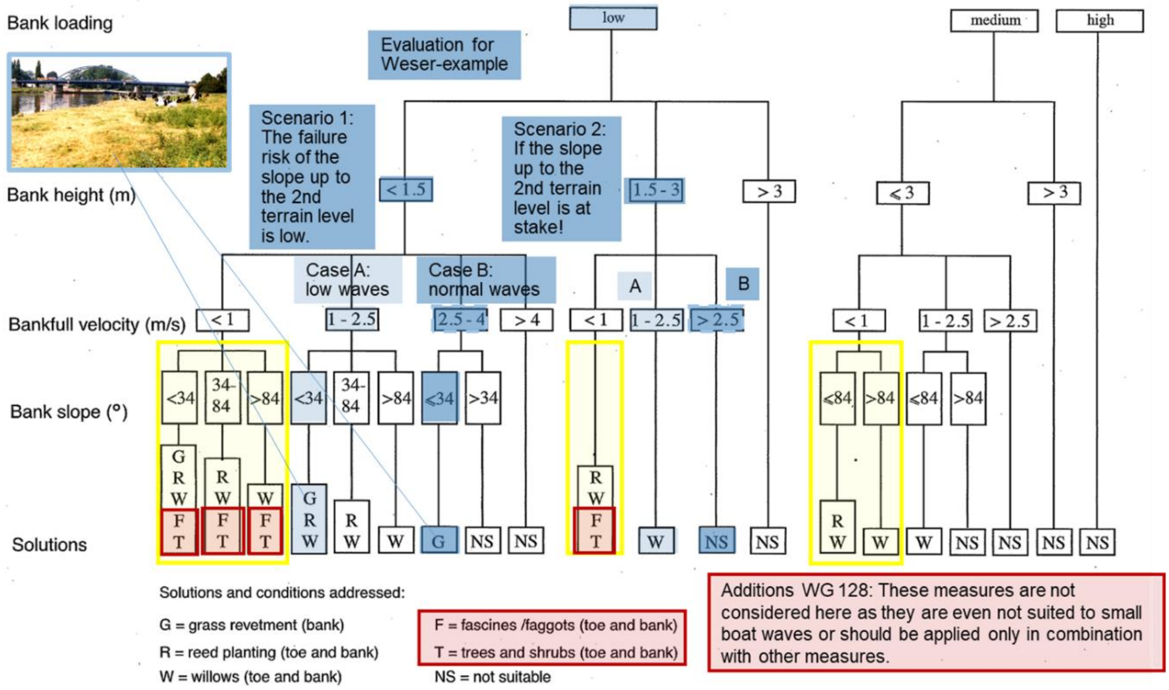


Figure 9: Example of the design charts in the UK guide concerning bioengineering methods, applied to the Weser Design Case (from Part 3, Appendix C)

Step 4: Practitioners should now regard Part 2 in greater detail, focusing on the measures from the preselection step. For example, Figure 11 shows an extract of the descriptions of measure 2.2.3 'Life Willow at Toe and Bank', which comparable to our standard AC. Remarks in the blue box reflect the application charts of bioengineering methods in Figure 9. Practitioners should especially regard the construction details, possible improvements to account for planner's aims, and possible adaptations to relevant BCs. This initial consideration of measure details will provide a preliminary sorting of the potential measures.

While regarding the measure descriptions in Part 2 is generally recommended for all practitioners, project managers may focus on the concrete design recommendations for the selected measures from the preselection step only.

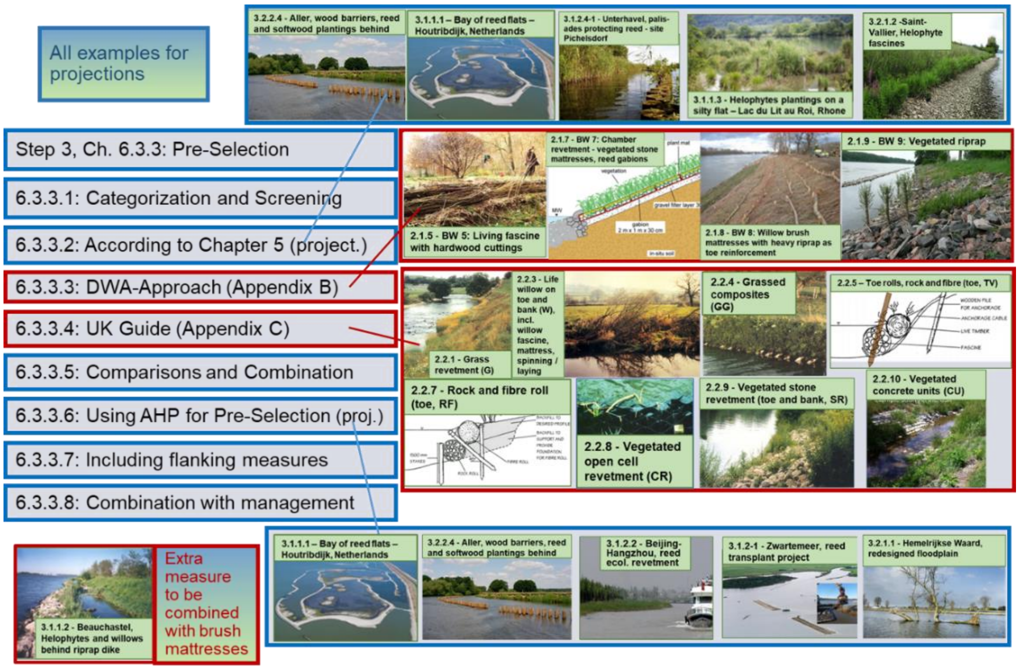
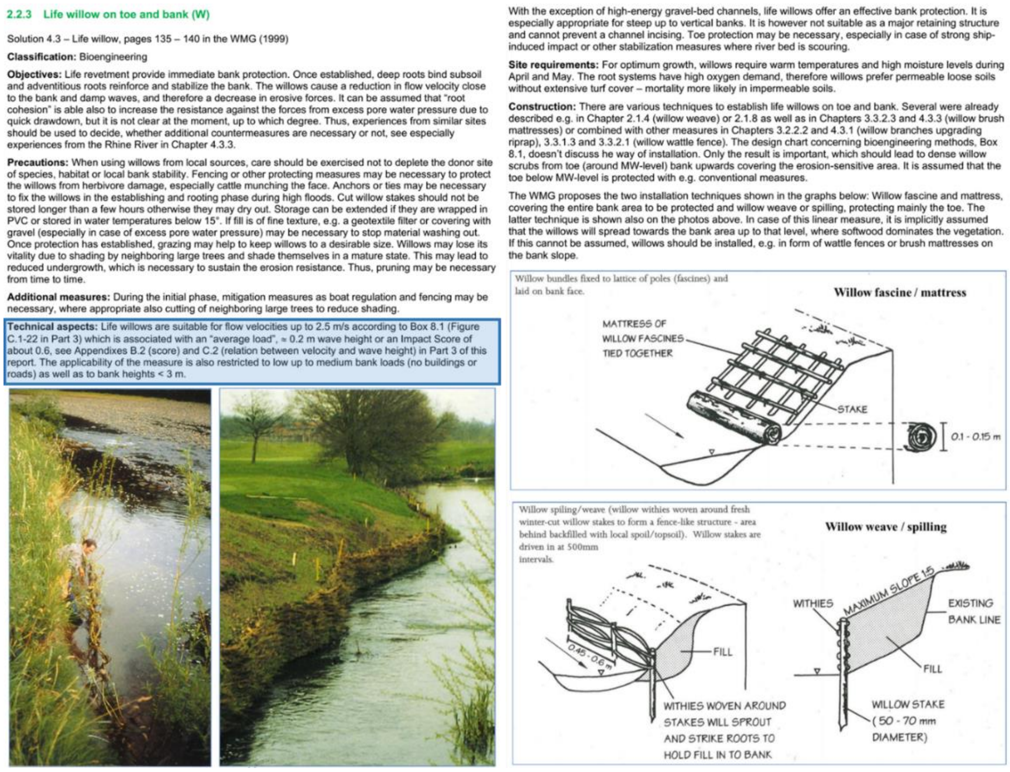


Figure 10: Selected results from preselection tools, applied to the Weser DC (ranked from left *to right)*



2.2.3 Life willow on toe and bank (W)

Solution 4.3 – Life willow, pages 135 – 140 in the WMG (1999)

Classification: Bioengineering

Objectives: Life revetment provide immediate bank protection. Once established, deep roots bind subsoil and adventitious roots reinforce and stabilize the bank. The willows cause a reduction in flow velocity close to the bank and damp waves, and therefore a decrease in erosive forces. It can be assumed that "root cohesion" is able also to increase the resistance against the forces from excess pore water pressure due to quick drawdown, but it is not clear at the moment, up to which degree. Thus, experiences from similar sites should be used to decide, whether additional countermeasures are necessary or not, see especially experiences from the Rhine River in Chapter 4.3.3.

Precautions: When using willows from local sources, care should be exercised not to deplete the donor site of species, habitat or local bank stability. Fencing or other protecting measures may be necessary to protect the willows from herbivore damage, especially cattle munching the face. Anchors or ties may be necessary to fix the willows in the establishing and rooting phase during high floods. Cut willow stakes should not be stored longer than a few hours otherwise they may dry out. Storage can be extended if they are wrapped in PVC or stored in water temperatures below 15°. If fill is of fine texture, e.g. a geotextile filter or covering with gravel (especially in case of excess pore water pressure) may be necessary to stop material washing out. Once protection has established, grazing may help to keep willows to a desirable size. Willows may lose its vitality due to shading by neighboring large trees and shade themselves in a mature state. This may lead to reduced undergrowth, which is necessary to sustain the erosion resistance. Thus, pruning may be necessary from time to time.

Additional measures: During the initial phase, mitigation measures as boat regulation and fencing may be necessary, where appropriate also cutting of neighboring large trees to reduce shading.

Technical aspects: Life willows are suitable for flow velocities up to 2.5 m/s according to Box 8.1 (Figure C.1-22 in Part 3) which is associated with an "average load", ≈ 0.2 m wave height or an Impact Score of about 0.6, see Appendixes B.2 (score) and C.2 (relation between velocity and wave height) in Part 3 of this report. The applicability of the measure is also restricted to low up to medium bank loads (no buildings or roads) as well as to bank heights < 3 m.

With the exception of high-energy gravel-bed channels, life willows offer an effective bank protection. It is especially appropriate for steep up to vertical banks. It is however not suitable as a major retaining structure and cannot prevent a channel incising. Toe protection may be necessary, especially in case of strong ship-induced impact or other stabilization measures where river bed is scouring.

Site requirements: For optimum growth, willows require warm temperatures and high moisture levels during April and May. The root systems have high oxygen demand, therefore willows prefer permeable loose soils without extensive turf cover – mortality more likely in impermeable soils.

Construction: There are various techniques to establish life willows on toe and bank. Several were already described e.g. in Chapter 2.1.4 (willow weave) or 2.1.8 as well as in Chapters 3.3.2.3 and 4.3.3 (willow brush mattresses) or combined with other measures in Chapters 3.2.2.2 and 4.3.1 (willow branches upgrading riprap), 3.3.1.3 and 3.3.2.1 (willow wattle fence). The design chart concerning bioengineering methods, Box 8.1, doesn't discuss he way of installation. Only the result is important, which should lead to dense willow scrubs from toe (around MW-level) bank upwards covering the erosion-sensitive area. It is assumed that the toe below MW-level is protected with e.g. conventional measures.

The WMG proposes the two installation techniques shown in the graphs below: Willow fascine and mattress, covering the entire bank area to be protected and willow weave or spilling, protecting mainly the toe. The latter technique is shown also on the photos above. In case of this linear measure, it is implicitly assumed that the willows will spread towards the bank area up to that level, where softwood dominates the vegetation. If this cannot be assumed, willows should be installed, e.g. in form of wattle fences or brush mattresses on the bank slope.

Figure 11: Extract from Part 2 concerning the Basic Type (BT) 'Life Willows at Toe and Bank'

What can be learned from the descriptions concerning the DC is, for example, that the different methods to initiate the growth of living willow bushes – by constructing a wattle fence or brush mattresses, for example – achieve about the same the result once the measure reaches maturity: dense willow bushes are able to withstand forces from the flow field and also to some extent ship-induced currents. More information can be found in Parts 2 and 3.

After reviewing Part 2, practitioners and planners should have a deeper insight into the main issues associated with the preselected measures – especially the tables of decisive demands and BCs, which make clear possible drawbacks of the preselected measures. The next step analyses these potential drawbacks, which further narrows down the potential solutions.

Step 5: Practitioners and planners should next review the demands and BCs that exclude some preselected measures as unsuitable: the *knockout criteria*. Knockout criteria include ice effects, such as frost heaving or ice drifts, and excess pore water pressure, which occurs when the drawdown speed of passing vessels overtops the permeability and therefore requires ballasting the bank slope; for example, with rip rap or gabions. This important step may further reduce the number of potential solutions.

Some example knockout criteria for the Weser DC are shown in Figure 12. In this example, because of the discrepancy of available space and budget for the Weser DC, especially large and comprehensive measures may not be suitable.

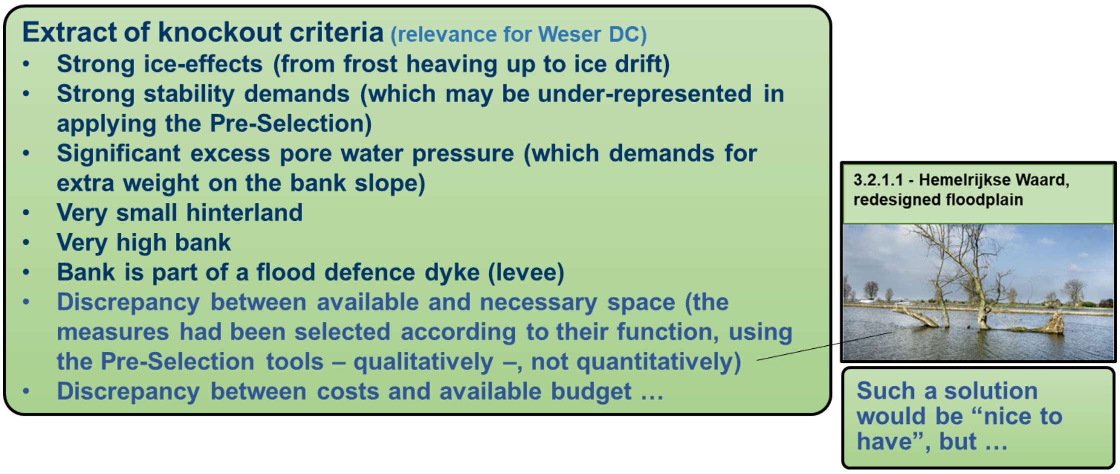


Figure 12: Extract from the large list of knockout criteria (relevance for DC Weser marked in blue letters*)*

Step 6: Practitioners and planners must now perform a final selection of measures. Consulting Part 2 again, practitioners and planners should also adapt and specify the selected measures for DC purposes. These measures are called *variants* or *the AC behind the variant*. Grouping the measures this way is necessary to use all the preselection scores as the basis for applying the AHP.

If a selected variant is a combination of two or more ACs, the Excel sheets offer several combining tools of variant properties so that corresponding preselection scores can be assessed. Practitioners and planners should modify these preselection scores where appropriate.

If, for example, ecological deficits of a preferred AC will be upgraded, then construction elements of another measure can be combined with the preferred solution: The standard AC example of willow-brush mattresses, protecting the bank slope above MW level, may be upgraded by building a small dam on the rip rap-covered bank in water depths below MW to create a shallow water zone such as in the Rhône River close to Beauchastel, France (measure 3.1.1.2). This upgraded measure is also a suitable solution for the DC at the impounded Weser River. Variants basing on these measures, shown in Figure 13, were therefore chosen for the final selection step, Step 7, which uses AHP.

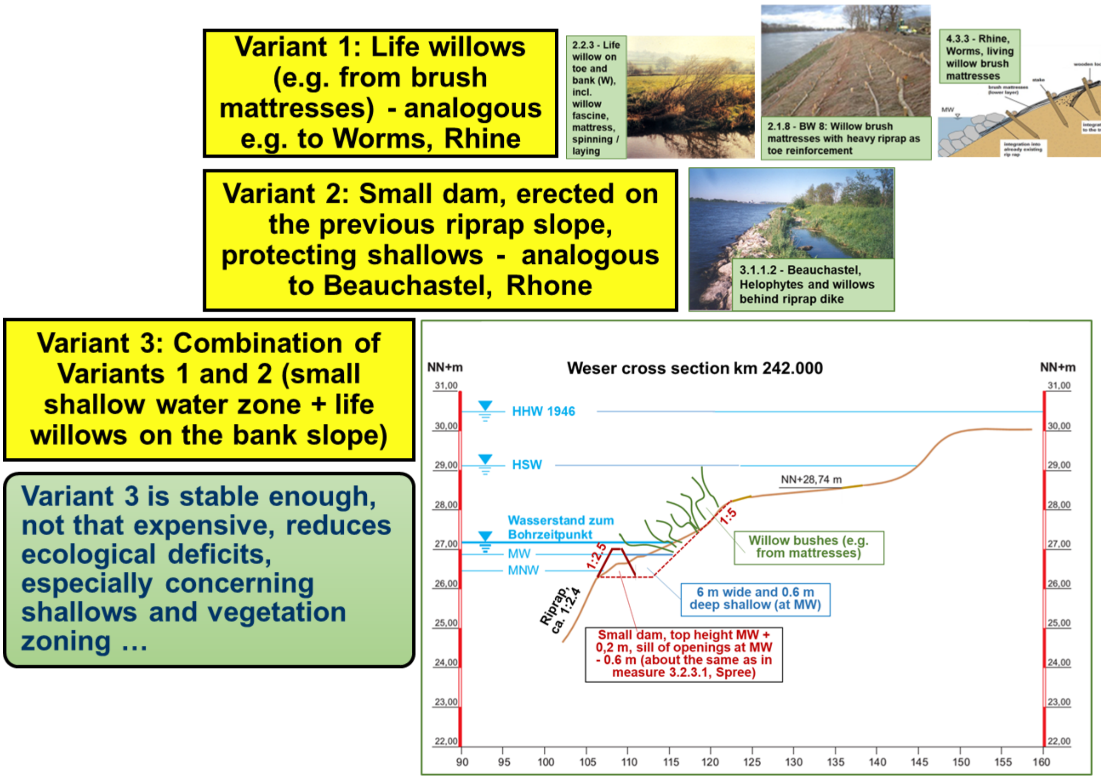


Figure 13: Examples (variants) chosen to explain the design approach of the WG 128 report

Again, as for all previous steps, practitioners and planners must specify all relevant issues, especially the construction details and adaptions made to the ACs behind the variants.

Step 7: Finally, practitioners and planners should compare selected variants in a structured way using the AHP. This standardised multicriteria evaluation method uses three criteria groups, as shown in Figure 6:

- Technical issues (subgroups feasibility, stability and sustainability, restriction of effort)
- Social aspects (human concerns, landscape, law, and acceptance)
- Ecological criteria (feasibility and adaptability, selected target organisms and habitats)

Its structure and its cross-linking to the preselection tools is shown in Figure 5. Here, too, assistance is provided on the importance and quantification of the individual criteria using the preselection scores and corresponding Excel tables, which allow, for example, a combination of measure properties and accounting for the influence of BCs on the functionality.

By the end of Step 7, practitioners will be supported in a rational and objective way towards choosing an appropriate variant optimally fitted to the DC site with its unique BCs. This optimal variant selection is achieved by applying comparative analysis techniques (as all measures and variants are assessed the same way), by tackling generally relevant design criteria, and by leveraging the knowledge and experience of the experts in WG 128 in the form of the predefined scores for all the measures in Part 2.

In choosing the final score, practitioners and planners must also consider the strong relation between BCs and functionality issues, which was ignored while using the preselection tools for practical reasons and was replaced by the numerous matching procedures. Thus, practitioners and planners using AHP must always answer the following two questions when choosing the final score:

- What would happen if the AC behind the variant were adapted to DC conditions (that is, consider the AC to be already implemented at the DC site)?
- In which way and to what extent can the AC measure be further upgraded; for example, ecologically?

To consider these questions, again, Part 3 offers scoring assistance and the corresponding Excel sheets. See Chapter 6.3 in this part and the corresponding chapter in Part 3 for more guidance on answering these two questions.

After the final selection of an appropriate measure, always provide feedback to all stakeholders – especially to decision-making and contract-making authorities. The BPA, like most design processes, requires a looped approach, because nature-protection authorities often express disappointment with the realistically practicable measures selected for a site. By contrast, waterway authorities may fear that the selected measures are not sustainable enough, especially concerning the long-term stability. Thus, discussion about these points often leads to modified planner's demands, and a second loop for an adapted design may be necessary.

FINAL REMARKS ABOUT THE BEST PRACTICE APPROACH (BPA)

As explained in the previous section, all approaches are supported by numerous Excel tools, which allow practitioners and planners to select suitable measures and define the BCs and demands of the DC only, which then automatically compares the DC to the numerous ACs, leading, for example, to the ranking lists and the ability to perform sensitivity analyses with a few clicks. The AHP is also supported by several aids, such as the links to preselection scoring, so that the entire selection process is supported.

But the design approach presented here, even if it is very comprehensive concerning the appropriate type of measure, does not go so far as dimensioning all the concrete construction details with corresponding expenses; for example, concerning the necessary bonding depth of a sheet-pile wall or the optimal plant species for a DC. However, Part 2 does provide guidance and suggestions for these concrete construction details.

Therefore, additional considerations may generally be necessary for specifying selected design features, unless the Boundary Conditions (BCs) of the design Case (DC) and the selected measure are so similar that it seems possible to transfer the knowledge of an implemented measure as described in Part 2 to the DC site. This ability to transfer knowledge directly where applicable is the general idea behind the BPA – not only concerning the measure type but also concerning construction details.

Therefore, the BPA outlined here may also be called an *Extended Decision Support Approach*, which provides excellent information for selecting suitable measures and enough information for concrete design in many cases but not for all measures and BCs.

1 GENERAL ASPECTS

The report on TECHNICAL-BIOLOGICAL BANK PROTECTIONS FOR INLAND WATERWAYS is split into three parts to support selective reading and applying of the report:

- Part 1 – BASICS OF A BEST PRACTICE APPROACH – provides background knowledge and the general layout of the recommended approach for selecting and constructing technical-biological bank protections (TBPs). Reading of this Part 1 is thus recommended for casual readers searching for background information on bank protection strategies in general over decision-makers in waterway authorities, contract-making entities, and planners in agencies and engineering bureaus. Subject-matter experts, who plan to apply Part 3 only, should at least review the introductory and closing chapters of Part 1, which discuss the report's proposed design approach and compare it with other well-known approaches.
- Part 2 – LIBRARY OF MEASURES – provides comprehensive details on the features, application suggestions, and functionality issues of numerous measure types and implemented measures.
- Part 3 – DECISION SUPPORT ADVICES – guides practitioners and planners step-by-step through the design process with the focus on the selection of appropriate measures in the sense of decision support advices. Thus, the present third Part 1s written mostly for users of the design approaches.

Because the three parts are closely interrelated, the report also offers guidance on chapters or concrete information from the other two parts that readers may find useful.

1.1 Scope

This report provides recommendations for the selection and layout of eco-friendly bank protections for inland waterways. It is assumed that it was already checked that natural succession is not acceptable, so that any form of protection is necessary. Nevertheless, the report offers design hints for allowing natural succession too.

The bank-protection measures provided assume that ship-induced impacts dominate the bank loads in the waterways. These green alternatives to traditional protections such as sheet piling or rip rap will be referred to as *technical-biological bank protections* (TBPs).

The design recommendations are based on positive experience with real-world, implemented measures. The design approach is thus a best-practice approach (BPA).

The approach focuses on measures using bioengineering methods. Erosion protection is achieved mostly by using plants and plant materials.

This report assumes that flanking measures such as the mitigation or reduction of impacts as well as the application of well-known river regulation measures such as the construction of groynes or parallel dykes have been taken where appropriate before starting with the design of the measures specified here. Thus, the report focuses on measures taken close to or directly on the bank slope. This focus is thus more on local measures compared with the more extensive river-engineering works.

The study depth is that of providing preliminary design rules, especially to select appropriate measures. Nevertheless, the report provides guidance on how to perform a more detailed design (process recommendations).

1.2 Introduction

1.2.1 Motivation and Difficulties to Overcome

Since the mid-1980s, demand has increased for softer forms of bank-protection techniques in navigation channels. These alternative protections enhance the ecological state, or at least the ecological potential of inland waterways, while also meeting technical and economic requirements. These alternative bank-protection techniques therefore ensure the stability of the bank zone where necessary, but their construction and maintenance expenses are preferably not greater than those of standard solutions such as rip rap.

The demand to use more eco-friendly protections results primarily from the legal situation, which has changed almost worldwide over the last few decades. But this increased demand also reflects the changing self-conception of humans towards a more sustainable handling of nature. So, even if alternative bank-protection measures may sometimes cost more than standard protections, even stakeholders such as authorities responsible for waterway infrastructure who favour traditional measures increasingly accept TBPs as a solution – if the TBPs meet the technical and economic requirements.

This compelling necessity to meet technical and economic requirements represents the crux of the matter. Practitioners responsible for bank protections often complain that there are no generally accepted design rules available that can be used according to existing technical standards. Also, traditional bank-protection methods generally fit various conditions on-site and offer resilience even if BCs change in the future. Softer protection methods, however, demand site-specific solutions to meet the local BCs and achieve ecological demands, which complicates the design process. Furthermore, those responsible for nature protection generally demand greater risk tolerance to allow for solutions as soft as possible, preferring to replace existing protections and renounce any additional measures to allow natural succession. This preference contradicts the traditional approach in waterway engineering; that is, to minimise risk absolutely and avoid ongoing maintenance.

This unsolved conflict between practitioners and environmentalists needs a workable design approach for eco-friendly bank-protection measures, preferably in the form of PIANC guidance, which is widely available and generally accepted by waterway authorities worldwide.

Producing this guidance is the objective of the PIANC InCom Working Group (WG) 128 on 'Alternative Technical-Biological Bank Protections for Inland Waterways'. In 34 meetings, the WG follows the approved PIANC principle to bring worldwide experts together to collect, discuss, and extract their subject-matter expertise and condense it into workable guidelines. In WG 128 these experts are from Argentina, Belgium, China, France, Germany, Japan, the Netherlands, and the United States, working with environmentally friendly bank protections.

The reason for this strategy is that design approaches concerning softer protections exist, with a few exceptions, predominantly in the form of subject-matter expertise or professional reports, less in generally accessible literature and guidelines. Also, there is still limited published guidance based on actual experiences.

The WG focused, therefore, first on reviewing available information in written form; namely, existing codes of practice, publications, and especially grey literature such as internal professional reports. From this review and the experience of the WG members, relevant measures were extracted, presented, and discussed in three categories:

- **Basic Types** (BT) – provide general information on measures without specific relationship to implemented projects; giving an overview on possible measures, which may be combined and adapted to fit local BCs using the 7 Steps and the BPA;
- **Fact Files** (FF) – describe generally combinations of Basic Types implemented at a specific site; present the local BCs and planner's aims and thus especially support the recommended preselection tools; and
- **Case Studies** (CS) – provide comprehensive information on implemented measures with background information to show readers the complex design approach that led to the described measures.

These descriptions form the basis of this report and were meant to link local BCs on-site with planner's demands for achievable functionality of the planned measures.

But this link was hard to achieve. The approach to assess the technical, economic, and ecological functionality in relation to the conditions on-site, which forms a link between site-specific BCs and the required functionality, turned out to be much more complex than expected. This complexity especially involves the assessment of the ecological functionality, which depends on the aims of the planners and the complexity of the ecosystems – and they may differ from planner to planner or site to site.

Another problem to be solved was the way how to match different criteria. To solve this problem, the WG developed a complex scoring system but still could not find a workable approach for the usual target group of PIANC reports because the system must be able to consider both the BCs and the planner's aims at the same time. It turned out that the BCs has to be tackled in the sense of a *comparative analysis*, meaning that existing experiences from realized measures and corresponding conditions on site, can be transferred to other sites all the better, the more the boundary conditions (BCs) match. By contrast, the scoring for the fulfilment of planner's aims is more or less absolute.

The second problem to solve was scoring of *existing* measures (from Part 2, called generally Analysis Cases, or ACs) may be not appropriate, because all these measures can generally be optimized. Thus, practitioners may assess the measures' functionality with or without improvements and adaptions (that is, projected functionality).

A third scoring problem was assessing the functionality of a selected measure (e.g. from the catalogue of ACs) in the Design Case (a planned measure at a new site, acronym DC). This scoring problem is even more complex because these measures have not yet been implemented. Thus, practitioners must *estimate* the corresponding degree of fulfilment of functionality.

Because of these difficulties and because of the unsatisfying results when applying the complex approach to concrete examples, the WG decided to propose a much simpler approach for selecting appropriate measures. This redesigned, simpler approach uses a low number of selected criteria, which turned out to be decisive in most cases.

This approach will be called *preselection of measures* (or simply preselection) in this report. With this approach, the Working Group avoided the difficulties of trying to address all possible local BCs or legal demands – and thus the task to replace a detailed design study – and focused instead only on those design aspects typical for the target group of a PIANC guideline.

This approach will certainly aid decision-makers in waterway authorities assessing whether TBPs may be a realistic alternative to sheet piling or rip rap. But the WG also decided to provide assistance to planners (for example, in engineering bureaus) by providing process recommendations on developing a detailed design, focusing on the special demands and properties of inland waterways. These recommendations form the main difference between this guideline and standard publications concerning bioengineering methods.

Nevertheless, analysing implemented measures with their site-specific BCs and developing from this analysis a generally applicable design approach in the form of the preselection tools and process recommendations (that is, the BPA), but more comprehensively than previous standard publications, seems to still be workable.

1.2.2 Terms of Reference (TOR) according to InCom

The PIANC InCom WG 128 was founded in 2009 but met only three times with varying membership. In 2010, the Inland Commission decided to reestablish both the WG and the Terms of Reference (ToR), and in 2015 changed the focus to the consideration of implemented measures; see Appendix B. This section briefly summarises the original ToR.

In 1987, PIANC produced guidelines on the design and use of such bank protection techniques, which were well received and used to create industry standards. In 2008, the PIANC WG 27 report 'Considerations to Reduce Environmental Impacts of Vessels' reported that an increasing number of alternative bank-protection measures were being implemented across the world in navigation channels; for example, bioengineering such as reed planting or live willow fascine; biotechnical engineering such as grass composite, vegetated pocket fabric geotextiles, rock and fibre rolls, and planted coir pallets; or structural engineering such as timber revetments, wattle hurdles, and timber piling, which under special conditions can replace standard erosion protections. However, there is still limited published guidance based on actual experiences with existing alternative bank-protection methods that can be used under specific project BCs.

Some of these documents were used in to select adequate mitigation measures. Further work has recently been undertaken by MarCom 56 ('Application of Geotextiles in Waterfront Protection') and CoCom 2 ('Best Practices for Shoreline Stabilisation Methods'), to analyse the use of geotextiles in a coastal environment. While there is limited existing knowledge, there is an increasing pressure for those involved in channel design and maintenance to adopt new techniques on the assumption that these will better meet the requirements of engineering, ecology, and economy rather than the use of traditional engineering solutions such as rip rap or sheet piling. Therefore, decision makers, planners, and practitioners need a BPA for objective decision making regarding for waterway improvement and management. This report meets that need by collecting and assessing existing experiences with alternative bank protection methods and by providing decision-making tools and process recommendations.

Thus, the objective of WG 128 was to understand, evaluate, and report on the effectiveness of best-practice examples of innovative (alternative) bank-protection measures, as related to different impact influences and BCs, to meet technical needs and improve the ecological conditions according to the mandate of the European Union Water Framework Directive. Because this mandate and other initiatives have created a requirement for results to be available as soon as possible, the WG placed restrictions on the range and extent of the field of inquiry. For example, bank protection in lakes, are not included in this report.

Maintenance costs and details of ecological monitoring for selected alternatives must be available for at least one year after installation and should be included in the report. Project details should include water-body type (for example, free-flowing or dammed river, canal), climate, water-level variation, flow velocity (both fast and slow), bank substrate, bank slope, distance to fairway, vessel types, and hydraulic impacts from shipping. Information should be collected on successful and, to the fullest extent possible, unsuccessful implementations over the last 20 years. Reviewing successful and unsuccessful implemented measures allows the WG to assess whether the vegetative protection techniques have matured.

The following publications give an overview on existing guide codes:

- Doyle, P.F. (1992): "Performance of Alternative Methods of Bank Protection", Canadian Journal of Civil Engineering.
- PIANC (1996): "Bank Protection Utilising Geotextiles and Vegetation".
- Cranfield University (on behalf of British Waterways) (1999): "Waterway Bank Protection: A Guide to Erosion Assessment and Management".
- Fischenich, C. (2001): "Stability Thresholds for Stream Restoration Materials", ERDC, USACE.
- Guide de Protection des Berges, Comité Zone d'intervention Prioritaire (ZIP) des Seigneuries, [Online], Available:

  http://zipseigneuries.com/wp-content/uploads/2018/05/Guide-protection-berges.pdf.
- Numerous reports on the German research project on TBPs, including field tests; see **https://ufersicherung-baw-bfg.baw.de/index.html**.
- Guideline of the German Association for Water, Wastewater and Waste (2016): "DWA-M 519 TBPs in Large and Navigable Inland Waters" (in German).

These guides, however, do not clearly state how effective these bank-protection techniques have proven to be in operation; they only list a few examples based on results soon after installation. Not enough information currently exists to avoid repeating the mistake of installing a TBP at a site unsuitable for that measure.

Because of public and legal pressure to implement environmentally friendly bank protections and because of the elapsed time setting up WG 128, the scope of work should focus on the collection and evaluation of existing guidelines and of both positive and negative experiences with implemented alternative bank-protection measures. This focus shall lead to a list of measures with as variable as possible local BCs and can be used in terms of a BPA, meaning that the planner of an alternative measure compares the local BCs to the BPA in the list of existing measures to decide whether listed measures could be successful. In addition to the general BCs related to one listed project, specific characteristic parameters shall be added, which come, for example, from the German DWA design rules, especially concerning the influence of wave impact, bank slope, or subsoil, because the WG's analysis showed that only a few parameters are decisive for design. These relevant parameters can thus also be used to facilitate the selection process.

As mentioned earlier, the intended product of WG 128 should be a best-practice document based on existing design guidance and experiences. Because of the dominant influence on local BCs such as, for example, the natural site conditions of plants, the result may not be a straightforward design rule. But it nevertheless will support planners with helpful information such as existing design codes and the list of reference projects, together with guidance on the data needed to apply existing guidelines and the recommended BPA.

The benefits of promoting the development and use of bioengineering techniques are considered vital for countries of all income levels (low, middle, and high) but especially for Countries in Transition and countries who need to protect against the pressures associated with increasing economic development and growth. Also, climate change may affect bank protection measures in many ways, especially those using plants, because of longer periods with low water and thus poor water supply for the vegetation cover, forcing the use of other plant species. For this reason, it is important to involve members from countries with generally higher average temperatures.

1.2.3 Specifications of the ToR according to WG Decisions and Chosen Approach

As outlined already in Chapter 1.2.1, the WG faced the problem that every Design Case seems to be unique according to the various BCs in the planning area, especially because of :

- different ΔW, which defines, for example, the efficiency of possible pre-embankment measures to break waves;
- climatic conditions such as the occurrence of ice drift, which may require the use of technical-structural elements;
- ship-induced or other impacts, which may be scaled, for example, by the fairway–bank distance; or
- bank soils' erosion resistance or the available space towards the hinterland, which may define the demands concerning the erosion stability of the measures to be taken.

So, it is generally not possible to recommend one specific TBP measure that fits all the various BCs in the same way as conventional measures such as rip rap revetments. Planner's demands may also widely vary, for example, because of

- different legal or administrative conditions such as the responsibility and capability of the authorities involved, especially to carry out maintenance measures, which is a critical part of using living plants for protections;
- different degrees of required stability, durability, and maintainability of the construction elements;
- different funding and costs;
- different specific local ecosystems; for example, the demand to promote special endangered species; or
- different social requirements, such as the demand to allow recreational activities, which may contrast with ecological aims.

Thus, the recommended design approach in this report must be able to specify tailor-made solutions for all these BCs.

Besides the fact that the number of relevant design rules has increased since establishing the WG (for example, by publications of the European ECOSHAPE project or the German Guideline for Using Bioengineering Methods, DWA-M 620) existing guidelines generally

- only address a few types of measures; for example, 10 in the German DWA-M 519 guideline;
- only fit the site-specific conditions under consideration; and
- only prioritise the technical and economic aspects of the measures.

Thus, in practice, existing guidelines will of course be considered, but concrete measures are nevertheless planned mostly using the knowledge and experience of local experts from, for example, administrations and planning bureaus, rather than applying guidelines. Therefore, WG 128 decided to adopt this way of planning for this report by summarising knowledge and experience in the form of documented implemented measures and by providing a way to transfer this knowledge and experience to concrete design problems. This report is not, of course, a strict design rule. It is rather a set of decision-making tools and guidance to enable users to find solutions that best fit the local BCs and the specific planner's aims.

In particular, this guidance will be achieved by documenting relevant measures as **Basic Types** (BTs), **Fact Files** (FFs), and **Case Studies** (CSs) in Part 2 and by providing:

- summaries on the content of selected existing guidelines and how to use them for generalised design purposes (some of them are documented comprehensively to enable their application; see Chapter 2);
- descriptions, general construction elements, and design principles of relevant measures (Chapters 3 and 4);
- tables with relevant design criteria in the form of selected BCs, functionality demands, and indicators and to what extent these criteria are in accordance with or can be fulfilled by selected measures; for example, from FFs (preselection approach, Chapter 5); and
- recommendations on executing the design process in an optimal way and, thus, how to perform a detailed study where appropriate (Chapter 6).

The recommendations consist generally of the following points, shown in Figure 1.1:

- Specification of relevant BCs and planner's aims (concretisation of the Design Case): For this purpose, checklists with criteria will be provided (Boxes 1 and 2 in Figure 1.1) in the report.
- Use of data and models: They may be necessary, for example, to specify ship-induced loads versus erosion resistance of the bank slope and what could be done to mitigate loads, at least in the initial phase of plant growth (Box 3 in Figure 1.1).
- Balance of all relevant design aspects: The report supports this point (Box 4 in Figure 1.1) with checklists of relevant design aspects.
- Planning for mitigation measures: Check the necessity and value of mitigation measures and plan for them where appropriate (Box 5 in Figure 1.1).
- Preselection of generally feasible measures: The report provides guidance on how to extract relevant information especially from the BTs and FFs and how they can be used for preselection (Boxes 6 and 8 in Figure 1.1).
- Concretisation of the planning and refined variant analysis: The report provides a process called *7 Steps* to refine measure selection (Boxes 7-9 in Figure 1.1).

The report helps planners by providing process recommendations such as

- how to apply modern decision-making tools to match all relevant information and rank appropriate measures;
- how to design a site-specific optimised measure by adapting, improving, and combining measures from the BTs and FFs; and
- how to add new design elements where appropriate (Box 8 in Figure 1.1), check all relevant design criteria such as costs versus budget for this optimised solution, and implement the planned measures.

As shown in Figure 1.1, users may need to repeat the preselection steps if there are doubts that even an optimised measure will not fit with the local BCs or that the aims will probably be not achieved (that is, a *looped approach*). This feedback is indicated by the *black arrow* running from point 9 back up to point 1 in Figure 1.1. Using this looped approach, for example, the planners might decide that their aims must be adapted again or that flanking measures such as additional river training works must be taken into account.

This report's contribution to the planning process and the report's extent are shown in Figure 1.1 using different colours. *Grey boxes* provide hints to planners without going into details; for example, how to find out the relevant BCs. *Blue boxes* provide process recommendations such as the aforementioned 7 Steps, and *red boxes* list activities with concrete results from this report; for example, preselection of measures. So, the contribution of the report to the planning process is, compared to the total amount of planning work to be done, not comprehensive but nevertheless essential because it focuses on waterway-relevant design aspects and guides the user through the whole design process.

The report's primary purpose holds especially true for all possible users of the report, categorised into the following three types with type-specific information.

1. Decision makers – This group of users will find useful the general information about alternatives to conventional bank protections. This report's screening approach to feasible measures uses only general information about BCs and planner's demands and therefore needs only minimal data coming from the categorisation of measures in Chapter 4.
2. Waterway authority employees – Whether they carry out the planning or prepare contracts, this group of users will find useful the preselection approach, which is outlined in Chapter 5. The preselection tools make possible alternatives more concrete and therefore easier to implement.
3. Planning bureau employees and contracting authorities – This group of users will find useful the whole approach shown in Figure 1.1, which reflects the content of Chapter 6 (Parts 1 & 3).

The main activities of these different user profiles are indicated in Figure 1.1 by *dotted frames*. They show, for example, that even the first user category listed above – decision makers – should have a clear understanding of the key planning aims and the most important BCs before they start the screening. So, Boxes 1 and 2 in Figure 1.1 are the most important in this report as they are mandatory for all user profiles.

Even if the screening or preselection of feasible measures is the only aim of the user, users should still start with Chapter 6 and follow all the instructions given there: for example, users should review up to what extent information is necessary for their user profile and then follow the jumps through the chapters (for example, back to Chapter 4.1 for the screening or back to Chapter 5 (in Parts 1 and 3) for the preselection; see Figure 1.2). This nonsequential way to use the report was necessary to benefit all three user types, even if the report is logically structured to support the detailed design of appropriate bank protections as indicated in Figure 1.1, and even if not all necessary steps can be carried out.

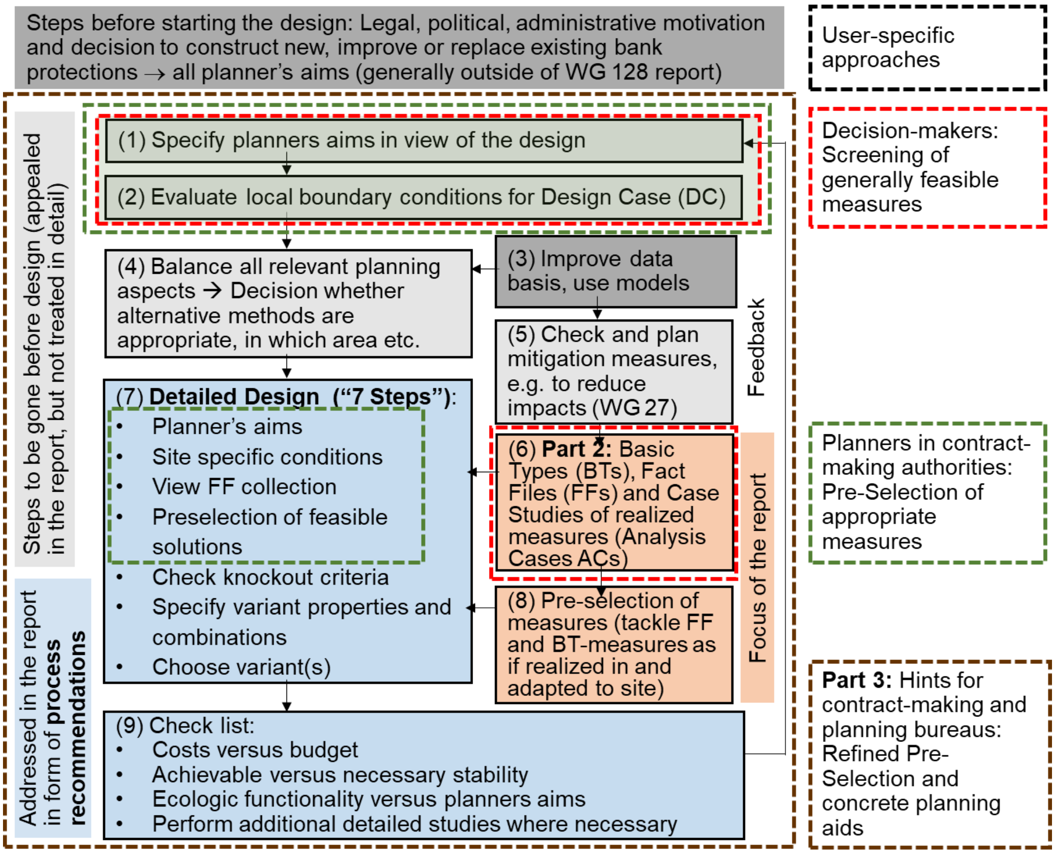


Figure 1.1: Contribution of the WG 128 report to the detailed design of bank protections in inland waterways

Besides these restricted contributions of the report to the planning process and the aforementioned reduced tasks compared to the ToR, discussions in the course of the WG meetings concerning the most serious knowledge gaps of the WG led to the WG deciding to further restrict the ToR to the following parameters (see also Chapter 1.2 in Part 3):

- measures close to the bank slope (local view), assuming that possible river engineering works and mitigation measures, for which relevant publications are available, were already taken;
- measures using as few as possible technical construction elements;
- predominantly humid climate conditions, where plant growth on the bank slope can be assumed;
- channels, where design-relevant loads are predominantly caused by navigation (focus on waterways for large vessels); and
- vessel-induced impacts, which are related predominantly to the ship-wave system and not to propeller action, presupposing that there is a proper vessel–bank distance, because the ship's screw race (also known as *propeller wash*) causes different damage profiles than those from drawdown and waves.

These restrictions and those concerning the guidance through the design process ensure the report can be published within an appropriate time. Even if the practical implementation experiences available here are limited in scope, they will still enhance the usage of alternative, preferably green, bank protections. Thus, it may be appropriate to extend or update this report in the future according to the increasing knowledge and experiences available, and the WG decided in consultation with InCom that another WG could develop more specific design rules and implement more measures than included here.

1.2.4 Structure of Report and Application Hints

As outlined in the EXECUTIVE SUMMARY (Figure 1) and in Figure 1.2 of this section, both Part 1 and Part 3 of the report complement each other. Both parts, thus, have generally the same structure and the same chapter designations.

The present part focuses on the basics of the recommended design approaches for readers who either do not want or do not need details, generally **non-experts** as decision makers or contract-making people, who just want to have an overview on the applicability of the report.

Part 3 focuses on the *application* of the design procedures and is written thus for **technical or ecological experts**.

Consequently, chapters 1-4 (introduction and design approach, literature review, description on typical measures, content of Part 2) are very comprehensive in Part 1 and chapters 5 and 6 (preselection tools, process recommendation for performing a detailed study) are quite short in the present document. By contrast, the corresponding chapters 1-4 in Part 3 provide only a few information from Part 1 and the application of the preselection tools and process recommendations are extensively described in Part 3.

Nevertheless, both parts are written in such manner that they can be read independently of each other and also in a selective way. This leads to numerous repetitions and redundant information, which are needed for this purpose.

The structure of both parts – and thus also Part 1 – follows generally the design approach outlined in Chapter 1.2.3 and Figure 1.1 as follows:

- **Chapter 1** explains the ideas behind the BPA and its basics;
- **Chapter 2** summarises relevant existing design approaches; for example, existing national guidelines and how they apply to this report;
- **Chapter 3** describes all relevant measures in detail, together with those specified in Part 2, with all their properties and usual application ranges. This chapter forms the basis for designing the optimal solution.
- **Chapter 4** describes all the recommended measures, starting with BTs, which come from existing guidelines and are described without real-world implementations, and include, for example, standard bioengineering methods. Next, the FFs and CSs are outlined. The latter are implemented measures, consisting generally of several BTs. These generally 'mixed' measures are adapted to the local BCs to meet the different demands, for example, concerning stability and ecological issues.
- **Chapter 5** presents the preselection tools. These tools are based on the consideration and selection of relevant BCs, such as ΔW, the strength of ship-induced waves and currents, and the bank properties, such as average bank slope and bank substrates. Next, the chapter considers design-decisive planner's aims such as the necessary degree of stability, the restriction of expenses, the ecological upgrade and social aspects and, as a special point, the consideration of knockout criteria for design such as, for example, the necessity to consider ice drift. The preselection approach (supported by an Excel sheet) then

synthesizes all this information using the BTs, FFs, and CSs as evaluated by the experts in the WG.

- **Chapter 6** provides process recommendations on how to perform a detailed study, following the approach outlined in Figure 1.1 and including the aforementioned 7 Steps. More concrete, chapter 6 in Part 3 forms the central switching point for appliers of this guide as it provides an overview of the entire design approach with references to all associated chapters and appendixes in Part 3.
- The design results will then be discussed in **Chapter 7**; for example, concerning application limits of the present approach and including guidance for planners intending to order a detailed study.

Part 1 closes with an outlook on **possible further activities** (for example, to establish a follow-up of the present WG) in **Chapter 8** and the **list of references** in **Chapter 9**.

As usual in PIANC reports, provides also lists of **abbreviations** used and a **glossary** of specific terms, see **Appendix A (Part 1)**. The original **ToR** are presented in **Appendix B (Part 1)**.

According to the focus of **Part 3**, the corresponding appendixes provide **worksheets** needed to apply the design approaches. **Appendix A** in Part 3 provides assistance for understanding and specifying **relevant design criteria**. **Appendixes B and C** contain comprehensive information necessary to apply two important existing guidelines, which were upgraded to be used in this report, the **DWA-M 519 Code of Practice** from Germany and the **UK Waterway Management Guide**. Both publications are recommended to be used additionally and for comparison purposes to the proposed approach.

It is recommended that a **casual reader** interested in the design of bank protections or a decision-maker, for example, from a water authority, should at least have a look into Chapters 3 and 4 in as well as read the content of some BTs, FFs or CSs from Part 2, before reading the brief design recommendations in Chapter 6 (and then Chapters 4 and 5). As mentioned before, **experts** and **planners** may start directly with reading Chapters 5 and 6 (in both parts) or at least with Chapter 6 in Part 3, which guides the applier through the whole report.

These and other recommendations how to ***read the report*** are shown in Figure 1.2 on the left-hand side, pointing on *boxes* around important chapters of the report, which are marked according to the recommendations. For example, a *red frame* was drawn around Chapters 3 and 4 in Figure 1.2 and examples of measure descriptions in Part 2 for interested laypeople and non-experts.

Planners of river engineering works and bank protections in particular may focus on reading Chapters 5 and 6 in Parts 1 (first) and then in Part 3, which address the concrete design process, together with a focus on relevant BTs, FFs, and CSs. For this purpose, planners should start with Chapter 6 in both parts and follow all the points, which will guide planners to all relevant parts of Chapters 5 and 7. These recommendations are shown by *green frames* around the boxes indicating Chapters 5 and 6 in Figure 1.2.

Experts in waterway engineering, especially bank protections and applying bioengineering methods, may concentrate on reading Chapters 5 in Parts 1 and 3, the preselection of measures, and Chapter 6, how to choose the optimal measure and adapt it to site – and of course on Part 2 of the report.

As Appendixes B and C in Part 3 offer further design alternatives, experts should also review these parts before starting with the concrete design, using the approach outlined in Chapter

6. This reading order is also shown in Figure 1.2, with *brown frames* around the relevant chapters and appendixes in Part 3.

The path to ***apply the report*** as outlined in Chapter 1.2.3, with necessary jumps from chapter to chapter, is shown by *dotted* and *coloured frames* and *arrows* in Figure 1.2.

But all paths start from the comprehensive guidance in Chapters 5 and 6 in Part 3, the specification of demands and BCs, which may vary greatly from DC to DC. As the necessary level of detail is different from user to user, both chapters offer information accordingly; for example, concerning the BCs used in the overview tables to perform the screening or the criteria used in the preselection tables for planners. Both chapters are marked by a *dotted black frame* to indicate their importance, even though the level of detail needed will vary from user to user.

More precisely, the three types of users described in Chapter 1.2.3 should proceed through the report in the following ways:

1. **Decision makers** – Decision makers may only be interested in an overview of feasible alternatives to conventional protections. By using the technique proposed in this report, they will be able to check whether any relevant TBP measures exist. Presumably, they will find it useful to compare a few planner's aims and local conditions, which are discussed in Chapters 6.1 and 6.2. The general idea can be stated as follows: according to the number of matches between demands and properties of the measures as well as the BCs of the DC and those in the measure descriptions, a list of feasible measures will come out and this process is called *screening* in this report. The corresponding path is shown in Figure 1.2 by a *dotted red arrow*, pointing backward from Chapter 6 to Chapter 4.1. The latter explains the chosen categorization of measures, provides an overview of all measures from BTs, FFs, and CSs, and explains the screening approach. After a brief look into Part 2 to review some of the measures recommended by the screening, decision-makers may then have enough information to take a general decision on whether to implement a TBP measure.

2. **Planners** in waterway authorities – Planners in waterway authorities should also start with Chapters 5 and 6, but this group of users should consider all the criteria used for preselection, which are more comprehensive than those needed for screening but not as numerous as those needed for a detailed design study. Nevertheless, when using this report, planners should apply the main conditions and demands of the DC, which generally define the selection of appropriate measures. The *dotted green arrow* in Figure 1.2 shows this reading order, pointing from Chapter 6 back to Chapter 5, which explains the preselection and the corresponding Excel tools. Planners may find enough information here to decide which alternatives to sheet piling and rip rap may satisfy the specified conditions and demands of the DC and should thus be considered in more detail.

3. **Employees in planning bureaus and contracting authorities** – Employees in planning bureaus and contracting authorities should, like planners, start with Chapter 6 and proceed to Chapter 5 for the preselection, but they may find it useful to proceed through the preselection a second time using information provided in Chapter 6; for example, concerning knockout criteria (*refined preselection*). After returning to Chapter 6, shown in Figure 1.2 by a *brown dotted arrow*, this group of users should consider the results of alternative design approaches from Appendixes B and C in Part 3, which may be compared to those from the refined preselection, and run through the 7 Steps, which

includes, for example, the adaptation of selected measures to local BCs and demands. After this further refinement, some optimised relevant measures may remain and lead to a proper choice of variants; for example, using modern multicriteria analysis tools as proposed here in Chapter 6.3 and in Chapter 6.3.7 in Part 3.

This overview of the structure of the report may be enough for some users to understand how the report should be read and applied. Those users should proceed to Chapter 6. The remainder of this chapter refers back to this section and especially to Figures 1.1 and 1.2; for example, when explaining why a user should return to a previous chapter.

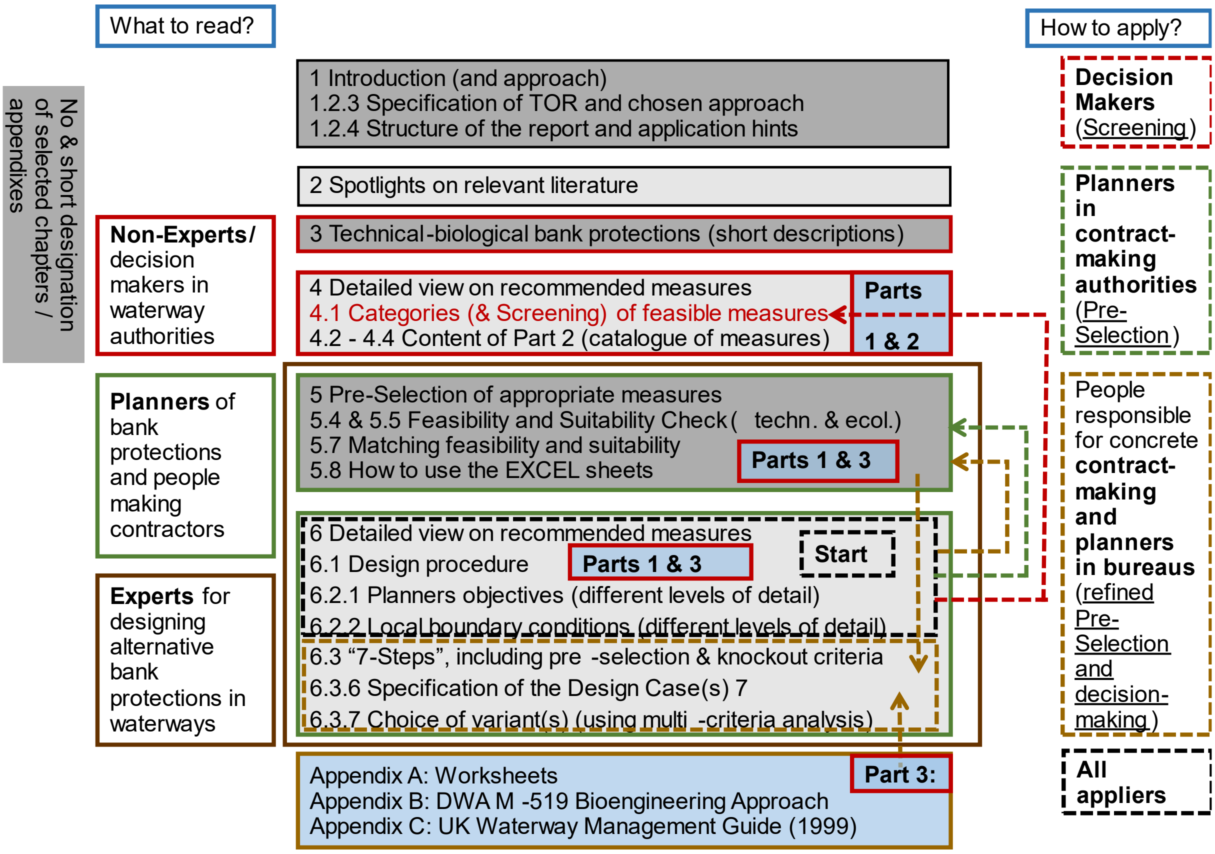


Figure 1.2: How to read and apply the report for different users

1.2.5 Related PIANC Reports

Besides InCom WG 128, which is considered here, the EnviCom WG 176 provides 'A Guide for Applying Working with Nature to Navigation Infrastructure Projects', which also addresses alternative bank protections but predominantly in the sense of process recommendations, not concrete design rules. Also, EnviCom WG 195 on 'Ecosystem Services' covers environmentally friendly bank protections according to their ecological benefits compared with technical solutions.

Further work has recently been undertaken by, for example, MarCom WG 56 on 'Application of Geotextiles in Waterfront Protection' and CoCom WG 2 on 'Best Practices for Shoreline Stabilisation Methods'. But both are analysing primarily technical solutions such as the PIANC report 'Guidelines for the Design and Construction of Flexible Revetments, Incorporating Geotextiles for Inland Waterways' from 1987, which defined standards for conventional solutions such as rip rap. There are also discussions related to softer bank protections in several other PIANC publications; for example, analysing sustainable waterways or climate change effects.

More concrete design approaches can be found in the report of WG 27 on 'Considerations to Reduce Environmental Impacts of Vessels' [PIANC, 2008], which prompted the establishment of WG 128. It focuses on possible measures to reduce or avoid direct impacts of vessels such as

- hull contacts and propeller hits on fish,
- flushing of fish larvae,
- secondary wave impact on plants,
- effects of wake wash and quick drawdown on bank stability,
- resuspension of bed and bank sediments and corresponding increased turbidity.

The report also considers corresponding mitigation measures such as

- adapted vessel and fairway design and
- constraints to navigation as speed limits,

but also, alternative bank-protection measures such as

- pre-embankment solutions with islands or parallel dykes, in-stream protection with floating booms, filled sack barriers or log barriers;
- modified revetments such as rip rap containing pockets for vegetation planting or open-cell revetments, using geotextiles in different ways such as grassed composites; and
- bioengineering methods such as reed plantings, willow fascines, willow weaves, accreting stick bundles, bundles with fill, and so on.

The report includes some rudimentary design criteria such as the specification of tolerable flow velocities or wave heights. But WG 27 focuses on bank stability and vessel impacts only, and the alternative bank protections considered came predominantly from the British Waterway Management Guide (1999), which mostly addresses small waterways such as those used for recreational vessels. But other BCs such as, for example, natural flow velocities, ΔW, ice drift, or exposure to sunlight, considered by this report were addressed by the WG 27 report.

The WG 27 report offers in Part 2 on CD a brief overview of bank-protection methods from the UK guide. In this report, the corresponding design approach will be shown in Appendix C in Part 3, because it seems to be generally applicable and not only for small waterways. The recommended measures from the WG 27 report are described in Part 2 and will be used here to extend the library of recommended measures.

Besides the recommended bioengineering solutions, the WG 27 report makes clear the dominant importance of ship-induced impacts on bank stability in inland waterways and, as WG 128 had predicted, the need to look not only at construction measures but also at feasible flanking measures such as adapted fairway design, especially to increase fairway-bank distance and to establish speed limits where appropriate. As mentioned earlier, this report assumes that these flanking measures have been exhausted, but because these flanking mitigation measures define possibly altered local BCs relevant for design, they will be addressed in this report nevertheless with several references to the report by WG 27.

1.2.6 Members of the Working Group (WG)

The WG 128 consisted of the following members (since 2018):

- Bernhard Söhngen (BS), Chairman, Federal Waterways Engineering and Research Institute (BAW), Karlsruhe, Germany, **bernhard.soehngen@baw.de**

- Katja Behrendt (KB), Federal Institute of Hydrology (BfG), Koblenz, Germany, **katja.behrendt@bafg.de**
- Dianguang Ma (MD), Tianjin Research Institute for Water Transport Engineering, Tianjin, China, **641683743@qq.com**
- Gonzalo Duro (GD), Witteveen+Bos, Consulting, the Netherlands, **gonzalo.duro@witteveenbos.com**
- Petra Fleischer (PF), Waterways Engineering and Research Institute (BAW), Karlsruhe, Germany, **petra.fleischer@baw.de**
- Tetsunori Inoue (TI), Ph.D., Port and Airport Research Institute, Yokosuka, Japan, **inoue-t@p.mpat.go.jp**
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- Roy Laseroms (RL), Rijkswaterstaat, Utrecht, Westraven, Lelystad, The Netherlands **roy.laseroms@rws.nl**
- Kathrin Schmitt (KS), Federal Institute of Hydrology (BfG), Koblenz, Germany, **kathrin.schmitt@bafg.de**
- Jeroen Verbelen (JV), De Vlaamse Waterweg NV, Merelbeke, Belgium, **Jeroen.Verbelen@WenZ.be**
- Jos Wieggers (JW), Rijkswaterstaat, Utrecht, Lelystad, The Netherlands, **Jos.Wieggers01@rws.nl**
- Christian Wolter (CW), Leibniz-Institute of Freshwater Ecology and Inland Fisheries, Berlin, Germany, **wolter@igb-berlin.de**
- Junwei Zhou (J), Tianjin Research Institute for Water Transport Engineering, Tianjin, China, **zhoujw@tiwte.ac.cn/jzhou93@foxmail.com**

1.2.7 Meetings with Major Decisions

After re-establishment of the WG in April 2016 (fourth meeting in total), the WG conducted seven personnel meetings through July 2019. All these meetings took place generally over two days at locations in Germany, Belgium, France, China, and the Netherlands. The meetings were always accompanied by trips to sites with implemented TBPs.

During this data-gathering phase, the WG focused on the collection and documentation of existing design guidelines, measure types and implemented measures, and the development of a BPA. For this purpose, the WG collected and discussed numerous BCs and functionality issues and matched them using multicriteria analysis tools.

As this approach turned out to be hard to apply, the WG discussed a new approach at the eleventh meeting in Brussels, Belgium, in July 2019 and later during the PIANC-Smart Rivers Conference (SRC) in Lyon, France, in autumn of 2019, where the WG performed a workshop and presented several papers. As a result, the WG started developing a simplified version of the BPA, which is called *preselection tools* in this report. The group was in principle re-established a second time starting after the SRC.

This renewal of the BPA was mostly prepared during five interim meetings from the German members and in four meetings of the *Extended Lelystad Group*, which formed after the tenth meeting as a follow-up of the split meeting in China (mostly Yangzhou) and Lelystad, the

Netherlands. Also, two student research projects at the University of Darmstadt, Germany, under the aegis of the WG chairman drove the simplification of the old BPA in its new direction.

After losing almost one year because of the COVID-19 pandemic, the WG met again, now with DFN video conferences, in autumn of 2020 at the WG's thirteenth official meeting. Synthesizing the proposals of the subgroups, the WG developed a very user-friendly BPA supported by a big Excel table, which will be part of the future report.

The finalisation of the measure descriptions ended in 2022, so that the English-language check could begin. Numerous comments of InCom were also considered, which led to several restructuring measures of the report, whereby finally three parts will be provided.

After the WG's 29th meeting in Autumn 2020, an editorial group was installed (Söhngen, Wieggers, Verbelen, McKay), which met five times up to summer of 2023, to perform the final editing, to organise the English-language check, and to carry out the final coordination of all contributions.

Getting final acceptance was discussed at the WG's 32nd meeting in the summer of 2023. The report was sent to InCom in late summer of 2023.

The WG's meetings lasted over almost eight years after reinstallation. This time line is mostly because engineers and biologists simply do not always agree, especially concerning the structure, content, and importance of the BPA, and coming to an agreement took time. But, as everybody in the group was willing and able to make compromises, the WG found in the end a simple-to-use approach that will in turn lead to corresponding software.

1.2.8 Acknowledgements

The members of WG 128 would like to say thanks first to their employers for granting sufficient resources to participate in the numerous meetings and to write and coordinate their contributions to the report. Members are especially grateful considering the long time-line for finishing this report.

The members also thank PIANC Headquarters and InCom for their patience with the working process and for providing review assistance.

Special gratitude is owed to the Information Science and Knowledge Management Branch of the US Army Engineer Research and Development Center's Information Technology Laboratory for performing the English-language check under USACE's Dredging Operations Technical Support Program for Parts 1 and 2.

Special thanks also go to the InCom member, Luc Boisclair (Acting Vice-President, Engineering & Technology, St. Lawrence Seaway Management Corporation, Canada) and the management of the Federal Waterways Engineering and Research Institute (BAW) for performing and funding the English check for Part 3.

Thanks is also owed to Carolin Gesing from BAW (Unit Shipping, Department Hydraulic Engineering in Inland Areas), who performed the editorial review of a large portion of Part 3.

Special gratitude is owed to the BAW also concerning the procurement of original copyrights, especially of screenshots from GoogleMaps and GoogleEarth.

The WG chairman extends special thanks to all members of the WG for their often controversial, but finally fruitful discussions, their patience, and their willingness and ability to find compromises.

1.2.9 Remarks Concerning Copyrights

The source of material from DWA-M 519 [DWA, 2016] and the UK Waterway Management Guide [British Waterways, 1999] is not separately indicated, because copyrights are granted generally by Andreas Stowasser (company Stowasserplan, Radebeul, Germany) and authors from WG 128, which were members also from the DWA report and Peter Birch (Canal River Trust, UK). Other material, e.g. photos, is indicated, if not produced from members of the WG 128. A full imprint list exists at PIANC Headquarters.

Special gratitude is owed to the employers of the WG's members, allowing them to sign the PIANC's copyright forms 'on behalf of' their assigned institution. This means that the employers bear unrecognised residual copyright risks.

2 SPOTLIGHT ON RELEVANT PUBLICATIONS

2.1 Definition of Bioengineering Methods

TBP methods are similar to natural bank-protection measures that use plants as building material. The measures can be applied directly on the bank slope (direct measures – Chapter 3.1) or in front of the bank slope (indirect measures – Chapter 3.2). A combination of both is also possible. If using additional indirect measures, direct bank protection on the slope may not be required (overview of possible measures; see Figure 2.1).

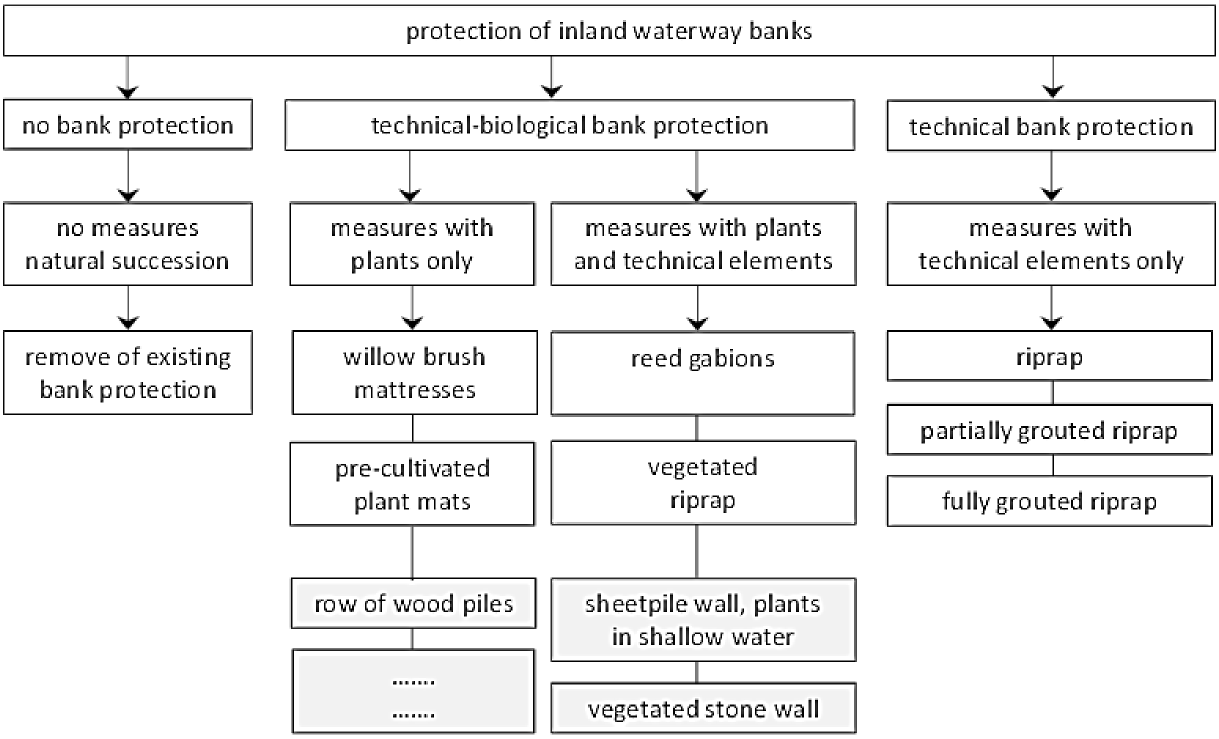


Figure 2.1: Overview by components of bank protection measures (fields with grey background show indirect measures, fields with white background show direct measures)

In principle TBP measures are either purely bioengineering construction methods (for example, willow-brush mattresses and pre-cultivated plant mats as direct measures or a row of wood piles as an indirect measure) or they consist of a combination of plants (bioengineering methods) and permanent technical construction methods (for example, vegetated rip rap and reed gabions as direct measures or stone wall with shallow water as an indirect measure). Purely plant-based direct bank protection can only stabilise the bank through the plants' roots and aboveground plant parts. When using plants and technical components, the latter can contribute to permanent bank protection. That is why measures consisting of both plants and technical components can be implemented at sites with larger hydraulic impacts.

Bioengineering methods are characterized by the use of living plants or dead plant parts. Living building materials include, for example, whole plants or entire pieces of vegetation. Dead plant parts could be deadwood fascines or deadwood crossbars and cuttings.

Technical building materials such as fixtures or geotextiles are only necessary until the plants can guarantee the required bank stability themselves.

Established plants can also take over technical tasks (biomechanical effects). On the bank the roots penetrate the soil, which leads to soil stabilisation, which can prevent slope slides. In addition, the roots can reduce or prevent material transport and soil erosion. With suitable root formation, plants can also take over filter function. The parts of plants aboveground can protect the slope surface and reduce or prevent erosion. They can increase the ground roughness and so reduce the hydraulic impacts further. Indirect pre-embankment measures can also reduce the hydraulic impacts on the bank.

If the requirements for bank stability are very high and very high hydraulic loads occur at the same time, TBPs measures may not be suitable. With those BCs, conventional technical bank protection must be used (Chapter 3.2.3).

TBP measures can be ecologically improved by installing additional structural elements; for example, deadwood elements on the slope or also under water to promote fishes (Chapter 3.3). They provide no bank-protection function but only ecological improvement.

In any case, practitioners should verify whether bank protection is necessary at all and whether bank developments may be permitted. If the conditions allow, natural succession (Chapter 3.4) is always ecologically preferable.

2.2 Waterway-Related Guidelines

2.2.1 German DWA-M 519 Code of Practice on TBPs for Inland Waterways

Only a few codes of practice currently exist; for example, the 2016 German technical bulletin DWA-M 519 by the German Association for Water, Wastewater and Waste. The main idea was to transfer existing experiences from waters without navigation to those with significant vessel-induced waves and currents and to account for the initial results of an ongoing research project by the German Federal Waterways Engineering and Research Institute (BAW) and the German Federal Institute of Hydrology (BfG) concerning the same subject for waterways.

The technical bulletin recommends 10 different mostly planar measures (that is, direct measures, covering the bank slope), which are ranked according to increasing tolerable wave loads as follows:

1. wattle fence
2. pre-cultivated slope protection mat with lawn
3. pre-cultivated slope protection mat with cuttings
4. vegetated roll with pre-cultivated reed mat
5. living fascine and brush layers
6. vegetated geotextile bodies with brush layers
7. living brush mattresses with rip rap as toe reinforcement
8. vegetated rip rap
9. subsequently vegetated rip rap
10. vegetated gabions

These measures, which are briefly described in Part 2, Chapter 2.1 of this report, are more or less fitted to waterways because of their resistance to ship-induced impacts (of different magnitudes). Besides a sophisticated design approach, which addresses several impacts on the bank with a focus on ship-induced loads and for which BAW offers a software tool

(GBBSoft+) [Gesing et al., 2016], this technical bulletin also presents a bioengineering approach.

The former consists of three tables – one for canals, one for impounded rivers, and one for free-flowing rivers – linking the local BCs (simplified by three criteria: load index, bank slope, grain size of bed sediments) to the suitability of the aforementioned 10 measures. This table-based approach may serve as an example for this report's BPA:

- if the BPA also considers three waterway categories, reflecting the magnitude of ΔW, which is one of the decisive criteria for choosing appropriate measures, because pre-embankment measures to reduce impacts such as palisades work effectively only if they are not flooded;
- if the BPA reduces relevant criteria to a minimum; and
- if the BPA links these criteria (for example, one line for each criterion in the tables) to different types of measures (columns in the tables) by marking their suitability; for example, using traffic-light logic (from red – poorly suited, to yellow, to green – well suited).

One problem with such a strongly simplified approach is how to identify suitable measures if the different criteria do not point to the same type of measure. Another even more important problem is how to assess the suitability precisely. For technical criteria such as stability or the cost relation to technical solutions such as rip rap this may be simple, but what about the ecological functionality? Can it be attested to be well suited (marked, for example, in green), if site-fitted vegetation will be supported until established, or is it only passable (marked, for example, in yellow), if the established vegetation is not in accordance with those in place before waterway improvement, or is the functionality poor, although there may be plenty of vegetation established, but not the planned one – and how to define *poor*?

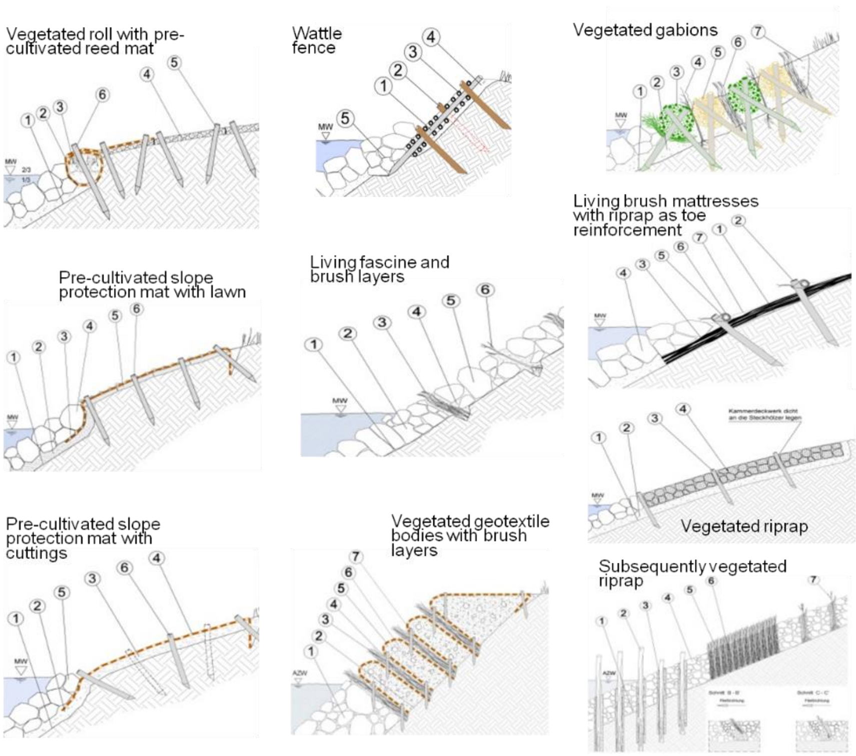


Figure 2.2: Visualisation of the recommended 10 measures of the DWA M-519 approach (Sketches: © STOWASSER, taken from DWA (2016))

So, the BPA user must first choose objectives and only then assess functionality. Hence, tables have to be provided not only for different waterway types but also for different objectives!

Nevertheless, the German DWA-M 519 bioengineering seems to be a good addition to the approach presented herein, if the BCs are comparable. Especially when the prerequisites of a humid climate without floating ice conditions are fulfilled, direct measures are needed, and the bank impacts are dominated by ship-induced loads, the DWA-M 519 proves useful in determining the preselection of generally applicable measures. Therefore, the DWA approach will be used in this report in Appendix B in Part 3. Finally, the DWA-M 519 bioengineering approach was, together with the DWA-M 620 code of practice, also inspired the development of the fact-file-based preselection approach to address BCs.

2.2.2 UK Estuary Edges Approach

In contrast to the DWA-M 519 approach and this report's preselection tools, which address very different BCs, the BCs considered in the estuary edges approach (UK 2019) of the UK Environmental Agency are almost the same: flat bank slopes with generally highly erodible bank substrates (sands, silt) in tidal-influenced coastal areas with weak ship-induced impacts, but wind-wave attack. Also, the objectives of the planners concerning technical issues (stabilization of the bank slope without using pre-embankment measures as they are not effective in the case of typical short-term ΔW) and ecological functionality seem clear: create habitats as they would be if there were no measures taken. Therefore, the selection of appropriate measures can be reduced to just one table, linking BCs and planner's aims (criteria) to selected measures. These criteria are

- land-based loads,
- ground conditions,
- bank geometry,
- duration of peak loads,
- inundation frequency,
- water chemistry,
- durability of construction components,
- design lifetime, and
- monitoring and maintenance demands.

This design approach is shown in Figure 2.3 using the example of the first two BCs listed above.

There is no matching of different criteria foreseen as in our preselection tools, but the UK Estuary Edges Approach influenced the WG's approach, for example, by helping to define decisive design criteria, whereby almost all criteria were used.

An analogous approach can be found in Part 3 in Chapter 3.2, whereby relevant BCs and planner's demands will be discussed according to design guidance for measure types. Links to single measures such as in the UK approach make no sense when considering the variety of all the measures considered in this report.

	Bioengineering	Biotechnical engineering	Fully structural engineering	Hard engineering
Land-based loadings and land values Loadings of substrate and features that put pressure on the tidal edge from the landward side. This is the factor considered first in combination with ground conditions to see if the tidal edge, at the proposed geometry, is 'intrinsically stable' (when protected from erosion).	Generally 'low' to 'medium' loadings (pedestrian to vehicle). In built-up areas these techniques may still be appropriate where other structures provide secondary line of flood defence.	Generally 'medium' to 'low' loadings (pedestrian to vehicle). In built-up areas these techniques may still be appropriate in a wide range of circumstances, where other structures provide secondary line of flood defence.	Generally 'high' loadings (buildings/heavy vehicles). The flood risk assessment often shows the land value to be high with little or no protection against flooding by secondary structures.	Generally 'high' loadings (buildings/ heavy vehicles). The flood risk assessment often shows the land value to be high with little or no protection against flooding by secondary structures.
Ground conditions (soil/geology) Ground conditions are considered at the outset along with land-based loadings and bank geometry to check for 'intrinsic stability'.	Ground conditions are critical to this technique. Roots of plants can undoubtedly contribute to bank stability and support loadings, but cannot be relied on due to the wide variability of the root penetration profile, root strength at different ages, etc. Accordingly, bioengineering is generally only selected when the erosion-protected estuary edge is 'inherently stable'. Plants can, however, be included to contribute to the resistance of the design. Soil must also be suitable to support the expected plant growth.	Ground conditions are critical to this technique. Biotechnical solutions are designed to prevent erosion rather than address problems of inherent stability in relation to ground-based loadings. Thus the erosion-protected edge must be 'inherently stable' at the geometry proposed. Soil must also be suitable to support the expected plant growth. The substrate will often be inherently weaker than where bioengineered solutions are proposed and plant rhizome/ root systems will often be slower to develop.	The substrate must be capable of being retained with stability. This technique should be used in preference to bioengineering or biotechnical systems only where the estuary edge is inherently unstable.	The substrate must be capable of being retained with stability. This technique should be used in preference to bioengineering or biotechnical systems only where the estuary edge is inherently unstable.

Figure 2.3: Example of the UK estuary edges approach linking BCs to selected measures

The UK estuary edges approach distinguishes between bio-, biotechnical, fully structural, and hard engineering measures. Apart from the hard measures, the following measures are discussed, which generally enhance grasses, sedges, and reeds, which is the typical vegetation in the coastal water-exchange zone, not softwood as in inland areas. So, the proposed measures may be useful for inland areas only in the case of low to moderate ship-induced impacts, flat slopes, and low long-term water level fluctuations ΔW (short inundation and dry periods), as these BCs are typical for tidal-influenced areas; see also Figure 2.4.

- Bioengineering – Establishment of reeds or other site-specific vegetation by planted coir rolls or woven coir matting and trapping silt by brushwood mattresses or fascines to initiate and enhance natural succession.
- Biotechnical engineering – Plants grow through turf-reinforced mats or in gravel-filled synthetic soil cells or turf-reinforced mats plus rock rolls for ballasting.
- Fully structural engineering with ecological upgrades – Planted geotextile bodies with rock rolls for ballasting, vegetated stone revetment filled with gravel, or hard-engineered terraces for enhancing natural colonisation.

What the reader of the UK report will observe from these solutions is the variety of ideas for establishing plants by direct measures.

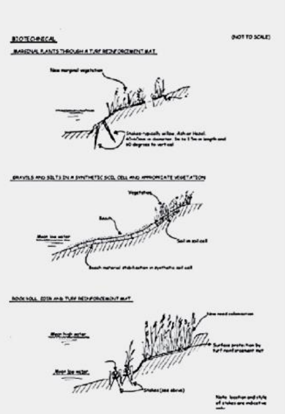
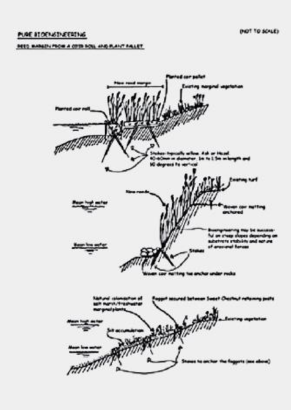
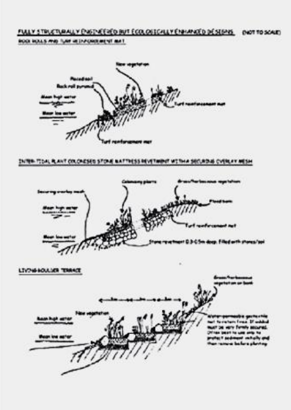
Bioengineering	Biotechnical engineering	Fully structural engineering	Hard engineering
• Reed margin from a Coir Roll or Coir Plant Pallet • Woven Coir Matting and Plug-Planting • Fascines or Brushwood Mattresses to trap silt • Natural colonisation promoted wherever possible	• Marginal plants growing through a Turf Reinforcement Mat • Gravels/ sands in a Synthetic Soil Cell plus appropriate plant regime • Rock rolls and Turf Reinforcement Mat	• Rock rolls or boulder packing and geotextile backing supports plant terrace • Stone Revetment promoting natural colonisation (may also be planted) • Hard engineered terraces to create beds for natural colonisation or planting • All revetments step BACK from existing intertidal not into it.)	• Sheet Piling • Concrete or Brick Walling • 'Block Stone' • Rip-Rap (1-tonne stones) • Concrete Block Systems
			Not illustrated.

Figure 2.4: Types of bank stabilisation according to UK estuary edges approach

2.2.3 Report on a Test Section on the German River Rhine at Worms

This report, created by the Federal Waterways Engineering and Research Institute (BAW), Federal Institute of Hydrology (BfG), and the Waterways and Shipping Office (WSA) Oberrhein, contains the results of the monitoring phase from 2012 to 2017 on the test stretch on the River Rhine near Worms, Germany. Since 2011, nine different TBP measures have been tested under waterway conditions on the right bank of the Rhine (km 440.6-441.6). In four test fields, the previously existing rip rap between the MW and the upper end of the bank slope was replaced with willow-brush mattresses, pre-cultivated plant mats, and reed gabions as well as stone mattresses. In one test field, the bank remained largely unprotected. In another four fields, the existing rip rap was ecologically upgraded through various measures: greening with willow cuttings, living fascines, brush and hedge layers, structural improvements with gravel, large individual stones and deadwood fascines, and the creation of protected shallow water areas by a stone wall in front of the river bank.

The Rhine in this section is a free-flowing river with large water-level fluctuations of over 6 m. About 120 cargo ships operate every day. The ship-induced and natural bank loads as a result of floods are comparatively large. The banks with relatively steep slopes (1:2 to 1:3) are periodically inundated. Under these conditions, the TBP measures had been (and are still being) tested with regard to their technical and ecological efficiency as well as their costs (installation and maintenance) compared to conventional rip rap revetment. The technical monitoring includes regular inspections of the measures and measurements of the bank geometry, ship-induced bank loads, and pore water pressures that appear while ships pass. The ecological monitoring includes the regular study of vegetation (plantings and natural succession potential) as well as studies of special faunistic indicator groups such as fishes, invertebrates, spiders, ground beetles, birds, amphibians and reptiles. Maintenance and reconstruction measures as well as the costs are also documented.

The large water-level fluctuations with simultaneous ship-induced loads have proven to be the decisive impact on the TBP measures. As expected, the initial state after installation (plants and roots are not yet sufficiently developed) turned out to be the critical state. The individual measures were evaluated with regard to the criteria – bank stability, ecological effectiveness, and cost – compared with conventional rip rap revetments for each criterion separately and also according to all three criteria. This evaluation was done primarily under the BCs of the test section on the Rhine and additionally in the sense of a projection onto other scenarios.

From a technical point of view, the various measures – with and without technical components – could not all guarantee bank protection in the applied construction and design under the tested BCs of the Rhine. But after the described optimisation of the measures (that is, *lessons learnt*) and taking into account the application limits found, all tested TBPs can in principle be used on inland waterways. For the first time, in addition to the bank stability, the ecological effects of TBP measures on selected taxa and vegetation has been scientifically proven under waterway conditions. Different taxa have benefited differently from the measures, but in summary, the measures achieved an ecological upgrade compared with rip rap. The installation costs are mostly higher than for rip rap revetments. Application limits for each measure are defined as well as recommendations for future applications of the measures on inland waterways. Monitoring will be continued in the future to investigate the long-term development and to evaluate possible maintenance strategies.

2.2.4 Vademecum Natuurtechniek – Inrichting en Beheer van Waterlopen (1994) – Belgian Guideline

Although the Vademecum was published almost 30 years ago, it still serves as an anchor point in the design of technical-biological embankments in Flanders, Belgium. The Vademecum was a result of a decision of the Flemish government in 1990 to integrate ecology and infrastructural works. The Vademecum acts as a consolidation of existing practices and insights that were treated in corresponding WGs. The Department of Civil Works and Traffic and the Department of Environment, Nature Conservation and Land Development were represented in the WGs.

The scope is defined as (1) an environment friendly design, implementation, and maintenance of infrastructural works and (2) possibilities to adapt existing infrastructure or to mitigate negative environmental effects. The Vademecum provides a complete overview on biotechnical techniques concerning navigable waterways, roads, maintenance, non-navigable waterways and local roads, and water treatment. A broad-angle approach on the planning and maintenance of biotechnical techniques along navigable waterways is given, with specific attention to bank-protection measures. Possible applications are discussed according to general dimensions, measure elements, and materials. Construction and maintenance aspects are covered. Detailed design approaches for loads and resistance of materials are not covered.

Concerning specific types of embankments on waterways and canals, the following examples are given in the Vademecum: rubble stone dam, double wooden pile wall, underwater *talud* (slope) with stone dam on top, underwater sheet-pile wall with stone dam on top, wooden pile wall with fascines, steel sheet-pile wall with top openings, and steel sheet-pile wall with stone dam on top.

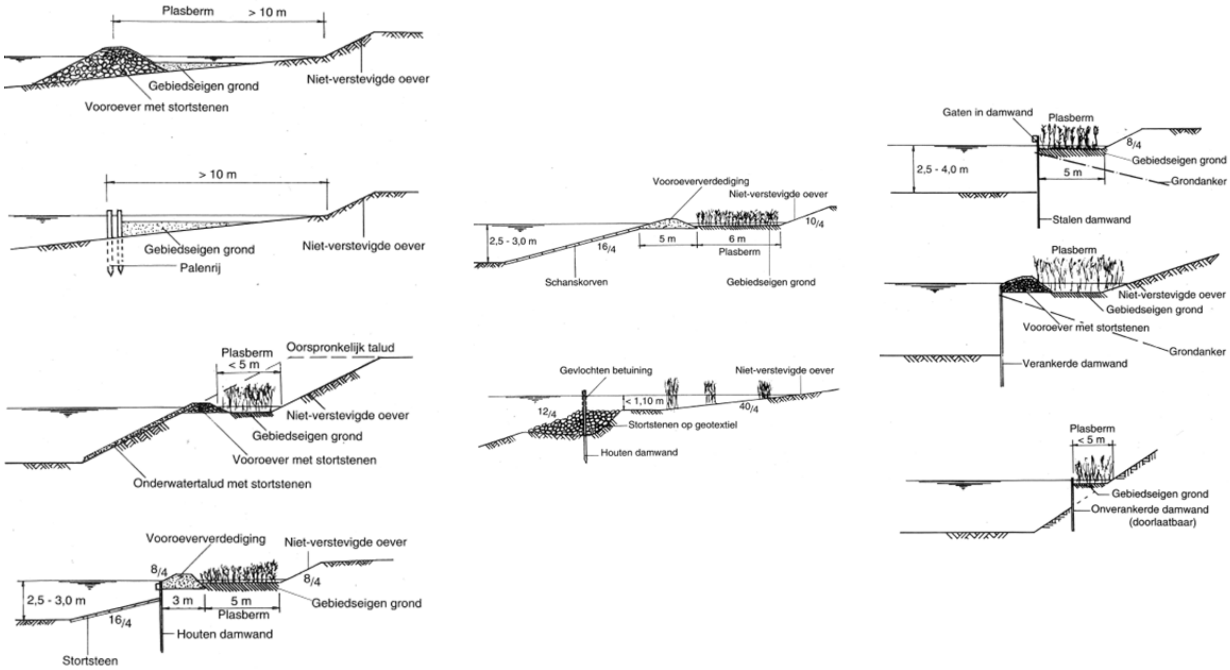


Figure 2.5: Cross sections of embankments for waterways (left and middle) and canals (right) in the Vademecum Natuurtechniek (1994)

A comprehensive update of the Vadecum is not available. Several implementations of technical-biological embankments were carried out using the Vademecum. An interesting addition on the Vademecum is given in separate monitoring reports on specific implementations.

2.2.5 CUR 200-205 Natuurvriendelijke Oevers (1999) – Dutch Guideline

All aspects of technical-biological aspects are covered in this extensive reference work: planning and applications, loads and resistance, bank-protection materials, fauna, vegetation alongside large water bodies, and aquatic and bank plants. The 1999 edition updates the 1994 edition (CUR 168 Natuurvriendelijke Oevers).

Hydraulic loads and how to estimate them are given and discussed. Guidelines for a preliminary design of several types of TBPs are mentioned. The application of typical measures on different waterways is discussed. An overview of bank-protection materials is given. Relevant ecological aspects of both fauna and flora in relation to TBPs are discussed, including planning and monitoring.

Specific attention is given to canal embankments with a protected shallow water zone. Concerning cross sections, three generic variants are provided: (underwater) slope, vertical wall, and vertical wall with dam on top (see also Figure 3.1).

The design of several biotechnical embankments that were implemented in the Netherlands and in Belgium was based on the guidance in the CUR Natuurvriendelijke Oevers.

2.2.6 British Waterway Management Guide (1999)

Cranfield University (Cranfield, England) was instructed by the Environment Agency of the United Kingdom to develop 'A Guide to Erosion Assessment and Management' [Cranfield University, 1999]. The 'Guide on Waterway Bank Protection' from 1999 "is aimed at helping the operational engineer and others concerned with bank erosion to make objective decisions on control measures and to encourage the use, wherever possible, of vegetative-based approaches which offer ecological advantages and long-term sustainability".

The approach is primarily tailored to small creeks and canalised waters with pleasure boats and the well-known narrow boats of UK's small canals. But as large flow velocities, which correspond to those in breaking ship waves, are addressed by the guide, it may also be applied to larger waterways. It is thus recommended herein, together with the DWA-M 519 bioengineering approach (Appendix B in Part 3), as a substitute for or supplement to the WG 128 preselection approach for comparisons, as it is written mainly for practitioners and discusses practical implementation experiences. The guide was thus simplified and adapted to the purposes in this report in Appendix C in Part 3.

The guide encourages the user first to survey the erosion problem through on a structured site visit. This approach is reflected in this report in the 7 Steps in Chapter 6.3, together with all other technical objectives to be met. Then, the user is prompted to classify the waterway as a nontidal river, tidal river, canal, or canalised river. This classification is similar to the one used by the BPA and is used, together with other attributes, to select appropriate strategies to cope with the erosion problem. Next, user determines the type of bank failure, especially taking care to assess whether the erosion problem is initiated by instabilities on the toe of the embankment or the bank slope. Together with the assessment of the sediment-transport regime of the channel, the assessment of the consequences of erosion, and several other criteria such as the demands of navigation, ecology, economic constraints, and bank users, the guide provides a decision framework for choosing the best strategy to cope with the erosion problem, generally distinguishing between non-engineering and engineering measures.

The guide categorises non-engineering measures as *management measures* (for example, fencing to avoid access to critical sections or pruning); *natural adjustment*, especially if the risk in case of a bank failure is acceptable; or *relocation* (for example, of buildings from unstable bank areas, where possible). The engineering measures were categorised as *bioengineering*, *biotechnical engineering*, or *structural engineering* measures. The structural engineering measures were implemented in this report as part of the BTs catalogue in Part 2, but only those able to counteract at least small ship waves and offer an ecological upgrade to rip rap such as, for example, by using organic materials or greening; see Part 3 for more details.

Different from both the DWA-M 519 bioengineering approach and preselection tools is that the bank height above MW and the bank loading (from vegetation with grasses and small bushes up to buildings just behind the embankment towards the hinterland) influence the design, together with the average bank slope and the flow velocity at bank full discharge, where flow impact generally reaches its maximum impact.

Also different from the DWA-M 519 approach and preselection tools, ship waves and ship-induced currents are not quantitatively addressed in the guide with the exception of the fact that ship waves may be relevant or not. This disadvantage, which restricts the application of the guide, is addressed in Appendix C in Part 3 of this report by providing wave-height-equivalent flow velocities. This addition enables readers to apply the British Waterways Management Guide to waterways for larger vessels, which are a focus of this report, because the inclusion of bank height and bank loading in its design criteria makes the Waterways Management Guide a valuable resource and is recommended, together with the DWA-M 519 approach from Appendix B in Part 3, as a supplement to the preselection tools.

2.2.7 UK Green Approaches in River Engineering – Supporting Implementation of Green Infrastructure

The approach of NERC – UK Natural Environmental Research Council (HR Wallingford – Working with Water) Wallingford [Roca M. et al., 2017] aims to provide guidance for practitioners on river engineering through the use of nature-based solutions. Within the continuum between natural river development and artificial grey river solutions, the Wallingford approach focuses mainly on green solutions but also describes green-grey and grey solutions. *Green solutions* are fully soft solutions or bioengineering solutions and use vegetative materials exclusively. *Green-grey solutions* are biotechnical or compound solutions that include nonvegetative or nonbiodegradable components. Finally, *grey solutions* are either hard, structural solutions or conventional engineering solutions (rock, geotextiles).

The approach is formed as a decision-support framework at two different levels: First, the business case support decisions to implement a green infrastructure approach. Second, the technical support provides the technical information base from which to select an appropriate green or green-grey measure or technique. Next to the two-level decision-support framework, the Wallingford approach provides a broad variety of examples for green, green-grey, and grey measures. Furthermore, essential decision-making stages ('defining driver of change and project objectives', 'assessing opportunities and consequences', 'identifying and appraising options') are explained within the business-case framework. Critical success factors, such as motivation, engineering performance, benefits (or ecosystem services), and costs as well as risks are explained. Within the technical-support framework, essential decision-making stages are also explained, including three more stages: 'select and design option', 'implementing the selected option', and 'monitoring, inspecting, maintaining, and evaluating'. Moreover, technical conditions for success or failure are explained.

In addition, 12 case studies are provided in detail. For each case study the success of the engineering performance, inspection and maintenance, costs, and additional benefits are provided in a table-based overview. For more information see also: **https://eprints.hrwallingford.com/1250/1/Green_approaches_in_river_engineering.pdf**.

2.2.8 CETMEF Aménagement des Berges des Voies Navigables (2009) and Digues et Berges et Berges des Voies Navigable (2010) and Other Reports

In France and Francophone countries, only limited guidance for the use of plant techniques on waterway banks exists.

The Centre d'Etudes Maritimes Et Fluviales (CETMEF) published a report in 2009 on the use of vegetal and mixed techniques on French waterways ('**Aménagement des berges des voies navigables – Retour d'expériences' | Publications du Cerema**, 95 pages). The report summarises the main processes of bank erosion linked to navigation then describes an approach to the choice of plant techniques, including a list of constraints (for example, public and structures safety, financial constraints, environmental opportunities and issues, bank morphology) and objectives (for example, functions of the structure, stability and durability, minimal maintenance).

The main techniques (vegetation and civil engineering) are listed qualitatively in summary tables with use cases, major interests and limits, indicative costs, and maintenance efforts. The general principles are then considered for the sizing techniques. These general principles mainly concern the equilibrium profile of the banks needed to optimise the use of the vegetal techniques and the morphological principles of the berm to cushion the waves.

The report shares the practical implementation experience of 16 case studies in the form of summary sheets based on the same model: 7 for vegetal techniques and 9 for mixed techniques. These case studies include qualitative and quantitative information and cover the context, a description of the technique (with a cross section), the progress of the work, the results obtained, and the maintenance carried out. A flow chart, in the appendix, presents a reflection on the choice of these techniques based on the geometry of the bank.

In June 2010, the CETMEF published a report on damages to and repairs of embankments and dykes in waterways (**'Digues et berges des voies navigables' | Publications du Cerema**, 282 pages). The report presents 25 detailed case studies, one of which deals with plant engineering from the 2009 guide. This reference mainly deals with the civil engineering aspects of embankments and dykes.

In 1994, the French Ministry of Land Use Planning and Ecology published a technical guide for the protection of riverbanks using vegetal techniques (**'Manuel de restauration hydromorphologique des cours d'eau' | BIOTEC Biologie appliquée SA**, 143 pages). A reference for practitioners, this manual has a good approach and technical descriptions of concepts and solutions for bank stabilisation. It presents case studies, but it lacks discussion of the issue of wave action related to navigation.

In Quebec, Canada, a technical guide from the Comité de la Zone d'Intervention Prioritaire des Seigneurie de la commune de Repentigny provides advice for the rehabilitation of the riparian strip of the Saint Lawrence River. This report is mainly intended for private owners: the main actors on the banks of the Saint Lawrence. It presents a very landscaped approach of the green-space type. An example of substitution of low walls by plant techniques is given (willow fascine and layer of willow branches). This guide does not include a technical approach.

2.2.9 Technical Guidelines for Green Constructions of Inland Waterways (2021) – Chinese Guidelines

The guideline is based on the large number of ecological inland waterway construction practices, such as the Beijing-Hangzhou Canal, Yangtze River inland waterway, Xijiang Inland Waterway, in China to guide and standardize the design and construction of ecological inland waterways. The guideline includes the project layout; the ecological construction method of the bank, revetment, beach, and dykes for the inland waterway; and the ecological dredging and reef-clearing method, which is applicable to the construction, reconstruction, and extension of inland waterway projects such as rivers, lakes, reservoirs, and canals.

For the layout of the bank protection, the guideline provides as follows:

- bank protection should smoothly follow the bank slope
- bank protection should be divided into different zones according to the characteristics of water level and flow, where different types of protective measures are taken
- both direct and indirect measures can be applied to the bank slope

The guideline also contains the preliminary contents for ecological bank construction and protection, including ecological material selection, structural form, and contents that should be paid attention to during the construction process. The guideline suggests that the ecological materials with high porosity and permeability, which are suitable for biological habitat and plant growth, should be applied to the bank protection. The bank protection structure of tourism waterways should be integrated with the surrounding environment. Furthermore, the structural forms commonly used in the construction of ecological waterways in China are presented, including steel wire mesh, ecological slope-protection brick, and three-dimensional reinforced mesh mat. The measures with plants are mostly suggested for the bank protection in the weak hydrodynamic areas, while the measures with anti-scour structure with high permeability should be applied in the inland waterways with strong hydrodynamics.

However, the guideline still lacks some quantitative reference standards and can only be used as a preliminary reference. According to the guidelines, more detailed methods will be proposed for the selection of bank materials, structural stability, and calculation of relevant hydrodynamic conditions in future ecological inland waterway construction guidelines.

2.2.10 EU ECOSHAPE Project

Building with Nature is a network of organizations and individuals working together to advance the application of Building with Nature in water-related societal issues. Building with Nature is a philosophy about the design and construction of water-related infrastructure that harnesses the forces of nature for the benefit of nature and humans, thereby strengthening nature, economy, and society.

EcoShape is a foundation under Dutch law that facilitates the Building with Nature network. EcoShape coordinates, facilitates, and orchestrates the activities within the Building with Nature network and community. The network aims to contribute to the implementation of the United Nations' Sustainable Development Goals (sdgs.un.org/goals), addressing societal challenges through Building with Nature solutions on a landscape scale.

To make this possible, EcoShape promotes knowledge development via pilot projects to demonstrate and monitor Building with Nature in practice (that is, *nature-based solutions*). Using the monitoring results, guidelines for replication and scaling up are developed and disseminated through the EcoShape website.

2.2.11 PIANC Report N° 195 – 'Ecosystem Services – a Multicriteria Evaluation Framework'

Planning, implementing, or monitoring alternative TBP measures could serve as an ideal showcase for applying an evaluation methodology that covers more than customary approaches like, for example, the pure economic cost-benefit analysis or single targeted nature-conservation assessment. To bring about the full view of measure-related effects, these measures must be placed and evaluated in an overall societal context.

A highly recommended approach is the concept of ecosystem services (ES). ES are defined as the benefits people obtain from ecosystems; for example, in an economic, material, health, or psychological context. The concept is based on the functions that natural features perform, and which communities make direct or indirect use of, consciously or not.

ES roughly can be classified into three categories: provisioning services (for example, food, water); regulating and maintenance services (for example, water budget, water quality); and cultural services (for example, recreational value). Abiotic as well as biotic services are included [Haines-Young and Potschin, 2018].

The ES approach provides a multicriteria framework for accounting for the costs and benefits of natural-resource management. It is applicable to evaluate, justify, or optimise decisions on how land- and waterscapes are managed, for a range of sectors, including the waterborne transport infrastructure (WTI) sector.

In good time, PIANC recognised the need to analyse options to introduce the ES concept into the WTI sector. In 2015, a basic workshop, 'Ecosystem Services: Identification, Assessment and Benefits for Navigation Infrastructure Projects', was held in Koblenz, Germany. To this end, the EnviCom Working Group 195 – 'An Introduction to Applying Ecosystem Services for Waterborne Transport Infrastructure Projects' was formed and published its results in April 2021 [PIANC, 2021].

River Scheldt, Belgium; the project area 'Wijmers' being part of the 'Sigmaplan', a river-management plan for flood prevention in combination with nature restoration and navigation. An ecosystem services analysis was used to compare different management alternatives, and the outcome of the societal cost-benefit analysis was used to develop the management plan in the initial concept phase. (© De Vlaamse Waterweg nv)

The WG 195 report is a basic introduction into the understanding and the application of the ES concept in WTI projects, illustrating how the application of ES concepts may benefit the day-to-day work of WTI designers, planners, operators, and managers. The analysis is underpinned by eight real-life case studies either having successfully applied the ES concept or are intending to do so (that is, are in the planning phase).

The report concludes that (i) the ES concept is applicable to both large and small WTI projects or even to single measures; (ii) the most benefits can be expected when an ES assessment is included in a project or measure planning right from the beginning; (iii) nevertheless ES can improve a project at any time during its life cycle; (iv) ES framing helps to evaluate a WTI project in a broader context, identifying opportunities and avoiding undesirable impacts; and (v) ES concepts provide a transparent basis for communication to a diverse range of stakeholders.

2.2.12 Working with Nature

Infrastructure managers and practitioners have broadly articulated the need to better integrate built, ecological, and social systems in water management. Internationally, programs appear under different titles, such as *Working with Nature* [PIANC, 2011 ; PIANC, 2018], *Engineering With Nature* [Bridges et al., 2014], and *Building with Nature* [EcoShape, 2021]; however, the underlying philosophies are similar. These planning and design approaches emphasise the need to expand the scope of infrastructure benefits and reduce unintentional costs with a particular focus on social and environmental outcomes, and collaboration, partnership, and community engagement play central roles in how multiple objectives are scoped and pursued.

The design of management actions in this arena often blends concepts from traditional infrastructure design and ecosystem restoration. Conventional and nature-based designs then become the end points of a spectrum of grey and green solutions. As with the underlying philosophy, the lexicon of these management actions appears with multiple titles, such as *nature-based solutions* [Ruangpan et al., 2020], *natural and nature-based features* [Bridges et al., 2015 ; WWF, 2018 ; Bridges et al., 2021], and *natural infrastructure* [Childers et al., 2019]. Although often presented as either-or options, a growing body of scientists and engineers acknowledge that grey and green methods may be blended, integrated, or hybridized to varying degrees [World Bank, 2017 ; Browder et al., 2019 ; Conservation International, 2019 ; Schoonees et al., 2019].

2.2.13 US Stream Restoration Guidance

This manual focuses on TBPs on inland waterways, but many of these methods have been more extensively developed and applied in the context of non-navigable waterways, in particular for stream restoration. Over US$ 1B per year is the estimated investment in the US stream- and river-restoration industry, and thousands of these projects are related to bank stabilisation [Bernhardt et al., 2005]. General restoration guidance documents often address stream-bank stabilisation in great detail (for example, FISRWG (1998), Watson et al. (1999), Bernard et al. (2007), Simon et al. (2011) and Yochum (2016)), and more detailed guidance is also available relative to specific topics on stream banks [Sotir et al., 1996 ; Allen and Leech, 1997 ; McCullah and Gray, 2005], reservoir shorelines [Allen and Klimas, 1986], and use of large wood [Bandrowski and Conyngham, 2016]. Despite this extensive knowledge base, the vast majority of guidance, case studies, and monitoring has occurred on smaller, non-navigable rivers. As such, this manual will draw heavily from the body of knowledge on stream-bank stabilisation, but guidance will be adapted to the context of navigable inland waterways.

2.2.14 US Living Shoreline Guidance

This manual focuses on TBPs on inland waterways, but a family of similar shoreline-protection methods known as *living shorelines* has grown in prominence in coastal environments, particularly in the United States. These shoreline-stabilisation techniques are typically presented as a range of solutions from entirely naturalised, vegetation-only methods to engineered bulkheads [NOAA, 2015 ; SAGE, 2015], although some notable examples have emerged using green solutions to protect or enhance grey infrastructure [Vuik et al., 2016]. Living shorelines have become extremely popular as a mechanism for expanding the benefits of shoreline stabilisation while reducing social and environmental costs. In fact, many coastal states and nonprofit organisations have developed their own guidelines for use of these methods (for example, Texas GLO (2020) and Delaware Living Shorelines Committee (2021)). Guidance on the topic ranges from technical design guidelines for engineers (for example, Webb et al. (2019)) to informal qualitative advice for coastal residents (for example, SAGE (2015)). Technical concepts from living shoreline methods have been integrated into the basic approach of this manual, with an explicit focus on inland waterways.

2.3 Other Relevant Literature and Case Studies

2.3.1 Case Studies on TBPs on Flemish Waterways (Updated Last Version on BSCW)

The Flemish Instituut voor Natuur- en Bosonderzoek (Research Institute for Nature and Forest) has conducted and is conducting a large number of monitoring campaigns on different types of TBPs on several sites along Flemish navigable waterways:

- Seacanal Brussels-Scheldt: shallow water zone behind parallel dam
- Canal Ghent-Bruges: shallow water zone behind parallel dam
- River Leie: shallow water zone behind a wooden palisade
- Canal Louvain-Dyle: shallow water zone behind gabion parallel dam

The monitoring results of each campaign at each site are processed, analysed, and evaluated, and maintenance recommendations are then given using general and site-specific experiences. The monitoring focuses on ecology-related parameters.

2.3.2 German DWA-M 620 Guideline on Bioengineering Methods for Small Waters without Navigation

The German guideline concerning bioengineering methods for non-navigable waters (DWA 2020) uses the so-called *Key-Lock Principle*. The *key* represents the local BCs and requirements for design.

In total 15 conditions and requirements are considered, forming the bits of the key: *flow-velocity regime*, *quality of substrates*, *water quality*, *land use*, *discharge capacity*, *target vegetation*, *stability demands*, *available space*, *method of functionality*, *tolerable duration of initial state*, *hydraulic load*, *inner or outer bank*, *construction time*, *access for construction machines and trucks*, and *exposure to sunlight*. Of these criteria the following were also used in the preselection tools: quality of substrates, water quality, land use, stability demands, available space, method of functionality, tolerable duration of initial state, construction time, and access for construction machines and trucks.

The associated *lock* consists of the properties and demands of a chosen measure, forming the pins of the lock tumbler: *geographical suitability*, *substrate demands*, *area covered by the measure*, *effect of adjacent areas*, *influence on conductivity*, *supported target vegetation, stability, area needed*, *planar or linear*, *necessary initial time*, *threshold hydraulic load*, *application area related to zoning*, *optimal construction period*, *construction demands*, and *sunlight demand.* All criteria except supported target vegetation were also used in this report.

If the bits of the key fit best with the corresponding pins of the lock (that is, the key turns the lock), whereby the degree of accordance will be assessed by scores, the chosen measure is suitable for the conditions on-site and fulfils the aims of the planners.

This report also uses the following concepts from the guidelines' approach:

- using scores to match different criteria (in principle weighted average of scores);
- distinguishing between the roles of the BCs for the design, called the *feasibility check*; and
- the way to balance demands and necessary and existing properties and functionalities, called the *suitability check* in the preselection tools.

This report does not, however, take the guidelines' recommended design approach, which is analogous to a CAD construction, meaning that the user is forced to choose a measure first according to previously defined objectives (especially taking ecological objectives, which are more or less covered by the target vegetation in the DWA report) and then to check if it fits with the situation on-site.

This top-down approach seems to be appropriate in cases where local BCs and properties are strongly interrelated; for example, because the effective hydraulic loads on the measure depend strongly on the properties of the construction. Especially because this interrelation is not that important in the case of large water bodies such as inland waterways, which would demand a case-by-case consideration and make it impossible to select appropriate measures before checking their suitability, WG 128 decided to prefer the usual bottom-up approach as it is used, for example, in the DWA-M 519 bulletin (here in Appendix B in Part 3) or in the British Waterway Management Guide (Appendix C in Part 3). This bottom-up preference means that the BCs and the planner's objectives predominantly define the optimal solutions for a site. The inherent correlation of BCs and measure properties is neglected in the preselection design step.

2.3.3 German LUBW Guideline on Bioengineering Methods for Streams (2013)

The LUBW (State Institute for the Environment Baden-Württemberg) is a central institution of the German federal state of Baden-Wuerttemberg, which, among other things, fulfils legal tasks in the field of environmental protection. The guideline considers bioengineering methods for bank protection on small streams. Part 1 of the guideline gives an overview about basics and definitions, descriptions of different kinds of measures and single elements, and information on installation and maintenance. Part 2 offers 33 detailed fact files of implemented bioengineering measures in Baden-Württemberg. These fact files provide readers with practical experiences to avoid future errors in the implementation of the construction methods. Part 3 provides worksheets with detailed drawings for practical use on-site during the construction phase.

The guideline gives a good overview of bioengineering bank-protection measures, but it mainly concerns smaller streams without commercial shipping. And it lacks any information about permissible impacts and the stability of those banks protected with the described methods.

2.4 Conclusions from the Literature Survey

The diversity of region- and country-specific investigations and design manuals indicates a significant global interest in TBP measures. These technical resources point toward the value of these features in providing a broader range of economic, aesthetic, and ecological benefits. However, these documents also emphasize the continued importance of engineering performance and technical outcomes. As such, this literature review highlights that a major challenge for the use of TBPs (and for this WG specifically) is balancing purposes and selecting the right management feature at the right time.

In these manuals, dozens of different TBPs have been proposed on the spectrum from no protection to bioengineering to purely technical methods (see Part 2). This continuum of green to grey approaches is widely acknowledged in other applications of nature-based solutions beyond bank protection [Browder et al., 2019 ; Conservation International, 2019 ; Schoonees et al., 2019], although it is particularly visible in this arena. The specific types of bank protection vary widely, but there is significant overlap in both the features themselves and the philosophy of their usage. A few consistent observations appear in nearly all of the manuals and resources:

- Context specificity is needed when working with ecological systems (for example, ecological benefits may depend on connectivity to neighbouring ecosystems), much more so than when working with purely technical solutions.
- Selection of features along the green–grey spectrum requires a clear understanding of the needs for technical performance, associated risks, and risk tolerance of the decision makers (and funding entities).

- Space constraints are often major factors in the selection of a particular method. For instance, degree of waterway encroachment or availability of upland hinterland can dramatically drive a preference toward or away from a TBP.
- Given the prior challenges, a clear understanding of project objectives and constraints is crucial for the selection and design of TBPs.
- Even with the challenges of context specificity, the manuals often point toward similar physical and ecological variables guiding the design process (for example, water-level fluctuation, bank slope), indicating the potential for a general assessment procedure.

At the time of writing, design processes for TBPs remain largely qualitative because of the need for tailor-made solutions meeting the above challenges. The body of knowledge and scientific evidence is growing, but quantitative design guidance remains elusive. Importantly, the field of application related to bank protection is evolving rapidly, and many novel techniques are being designed and applied with limited empirical data on long-term performance (with notable exceptions such as the River Rhine and Worms, Germany, and other case studies highlighted in Part 2). The subsequent chapters of this manual attempt to extend the current state-of-the-science and state-of-the-practice by articulating clear procedures to work through the challenges and compiling examples for practitioners.

3 TECHNICAL-BIOLOGICAL BANK-PROTECTION (TBP) MEASURES

3.1 INDIRECT MEASURES (PRE-EMBANKMENT)

An *indirect measure* is defined as a pre-embankment construction in front of the main embankment. The measure delivers a specific combination of stability and ecological potential to the embankment. Without the measure the embankment will be less stable and hence have another ecological potential, or the embankment will need a flatter slope or another protection to obtain a comparable stability and hence, again, have another ecological potential.

In the following categorisation a difference is made between measures close to the embankment (say less than 20 m) and far from the embankment (say greater than 20 m). Both types of indirect measures serve the same goal: help to protect the embankment from erosion due to flow or ship-induced loads, or both. A difference between both types of measure is that a measure close to the embankment usually forms one combined construction comprising the embankment, the shallow water zone, and the pre-embankment, where a measure far from the embankment can be seen as a construction that stands on its own, although it has a clear influence on the embankment.

An indirect measure reduces the effect of the current or ship-induced loads, or both, on the embankment by damping the incoming loads or shielding the embankment completely. The effect of the current and ship-induced loads on the embankment is determined by the intrinsic size of the load and the rate of damping between the point of origin and the embankment. That damping or shielding effect can be obtained by creating a literal distance between the point of origin of the load and the bank or by conceiving some kind of construction that damps the incoming loads.

Another characteristic of an indirect measure is the presence of a zone between the pre-embankment and the main embankment. If the indirect measure lies close to the embankment, this intermediate zone is a shallow water zone in many cases. In the absence of an indirect measure, that shallow water zone could only be present if there would be an ample amount of available space for a flat or stable underwater slope. And if the indirect measure lies further away from the embankment, the zone between pre-embankment and main embankment is clearly influenced by the indirect measure giving another combination of loads a different ecological potential from the bank without the measure.

The two characteristics mentioned above, damping of the loads and creating a shallow water zone, determines the ambiguous nature of the indirect measure. To achieve both purposes, an equilibrium is needed between the barrier effect and the link between the shallow water zone and the waterway. The rate of damping is determined by the amount of obstruction between the waterway and the shallow water zone and the embankment.

The obstruction pursued in an indirect measure can be materialised underwater (for example, at high stages); above the water level; under a certain slope such as vertical; or under all possible combinations. A sheet-pile wall with a top edge above the (actual) water level can, for example, be alternated in a longitudinal sense with a sheet-pile wall with openings above or below water level to ensure the exchange between waterway and shallow water zone where appropriate. Also, in a specific cross section, a combination of typical measures can be conceived, when, for example, a parallel stone dam is placed on top of a sheet-pile wall with a top edge under the water level.

The different indirect measures considered here are constructed from a variety of materials ranging from steel (sheet-pile walls), wood (palisades), quarry stones (parallel dams and groynes), gabions (for example, on top of impounded sheet-pile walls) to earth (chevron dykes). Each material will occur in a typical measure either for a specific combination of BCs such as loads, available space, and budget or for characterizing the ecological values.

3.1.1 Measures Close to the Bank Slope Using Sheet-Pile Walls

A vertical indirect measure close to the embankment distinguishes itself from a parallel dam close to the embankment in terms of the required space for the pre-embankment itself. The difference is clear; for example, consider a water depth of 4 m in a waterway: the vertical measure takes less than 0.5 m of construction width, while a parallel dam made, for example, from loose, dumped rip rap, will have a base width of at least 8 m (plus top width, plus 2× bonding depth) given a (unusual) very steep slope angle of 45°.

This clear difference concerning needed construction breadth is also linked to construction costs. For a modest water depth (less than 2 m) or a modest difference in bed level between the waterway and the shallow water zone, a nonvertical indirect measure, such as a parallel stone dam, can be achievable if space is available. For larger water depths or larger differences in bed level (greater than 2 m) a nonvertical measure could lead to excessive space occupation or material use in favour of the choice for a vertical measure; for example, a steel sheet-pile wall.

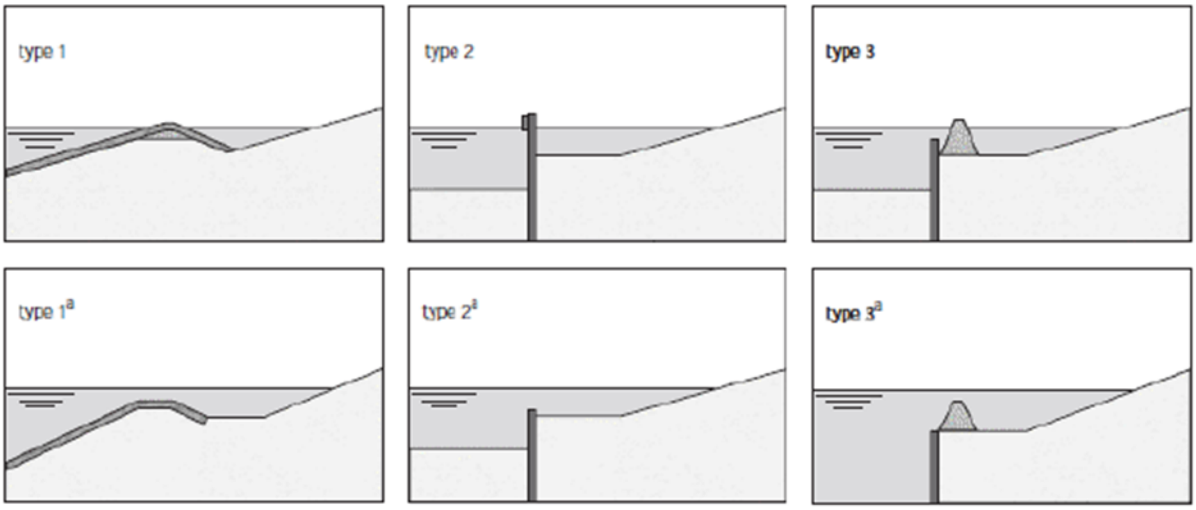


Figure 3.1: Types of indirect measures close to the embankment
Type 1: parallel dam; Type 2: vertical wall; Type 3: combination
Above, *top level above MW;* below, *top level below MW [CUR 201, 1999]*

Within the group of vertical indirect measures, a distinction can be made according to the manner of connection between the waterway and the shallow water zone: openings reaching from the water surface at MW downwards (for example, constructed by section-wise lowered wall-top height) allow water to flow through and waves to pass the shallow water zone in the water-exchange area, will be called *top openings*. By contrast, if the openings are totally submerged at MW and exchange between the waterway and the shallow water zone takes place mainly below the water level, the measure is called a *wall with underwater openings*. Both types can be implemented next to each other in a certain stretch or combined.

The efficiency to damp waves using pre-embankment measures strongly depends on relevant ΔW, say between MW and the highest shipping level (HSW; most important load come from ship waves) or MW and the average mean highwater level (MHW; relevant loads from wind waves). Experiences show that if the top of the dam is situated to be not very much lower than about 0.2-0.3 m below HSW or MHW, then the damping effect is optimal even at high stages. If this difference is about 0.5-0.7 m, typical ship waves will still be damped sufficiently, but there may be measures necessary to avoid erosion inside the shallow water zone. Even if the top of the dam is 1.0-1.5 m below critical water levels, the construction may still function if there are efficient restrictions to navigation in place. But for very much higher stages or ΔW, the pre-embankment measure loses its wave-damping function for high stages. Nevertheless, its flow-damping effect may still exist, especially in areas far below the water level, and thus the construction still functions to enhance aquatic life. So, dams may still make sense from an ecological perspective even if the wave-damping effect is minor.

The highest relevant water levels define the top height of the dam related to damping effects. But to allow, for example, animals to enter or leave the water body at the pre-embankment construction, low water levels such as the mean low water level (MNW) should be considered too. As a general rule for sheet-pile walls, the top height should be not very much higher than MNW unless it is frequently lowered below this level at the top openings. If the pre-embankment construction uses sloped embankments, this criterion is not relevant.

Aesthetic aspects also play an important role. So, the top shall often be invisible as long as possible during the course of the year and thus should stay at least below MW.

For more information see the following chapters and Appendix A in Part 3, where, among other things, ΔW will be discussed related to pre-embankment solutions. However, no standard solution for all BCs exists. Instead, users should consider the following BCs:

- high water levels (the greater in relation to top height, the lower the wave-damping effect, the lower the aesthetic value, and the higher the construction costs);
- low water levels (the lower in relation to top height, the greater the wildlife-exchange restriction between waterway and shallow water zone);
- MW and top height; for example, because of aesthetic reasons;
- available construction space between the bank zone and fairway (the smaller the available space, the more efficient the construction's vertical elements must be);
- water depths before the planned construction (the deeper, the more costly); and
- amount of water exchange needed to induce flow velocities in the shallow water zone that restrict sedimentation or unwanted vegetation.

The magnitude of these BCs defines construction details such as the top height and the achievable ecological value of the measure, together with the available space for the shallow water zone.

3.1.1.1 Walls with Top Openings

Starting from a vertical wall with a fixed top level and without underwater openings, the top level can be lowered continuously or varied to a level just above or below MW (say 0.5 m). There will be an exchange between the waterway and the shallow water zone when the water level in the waterway reaches the top level of the vertical wall, either briefly because of ship-induced impacts or longer lasting because of current-induced impacts due to a higher discharge.

Figure 3.2: River Spree at Berlin-Charlottenburg, Germany
Top level about 0.3 m above MW; Sill level at openings about 0.8 m below MW

The vertical wall elements themselves will not have any ecological potential for vegetation and wildlife unless a secondary element with preferably natural materials is placed just behind the wall. Thus, and because of economic and aesthetic reasons, the creation of shallow water zones by sheet-pile walls with top openings will be recommended only in the case of narrow conditions; for example, if the fairway borders directly with the wall, as shown in Figure 3.2.

According to practical implementation experiences, ship-induced drawdown (Δh) will cause most of the water exchange. Drawdown creates surges, which propagate from the opening up- and downwards in the shallow water zone, and induces significant flow velocities, especially in shallow water (order of magnitude of about $\Delta h \cdot (g/h_m)^{1/2}$, g = acceleration due to gravity, h_m = average water depth in the shallow), see Fact File 3.2.3.1 and Case Study 4.2.1 in Part 2.

These flows can be efficiently used to control the sedimentation in the shallows. Erosion starts around 0.1 m/s for mud, 0.2 m/s for silt, 0.4 m/s for sands, and 1.0 m/s for gravel, so that, for example, a typical drawdown of about 0.15 m in impounded rivers or 0.3 m in canals may lead to equilibrium water depths in the shallows (those where erosion stops if the original depth was smaller or where sedimentation stops if it was larger), between 1.4 m for sands and 0.2 m for gravel in impounded rivers, and between 5 m for sands and 0.9 m for gravel in canals. This trend shows that mud or silt will probably be eroded from the surges, even in large depths, or that dumped material in the shallow (for example, coarse gravel) can efficiently be used to control erosion – or the size and especially the depth of the sill related to relevant water levels can be used too to control sedimentation or erosion in the shallows. If, for example, the sill height at the openings will be constructed by stop-log weirs or if gabions, standing on the sill, will be used to block parts of the openings, the morphodynamics and plant growth conditions can be adjusted where necessary; for example, after some years of allowing free development in the shallows.

Experiences from Fact File 3.2.3.1 show that the distance between openings should be around one-third to one-half the length of the dominant freight vessel and the opening width around the breadth of the shallow water, or at least 6-8 m from practical experience.

Additional measures in the shallows and towards the bank slope depend on the wave attack, especially of short waves such as ship-induced secondary waves, which will be damped about 50 %-60 % of the original wave height by the sharp-edged crest of the sheet-pile wall or the sill construction at the openings as well as the bulkheads of the stop-log construction or gabions. If excess pore water pressure is design-relevant and large drawdown must be considered, it may be necessary to protect the bank slope towards the hinterland with revetments, as the example on the River Spree in Berlin, Germany, in Figure 3.3 shows, because the bank soil is highly erodible in this waterway section and extremely sensitive to excess pore water pressure (muddy sands).

3.1.1.2 Walls With Underwater Openings

Instead of or in addition to top openings, a vertical wall can be built with preexisting underwater openings. A single wooden-pole wall, made from roughly finished poles, will have an underwater opening between every two poles, even if the poles are placed exactly against each other. Depending on the sedimentation behind the pole wall, the flow through the wall can decrease over time.

Another intentional way to effectuate an underwater opening is placing two vertical-wall elements at a certain distance; for example, by skipping one sheet pile in a sheet-pile wall, by placing two wooden poles in a pole wall with a certain spacing in between, or by filling a double-pole row with a permeable material such as willow fascines.

Figure 3.3: Canal Brussels-Scheldt, Belgium
Height of the underwater opening about 1.3 m from the underwater slope to MW

By contrast to the water exchange with top openings, which strongly depends on the water level and thus the water depths at the openings (which may help to simulate the natural situation with high morphodynamics at high water levels but will not for a milder regime with more frequent low stages), underwater openings lead to almost the same exchange flows at low or high stages if the drawdown of large vessels Δh drives the water exchange. By denoting the relation of the opening area to the cross-sectional area in the shallows as β (opening ratio) and assuming that the drawdown-induced outflow Q will divide in half to both sides of the opening (upstream and downstream), the induced flow velocity in the shallow water zone becomes approximately $v = \mu \cdot \beta \cdot (2 \cdot g \cdot \Delta h)^{1/2}$ (outflow coefficient $\mu \approx 0.6$), leading to necessary opening ratios β of about 0.3 and 0.4 for typical Δh of 0.3 m (canals) and 0.15 m (impounded rivers), if sandy sediments shall stay in equilibrium (erodible velocity ≈ 0.4 m/s), or 0.7 (canals) and 1 (impounded rivers) for gravel (erosion starts around 1 m/s; numbers for mud with $v = 0.1$ m/s are: $\beta = 0.07$ – canals – and 0.1 – impounded rivers). These large opening ratios, which would be necessary to control sedimentation, are completely unrealistic from practical reasons. Thus, underwater openings make sense only in the case of very large ship-induced impacts and a very mild flow regime in the shallow water zone is the aim.

Nevertheless, even very small openings (for example, 0.1 × 0.1 m) in short longitudinal distances (for example, 0.5-1 m) proved to efficiently control the water depth just behind the openings. At these openings, a water jet is formed while ship waves pass that erodes the sediments in that area. So, this series of openings can be used to keep a small stretch just behind the wall free from sedimentation or vegetation, which helps to maintain the shallow water zone by allowing small boats to enter.

These considerations show that sheet-pile walls with underwater openings are especially suited to areas with large ΔW for very large ship-induced impacts and if a very mild flow regime behind the wall is required, as the drawdown-driven water exchange is almost independent from water level.

3.1.1.3 Layout of the Shallow Water Zone

Characteristic design parameters of the shallow water zone include the following: exchange with the waterway, cross sections of the shallow water zone, longitudinal profile of the shallow water zone, and bed material.

The water exchange between the waterway and the shallow water zone is determined by the section (width, height, sill level) of the openings and the size of openings in one longitudinal section of the shallow water zone.

When there is only one opening in a longitudinal section, both inflow and outflow will pass through the same opening. With two or more openings a longitudinal flow can occur in the shallow water zone, which could help limit sedimentation.

There is a higher possibility for erosion in the vicinity of the openings. Both the main embankment behind the wall and the bottom of the shallow water zone can erode when there is a lot of exchange between the waterway and the shallow water zone. The main embankment can be affected by incoming waves that pass through the opening if not hindered or at least damped. The bottom of the shallow water zone can erode when the water level in the shallow water zone is drawn down when a ship is passing or when the induced longitudinal flow velocity is too high.

The cross section of the shallow water zone is determined by the average water depth, the width and slope towards the vertical wall, and the slope towards the bank. As the name suggests, a low water depth of 0.5-1.0 m is pursued in the shallow water zone, depending on the fauna and flora target species. A gradient in bed level can be pursued not only in the transverse direction but also in the longitudinal direction. The slope connecting the shallow water zone with the bank should not be too steep to prevent as much erosion as possible and to avoid a barrier effect between the shallow water zone and the embankment.

The bed material serves two purposes: it must be both erosion resistant and suitable for the flora and fauna target species. If the water exchange with the waterway is strong enough, a very fine and non-cohesive bed material will erode first and predominantly around the openings in the wall. Some kind of bottom protection can be advisable in this area. Also concerning flora and fauna target species, the naturally occurring or artificially posted bed sediment in the shallow water zone present in a quasi-equilibrium phase after initial erosion or sedimentation can be favourable or unfavourable.

The water exchange should reach a certain minimum to guarantee a good water quality in the shallow water zone. A water exchange that is too high is also disadvantageous, causing a higher turbidity and possibly the erosion of animals, plants, and bed sediment.

3.1.1.4 Additional Protections of the Embankment

If the system of pre-embankment, shallow water zone with its bathymetry and vegetation and the embankment with its vegetation is well conceived or well developed, the embankment will not need any additional protection.

The area of the bank slope just behind the openings in the wall is prone to wave or current attack and should be protected either by deflecting the incoming waves or by adding direct protections on the bank slope.

In the critical initial state when the vegetation in the shallow water zone and on the embankment has not yet grown sufficiently to provide erosion resistance, a provisional temporary protection may be necessary. This temporary protection can be achieved by heightening the top level of the wall by placing a secondary, easily removable structure behind the wall such as quarry stones, stone gabions, or a wooden retaining wall, or the primary vertical wall itself could also be installed at a higher initial top level and then lowered afterwards.

Also, the fixation and development of vegetation on the embankment and in the shallow water zone can be induced and favoured by placing biodegradable pre-seeded or pre-planted elements.

3.1.2 Measures Close to the Bank Using Parallel Dams

When space is available, a parallel dam with a certain base dimension that will always be bigger than the base of a vertical wall can provide interesting characteristics in comparison with vertical walls.

A first aspect is the ecological potential of the dam itself. Whereas the vertical wall, without any other modifications, is almost without any ecological potential, a parallel dam has more chances of being colonized by flora and providing a habitat for fauna on top as well as in between the stones.

When the dam is built entirely out of quarry stone without an impervious core or penetration, the incoming impacts are transmitted (but of course strongly damped) through the voids between the stones. A more continuous water exchange along the dam is obtained in comparison with discrete (underwater) openings.

As with the vertical walls a parallel dam can be adapted with top openings, underwater openings, or a combination of both. The material – parallel dams are composed of loose quarry stones in most cases – lends itself to a flexible initial construction or a later adjustment upward or downward.

Figure 3.4: Canal Brussels-Scheldt, Belgium
Quarry stone parallel dam with underwater openings

In combination with an underwater slope that connects the waterway bed with the foot of the shallow water zone, a parallel dam will almost always be financially more beneficial than a steel sheet-pile wall. In the absence of an underwater slope but under a significant water depth or bed difference between the shallow water zone and the waterway, a parallel dam consumes a lot of material.

Vertical walls made of other materials such as a wooden-pole wall or wooden poles combined with a retaining element can be an alternative for a parallel dam if the water depth and the bed difference between the shallow water zone and the waterway are not significant and if loads are not significant.

Concerning the layout of the shallow water zone and possible additional protection of the embankment, comparable points of attention are relevant in the case of a parallel dam as with a vertical wall.

3.1.3 Measures Far from the Embankment

A variety of river-management strategies can reduce shear stress on the bank environment with increasing distance from the bank itself. Many of these features are beyond the scope of this report (Chapter 1.1). However, these features merit mentioning to fully characterise the breadth of potential options for bank protection. Some particularly notable approaches include the following:

- River training structures – A variety of traditional river-engineering features can be used to reduce bank shear stress and thus provide bank protection. For instance, chevrons, Z-dykes, and round-point structures have been used to redirect flows in the Middle Mississippi River, Missouri and Illinois, United States [Bridges et al., 2021].
- Modification of river-engineering features – Historical structures can be modified or adapted to reduce environmental impacts and alter effects on bank erosion. For instance, dykes may be notched to facilitate fish movement and improve water quality while continuing to provide the original engineering purposes [Burgess-Gamble et al., 2021].
- Midchannel features – Islands have been shown to be a useful mechanism for blending ecological and engineering outcomes. For instance, midchannel islands in Mississippi River Pool #8 (Minnesota, United States, Bridges et al. (2021)) and strategic material placement features in Horseshoe Bend (Louisiana, United States, Bridges et al. (2018)) have provided significant ecological benefits and improvements in channel maintenance.
- Weir structures – V-notch and W-notch weirs have been proven to be extremely effective cross-channel structures in smaller systems for redirecting flow and reducing bank shear stress.
- Water and pool management – In addition to physical or geomorphic changes, hydrologic management provides another mechanism for bank protection. For instance, water-level management in a navigation pool or flow release from a flood-control reservoir could be manipulated to reduce erosion risks (for example, Upper Mississippi River, Missouri, United States, Bridges et al. (2021)).

3.2 Direct Measures (on the Bank Slope)

3.2.1 Measures Using Only Plants (Green Solutions)

Green solutions are measures that use vegetative materials such as seeds, young plantings, or regenerative plant parts exclusively to achieve long-term protection from erosion. The vegetation established on bare soils shields the bank's surface from raindrop impact, increases infiltration, slows runoff, and reduces ship-induced and natural near-bank flow velocities via an increased soil roughness. Of particular importance is that plants anchor the subsoil through root reinforcement. In addition, take-up of soil water by healthy bank vegetation reduces the frequency of saturated conditions and generates negative pore water pressures that increase bank stability when the bank is unsaturated. Non-living materials such as wood, stones, or geotextiles serve only as auxiliary building materials until plant growth can guarantee the necessary bank stability. In the initial state, measures with only plants are usually more sensitive than measures with both plants and technical components. Examples of plant-only direct measures include willow-brush mattresses (Chapter 3.2.1.1) and plant mats (Chapter 3.2.1.2); direct measures with plants are preferred when only protection against erosion is required and excess pore water pressure is not relevant.

To ensure the maximum chance of plant establishment and to best develop the described stability effects, the plantings must use site-appropriate species and plant communities. *Site appropriate* means that vegetation selected for planting as part of a green solution on the banks should match the climatic, soil, and hydrologic conditions of site and natural variability in water surface elevations to ensure that species chosen have sufficient flood and drought tolerance to survive the site's hydrological regime. Therefore, practitioners should introduce plants according to the natural vegetation zoning (for example, reeds (*Phragmites)* need to be submerged most of the time, whereas grasses (*Poaceae)*, for example, can withstand only infrequent, short-duration submergence and should therefore be placed only on upper parts of the banks). In all cases, native species of local provenance should be preferred. The composition of the riparian community in adjacent locations can be a good guide and is often used as a starting point for a preliminary planting plan.

Vegetation used for TBPs usually consists of a mix of trees, shrubs, and herbaceous plants native to the region and well adapted to the site conditions. Plants are chosen that have advantageous biomechanical properties for bank protection:

- adventitious shoot and root formation
- deep, well-anchored root system
- high regeneration and self-healing capacity
- pliability
- rapid growth in the adolescent phase (initial phase)
- good and multiplicative built on several strategies

Figure 3.5: Willow growth in the direction of flow (flexible shoots) (Photo: K. Behrendt, BfG)

Figure 3.6: Formation of new shoots from the stem (self-healing capacity) (Photo: K. Behrendt, BfG)

Plants that meet several of these properties are willows (see Figure 3.5 and Figure 3.6). They are often used as cuttings or setting bars (punctual bank protection), as living fascines (linear bank protection), or as brush mattresses (areal shore bank protection).

The choice of plant type and species composition depends not only on the requirements for bank protection itself but also on requirements for the target vegetation (ecological or economic objectives) and anticipated maintenance requirements. Planting a diverse array of different species and growth forms and also the effort to map the near-natural vegetation zoning is recommended for multiple reasons:

- It increases a riparian system's ability to provide and to sustain a number of functions.
- A relatively large number of species and growth forms provide an array of environmental tolerances. Fluctuations in hydrology, temperature, herbivory, and other environmental conditions will cause some plants or species to die; others may thrive (that is, a measure dominated by only one or two species may fail with the death of only one species).
- It increases structural diversity and, thus, habitat availability for wildlife (therefore, the ecological value increases).
- The ecological value of such a design can come close to that of a natural bank.

When choosing plants, the availability of the living material also plays a major role. Plant material can be grown under contract, acquired through a commercial nursery, or collected from natural populations. If collecting from local populations, verify no local, state, provincial, federal or national laws prohibit the acquisition of certain plants or the extraction of plant material outside defined time windows. For example, pruning of woody plants (for example, for willow-brush extraction) may only take place in Germany in the period from 1 October to 28 February (outside the breeding season). Furthermore, no plant material may be obtained in protected areas (for example, nature reserve). The material should be dormant and free of splits, rot, diseases and insect infestation.

When obtaining plant material from a commercial nursery, a sufficient lead time of at least one year (one vegetation period) must be considered.

The handling of the plants between nursery or collection site and the project site must be done with great care and planning. Suitable places for storage (minimal exposure to sun and wind, sufficient moisture) will be needed if it is not possible to install the plants immediately.

During installation, planting and seeding operations should be conducted at the optimal time. The optimal window of opportunity in the northern hemisphere for most planting extends throughout the dormant winter season (October-March). In the period immediately following installation, ensure adequate watering and monitoring for plant health.

Measures using only plants require a high level of expert knowledge (BCs at site, erosion-control requirements, prior experience of plantings, plant and site knowledge based on site analysis and on evaluation of plant communities in the nearby region); a proper planning (main project objectives; for example, technical and ecological functionality, target vegetation, maintenance requirements); care in material acquisition, handling, and installation to ensure success. However, successful green solutions can provide an effective bank protection and offers a wide range of additional benefits. Their main strengths include the following:

- increasing structural and habitat diversity (step-stone habitats)
- improving wildlife (biodiversity)
- improving the starting conditions for natural succession
- integrating better into the natural landscape than grey solutions

- using predominantly or exclusively sustainable materials
- helping to establish or restore natural processes
- providing a range of ecosystem services (for example, retention of carbon dioxide, improvement of water, air, and soil quality)

In the portfolio of TBP measures, measures using only plants are the softest and most sustainable solutions, and their ecological value comes closest to that of near-natural bank zones.

3.2.1.1 Willow-Brush Mattresses

Willow-brush mattresses combine layers of live but dormant willow cuttings with soil to revegetate and ensure bank stability against surface erosion induced by currents and waves, slope sliding, and, according to practical implementation experiences, partly also hydrodynamic soil displacement due to excess pore water pressure induced by rapid drawdown generated by passing ships.

The part of the branches belowground takes root and consolidates the soil. The finely branched root network in the upper soil layer also acts as a filter. The exposed part develops into either a tree or a bushy riparian plant (Figure 3.9), depending on the willow type selected (shrub willows with heights from 50 cm to about 3 m; tree willows with heights up to 30 m) and the manner in which bank vegetation is managed and maintained (also depending on defined target vegetation). The elastic aboveground parts of the willows increase bank roughness and, therefore, dissipate flow energy (Figure 3.8 and Figure 3.9).

This technique can be applied to slopes with a slope ratio (height versus distance) of 1:3 (1:2) or flatter. The range of use for willows should be between MW and high water (HW). The range above HW to above the highest observed water level (HHW) is suitable for the use of other types of wood (hardwood floodplain species). The stability of the banks below MW should be ensured by technical measures (for example, rip rap as toe protection).

The layer of willow branches is installed on the roughly levelled embankment subgrade. The branches cover the entire area of the slope densely perpendicular to the direction of flow, with the thick (basal) ends downwards. Rods are 200-300 cm long, annual and biennial, with barely branched shoots (mixture of thin and thick branches; thick branches with stronger sprouting capacity, thin branches for more ground-fitting position). The willow-brush layers are firmly fixed by stakes and living willow crossbars parallel to the bank line to achieve firm ground contact (essential for root growth; Figure 3.9). Immediately after installation, the willow-brush mattresses should be covered with 5-10 cm of fine-grained soil.

Figure 3.7: Installation of willow-brush mattresses on the River Rhine (end of November 2012) (Photo: P. Fleischer, BAW)

Figure 3.8: Willow sprouting in the first vegetation period (end of May 2012) (Photo: K. Behrendt, BfG)

Figure 3.9: Dense willow five years later (4 August 2016) (Photo: K. Behrendt, BfG)

To be best suited to the site conditions, willow species used for brush mattresses should be locally adapted (species of local origin). The plants must be able to tolerate periods of total inundation or dry periods during low water or strong flow velocities, depending on the type of waterway and hydrodynamics (including ship-induced impact). For these reasons, obtaining willow branches on-site (best in the immediate vicinity of the project site) is preferable to purchasing them from a nursery. The main time for harvesting willow is the winter half of the year, because then the branches remain usable until the end of March or beginning of April in the northern hemisphere if they are stored in a suitably cool, shady, and moderately moist place. Furthermore, this is the harvest window specified by nature-conservation legislation. The installation should also take place during vegetation dormancy.

The investment costs for this measure are slightly higher than for conventional rip rap. The maintenance is to be adapted to the technical and ecological aims and in accordance with the defined target vegetation (riparian forest or willow shrub). To maintain the bank-protection function, the willows should remain flexible. Furthermore, the flood discharge must be guaranteed at all times. A pruning at intervals of three to six years may be necessary. From the ecological point of view, pruning should be done carefully, and a diverse, multilayered willow forest should be maintained.

From an ecological perspective, a well-functioning and well-grown willow-brush mattress (with maintenance focused not only on technical but also on ecological objectives) can help to develop a typical riparian vegetation. Compared with a conventional bank-protection measure (for example, rip rap) the plants (shrubs and trees) can enhance the structural diversity and contribute to the improvement of habitat quality of the riparian zone and floodplain. Additional ecological benefits can be, for example, binding of carbon dioxide and retention of phosphorous and nitrate through plant and root development; see also Chapter 3.2.1.

3.2.1.2 Pre-Cultivated Plant Mats

Plant mats consist of a mostly nonbiodegradable carrier material (polypropylene net) and rooted herbaceous plants, pre-cultivated over at least one vegetation period (Figure 3.10). Depending on the soil properties on-site, a geotextile filter layer under the plant mats may be necessary. The plant mats are laid on the soil subgrade and fixed with stakes and crossbars. In the long term the dense root horizon penetrating to different depths (on average 30-70 cm deep) serves as protection against surface erosion.

Figure 3.10: Well-rooted plant mat in nursery growing basin (Photo: K. Behrendt, BfG)

Figure 3.11: Exposed roots of a planting mat with grasses and herbs, installed as bank protection on the River Rhine.
The stock-like structure of the root system is clearly visible (development time 2012-2017)
(Photo: K. Heinzner, WSA Weser)

The use of plants suitable for the specific site, as well as attention to the expected technical requirements and stresses, are decisive factors for the success of such measures. Plants frequently used in the shallow bank area around MW are various reed and sedge species. In particular, reeds (*Phragmites australis*, note: don't use this species in places where it is considered an invasive pest) have proven to be suitable bank protection along streams with relatively constant water levels and minimum wave action.

Grasses and herbs can be used in the upper part of the slope, where the BCs are less dominant. As already described in Chapter 3.2.1, planting a diverse array of different species and growth forms can establish a very dense root system up to large depths (Figure 3.11), which contributes to a functioning bank protection, especially in this measure.

Experience gathered on waterways with high ship-induced impacts as well as high water-level fluctuations has shown that plant mats are very sensitive in many ways. Especially in the zone with the highest, impact the following has been observed:

- Plant mats have only a small dead weight and are therefore susceptible to sunk and surge movements when ships pass by. Rooting of the plants is hardly possible.
- There are only a few plants that can withstand this load and at the same time have engineering properties.
- When the plants fail, bank protection is no longer guaranteed.

The measure is recommended for standing or slow-flowing waters without high ship-induced impacts. In the case of high ship-induced loads, a combination with measures in front of the bank such as stick bundles or fascines is conceivable. Under the conditions described, pre-cultivated plant mats can be applied to slopes with a slope ratio of 1:3 and flatter. The flatter the bank, the more effective the measure.

If the plants successfully establish, the measure can hold great ecological potential:

- promotion of near-natural riparian zoning
- enhancement of natural succession through initial planting

- increase in structural and habitat diversity (step-stone habitats)
- increase in wildlife (especially for flower-visiting insects, spiders, and birds; for example, reed breeders, ground-nesting birds)
- provision of ecosystem-services (see also Chapter 3.2.1.1)

The investment costs for this type of measure are higher than for conventional rip rap. The maintenance effort depends on the defined target vegetation. Regular controlled mowing is necessary to maintain biodiversity and to regulate emerging competing vegetation or woody plants. Reeds should be exempted from the maintenance from a nature-conservation point of view.

3.2.1.3 Reed, Vetiver, and Bermuda Grass

This bank-protection method uses plant roots only to reinforce the bank slope and increase its stability. The ability of plant roots to absorb pollutants and nutrients can reduce the pollutants entering the water through the bank slope. Furthermore, plant slope-protection measures can also provide effective survival zones and shelter for fish, amphibians, mammals, and birds and improve the material-exchange efficiency of the bank slope and water body.

According to the practical implementation experiences of plant bank construction for inland waterways in China, the physical properties of the bank slope and the prevailing hydrodynamic conditions should be considered first. If the stability of the slope is guaranteed, the plants can be selected according to the following properties: the plant's growth capacity, root development, submergence resistance, growth and recovery rate and the projected area of application on the slope. For example, the emergent type (such as reed) can effectively block and reduce the direct impact of ship-induced waves on the soil (Figure 3.12). For plants with developed roots (such as vetiver grass), the friction between plant roots and soil is used to increase the shear capacity of the soil (Figure 3.13). Considering the short-term and long-term variation of water level in the river, the selection of water-tolerant plants (such as Bermuda grass) can reduce the amount of replanting in the zone between low water and HW and effectively reduce the maintenance cost of the measures.

Figure 3.12: Bank protection with reeds along the Huai'an-Huaiyin section of Beijing–Hangzhou Canal, China

Figure 3.13: Vetiver grass planted on the bank slope in the Xiaojiang River, China

It is suggested that when the flow velocity close to the bank is less than 3 m/s, appropriate plants can be selected according to the slope stability in a mature state The construction of a plant bank slope requires the following:

(1) Priority should be given to native plants, but when the native plants do not meet the requirements, introduced species with no negative impact on the native plants can be selected.
(2) Plantings should be as dense as possible to reduce the bare bank slope area.
(3) The plants for bank protection should be planted following the local conditions. For instance, emergent plants such as reed and calamus should be planted in the strong hydrodynamic areas to reduce the impact loads on bank. In the area between the flood- and dry-water levels, the vegetation with strong submergence resistance should be selected. Above MW, the plants with developed roots should be considered to increase the stability of the bank slope.
(4) During the vegetation planting and growth period, it is suggested that using ecological bags (bags made from degradable materials) will accelerate the growth rate.

3.2.2 Measures Using Both Plants and Technical Elements (Green-Grey Solutions)

In addition to the measures using only plants, there are also measures with plants and technical elements. They consist of a combination of plants (bioengineering methods) and permanent technical construction components, where the technical elements serve two purposes: improving the initial growth of the plants and permanently securing the bank's stability; for example, by their weight per unit area. As measures with plants and technical elements are more robust than measures with plants alone, these measures can also be applied in cases of higher hydraulic loads and steeper slopes. In terms of bank protection and ecological effectiveness, they are located between the green bank-protection measures (plants only – Chapter 3.2.1) and the grey technical bank-protection measures (non-living components only – Chapter 3.2.3).

For a successful application of measures with plants and technical elements, the right choice of plants, plant cultivation and installation, care, and maintenance are just as important as for measures with plants alone. See Chapter 3.2.1.

Examples include vegetated rip rap (Chapter 3.2.2.1) and vegetation gabions (Chapter 3.2.2.2). More information on prefabricated structures with further examples can be found in Chapter 3.2.2.3.

3.2.2.1 Vegetated Rip Rap

A rip rap revetment (see Chapter 3.2.3) can be ecologically upgraded with plants. Vegetation can be added during installation and afterwards (Figure 3.14). An integration (according to the natural zoning) of indigenous and site-adapted woody plants (trees and/or shrubs – according to plant species and maintenance objectives) into rip rap can serve as a stepping stone for further species (plants and animals). Native and habitat-adapted species of softwood riparian forests such as willows can be inserted in the rip rap as cuttings, log-branch cuttings, living fascines, or brush layers. Hedge layers from different types of hardwood riparian forest species can be installed in the hardwood riparian zone. The required bank protection is ensured through rip rap.

Vegetated rip rap can be applied in the case of higher hydraulic loads or if excess pore water pressure is relevant. With regard to vegetation and fauna, the ecological advantages of vegetated rip rap have been proven compared with rip rap without vegetation (report BAW/ BfG 2020).

Figure 3.14: Vegetated rip rap after installing cuttings and log-branch cuttings (left), while installing hedge layers (middle), some months after installation (right; Rhine km 440.7)

3.2.2.2 Vegetation Gabions

Vegetated gabions are wire baskets lined with geotextile, filled with small armour stones and lava rock granules or soil. The baskets are made of corrosion-resistant, galvanised, and drilled steel wire – alternatively plastic nets – with a pre-grown plant mat (Figure 3.15). The vegetation should be native and habitat adapted; for example: reeds, tall forbs, grass, and herbs. The installation zones depend on the tolerance range of the respective plants according to site properties. The filter stability to the subsoil must be guaranteed, where necessary by an additional filter.

The weight per unit area of the vegetated gabions depends on the density of the armour stones and the thickness of the gabions. It ensures the bank's stability if excess pore water pressures in the soil are relevant.

Unlike purely plant-based measures (Chapter 3.2.1), these plant mats are incorporated into the wire baskets and need no additional fixing. The right choice of plants, adapted to the respective location, is very important. The application on free-flowing rivers is particularly problematic, as it can lead to long periods of flooding and drought, which severely restricts the suitable plant species. A long-term bank protection can only be ensured if the installed plant's properties correspond to the BCs (for example, flooding tolerance under simultaneous hydraulic loads, regenerative capacity). For more information on the use of plants, see Chapter 3.2.1. When installed correctly, they offer ecological advantages over merely technical rip rap revetments (report BAW / BfG 2020).

Figure 3.15: Reed gabions (before, during, and after installation)

3.2.2.3 Prefabricated Structures

Prefabricated structures are grey measures applied to keep the bank stable. They are favourable in the area with the action of waves caused by ships. The main advantages of prefabricated structures on the bank slope are that it speeds up the construction, reduces the use of concrete, and has little impact on the river during the construction period. Prefabricated structures have different forms. For example, grass planting ecological frame (Figure 3.16), ecological gabion (Figure 3.17, and 'Fish nest' brick (Figure 3.18).

The grass planting ecological frame utilises cement to make frames for planting plants, is applied to provide a habitat for some birds and mammals, and also provides a waterfront hydrophilic place for humans. This method still retains the way for energy and material exchange between the bank slope and the water body through prefabricated blocks, but it is not completely friendly to aquatic animals.


Figure 3.16: Prefabricated structures during site construction (left) and after completion (right) along the Danjin Licao River, Jiangsu, China, channel-regulation project

An ecological gabion retaining wall is a kind of bank protection formed by the use of ecological wire cages as the main material. The crushed stones, plant seeds, and other materials were put into the cage. It has strong anti-erosion ability and high stability, which makes it more suitable for the inland waterway with large flow velocity and steep slopes. In addition, gabions provide enough living space for aquatic organisms and have a good ecological effect, which has been applied in the downstream dyke section of the Three Gorges Dam. However, due to the single material, the final landscape form is dull.


Figure 3.17: A single ecological gabion (left) and the ecological gabion retaining wall (right) in the downstream dyke section of the Three Gorges Dam

'Fish nest' bricks are mainly set on the water-facing side of an inland waterway, which acts as a retaining wall, and the ecology is mainly reflected in its own ecological effect. The brick is designed in the concept of 'concave' and has air permeability. Generally, when the 'fish nest' brick below is at normal water level, the 'concave' brick body is more conducive to the application of river ecological revetment technology. Furthermore, the 'fish nest' brick itself has very obvious permeability with many air holes, and a large number of holes will be reserved in the design to use for ventilation. A large number of vegetation can be planted in holes in the brick structure, such as canna and marigold, which has good air permeability and can improve water quality. Thus, the diversity of the whole ecosystem can be increased and protected.

Figure 3.18: The fish-nest brick revetment (left) and with vegetation (right) along the Yangtze River

3.2.2.4 Composite Ecological Revetment Using Boxes and Flappers Prefabricated Structures

Composite ecological revetment using prefabricated structures in form of boxes and flappers are generally designed to replace the traditional rigid revetments, as shown in Figure 3.19. The primary rigid revetment is composed of precast previous reinforced concrete boxes and flappers. Two adjacent boxes are connected by a flapper, which is fixed between the slots in the middle of the outer sidewalls of the boxes, as shown in Figure 2.20. This proposed structure can reduce the environmental stress imposed by rigid revetments and find a balance between the protective and ecological functions of ecological revetments.

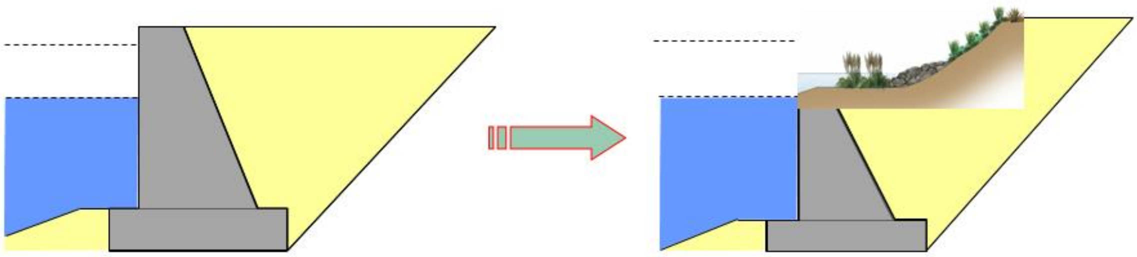
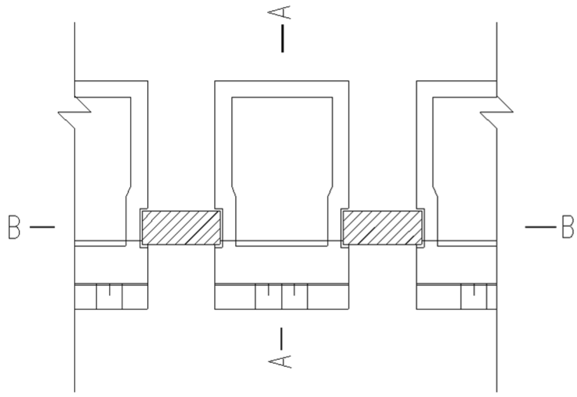
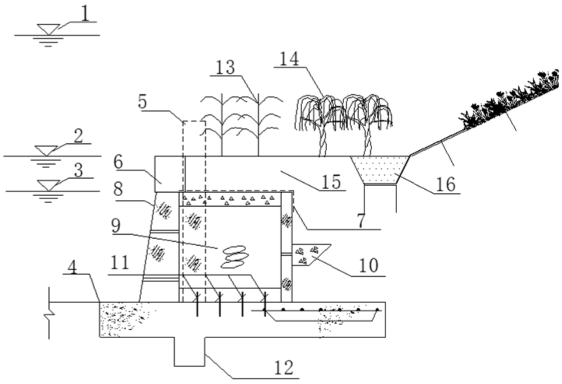


Figure 3.19: Recent evolution of revetment structure for restricted waterways in the Yangtze River Delta

Figure 2.20. hows the detail of the proposed structure. The primary rigid revetment uses precast pervious reinforced concrete boxes and can provide the revetment structure with stability, durability, and anti-scouring performance. These boxes have holes in their walls to allow water to penetrate and are loosely filled with stone or waste concrete blocks, making it possible to recreate a wetland environment. The grid-like structure formed by the water-facing facades can promote siltation to some extent, which will help creating a diverse flow of banks and restore aquatic ecosystems in part. By using precast structural members, factory production, mechanised construction, a higher construction quality and efficiency can be largely achieved.



(a) Plan view of the structure



(b) Cross-sectional view of the structure (A-A)

1 – Highest navigable water level; 2 – Mean water level; 3 – Lowest navigable water level; 4 – Revetment baseplate; 5 – Precast reinforced concrete flapper; 6 – Cast-in-place concrete coping; 7 – Geotextile; 8 – Precast pervious reinforced concrete box; 9 – Backfill stone blocks in box; 10 – Gravel drain; 11 – Anchoring steel bars; 12 – Anti-slip tenon on baseplate; 13 – Reeds; 14 – Protective plants; 15– Backfill soil; 16 – Anchorage trench.

(c) Picture of construction site

Figure 3.20: Composite revetment structure using boxes and flappers

The top elevation of the primary revetment platform is set close to the mean water level, thereby reducing the construction costs and the stress on the local environment and landscapes. The key factor considered in designing the height, width, and positions of flappers is the wave dissipation performance of the permeable slab wave-dissipating structure formed above flappers and the grid-like anti-wall structure formed by facades, which can be measured by testing (see Figure 3.21).

500 t ship in the test section (high water level)

500 t ship in the non-test section (high water level)

Figure 3.21: Instantaneous status of water surface as test ship passes under different conditions

3.2.3 Measures with Technical Elements Only (Grey Solutions)

This section reviews some features of a standardised technical protection, a rip rap revetment, because TBPs will be compared predominantly with rip rap concerning stability, durability, maintainability, and especially cost. TBP measures consist solely of inanimate building materials; for example, natural stones, steel, or concrete. On waterways with navigation, rip rap revetments are generally used for sloped banks (Figure 2.22). Vertical banks are mostly protected by sheet-pile walls, rarely also with retaining walls.

Rip rap revetments protect the entire bank and, if necessary, also the bottom of the waterway. The primary goal is a stable bank. Rip rap revetments consist of an erosion-proof cover layer made of loose armour stones and a filter (grain filter or geotextile filter) between the cover layer and the ground (Figure 3.23). The filter function to retain soil under possible hydraulic loads (mechanical filter effectiveness: erosion protection). At the same time, it must allow the flow of groundwater without increasing the seepage line in the bank slope (hydraulic filter effectiveness).

The armour stones have to be erosion resistant. Therefore, the size or weight of the stones depends primarily on the hydraulic loads and the bank slope. These factors, in addition to soil type and possible excess pore water pressure, also determine the required weight per unit area and, thus, the thickness of the cover layer. The calculation of ship-induced loads on the bank and the dimensioning of revetments is described in detail, for example, in GBB (2010).

If only the bank slope has to be protected and not the bottom, an additional toe protection is usually required. It can be designed, for example, as an embedded toe or a toe blanket on the bottom (Figure 3.24).

Figure 3.22: Rip rap revetment on the sloped bank in the foreground and sheet-pile wall on the opposite vertical bank (Havel-Oder-Waterway km 66)

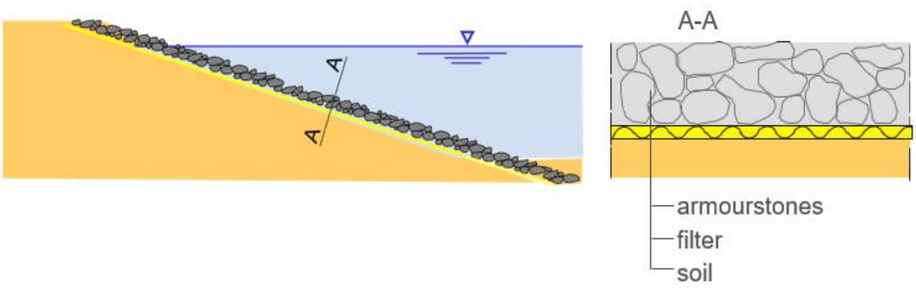


Figure 3.23: Rip rap revetment structure

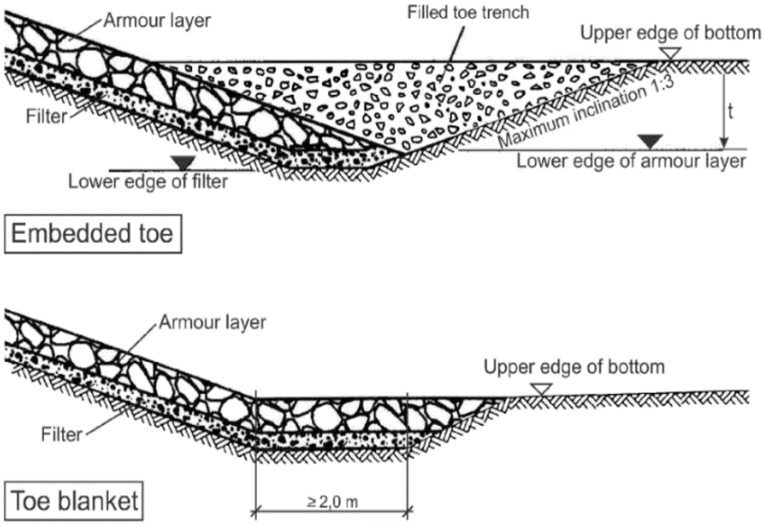


Figure 3.24: Design of a toe protection [MAR, 2008]

3.3 Ecological Enhancement

As explained in Chapter 1.2.3, this report focuses on measures close to the bank. These measures are generally initiated by local erosion problems (local view); for example, because of ship impact. If there would be no such bank instabilities, management strategies are generally the measure of choice, unless ecological upgrade is the aim of the measure. Such ecological-upgrade measures will be considered in this section.

The contribution of local measures to the upgrade of river ecology is of course restricted, knowing that the ecological benefits from river-engineering works (large-scale measures), such as the opening of oxbows or the creation of artificial islands, are generally very much greater. This report assumes that such comprehensive measures were already carried out before looking at local sites.

Nevertheless, local measures can also make a significant contribution to the renaturation of inland waterways – even very low-cost measures. Generally, these measures seek primarily to upgrade the river ecology, whereas stabilising effects are either already solved or not relevant.

Especially in cases where a technical bank protection is required, the possibility of measures for ecological enhancement or the reduction of impacts such as those from ship-induced waves (see Chapters 3.1 and 3.5) should be explored and applied wherever possible. Examples for ecological enhancement of technical bank protection include initial plantings in rip rap in the form of inserted cuttings, live stakes, or live fascines (see Chapter 3.2.2.1). In the process, the individual elements can reduce flow pressure and create additional structures. For example, developing woody plants comb out driftwood (Figure 3.26, *right*), leaves, and sediment at higher water levels. The sediments and organic accumulations create seedbeds, food, and habitat mosaics for plants and animals. The introduction of deadwood structures (for example, deadwood fascines, Figure 3.26 and Figure 3.27), trees or root plates (Figure 3.26, *left*) in the riparian area can locally increase the diversity of flow, substrate and structure (DWA-M 519). The increase in flow and structural diversity resulting from deadwood leads to the creation of fish-relevant partial habitats such as spawning areas, juvenile fish habitats, feeding areas, resting zones, and flood shelter. Deadwood in particular is an important hard substrate, and some invertebrate species are mandatorily dependent on deadwood, which is often deficient in and along waterways and canals because of traffic safety concerns. Also, deadwood serves as nesting places and perches for birds. Wherever there is the possibility of a stable and permanent anchorage of deadwood structures, they should be placed in both aquatic and terrestrial environments.

Furthermore, an ecological upgrading of an existing bank protection can be achieved by introducing a substrate mixture with different river-type-specific grain sizes. This input contributes in particular to the revitalisation of suitable fish habitats, increases the variability of gap systems, and promotes re-sedimentation and deposition processes.


Figure 3.25: Installation of fish-effective deadwood fascines on the River Rhine, near Worms (left, in October 2011; right, in September 2012) (Photo: K. Behrendt, BfG)


Figure 3.26: Left, creation of a stone wall in front of the bank as protection against ship-induced loading, calmed water zone with root plates behind and vegetated rip rap as TBP (River Rhine, near Worms in July 2012) (Photo: K. Behrendt, BfG); Right, establishment of a willow ridge in a rip rap bank with accumulation of driftwood (River Rhine, near Daxlanden, Germany, in August 2020) (Photo: K. Behrendt, BfG)

Figure 3.27: *Fish shelter made of deadwood on the River Rhine near Daxlanden in October 2019 (Photo: S. Wieland, BfG)*

To improve the structure of the watercourse and create habitats typical of the watercourse, TBPs with a predominant proportion of living plants can also be combined with the installation of deadwood, flow-steering structures, flow-buffering structures, or other methods of near-natural hydraulic engineering. For example, pilings made of brushwood, wooden palisades, or stones can be built as breakwaters in front of the bank (Figure 3.26, *left*). These breakwaters minimise the hydraulic loads on the bank, and its protection may be dimensioned less strongly or be dispensed with entirely under certain circumstances. Furthermore, the breakwaters create wave-protected water zones that promote the establishment of aquatic plants and reeds and can serve as calm-water zones for juvenile fish and other aquatic life (see also Chapter 3.1).

Increasing structural diversity positively influences both species diversity and individual density of individual species. The more diverse the structures of a watercourse and its banks, the higher the species diversity.

Creating step-stone biotopes via introduced structures and initial plantings can increase habitat accessibility and, thus, serve as interconnection in the transition between the aquatic and the terrestrial zones.

In general, the following should always apply: where the watercourse has sufficient area for undisturbed self-dynamic development and no bank-protection measures or structural-improvement measures are required, measures should be deliberately dispensed with in favour of self-dynamic development (see Chapter 3.4). As a result, the morphodynamic processes create a near-natural watercourse (DWA-M 620-2).

3.4 Natural Banks

The removal of revetments offers the opportunity to reactivate natural processes of erosion and increase the morphological diversity of a trained river. In general terms, the exposure of a riverbank to currents and waves leads to the development of a milder slope, typically with shallower water depths and lower flow velocities. Aquatic and terrestrial fauna benefit from greater habitat diversity. Terrestrial vegetation can grow and develop at normally emerged (dry) areas of the bank, depending on soil and climate conditions. In the long term, natural succession has increasing opportunities to occur, which may be enhanced by uprooting by flow and scour.

The availability of space to allow banks to evolve is a key requirement if protections are removed. The morphology and width of natural riverbanks in waterways primarily depend on whether a river is regulated, the ship traffic, and bank-soil characteristics.

Regulated rivers with cohesive banks typically respond to revetment removal by creating a mild-sloping terrace near the minimum water level. The slope and length of this terrace is related to the erodibility of the bank material and the height of the largest ship waves produced in the waterway. Generally, silty banks develop a 1:20 slope, very clayey banks 1:10, and sandy banks 1:30. For each case, the temporal bank retreat depends on the ship traffic and sailing conditions. Similarly, the long-term development of each bank and its maximum extent depends mainly on the height of the largest primary ship waves. For example, with high traffic and primary waves of approximately 0.5 m height, sandy banks are expected to retreat roughly 50 m, while highly cohesive banks retreat less than 20 m.

Figure 3.28: The regulated Meuse River near Gennep, the Netherlands, where cohesive banks present a shallow submerged terrace and vegetation naturally growing after a few years

Figure 3.29: Brussels-Scheldt Canal, Belgium, quarry-stone parallel dam with underwater openings

The unregulated IJssel River in the Netherlands, with unprotected composite banks between transverse groynes near Olst, presents a variety of shapes and soil types after a few years.

In the long term, banks in unregulated rivers trained with transverse groynes present a mild-sloping terrace or beach in between them. The toe of the beach lies within the groynes and has an elevation related to the MW. Typical for this area are shallow waters and lower flow velocities.

Figure 3.30: The unregulated IJssel River in the Netherlands, with unprotected composite banks between transverse groynes near Zwolle, in the long term

The sediment yield resulting from bank erosion may hinder the waterway navigability through increased deposition on the riverbed. An approach to reduce this expected consequence is to excavate the bank after removing the protection. The above cases may be taken as reference for excavating the bank in an extent and shape that resembles the expected morphology in each case. In this way, maintenance efforts can be reduced.

3.5 Flanking Measures

As mentioned already in Chapter 1.1, the focus of this report is on constructional bank protections (engineering methods), not on strategies to avoid such measures, by, for example, mitigation or reduction of impacts or the application of management methods up to the acceptance of natural succession (non-engineering methods).

This focus is because planning of such non-engineering measures would demand an analysis of the bank's development from natural bed-forming processes and ship-induced impacts, including the influence of vegetation, to mention just three aspects. The necessary modelling of these effects is still a scientific challenge and far from a standard tool in engineering bureaus, so that here only limited guidance will be provided for considering such strategies from the perspective of practitioners, without being forced to perform detailed scientific studies or long-term field investigations.

This guidance will be provided in Part 3 in Chapter 6.1, while discussing special planner's demands. Comfortable BCs, which may allow such strategies, will be discussed in Chapter 6.2 in Part 3; in Appendix C of Part 3 as part of the preselection tools, here from the UK guide; in

Chapter 6.3.3.7 of Part 3 in the context of discussing combined measures; and in Chapter 6.3.5 of Part 3, considering knockout criteria. This guidance will be provided in brief in the following section, with several references to Part 3.

3.5.1 Influence of River Engineering on Bank Stability

River engineering as flow impoundment or training with parallel dykes and groynes (spur dykes) in free-flowing rivers is implemented mostly for sustaining, stabilizing, or improving the fairway conditions, especially to increase the fairway depths, using the natural bed-forming processes of the river as far as possible to avoid fairway dredging. To some extent, flow impoundment and training measures may also be induced by bank instabilities, mostly to avoid ongoing erosion.

Because large-scale bed-forming processes such as the erosion below a barrage or as a result of strong river-training measures, are normally the main cause of related bank instabilities in large rivers, river engineering works generally focus on coping with these large-scale sediment-transport processes. Therefore, it is assumed in the following that usual river engineering works were taken almost regardless of measures discussed here to solve predominantly small-scale erosion problems in bank areas. Hence, the river engineering works will be considered here not in the sense of recommendations for their design but only concerning their effects on bank stability and thus, on necessary additional bank protection measures.

Because of this narrowed focus, the following section first reviews the 'toolbox' of river-engineering works, which are discussed according to their influence on bank stability.

Impoundment:

Generally, the flow velocities, the bed-forming processes, and the water level difference ΔW between MW and HSW are strongly reduced by impoundment compared with a free-flowing river. Analysing bank stability, this reduction means that the erosion forces from the flow field (without navigation) are lower and that wave breakers, built to reduce ship-induced impacts such as pre-embankment dams are working better than in free-flowing rivers. This is, because they work optimally only up to a certain flooding depth (generally: transmission coefficient around 0.5 up to a flooding depth of 0.5 m).

Also, the fairway–bank distance is often greater compared with non-impounded channels, especially just upstream of a barrage, so that ship-induced wave impact is lower. This difference is accounted for in the preselection tools by considering Table I.1 in Appendix B, where correlations between ship–bank distances *u* and typical wave heights from large freight vessels will be provided. If *u* is, for example, greater than the largest vessel's length (L_{max}), the wave height may be lower than about 0.1 m, which generally allows foregoing any bank protections to counteract ship impact; see Appendix C in Part 3. For shorter distances, the largest vessel's breadth (B_{max}) is also relevant, leading, for example, to the rule $5 \times B_{max} \leq u \leq L_{max}$, assigned with wave heights around 0.2 m, which corresponds to an (wave height) equivalent flow velocity of about 1.5 m/s (according to Appendix C.2) and allows generally the application of almost all bioengineering measures. For more details see Appendixes B and C in Part 3.

However, larger waterway widths and lower flow velocities and thus, lower river turbulence supports the occurrence of large wind-generated waves as in the impounded River Rhône, which may then be the most important impact. Also, the often larger and more reliable fairway conditions (especially larger fairway depths) in an impounded river allow larger or at least deeper draught vessels, which may then generate larger waves. This effect can, for example, be accounted for by using the correlations in Table I.1 between typical wave heights and the CEMT Class or the coverage ratio at MW (channel cross section divided by wetted midships cross section).

Thus, bank protections may often be unavoidable, especially in the river reach just upstream of the barrage, where the impounded water level is usually higher than the surrounding land, so that levees are necessary whose slopes require strong protections against any erosive processes, generally using conventional revetments. In these river sections, which may reach over more than half of the entire pool length, often only measures to enhance ecology may be possible; for example, by implementing a reed belt ahead of the levee or by including pre-embankment measures to support shallow water zones. Nevertheless, practitioners should always check, for example, in the case of very large fairway–bank distances in sections without levees, whether it is possible to forego any protections, even to allow natural succession or to use very weak protections such as grass, reed, or sedges. The question is always, if the risk and consequences of bank failure can be accepted. For more information and a discussion of knockout criteria, see Chapter 6.3.5 of Part 3. For consideration of non-engineering measures, see inter alia Appendix C.1.3.1 in Part 3 or Chapter 3.5.3.

Another problem that should be mentioned here while discussing the effects of impoundment, which are generally not that severe in free-flowing rivers, arises from unwanted sedimentation of fine sediments in the bank area, which may suffocate vegetation. Because impounded rivers tend to collect fine sediments, which are resuspended during floods, the settling sediments can then blanket vegetation, causing die-off. For example, reed plantings vanished after some years in the Rhône River because of silting.

Another special problem that occurs often in impounded rivers is excess pore water pressure with corresponding destabilizing effects such as hydrodynamic soil displacement up to fluidisation and shallow slides. Shallow slides and fluidization occur especially in muddy bed sediments and were considered concerning technical and ecological issues, for example, in the PIANC WG 27 report (2008), fine-grained poorly permeable sediments without cohesion (for example, silts and silty sands) but very impermeable sediments with low cohesion (for example, muddy sands) may also be relevant in the bank area and even as construction material for levees. Thus, excess pore water pressure can represent the most important impact for designing appropriate bank protections and demand for revetments with a surface load, as is the case when using standard rip rap revetments to counteract the pressure.

The sensitivity to excess pore water pressure predominantly depends on the soil type and the ship-induced rapid drawdown, which depends strongly on the ship–bank distance. A 'rule of thumb' to assess in which cases at least fluidization of the top soil layer of the bank sediments may occur was derived. It uses formulas given in GBB (2010), whereby the possible fluidisation near the soil surface was considered. This is, because excess porewater-induced surface erosion will be caused mostly due to strong hydraulic gradients as a result of excess pore water pressure near the soil surface (because the excess pore water pressure gives rise to seepage flow towards the ground surface. Here the effective tensions can be reduced to such an extent that the frictional forces become zero and soil fluidisation near the surface occurs. These processes promote surface erosion – 'hydrodynamic soil displacement').

This approach led to an approximative relation between the soil permeability and parameters; the drawdown velocity (assuming that the largest velocity occurs at the bow), depending especially on the bank distance *u*; the vessel speed; and the bow drawdown, using the geometric mean of permeabilities for standard soil types given in MAR (2008). The results are shown in Table 3-1. It was further assumed that the typical vessel speed is on average between 9 and 12 km/h and that a typical value of the bow drawdown is around 0.4 m.

What results is that, for uncritical soils regarding excess porewater pressure such as *sands and gravel* (soil type B1 in MAR) or *sands* (type B2), a fairway–bank distance *u* of more than about 20 m seems to be uncritical, but for *silty sands and gravel* (soil type B3), the fairway-bank distance should be at least 40-60 m to avoid excess porewater-induced surface erosion. Ffor *silt and strongly silty sands and gravel* (soil type B4), which is assumed to have no cohesion (worst case), the distance to avoid surface-fluidisation should be larger than the vessel's length (> 150-200 m in large waterways).

If the soil has a cohesion greater than zero, there is generally no danger of destabilisation due to excess pore water pressure. If the soil has a significant cohesion (c' > 3 kN/m^2), there is no danger of shallow slides due to excess pore water pressure. So, if there is any indication of critical soil properties at the project site, a detailed consideration on the influence of excess pore water pressure (for example, by GBBSoft+) should be carried out to check its influence and to design the extra surface load, which is unavoidable in such cases (for example through the application of vegetated rip rap or vegetated gabions).

Soil type according to MAR	Minimum ship-bank distance for ship speed 9 km/h overground	Minimum ship-bank distance for ship speed 10 km/h overground	Minimum ship-bank distance for ship speed 12 km/h overground
B1: sand and gravel	4 m	5 m	6 m
B2: sand	10 m	11 m	13 m
B3: silty sand and gravel	42 m	47 m	56 m
B4: silt, strongly silty sand and gravel (without significant cohesion)	155 m	172 m	205 m

Table 3-1: Necessary fairway-bank distances to avoid fluidization of bank sediments, derived by using several assumptions and approximative formulas from GBB (2010) and MAR (2008)

Finally, it is generally possible and accepted by skippers to restrict the ship speed in impounded rivers, because the safety of navigation can be assured in most cases and often even for strongly reduced speeds, because the flow velocities are small. Of course, the ease of navigation is reduced, so that compromises are necessary; for example, by restricting the speed only in the initial phase after installation of bioengineering constructions.

Free-flowing rivers – training with groynes:

By contrast, such speed restrictions may not be acceptable in free-flowing rivers, depending on the magnitude of the flow velocity, because at least some minimum ship speed overground is necessary simply to avoid creating a traffic obstacle (on the upper Rhine, 5 km/h overground in an upstream drive or some speed relative to water to ensure steerability, say around 9 km/h) and thus to perform evasive manoeuvres in a downstream drive. Thus, in free-flowing rivers with large flow velocities, mitigation measures such as speed restrictions are often not feasible, but other temporary mitigation measures such as fairway relocation may be acceptable in the initial phase. Reference is made again concerning the relation of fairway–bank distance to wave heights to Part 3, Appendix B, Table I.1. More information about related issues can be found in the report of PIANC WG 141 on inland waterway dimensions (2019).

Groynes (spur dykes) are the standard training element in free-flowing rivers, as they are less expensive than parallel dykes and easily adjustable but may often increase flood levels.

Therefore, longitudinal control dams are often used instead because they ensure the same concentration of flow and, thus, the same morphodynamic effects such as the increase of fairway depth due to intended bed-erosion improvement. Besides the nautical advantages of groynes compared with longitudinal control dams such as the possibility to drive into a groyne field with ground contact to avoid an accident, the *sheltering effect* of groynes also merits mentioning here. The sheltering effect refers inter alia to the strong reduction of the flow velocities within the groyne fields, not only at low water but also in the case of flooded groyne heads (depending of course and especially on the inclination of the groyne heads towards the flow direction. This reduction results in less bank impact from the flow field without navigation and – additionally – to sedimentation of bed sediments in the groyne field (depending again on the construction, e.g. groynes heading upstream collect more sediments than those heading downstream).

But ship-induced long (as drawdown) and short waves (secondary waves) are also damped, first because of geometrical reasons such as the increased ship-bank distance (influence was discussed just ahead), but also because especially short waves will be diffracted at groyne heads on non-flooded groynes, leading to strongly reduced wave heights on the bank and – in the case of flooded groynes – because of transmission energy losses if waves pass the groyne ridge towards the bank.

The diffraction effects can be assessed, among other ways, using numerous charts developed from Daemrich (1978). For typical secondary wave lengths of around 5-10 m for large freight vessels and of around 20-30 m for large inland recreational vessels with boat lengths of around 10-15 m (average-sized yachts), the following general rules may be extracted; see also Figure 2.31:

- Stern waves (orthogonal to boat axis) will be strongly diffracted, leading to about 10 % of their former height just ahead of the groyne head in a bank area close to the groyne, which is as long as the groyne length.
- Diverging, oblique waves will be less diffracted, but they lose at least 50 % of their original height in the areas indicated in Figure 2.31.
- The corresponding length with reduced wave heights, starting from the groyne root along the shoreline towards the middle of the groyne field, is between 0.7× up to 1.4× the groyne length l_B long, depending on the vessel's type and its driving status (large freight vessel, sailing slower than the critical ship speed, or pleasure boat, sailing with planing speed – worst case).

So, there are always parts of the shoreline in the groyne fields impacted much less than other areas, especially in the middle of the groyne fields.

This general rule holds true for water levels below the groyne crest or up to around 0.5 m deep flooded crest because typical secondary waves from inland vessels will be damped again by transmission effects, which leads again to a reduction of about 50 %.

With these general rules, the relevant secondary wave heights, acting in the shaded area, may be assessed using Table I.2 in Appendix B for the waves in front of the groyne, which may then be reduced by about 50 %. These numbers or equivalent flow velocities from Appendix C.2 in Part 3 can be used to check whether bank protections in the shaded area below the aforementioned water level are necessary at all (using, for example, the numbers given on Figure 2.32 from PIANC [2008] or those provided in GBBSoft+) or which protection methods may be applicable in these areas, using all the selection tools described above with reduced wave heights.

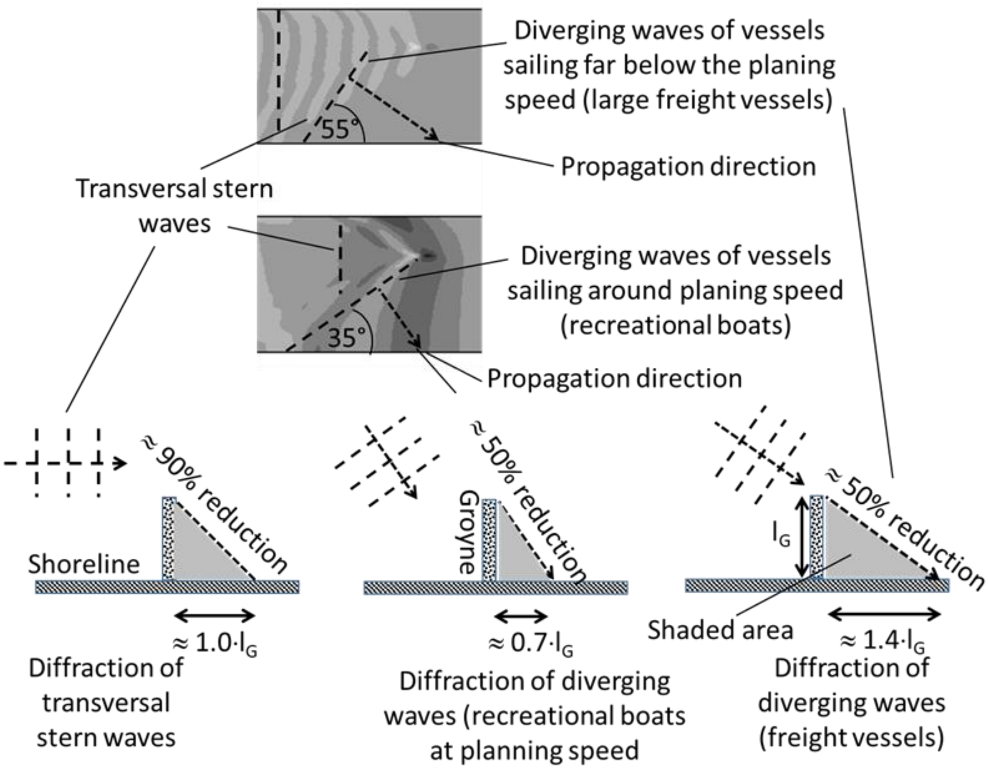


Figure 3.31: Strongly simplified diffraction of ship waves of inland vessels at groyne heads

For higher water levels, the wave-damping effect of groynes still exists, although not that much for secondary waves, but especially for long waves such as the drawdown, among other reasons simply because of the larger fairway–bank distances compared with a river reach without training measures. In this case, again, the aforementioned methods can be applied to assess the corresponding wave heights and the significance of excess pore water pressure, using, for example, the general rules given above or more precisely using, for example, GBBSoft+. Table 3-1 shows that, with the exception of very sensitive soils such as B3 and B4, excess pore water problems, leading to fluidization, are generally not relevant in typical groyne fields, as the length of the groynes l_B is usually larger than 50 m. Only in the up- and downstream ends of groyne fields do these problems arise.

To summarise, ship-induced impacts are generally strongly reduced in groyne fields – and, as the erosion speed is dominated usually by the main flow field with its bed-forming processes, it is reasonable to monitor the development of the bank areas in groyne fields and to take bank-protecting measures only if really necessary; for example, if there are structures or buildings close behind the bank.

Groynes can be constructed in very different ways, depending mostly on the main issues to be addressed so as to address sedimentation problems, to reduce water-level increase during floods, to restrict crosscurrents, or to achieve an ecological upgrade, besides the usual aim to concentrate the flow in the middle of the channel and thus to increase fairway depths.

Boundary category	Boundary type	Permissible velocity (m/s)	Permissible breaking wave height (m)
Soils and gravel	Non colloidal alluvial silt	0.6	-
	Stiff clay and alluvial colloidal silt	1.1	0.15
	Graded silts to cobble	1.2	0.15
	Gravel, d_m = 0.02 m	1.1	0.15
Vegetation	Turf on non erosive soil	2.3	0.6
	Long native grasses	1.5	0.2
	Reed plantings	0.8	0.1
	Hardwood tree plantings	1.6	0.25
Riprap	D_{50}=0.2 m	2.6	0.65
	D_{50}=0.4 m	4.0	1.25
Bioengineer-ing	Reed fascine	1.5	0.20
	Live fascine	2.1	0.4
	Vegetated coir mat	2.9	1.0
	Live brush mattresses (grown)	3.7	1.25
	Live willow stakes	2.0	0.45
Hard surfacing	Gabions	5.0	2.2

*Figure 3.32: Rough reference values for erosion-causing flow velocities (*third column*) and corresponding heights of breaking waves (*fourth column*) from PIANC (2008)*

Free-flowing rivers – training with longitudinal control dams:

As groynes, parallel dykes shelter the bank areas against flow and wave attack. Usually, the protection is full up to crest height plus 0.5 m. But even for higher stages, wave impact is smaller than without training measures, among other reasons because of the larger fairway–bank distances. Use the methods discussed in the previous section to assess the impact.

With parallel dykes, about the same morphodynamical effects can be achieved as with groynes, especially to support a deeper fairway. Current practice often replaces groynes with parallel dykes, among other reasons to avoid the increase of flood levels, but parallel dykes are of course generally much more expensive and less flexible than groynes.

Other typical river-engineering works include fairway dredging, bed-stabilisation measures such as scour filling, or bottom groynes up to artificial-sediment supply, all of which influence bank stability.

Concerning these issues, the following sections provide an overview of the standard literature on river engineering and its ecological effects. But the impact on bank-stabilisation measures against ship-induced impacts, the focus of this report, will not be considered in detail. Instead, the following sections focus on special aspects of river training and management available in the Chinese guidelines.

3.5.2 Consideration of River-Engineering Works with a Focus on Ecological Issues

3.5.2.1 General Perspective on Integrating Navigational and Ecological Aims

The following section stems mainly from the new Chinese *Technical Guidelines for Green Construction of Inland Waterways* from June 2021 (Chinese Guidelines 2021), which provide comprehensive information on river-engineering works, including bank protection with a special focus on environmental aspects.

Figure 3.33: Finless porpoises, rare aquatic animal living in the Yangtze River, China

Basic regulations: For waterway works, relevant requirements of ecological and environmental protection shall be met, and construction techniques and measures for deep integration of ecological protection and navigation functions shall be adopted.

The longitudinal continuity of the river, horizontal connection of the river, and vertical permeability should be maintained in training works. Environmental-protection equipment and processes should be adopted in the construction of training works.

Fish-repellent operations shall be conducted in the construction area and adjacent waters in accordance with ecological – and environmental – protection requirements before construction. Contingency plans for accidental injury of rare aquatic animals (such as finless porpoise in the Yangtze River) should be kept at hand.

Engineering layout: The waterway-engineering layout shall mitigate the adverse effects on environmentally sensitive areas in the waterway. In the layout of training works, the effect of waterway training and habitat protection for aquatic animals shall be considered comprehensively. According to the principle of zoning design, navigable-function areas and water-ecology-protection areas shall be set in the main river channel (the habitat of aquatic organisms, especially the 'spawning field, feeding field, wintering field, and migration channel' of fish, hereinafter referred to as *three fields and one channel*), functional areas for ecological protection (habitats of aquatic organisms) shall be constructed in non-navigable secondary or side channels, river bends, waterway-training structures, and their adjacent waters.

The connectivity of non-navigable secondary or side channels should be preserved in the braided reaches as ecological-protection zones (habitats for aquatic organisms), which should be protected in accordance with the survival requirements of aquatic organisms. The split ratio of secondary and side channels may be adjusted with fish-bone dykes (Figure 3.34), fish-mouth works (Figure 2.35) or other new dam structures to improve navigation conditions of waterways in navigable-function areas.

Because of the diversity of flow patterns, the function area for ecological protection (habitats for aquatic organisms) can also be built up in the dam field and its vicinity of these dykes in accordance with the above requirements. In damming works with a toe, the dyke body can be arranged as an L-head (Figure 2.37), and notches can be reserved in the appropriate part of the dyke body or partially set as a permeable dyke body. The site selection of the mud-dumping area, mud storage pit, and spoil area should avoid environmentally sensitive areas.

All these principles applied to the engineering layout will make good attribution to the protection of the aquatic organisms in the river. Besides, the engineering layout should take the bank protection design as a critical component and encourages more ecological methods to be applied to the riverbank design. Thus, the ecological bank protection method can contribute to preserving non-navigable secondary/side channels, river bends, waterway training structures, and their adjacent waters

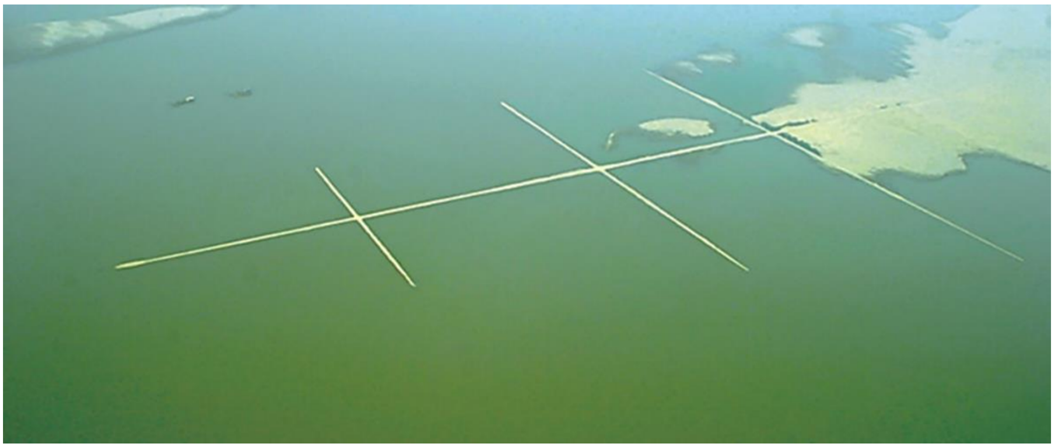


Figure 3.34: Fish-bone dyke in the east channel of the Yangtze River, China

Figure 3.35: Fish-mouth dyke in the east channel of the Yangtze River, China

Figure 3.36: Ecological protection of banks in the middle reaches of the Yangtze River, China

Ecological protection of banks, beaches, and revetments: To ensure effective waterway training, the stability and durability of training structures, both ecological materials, and ecological structures should be adopted in buildings for the ecological protection of banks, beaches, and revetments. The bank shall be the slope-type bank protection. For the bank protection with land resources in short supply or difficult land requisition and demolishing, the vertical or mixed bank protection can be adopted. For underwater ecological protection of banks, beaches, and revetments, small structures and rip rap can be built to create diversified habitats.

Ecological material with high porosity, good water permeability, and good suitability for biological habitat and plant growth should be used in the ecological protection of banks, beaches, and revetments. Structures with good water permeability that are conducive to material exchange and suitable for biological habitat should be used in the ecological protection of banks, beaches, and revetments. For bank protection in areas with weak hydrodynamic force, aquatic plants should be mainly used; for bank protection in areas with strong hydrodynamic force, an anti-scour structure with good water permeability should be used.

Figure 3.37: L-head groyne works in the Chishui River, a tributary of the upper reaches of the Yangtze River (with ecological benefits)

Ecological dyke engineering: The layout plan and structure with a habitat-improvement function should be adopted on the premise of ensuring the training function of ecological dyke engineering. Structures with good water permeability and suitability for biological habitat should be used in ecological dykes. Dyke-building materials should be local materials, and pollution-free slag-removal materials (gravel) shall be fully used. Other ecological materials shall be selected for the stone shortage area. For the longitudinal dyke, a notch or a set of local notches can be set up in a position where the training effect and dam stability are not affected. When the dyke body needs to be provided with a protective layer, prefabricated blocks, steel-wire mesh, or prefabricated structures with ecological functions shall be selected.

Ecological dredging engineering: The dredging design shall consider the ecological requirements so as to reduce the impact on benthic organisms in the construction area. When contaminated soil is involved, the dredging and disposal scheme of contaminated soil shall be developed in advance. the construction precision shall be controlled in the dredging construction, and the disturbance to the underwater soil shall be reduced. The dredged soil should be beneficially reused and can be used for land backfilling, ecological beach consolidation, sand-pillow filling, artificial-island construction, wetland construction, or for structural materials such as concrete artificial blocks. In general, dredging work should not contaminate the riverbank. The period of dredging work should be limited as short as possible so that its negative effects on shallow water zone near the riverbank can be constrained. To reinforce the ecological function of the bank protection work, a small portion of the dredged soil can be applied to the riverbank utilised to fertilise the land.

Ecological reef-removal engineering: The non-blasting reef-removal method should be adopted, and the reef removal by blasting shall be conducted only if necessary. The cutter-suction, bucket, reverse-bucket, grab-bucket, and other dredging vessels should be used for non-blasting reef removal. The drilling-blasting method shall be adopted for reef removal by blasting, and millisecond blasting, presplitting blasting, or directional-control blasting shall be conducted. The waste slag should beneficially reused and can be used in training projects or to build ecological conservation areas. If there are no opportunities for beneficial reuse, the waste slag shall be abandoned in the designated area or disposed ashore. Utilising ecological reef-removal methods can significantly reduce its harmful impacts on the aquatic environment and keep the riverbank strong. Therefore, ecological reef-removal engineering is a good option when it comes to a need that combining reef-removal and bank protection work together, especially when the riverbank has already been protected ecologically, and reef-removal is needed afterward.

Figure 3.38: Large dredging-suction vessel and bucket-ladder dredger

The abandoned slag disposal of reef-removal works should meet the following requirements:

(1) It does not affect the protection zones of drinking water sources and other water intakes.
(2) It can reduce adverse impacts on nature reserves and their main protected objects.
(3) It can reduce the adverse effects of three fields and one channel on fish in the project reach.
(4) The onshore spoil area shall be covered with planting soil for greening.

In addition to the above-mentioned requirements in standard documents, ecological environment assessment and analysis form the basic supports of ecological construction of waterway projects and project effect evaluation, including log down and analyse its impact on river bank area.

The scope of ecological environment assessment and analysis should not be smaller than the project area and the affected upstream and downstream reaches, and the assessment should include biological factors and habitat factors. The ecological environment assessment should be conducted two to four times per year, and it should be carried out before and after project construction.

The overall survey of the project reach should generally be based on the layout of sections. The up- and downstream sections of the engineering area shall be provided with one (1) section, respectively, and at least two (2) sections shall be provided within the engineering area. If tributaries intersect the reach, one (1) section shall be set at the intersection. Refer to Table 3-2 for the perpendicular line layout of the section.

Water width	Number of perpendicular Lines	Description
≤50 m	1 line (shallow area)	1 branch reach is arranged separately according to each secondary or side channel; 1 lake or reservoir can be arranged by reference
50-100 m	2 lines (left and right)	
>100 m	3 lines (left, middle and right)	

Table 3-2: Perpendicular line layout of the section

Assessment in local key areas shall comply with the following provisions:

(1) Sample points shall be arranged in typical habitats, such as riparian area, shoal, deep trough, rapid-flow area, slow-flow area near the riverbank, backwater area, and transition area, and the number of sample points shall not be less than one (1).
(2) Sample points shall be laid in key areas of waterway training, such as the area near waterway-training buildings and the dredging and reef-removal areas. The number of sample points shall be determined according to the specific details of the project.

Combined with habitat analysis, the aquatic and fish communities in the project area shall be analysed and evaluated. The species composition, community structure, density, biomass, productivity level, biodiversity, and distribution characteristics of aquatic organisms, fish (endemic species), and rare aquatic animals in key areas of waterway training and possibly affected areas shall be analysed and evaluated as key points. The species composition, community type, biomass, and biodiversity of plant communities (aquatic vegetation and terrestrial vegetation) in the project area shall be analysed and evaluated, and the status of the terrestrial ecosystems shall be evaluated. The influence of riverbed and reach evolution on habitat shall be analysed and evaluated. The influence of the project on fish three fields and one channel, shall be analysed, and the protection measures such as avoidance and mitigation shall be proposed.

3.5.2.2 Shoal Remediation

The shoal area gets close to the riverbank and maintaining the shoal area in a good shape can significantly improve the ecological condition alongside the riverbank. Good shoal remediation should be conducted before or coexist with the ecological bank protection project.

Shoal remediation generally follows the following principles: the overall river regime of the river section where waterway remediation is implemented should be basically stable; for rivers with unstable river regimes, comprehensive treatment measures combining river-regime control and shoal remediation should be adopted. When dealing with rocky riverbeds, shoal remediation should be combined with reef removal and dam construction; sandy gravel riverbeds should be treated with a combination of dredging and dam construction. Dams or a combination of dredging and dams should be adopted in the shallows of plain rivers that hinder navigation to form a flow structure conducive to deepening the navigation channel. Dredging measures should be undertaken for the stable and seldom-changing shoals. For sandy shoals whose channel conditions meet the construction standards but have unfavourable trends, guardian remediation should be adopted to maintain a favourable beach-and-trough pattern and to stabilize channel conditions. Shoals with large interannual scouring and silting changes or variable river regimes should be renovated by taking advantage of favourable opportunities in the evolution of the riverbed. During the implementation process, the goal should be to ensure effective remediation. Adopt dynamic management and optimized design. During the remediation of shallow shoals that hinder navigation in both level and dry seasons, the remediation flow can be determined separately according to different periods of obstructing navigation, and corresponding remediation measures should be taken.

The protective remediation project needs to determine the location of the protect riverbank and the corresponding elevation according to the topography of the protected riverbank and the shape of the river shoal. The remediation water level and the regulation width of the remediation river (the upper, middle, and lower reaches or the different parts of the beach group) should be determined according to different bank characteristics. The shoal-remediation water level and the regulation width should be considered and coordinated with each other and should be verified according to different combinations, and the combination of scouring strength and scouring duration after the implementation of the project should be optimised. For particularly complex shallow and “rapid shoals” (where high velocity currents occur), the remediation water level, regulation width, and remediation layout should be comprehensively determined through river-engineering model tests or numerical simulation studies. The water level for shoal regulation can be determined through comprehensive analysis using that river section's remediation experience, combined with the river-section flat water-level method, multiyear average flow method, bed-making flow method, or the relationship between water level and navigation depth.

(1) Remediation of sandy shoals

Remediating sandy shoals requires understanding the causes of beach formation; the upstream inflow and sand conditions; the water level of erosion and siltation; analysis of the interannual changes of the riverbanks, beaches, and navigation channels; analysis of upstream and downstream river-regime changes; and other involved engineering activities nearby like sand-and gravel-mining activities on the beach. To remediate the shoal in the transition section, the beach should be fixed and heightened, the flow rate of the channel should be adjusted, and the water flow should be concentrated to wash the channel. To remediate the bend shoal, the shoreline should be regulated and the bend radius should be adjusted if it is too small. To remediate the shoals of the branch, after careful selection of the branches, engineering measures should be taken to stabilise or adjust the diversion ratio between the branches and to improve the navigation conditions of the navigation branches. To remediate scattered shoals, measures such as beach consolidation, dam construction, and bank protection should be adopted to improve the shoal and trough shape, concentrate the water flow, and stabilise the medium-low water flow path. To remediate the shoals of the tributary estuary, appropriate measures should be taken to reduce the junction angle, improve the confluence conditions, and increase the ability of shallow areas to scour.

(2) Remediation of pebble shoals

In the analysis of the data of pebble-shoal remediation, the arrangement and deposit density of the pebbles should be analysed.

When remediating the transition section of the shoal, when the shoal is shallow in the upstream and dangerous in the downstream, a spur or submerged dam can be built in the lower deep trough to adjust the flow rate and improve the flow pattern. To remediate the bend shoal, a spur dam or a spur dyke at the appropriate part of the concave bank can be built to smooth the nearshore water flow. If necessary, dredge the shallow area of the convex bank and increase the bending radius or build a longitudinal dyke to block the bend groove and excavate the straight groove. To remediate the shoals of the branch, after careful selection of branches, engineering measures should be taken to stabilise or adjust the diversion ratio between the branches to improve the navigation conditions of the navigation branches. To remediate the shoal at branch entrances, build a parallel dyke at the head of the sandbar. It can intercept the crosscurrent, adjust the dry flow direction, and stabilise the head of the sandbar. When there is an obstructive flow regime, a submerged dam can also be built to improve the flow regime. To remediate the shoal at the exit section of the river branches, parallel dykes can be arranged at the tail of the sandbar, and, if necessary, a spur dam should be built on the navigable branch. When a branch with relatively small diversion in the dry season is used as a low-water channel, it should first be fully verified by numerical simulations. To remediate silt shoals that are alternately navigable at the two ends of the branched river section, the water level at which the silt shoals begin to scour should be ascertained, and damming measures can be taken to scour the silt channel in advance and raise its navigating water level. Reef explosion or excavation of the non-silted navigation channel can be used to lower its sealing water level.

Appropriate measures should be taken to reduce the junction angle, improve the confluence conditions, and increase the scouring capacity of shallow areas in the remediation of tributary estuary shoals. For the remediation of narrow shoals, the water level at the beginning of the erosion of the silt during the retreat period of the shoal waters should be used as the remediation water level, the remediation structures should be arranged, and the water flow should be concentrated to accelerate the erosion of the channel. When conditions permit opening a new navigation channel as a transitional channel, new river bifurcation can also be excavated.

(3) Remediation of rocky shoals

To remediate rocky shoals with little change in sediment erosion and sedimentation, analysis of the speed, gradient, and flow pattern of the beach section should be carried out; to remediate stony shoals with changes in sediment erosion and sedimentation, the pattern of sediment movement should be analysed. Renovation of rocky shoals should be based on whether there are changes in sediment erosion, and siltation, and trenching, or damming measures should be adopted. When grooving on a rocky shoal without changes in sediment erosion and siltation, the form of the excavation section and longitudinal slope should be reasonably determined, and it should be smoothly connected with the upper and lower deep squeezing. Avoid crosscurrents and rapids at the entrance and exit. To remediate rocky shoals with changes in sediment erosion and sedimentation, reasonably determine the direction of the navigation channel according to the flow direction of medium and low water. In addition to blasting reefs and digging river branches, dams can be built to increase the sand transport capacity when necessary. After excavation of a rocky shoal, when the water surface drops and causes adverse effects, build a spur dam or submerged dam downstream of the shoal.

3.5.2.3 Rapid Beach Remediation

Rapid beach remediation should calculate the water-surface line and cross-section velocity distribution before and after remediation and predict the velocity, gradient, and impact on the upstream reaches of the route after remediation. When there is an adverse impact on the upstream reach, measures should be taken to eliminate the adverse impact. The layout of the excavation line, the form of the excavation section, and the area to be expanded should be compared and determined by numerical simulation calculations, and the gradient before and after the remediation and the change in the velocity distribution of the section should be calculated. For rapid beaches with complex flow regimes or large water drops, river-model tests and ship-model tests should be used to determine the remediation plan, if necessary.

The layout of the excavation line for rapid beach improvement should try to ensure that no back-siltation occurs in the excavation area, which is conducive to the smooth connection of the route after the improvement. The excavation line should not form a large angle with the direction of the water flow. The excavation line should be arranged on the bank with slow flow for the remediation mainly to widen or open the slow flow channel. For remediation aiming mainly to widen or open a slow-flow channel, the excavation line should be arranged on the bank with slow flow. The main remediation is to expand the cross section, slow down the flow rate, and reduce the gradient, and the excavation line should be arranged on the bank deviating from the main stream. Regarding the formation of staggered beaches, the excavation line should be arranged by cutting off the downstream part of the upper protruding mouth and the upstream part of the lower protruding mouth to extend the length of the staggered mouth. For rapid beaches with large changes in water level, the arrangement of excavation lines should be adapted to the navigation needs of different water levels. If necessary, multiple excavation lines can be arranged at different elevations.

For rapid beaches with mouth-shaped protruding mouths, one bank or both sides of the protruding mouth can be cut off at the same time to enlarge the cross section of the water and slow down the flow rate and gradient. For staggered mouth-type rapid beaches, when the amount of reef blasting to meet the ship's self-propelled beaching by cutting the mouth is too large, part of the mouth can also be removed according to the position and shape of the mouth to extend the length of the staggered mouth. Ships alternately use the slow currents on both sides of the strait to go to the beach. For the remediation of rapid beaches with multiple protruding nozzles adjacent to each other, the resection plan of each protruding nozzle can be determined according to the mutual influence between the protruding nozzles and the remediation method of the opposite and staggered protruding nozzle rapids, and model tests can be carried out if necessary.

In the remediation of pebble rapids, a combination of remediation and dredging should be adopted to remediate pebble rapids with stable riverbeds, expand the cross section of the beach mouth, and adjust the beach sections with conditions in the beach mouth so that ships can alternately use the slow current to go to the beach. To remediate pebble rapids with certain changes during or between years, while expanding the cross section of the beach mouth, appropriate types of structures should be arranged to guide the flow of the water, and the pebble-transport lines should be changed to reduce siltation according to conditions such as the discovery of pebble movement.

The remediation of continuous rapids should be considered in a comprehensive manner, and according to the distribution of beach mouths in the beach section, engineering measures combining dredging and excavation with dam construction should be taken to disperse the concentrated drop on the water surface and slow down the flow-rate drop. Continuous rapids where the warping beach cannot be completely eliminated through remediation can be achieved through remediation to make relatively a large flow velocity and gradient relatively concentrated in one place and merge multi-streams into a single stream.

For the improvement of rapids of a branched river section, the change of the branching ratio of the branch should be considered after the improvement. When the branching ratio increases after the excavation of the navigable branch, the negative effect of the corresponding increase in the velocity and the gradient should be generated in the non-navigable branch. Take appropriate diversion measures. The plane excavation line layout of the channel at the entrance section of the navigable branch can be trumpet shaped, which facilitates safe advancement of ships.

3.5.2.4 Dangerous Shoal Remediation

The remediation of dangerous shoals should implement engineering measures such as blasting, damming, rivulet filling, and dredging according to the characteristics of obstructing navigation and the shape of the riverbed to widen and deepen the channel, increase the bending radius, and eliminate or improve the undesirable flow pattern.

For the remediation of dangerous reef shoals, the navigation channel should be reasonably arranged, blasting reefs or dams should be implemented to improve the flow pattern and increase the size of the channel. The elevation of the bottom of reef blasting in the navigation channel should be appropriately evaluated by considering factors such as the increase of the ship's dynamic draught, and the water depth of the channel should be adjusted in place at one time in accordance with the long-term planning. Finally, reefs that hinder navigation need to be cleared, and a longitudinal dyke can be built on the edge of the navigation channel to smooth the current.

Remediation of sharp bends and dangerous shoals should increase both the width and bend radius of the channel and eliminate or improve the undesirable flow patterns such as sweeping water and backflow so as to ensure safe navigation of ships. The following remediation measures can be undertaken for sharp bends and dangerous shoals in a single channel: excavate part of the protruding shore beach, increase the bend radius of the channel, fill in deep grooves on the concave bank or build submerged dams when necessary, adjust the shape of the riverbed section, and improve the flow conditions. When the concave bank has a bulging mouth, a spur or dam should be built upstream of the bulge to remove the main stream from the bulge to slow down the undesirable flow patterns such as sweeping water and swirling water. Mainly to renovate protruding stone beams, for sharp bends and dangerous shoals in branched rivers, the following remediation measures can be taken: build a dam at the entrance of the branch or excavate a protruding shallow mouth at the head of the branch to weaken the cross flow to the concave bank; build a tail dam at the exit of the branch to intercept the cross flow and build a spur dam or spur dam on the concave bank if necessary; discard the old canal, create a new canal, so that ships can sail in a new and separate canal.

During the remediation of boil-vortex shoals, the shoal formed by the reefs in the centre of the river or the protruding stone beams on the bank can blow up the reefs or the beams to smooth flow and adjust the flow structure around the riverbed. Depending on how long the width of the river channel is, an unsubmerged dam or submerged dam can be built in the upper reaches of the rock. If necessary, the sudden mouth of the beach can be cut off. At the entrance of the river branch, the main flow tops the riverbank forming extremely turbulent rapids, where a dam can be built to adjust the main flow direction of the inlet section to reduce the bubble-swirling water.

For water-shoal improvement of ‘sliding beams’ (riverbank where there is a large rock or natural structure next to the river that causes an ‘over-ledge flow’), analyse the causes of water formation and the degree of obstruction to navigation and investigate the obstructive voyage velocity, gradient, direction, and intensity of cross flow; the depth of water on stone beams; and the impact on the safe navigation of ships. To remediate rapid water shoals formed by a rock beam on one bank, the rock beam can be blown down to below the lower-limit water level of the beach, or a dam can be built on the rock beam, with the dam crest elevation higher than the upper-limit water level of the beach. To remediate dangerous shoals with sliding-beam (over-ledge flow) water on the stone beams on both sides, measures should be taken to eliminate the sliding-beam water on one bank. The stone beams can be blown down or a dam can be built on the stone beams so that ships can avoid the sliding-beam water on the other bank.

Emergency, shallow, and dangerous composite-beach hazard remediation should be based on the characteristics and corresponding relationships of each obstructing part, and different engineering measures should be taken from top to bottom. For complex compound beaches, physical models or numerical simulation calculations should be used to determine the engineering plan. The remediation of compound beach safety should still meet the following regulations:

1) For the treatment of the upper shoal, the negative impact of the concentration of water flow in the upper channel on the lower section of the dangerous situation should be fully considered when the upper section of the shallow and lower risk is a compound beach hazard.
2) For compound beach risk of upper shallows and lower rapids, when the lower rapid shoal section is treated by expanding the water cut, the impact on the upper shallow water surface settlement should be checked, and the remediation parameters of the upper shoal treatment shall be adjusted appropriately.
3) For compound beach safety with alternating emergency and dangerous sections along the route, the distribution of the emergency and dangerous sections, degree of navigation obstruction, and mutual influence should be considered; multiple schemes should be analysed and compared; and comprehensive treatment should be carried out.

3.5.3 Non-Engineering Measures

With reference to Appendix C.1.3.1 in Part 3, where non-engineering measures are tackled according to the approach in the UK Waterway Management Guide with some additions from the authors of this report, only some concluding remarks shall be reported here as follows:

The non-engineering measures are grouped into *allowed natural adjustment*, *management*, and *relocation*, but it is generally assumed here that all these measures may be combined.

Allowed natural adjustment:

With additional reference to Chapter 3.4, presenting general perspectives on when natural development may be appropriate, and Chapter 3.5.1, which provides general rules for in which cases measures may be avoided, when comparing bank impact versus bank resistance only, Appendix C.1.3.1 in Part 3 provides a practical way to cope with the avoidance of bank-protection measures.

Allowed natural adjustment means where the bank retreat may continue until such time as the channel adjusts and the bank restabilises by itself. The strategy is thus based on the principle that all channels adjust naturally over time to a state of dynamic equilibrium without the need for interference. It is appropriate, therefore, if the channel is already beginning to stabilise naturally.

Because this may be assumed only for natural bed-forming processes, not for those initiated by navigation, natural adjustments seem to be acceptable in waterways only in the following cases:

- Consequences of continued erosion and bank collapse are acceptable; for example, because the waterway authority owns the land.
- Critical areas such as buildings, roads, pipelines, transmission towers, or other infrastructural measures, or private land, are sufficiently far away from the channel bank.
- Corrective measures such as the reduction of ship-induced impacts by boat regulation or the construction of bank protections ahead of critical areas can be taken easily, quickly, and cost effectively to stop the erosion towards the hinterland where necessary.
- The erosion speed is expected to be not that large, depending on the magnitude of impact versus the erosion resistance, which mostly depends on the soil type and expected vegetation density.
- The erosion speed will degrade successively with widening; for example,
  - as the erosion leads to flattening of the bank slope or an increased vegetation density;
  - the fairway-bank distance increases according to the widening; or
  - as the widening is geometrically restricted because of limitation of the stretch length with allowed natural adjustment; for example, by setting erosion-control points such as spur dykes or other strong bank protections in between a larger stretch with allowed bank retreat; see Figure C.1-17 in Appendix C for illustration.
- Further consequences of erosion; for example,
  - an increased roughness of the foreland and thus a significantly reduced conductivity of the channel in case of floods or
  - inacceptable social drawbacks such as reduced access to the water side for recreation activities may be tolerable or compensable.
- The water authority or other institutions and stakeholders are able and willing to accept and accompany the adjustment process among other things by appropriate monitoring and maintenance measures and take corrective measures quickly where necessary.

These points lead to the following general operational recommendations, remembering that natural adjustment is different case to case:

- Evaluate the main causes of the allowed erosion, especially the natural bed-forming process or the ship-induced loads (where Appendix C offers assistance in several ways).
- Decide whether the existing situation can be accepted as is, including partly damaged protections, thus allowing natural adjustment, including increased erosion, without taking further measures.
- Decide whether existing protections shall be replaced to promote the widening process for the purpose of increasing the ecological value of the bank area considered.
- Install a test reach where the revetments will be replaced on a restricted (opening) length and observed over at least 1-2 years (two vegetation periods).
- Assess the erosion speed; for example, from observations at the site considered or from the aforementioned test reach at the same place or rather by assessing the relation between natural and equivalent flow velocities from boat wash to those expected from the type of soil and vegetation properties (where Appendix C in Part 3 again offers assistance).
- Check the availability and ownership (and costs in case of necessary land acquisition) of land behind the existing bank, which defines the maximum acceptable widening, together with the position of critical points in the hinterland, and assess the period of time when the maximum acceptable widening may be reached. If this time is 'long enough', natural adjustment may be acceptable at least over some years.
- Check the possibilities, the costs, and acceptance of remedial measures; for example, starting from the beginning or after some years of free erosion in the case of approaching critical points. These may include the following:
  - regulating boat traffic
  - installation of appropriate vegetation (shorten the natural process)
  - application of bioengineering methods
  - installation of erosion-control points
  - construction of erosion barriers in the hinterland
- Check all possible positive and negative effects and the costs of the allowed natural adjustment versus other environmentally friendly measures.

The cost effectiveness of the measures represents an important point in all considerations of the UK waterway management guide. As ecological aspects are the focus of this report, they will not be addressed in detail here. Nevertheless, the costs of land acquisition or countermeasures such as building erosion barriers in the hinterland as well as the construction of erosion-control points has to be assessed and balanced against all the possible benefits of the solution. If the costs outweigh the benefit too greatly, natural adjustment will not be an acceptable solution.

Management:

Management is concerned with controlling the human (including navigation) and animal activity on the banks so that their impacts can be minimised. Management should always be the preferred option whenever natural adjustment is not a suitable strategy. Management measures will be understood here in a more comprehensive way, addressing also all other remedial measures to accompany, for example, the allowed natural adjustment.

Thus, the main requirements of this strategy include the following:

- The erosion problem must be related to some cause that can be identified, removed, or controlled.

- The channel and banks are likely to stabilise within an acceptable period of time once the main cause of the problem has been removed.
- A monitoring program exists to ensure that the situation does not worsen and that the expected benefits materialise.

The management strategy is not suitable

- in cases of high rates of erosion and bank failures by rotational slips,
- if the consequences of allowing erosion to continue are severe and management alone is unlikely to control the problem,
- the channel will not be able to adjust to a stable and acceptable condition in an acceptable time period, and
- the restrictions to human (inclusive navigation) and animal activity are unacceptable,

as well as where

- the integrity of flood defence is threatened or
- the ongoing erosion may quickly reach adjacent sensitive parts of the hinterland with, for example, buildings or infrastructure measures.

From the large list of possible management measures, the UK guide considers the following in more detail: *boat regulation*, *fencing*, *tree management* and *relocation*.

- *Boat regulation:* Users should review Appendix C.1.3.1 in Part 3 and PIANC (2008), where several mitigation measures are discussed comprehensively. Note, if restrictions to navigation are foreseen such as the implementation of *ship speed limits*, *draught restrictions* and *fairway relocation* (farther away from the bank), that these restrictions are often ineffective because of lacking acceptance. Therefore, they may *theoretically* work but often do not in reality.

- *Fencing:* If the main cause of the erosion problem is the *impact of animals* (for example, grazing sheep, as shown in Figure C.1-19, Part 3) or *human access* (for example, fishing, camping, swimming, or other recreational activities), which destroy existing vegetation or hinder a dense growth of bushes or trees, fencing or other measures to hinder animal and human access to the bank area may be an appropriate.

- *Tree management* is another concrete management strategy mentioned in the guide, also in combination with other measures. The main objective is to support or maintain the vitality of (existing) trees by taking the following measures:
  - Support undergrowth, which helps to stabilise the soil below the tree crown by cutting or at least by pruning to reduce shading.
  - Reduce overhanging limbs to increase the conductivity of the channel.
  - Control overhanging trees and limbs to avoid blowing over in strong wind.
  - Cut large trees if fallen trees may cause flow blockage or scouring.
  - Management such as pollarding (cutting back where necessary to the trunk) gives trees new vigour to root growth, helping to reinforce the bank substrates.

  These measures should be balanced with stakeholders and fixed in a corresponding inspection and maintenance programme.

- *Relocation* deals with removing the causes of bank erosion or installations at risk elsewhere instead of restricting their level of impact on-site. From the numerous possible solutions, the following provide examples of this solution:

- Removal of access paths to recreation areas, including corresponding constructions such as piers, to more stable bank areas.
- Replacement of buildings, installations such as power poles, culverts, or other infrastructure measures at risk in areas not affected from possible ongoing erosion.
- Moving summer dykes or other flood-defence dykes towards the hinterland.
  Relocation is a very effective measure but often hard to realise because of expenses or lack of acceptance.

The UK guide also offers flow charts to check whether management strategies may be suitable or not, see Figures C.1-14 and C-1-15 in Part 3. The check is basic, but it gives a good idea about which issues may be relevant.

3.6 Synthesis

This chapter cannot, of course, address all possible protection and remedial measures. The huge variety of local BCs and planner's demands, which lead to accordingly very different solutions, precludes this treatment. Nevertheless, all relevant measure *types* are considered here.

This focus holds especially true for management strategies with the special measure of allowing natural adjustment. Because these measures are strongly linked to general river-engineering works, detailed design studies are inevitable.

Also, Part 2 offers only a small extract of possible measures, even if in total 63 measures are discussed. So, the examples in this report are of course not complete, but they offer nevertheless the main features, BCs, and planner's demands to be considered.

Thus, the report's design recommendations, which are called the BPA and which are based on the description and collection of measures, cannot address all relevant conditions and, thus, cannot replace detailed design studies, but the recommendations nevertheless offer the most important design guidance according to the practical implementation experiences and subject-matter expertise of the authors.

4 DETAILED VIEW ON RECOMMENDED MEASURES

This chapter provides, in detail, all necessary information for understanding and applying the screening approach (SCREENING-TAB in the Excel worksheet) and the content of Part 2 of this report. The study of the following subchapters is recommended especially for first-time users, together with the numerous additional explanations for all criteria provided in Appendix A.2 in Part 3.

Users performing a detailed study who have already applied the screening approach several times before may only need to consult Chapter 4.1 and Chapter 6.3.3.1 in Part 3, which deal with the use of the screening results as part of the decision-making in the framework of performing a detailed study.

4.1 Categorisation of Measures According to Waterway Properties, Ship-Induced Impacts and the Documentation Categories Used in Part 2

Table 4-1 shows that the collection of measures is divided generally into the three categories used in Part 2: BTs, FFs and CSs (that is, *Basic Types*, *Fact Files*, *Case Studies*). They are also categorized according to important features of the waterway: water-level fluctuations ΔW (low to moderate to high) and strength of ship-induced impacts (weak to average up to strong).

The complete collection of measures is divided as follows:

Type	Overview in	Group		Number of measures	Paragraph in part 2
Basic Types BTs	4.2	German code of practice DWA-M 519		9	2.1.1 to 2.1.9
		British Waterway Management Guide		10	2.2.1 to 2.2.10
		UK Green Approaches in River Engineering		4	2.3.1 to 2.3.4
Fact Files FFs	4.3	Waterways with low water-level fluctuations	Weak ship-induced impacts	3	3.1.1.1 to 3.1.1.3
			Average ship-induced impacts	6	3.1.2.1 to 3.1.2.6
			Strong ship-induced impacts	5	3.1.3.1 to 3.1.3.5
		Waterways with moderate water-level fluctuations	Weak ship-induced impacts	2	3.2.1.1 to 3.2.1.2
			Average ship-induced impacts	4	3.2.2.1 to 3.2.2.4
			Strong ship-induced impacts	2	3.2.3.1 to 3.2.3.2
		Waterways with high water-level fluctuations	Weak ship-induced impacts	3	3.3.1.1 to 3.3.1.3
			Average ship-induced impacts	3	3.3.2.1 to 3.3.2.3
			Strong ship-induced impacts	3	3.3.3.1 to 3.3.3.3
Case Studies CSs	4.4	Waterways with low water-level fluctuations		1	4.1.1
		Waterways with high water-level fluctuations		3	4.3.1 to 4.3.3

Table 4-1: Categorisation of measures with references to chapter names in Part 2 (Note: BT – Basic Type; FF – Fact File; CS – Case Study)

A measure mentioned under a specific paragraph in Part 2 – for example 3.1.2 (low water-level fluctuations, average ship-induced impacts) – may also be suitable under the BCs of another paragraph, for example 3.2.1 (moderate water-level fluctuations, weak ship-induced impacts).

Therefore, users should first 'screen' the collection of measures using the following criteria: BCs, design features, objectives, and achieved goals. That is, users must first define the current and desired values of the criteria and then use those values to screen for possible suitable measures in the collection. Tables with guidance on these screening criteria are provided in the following chapters for BTs, FFs, and CSs. Comprehensive information about the screening approach is provided in Part 3, Chapter 6.3.3.1.

The screening criteria are listed in the following Table 4-2:

Screening: relevant (site) BCs			
Waterway type			
Canals and lakes	Impounded rivers	Free-flowing rivers	
Average bank slope			
Flat	Normal	Steep	
Subsoil			
Stony or coarse gravel	Gravelly or sandy	Loamy and silty	
Ship-induced impact			
Low	Average	High	
Space availability			
Aquatic zone	Amphibian or terrestrial zone		
Surrounding land use			
Naturalized	Extensive	Intensive	
Invasive plant species			
Low	Dominant		
Water quality			
Good	Major deficit		

Screening: important design features			
Flanking measures			
River training	Speed limits	Fairway relocation	
Pre-embankment			
Far from bank	Close to bank		
Direct measures			
Linear	Planar	Combined	
Construction components			
Bioengineering	Biotechnical	Structural engineering	Fully conventional

Screening: (possible) key objectives			
Stability demand			
High	Average	Low	
Economic aims			
Lower than rip rap	Comparable with rip rap	Higher than rip rap	
Strived ecological output			
Habitat connectivity	Aquatic habitats	Amphibian or terrestrial habitats	
Vegetation complexity	Sustainability	Ecosystem services	

Screening: (potentially) achieved goals			
Technical			
High stability or durability	Acceptable local damages	Erosion	
Economical			
Costs lower than rip rap	Costs comparable with rip rap	Costs higher than rip rap	
Achieved ecological output			
Habitat connectivity	Aquatic habitats	Amphibian or terrestrial habitats	
Vegetation complexity	Sustainability	Ecosystem services	

Table 4-2: Screening criteria for using the measure characterisations (Note: BC – boundary condition)

Hence, consulting the collection of measures using one or more of the above criteria makes it possible to do a straightforward screening. Two different types of data are relevant for screening: (1) available or analysis values (analogous to the Analysis Cases – ACs – of the preselection approach of Chapter 5), which are available for all 63 measures in Part 2) and (2) wanted or design values (analogous to the Design Case – DC – of the preselection approach).

The analysis values for the screening criteria are listed:

- for the Basic Types (BTs) in Table 4-5 and Table 4-6
- for the Fact Files (FFs) in Table 4-9 and Table 4-10, and
- for the Case Studies (CSs) in Table 4-12: Overview of search criteria concerning BCs and design features - CSs
- And Table 4-13.

The design value for the screening criteria is defined in the screening process itself.

Table 4-3 provides a screening example for considering Boundary Conditions (BCs). The relevant criteria valued in the screening are part of the relevant (site) BCs (at Design Case site -DC).

In the example, a total of 14 wanted or design values serve as input in the first, *light orange* coloured row with crosses *X* and *(X)*:

- A design value *X* means that this BC exists at DC site and should match with corresponding markings of the numerous AC's. Thus, if the same criterion matches with a *X* of an Analysis Case, this measure is suitable for that criterion (here, for that BC).
- A DC-value *(X)* means that this BC is partly existing at DC site. If its AC-counterpart is an *X* or an *(X)*, the match is also given, but if a DC-*X* meets a corresponding (X) on an AC, the match is not that optimal.
- The worst match occurs if a DC-*X* or *(X)* meets an empty cell in the AC. This means, the AC-measure is not suitable for that criterion (BC).
- A blank cell in the *Design Case* row simply means that that this screening criterion is not relevant to that project or the BC not fulfilled, so that matches with the ACs are not relevant.

		relevant (site) boundary conditions																				
paragraph Part 2	name measure	waterway type			average bank slope			subsoil			ship-induced impact			space availability		surrounding land uses			invasive plant specie		water quality	
		canals and lakes	impounded rivers	free flowing rivers	flat (as inner bank)	normal (≈1:3)	steep (as outer bank)	stony, coarse gravel	gravelly - sandy	loamy and silty	negligible to low (H ≤ 0,2 m)	average (H≈ 0,3- 0.4 m)	high (H > 0.5 m)	in the aquatic zone	in the amphibian/terrestrial zone	largely naturalized	extensive land use	intensive urban or agricultural	low extent, introduction or spread	dominate and introduction likely	good physico-chemical quality	major deficits in physico-chemical q
Design Case: Existing riprap protection at impounded Weser River at Stolzenau, Germany to be ecologically upgraded, including enhancement of shallow water zones by using TBPs			x	(x)	(x)	x		(x)	x			x	(x)	x	(x)	(x)	x		x		x	
3.2.2.4	Wood barriers, reed plantings, softwood planting – Al	x	x	(x)	x	x			x	x	x	x		x	(x)	x	x	x	x		x	(x)
2.1.9	Vegetated riprap	x	x	x	x	x	x	x	x	x	x	x	x		(x)	x	x	x	x	x		
3.3.2.1	Gravel bank stabilization by a parallel dyke and wattle		(x)	x	x	(x)		x	x		x	x		x	x	(x)	x		x	(x)	x	
2.1.7	Chamber revetment (vegetated stone mattresses, ree	x	x	(x)	x	x		x	x	x	x	x	(x)		(x)	x	x	x	x			
2.3.1	Willow spilling/bundles	x	x	x	x	x	x	(x)	x	x	x	x	(x)		(x)	x	x	x	x	x		
2.2.8	Vegetated open cell revetments	(x)	x	x		x	x	x	x	x		x	(x)	x	(x)		x	x	x		x	
2.2.10	Vegetated concrete units revetment	x	x	x		x	(x)	x	x			(x)	x	x	(x)		x	(x)	x	(x)	x	(x)
4.3.1	Vegetated riprap, erected 2011 on the right bank of th	x	x	x	x	x	x	x	x	x	x	x	x		(x)	x	x	x				
3.3.1.3	Groyne Field and Slope Stabilization by a Strong Wattl		(x)	x	x	(x)			x	x	x	x		x	x	(x)	x		x	(x)	x	
2.1.8	Willow brush mattresses with heavy riprap as toe rein	x	x	x	x	x			x	x	x	x	(x)		(x)	x	x	x	x	x		

Table 4-3: Screenshot from the SCREENING-TAB in the corresponding Excel worksheet (The measure designations partly not completely visible. To read the full designations, the second column has to be enlarged by the user. The same holds true for the following tables): Example for the Design Case on the Weser River (best 10 results shown)

Comprehensive information on how the screening approach works in detail, for example by simply sorting-out measure with no matches of selected criteria (hard, binary screening) or by using a scoring algorithm for combining different criteria (balanced screening), provides Chapter 6.3.3.1 in Part 3. In the example of Table 4-3, the balanced way of screening is used: The measures that fit best as a result of the screening do not match with all design criteria, but in an approximative way. Thus, and because the preselection tools use similar balanced algorithms, it is recommended that practitioners should use the hard binary screening and for a small extent of criteria only. Application examples show that the corresponding results provide a good overview on generally appropriate measures and relevant design criteria, if the selection will be done with altered criteria.

4.2 Collection of Basic Types (BTs)

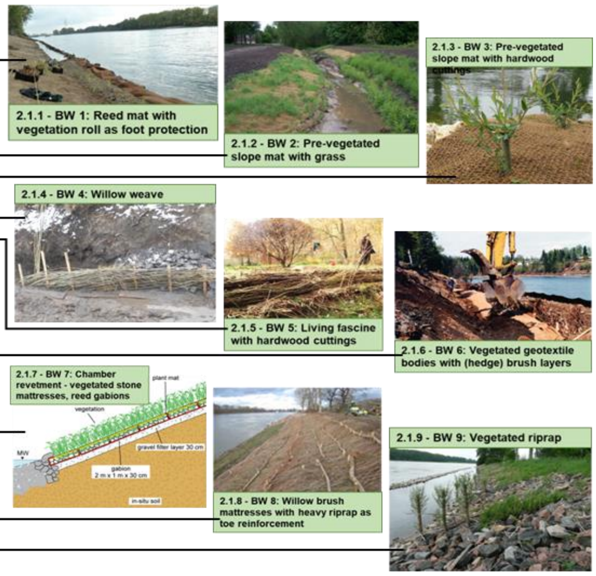
The BTs come from existing guidelines. They are mainly singular measures, not measure combinations. The BTs are provided to give insight into the effects of a singular measure, where multiple measures can be combined in a concrete implementation. As the BTs are not from a particular site, only 'typical' BCs, including realistic application ranges and objectives, and achievable instead of actual achieved goals will be considered. The implemented measure, described in FFs and CSs, can include both singular measures and, generally, combined multiple measures. Where standard data are available, an FF is provided. Measures with extensive monitoring available are listed as CSs.

The following tables (Table 4-4, Table 4-5 and Table 4-6) provide first the measure name, which was chosen according to the number of the chapter in Part 2, and then the designation, which is simply the headline of the corresponding chapter. Finally, the measures are shown in the same way as the overview of all measures in Part 2, Chapter 5.

These same illustrations occur at several points in this report; for example, in Chapter 6, where all the recommended approaches are applied using examples to visualise the results. Use the following lists and visualisations especially when applying the preselection tools, which offer, for example, ranking lists of appropriate measures where only the chapter name of the measure is listed. Note that the visualisations use abbreviated measure names.

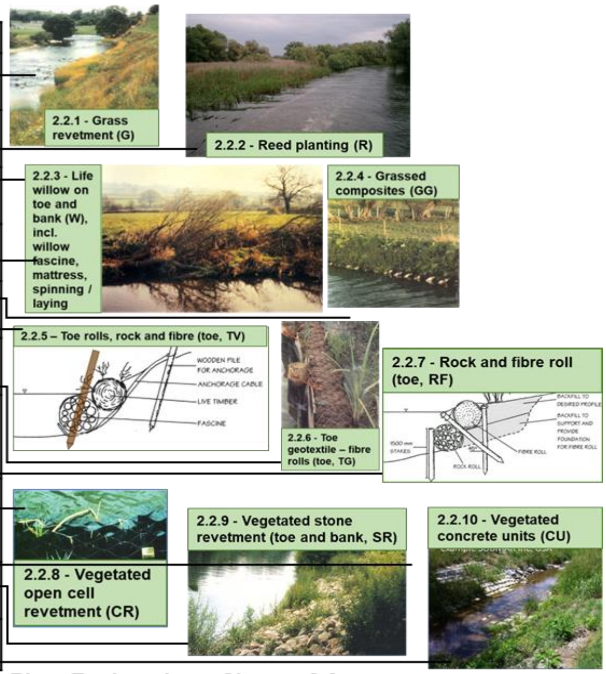
Basic Types – German DWA M-519 Code of Practice – Chapter 2.2.1 and Appendix B

Chapter	Designation
2.1.1	BW 1: Reed mat with vegetation roll as foot protection
2.1.2	BW 2: Pre-vegetated slope mat with grass
2.1.3	BW 3: Pre-vegetated slope mat with hardwood cuttings
2.1.4	BW 4: Willow weave
2.1.5	BW 5: Living fascine with hardwood cuttings
2.1.6	BW 6: Vegetated geotextile bodies with (hedge) brush (bush) layers
2.1.7	BW 7: Chamber revetment (vegetated stone mattresses, reed gabions)
2.1.8	BW 8: Willow brush mattresses with heavy riprap as toe reinforcement
2.1.9	BW 9: Vegetated riprap



Basic Types – British Waterway Management Guide (1999) – Chapter 2.2.6 and Appendix C

Chapter	Designation
2.2.1	Grass revetment
2.2.2	Reed planting
2.2.3	Life willow on toe and bank
2.2.4	Grassed composites
2.2.5	Toe rolls, rock and fibre – timber and vegetation
2.2.6	Toe geotextile - fibre rolls
2.2.7	Rock and fibre roll
2.2.8	Vegetated open cell Revetments
2.2.9	Vegetated stone revetment
2.2.10	Vegetated concrete units revetment



Basic Types – UK Green Approaches in River Engineering – Chapter 2.3

Chapter	Designation
2.3.1	Willow spilling/bundles
2.3.2	Turf vegetated reinforced mattresses/seeded geotextile
2.3.3	Life root wads
2.3.4	Willow brush mattresses on coir matting

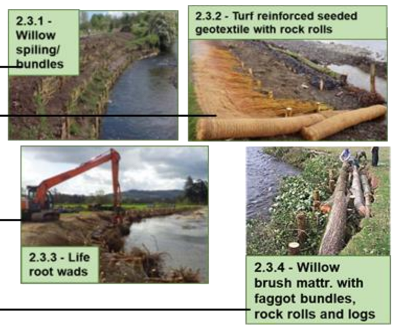


Table 4-4: List and visualisation of all BTs considered in this report with chapter name in Part 2

Using the search criteria mentioned in Chapter 4.1, the BTs in the measure collection can be characterised according to the next two tables (Table 4-5 and Table 3-6).

The tables give an overview on key characteristics grouped as follows: site conditions, design features, objectives, and achievements. For every subdivision of the characteristic groups, possible categories are given. For every measure, the corresponding key characteristics are marked in the table with an *X*. More than one category can be marked in a specific subdivision. In this way, the table provides an overview of key characteristics in relation to all measures.

		relevant (site) boundary conditions																					important design features											
paragraph Part 2	name measure	waterway type			average bank slope			subsoil			ship-induced impact			space availability		surrounding land uses			invasive plant specie		water quality		flanking measures			pre-embankment			direct measures			construction components		
		canals and lakes	impounded rivers	free flowing rivers	flat (as inner bank)	normal (≈1:3)	steep (as outer bank)	stony, coarse gravel	gravelly - sandy	loamy and silty	negligible to low (H ≤ 0,2 m)	average (H≈0,3-0,4 m)	high (H > 0,5 m)	in the aquatic zone	in the amphibian/terrestrial zone	largely naturalized	extensive land use	intensive urban or agricultural	low extent, introduction or spread	dominate and introduction likely	good physico-chemical quality	major deficits in physico-chemical q	river training measures	speed limits	fairway relocation	far from bank	close to bank	mostly linear	mostly planar (covering)	combined measures	bioengineering (plants)	biotechnical (techn. comp.)	structural engineering	fully conventional
2.1.1	Reed mat with vegetation roll as foot protection	x	x		x	x			x	x	x	x			x	x	x	x	x					(x)					x		x			
2.1.2	Pre-vegetated slope mat with grass	x	x		x	x			x	x	x				x	x	x	x	x					(x)					x		x			
2.1.3	Pre-vegetated slope mat with hardwood cuttings	x	x		x	x			x	x	x				x	x	x	x	x					(x)					x		x			
2.1.4	Willow weave	x	x				x		x	x	x					x	x	x	x					(x)				x	(x)		x			
2.1.5	Living fascine with hardwood cuttings	x	x	(x)			x		x	x	x	x				x	x	x	x					(x)				(x)	x		x			
2.1.6	Vegetated geotextile bodies with (hedge) brush (	x	x	(x)			x		x	x	x	x	x			x	x	x	x	(x)				(x)					x			x		
2.1.7	Chamber revetment (vegetated stone mattresses,	x	x	(x)	x	x		x	x	x	x	x	(x)		(x)	x	x	x	x					(x)					x			x		
2.1.8	Willow brush mattresses with heavy riprap as toe	x	x	x	x	x			x	x	x	x	(x)		(x)	x	x	x	x	x				(x)					x		x			
2.1.9	Vegetated riprap	x	x	x	x	x	x	x	x	x	x	x	x		(x)	x	x	x	x	x				(x)					x		x	x	x	
2.2.1	Grass revetment	x	x	x	x	x	(x)		x	x	x				(x)		(x)	x	x		x								x		x			
2.2.2	Reed planting	x	x		x			x	x	x	x			x	(x)	x	(x)		x		x		x				x		x	x	x			
2.2.3	Life willow on toe and bank	x	x	x	x	x	x		x		x				x	x	x		x		x							x	x	x	x			
2.2.4	Grassed composites	x	x	x	x	x			x	x	x	(x)			(x)		(x)	x	x		x								x			x		
2.2.5	Toe rolls, rock and fibre	x	x			x	x		x	x	x			x	x	(x)	x		x	(x)	x	(x)						x		x		x		
2.2.6	Toe geotextile - fibre rolls	x	(x)		x	(x)			(x)	x	x			x	(x)	(x)	x	(x)	x	(x)	x	(x)						x		x		x		
2.2.7	Rock and fibre roll	x	(x)			x	x		x	x		x	(x)	x	(x)	(x)	x	(x)	x	(x)	x	(x)						x		x		x		
2.2.8	Vegetated open cell revetments	(x)	x	x		x	x	x	x	x		x	(x)	x	(x)		x	x	x		x								x			x		
2.2.9	Vegetated stone revetment	x	x	x		x	(x)	x	x				x	x	(x)		(x)	x	x	(x)	x								x				x	
2.2.10	Vegetated concrete units revetment	x	x	x		x	(x)	x	x			(x)	x	x	(x)		x	(x)	x	(x)	x	(x)							x	(x)			x	(x)
2.3.1	Willow spilling/bundles	x	x	x	x	x	x	(x)	x	x	x	x	(x)		(x)	x	x	x	x	x								x			x			
2.3.2	Turf vegetated reinforced mattresses/seeded geo	x	x		x	x	(x)		x	x	x	x			(x)	x	x	x	x										x		(x)	x		
2.3.3	Life root wads	x	x	(x)	x	x		(x)	x	x	x	x	(x)		(x)	x	x	x										x			x			
2.3.4	Willow brush mattresses on coir matting	x	x	x	x	x			x	x	x	x	(x)		(x)	x	x	x	x	x									x		x			

Table 4-5: Overview of screening criteria concerning BCs and design features – BTs

paragraph Part 2	name measure	(possible) key objectives												(potentially) achieved goals											
		stability demands			economic aims			strived ecological output						technical			economical			achieved ecological output					
		high, because of high risk	average	low as low risk if bank fails	low costs olution needed	expenses ≈ riprap	higher costs acceptable	aquatic habitats	amphibian/terrestrial habitats	vegetation complexity	habitat connectivity	sustainability	ecosystem services	high stability & durability	acceptable local damages	erosion occurs	low costs olution	expenses ≈ riprap	higher costs acceptable	aquatic habitats	amphibian/terrestrial habitats	vegetation complexity	habitat connectivity	sustainability	ecosystem services
2.1.1	Reed mat with vegetation roll as foot protection		(x)	x			x		x	x	x	x	(x)												
2.1.2	Pre-vegetated slope mat with grass			x			x		x	x	x	x	(x)												
2.1.3	Pre-vegetated slope mat with hardwood cuttings			x	x		x		x	x	x	x	(x)												
2.1.4	Willow weave			x	x				x	x	x	x	(x)												
2.1.5	Living fascine with hardwood cuttings			x			x		x	x	x		(x)												
2.1.6	Vegetated geotextile bodies with (hedge) brush (I	(x)	x				x		x	x	(x)	(x)													
2.1.7	Chamber revetment (vegetated stone mattresses,	x	x				x		x	x	x														
2.1.8	Willow brush mattresses with heavy riprap as toe		x	x		x			x	x	x	x	x												
2.1.9	Vegetated riprap	x	x			(x)	x		x	x	x	(x)	(x)												
2.2.1	Grass revetment			x	x				x	(x)	(x)		(x)		x		x					(x)	(x)		x
2.2.2	Reed planting			x		x		x	x	x	(x)	x	x		x		x			(x)	x	(x)	x	(x)	x
2.2.3	Life willow on toe and bank		x	x	x				(x)	x	x	x	x		x		x	x			(x)	x	x	(x)	x
2.2.4	Grassed composites		x			x			x	(x)	(x)	(x)	(x)		x			x			(x)	(x)	(x)		x
2.2.5	Toe rolls, rock and fibre		x	x	x	x		(x)	x	(x)		(x)	x		x		(x)	x		(x)	x	(x)	(x)		x
2.2.6	Toe geotextile - fibre rolls		x	x	x	x		(x)	x	(x)		(x)	x		x		x	x		(x)	x	(x)			x
2.2.7	Rock and fibre roll	(x)	x		x	x		(x)	x	(x)		(x)	x	(x)	x		x	(x)		(x)	x	(x)			x
2.2.8	Vegetated open cell revetments	(x)	x			x			x		(x)		(x)	(x)	x			x			x		(x)		(x)
2.2.9	Vegetated stone revetment	x	(x)			x	(x)		x		(x)		(x)	x	(x)			x			x	(x)	(x)		(x)
2.2.10	Vegetated concrete units revetment	x	x			(x)	x		x					(x)	x			(x)	x		x				
2.3.1	Willow spilling/bundles		x	(x)		x			x	(x)	(x)	x	x												
2.3.2	Turf vegetated reinforced mattresses/seeded geo		x	x	x	(x)			x	x	(x)	x	x												
2.3.3	Life root wads		x	x		x			x	x	x	x	x												
2.3.4	Willow brush mattresses on coir matting		x	x			x		x	x	x	x	x												

Table 4-6: Overview of screening criteria concerning key design objectives and achieved goals – BTs

4.3 Fact Files (FFs) of Implemented Measures

FFs of measures provide more comprehensive information that the BTs: objectives of the planners; construction details (materials used, cross section, plan view); on-site implementation details (location, time line, maintenance measures taken); relevant local BCs (commercial and recreational navigation and ship-induced loads, hydraulic impacts, climate, natural vegetation, fauna, waterway properties, bank geometry and hinterland, soil properties); and evaluation results (monitoring, stability, economic aspects, ecological benefits, maintenance, and long-term effects) as well as overall results, lessons learned, and recommendations for further applications.

Especially all the data needed to understand the preselection tools can be found in the FFs. The FF measures are generally a combination of BTs that were adapted to the local BCs and planner's aims. Nevertheless, they also provide guidance on how to improve their functionality even and how they may be adapted to other conditions. FFs are thus – where applicable – more useful than the BTs.

The FFs collection in Part 2 of this report is structured around two parameters: water-level fluctuations and ship-induced impacts. As stated in Chapter 4.1, another way to search the FF collection is to use the next two tables (Table 4-7 and Table 4-8), which provide an overview of the applicability of the measures in relation to the complete set of criteria.

The following tables provide first the measure name, which was chosen according to the chapter number in Part 2, and then the designation, which is simply the headline of the corresponding chapter. Finally, the measures are shown in the same way as the overview of all measures in Part 2.

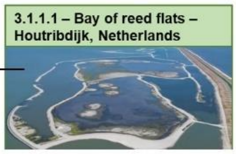
These same illustrations occur at several points in this report; for example, in Chapter 6, where all the recommended approaches are applied using examples to visualise the results. Use the following lists and visualisations especially when applying the preselection tools, which offer, for example, ranking lists of appropriate measures where only the chapter name of the measure is listed. Note that the visualisation uses abbreviated measure names.

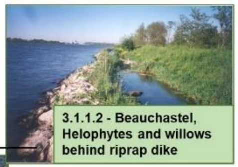
Type	Group		Number of measures	Paragraph in Part 2 of Report
FFs	Waterways with low water-level fluctuations	Weak ship-induced impacts	3	3.1.1.1 to 3.1.1.3
		Average ship-induced impacts	6	3.1.2.1 to 3.1.2.6
		Strong ship-induced impacts	5	3.1.3.1 to 3.1.3.5
	Waterways with moderate water-level fluctuations	Weak ship-induced impacts	2	3.2.1.1 to 3.2.1.2
		Average ship-induced impacts	4	3.2.2.1 to 3.2.2.4
		Strong ship-induced impacts	2	3.2.3.1 to 3.2.3.2
	Waterways with high water-level fluctuations	Weak ship-induced impacts	3	3.3.1.1 to 3.3.1.3
		Average ship-induced impacts	3	3.3.2.1 to 3.3.2.3
		Strong ship-induced impacts	3	3.3.3.1 to 3.3.3.3

Table 4-7: Structure of the FFs collection in Part 2

Fact Files – Low water level changes

Chapter	Impact	Designation
3.1.1.1	low	Bay of reed flats - Houtribdijk & Trintelzand Lelystad, Netherlands
3.1.1.2	low	Reed bed, helophytes and willows protected by a riprap dike – Left bank of the Rhône River - Beauchastel – France
3.1.1.3	low	Helophytes plantings on a silty flat – Lac du Lit au Roi on the Rhône River – Massigneude Rive – France
3.1.2.1	average	Reed Transplant Project Ramspol & Zwartemeer
3.1.2.2	average	Reed Ecological Revetment Project in Huai'an-Huaiyin Section of Beijing-Hangzhou Canal
3.1.2.3	average	Precast-box bank revetment - Danjin-Licao River Channel Regulation Project, Jintan City, China
3.1.2.4-1	average	Palisades protecting reed belts and bank slopes in the impounded Lower Havel River at Berlin, Germany - site 1 (Pichelsdorf)
3.1.2.4-2	average	Palisades protecting reed belts and bank slopes in the impounded Lower Havel River at Berlin, Germany - site 2 (Schildhorn)
3.1.2.4-3	average	Palisades protecting reed belts and bank slopes in the impounded Lower Havel River at Berlin, Germany - site 3 (Imchem)
3.1.2.5	average	Artificial Bay Habitat - Oder-Havel-Canal, Berlin, Germaany
3.1.2.6	average	Recreation of a helophyte's reed bed on a silty flat - Rhône River – Rochemaure, Fr
3.1.2.7	average	Projected fish-friendly sheet pile wall
3.1.3.1	high	Shallow water zone behind stone wall and slope protection with vegetated concrete blocks towards the hinterland at Yanhe River, China
3.1.3.2	high	Wake wash protected shallow water zone - Example: protection by sheet pile wall in the Teltowcanal
3.1.3.3	high	Shallow water zone protected by parallel dam – example Canal Ghent-Bruges
3.1.3.4	high	Shallow water zone with reed plantings between existing eroded embankment and gabion parallel dam – example urban area, Canal Leuven-Dijle
3.1.3.5	high	Ecological upgrade by dumping sewer pipes – Riodam Project Groene Poort Rotterdam

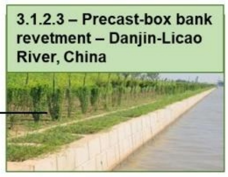

3.1.1.1 – Bay of reed flats – Houtribdijk, Netherlands


3.1.1.2 - Beauchastel, Helophytes and willows behind riprap dike


3.1.1.3 - Helophytes plantings on a silty flat – Lac du Lit au Roi, Rhone


3.1.2-1 - Zwartemeer, reed transplant project


3.1.2.2 - Beijing-Hangzhou, reed ecol. revetment

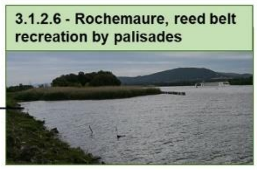

3.1.2.3 – Precast-box bank revetment – Danjin-Licao River, China


3.1.2.4-1 - Unterhavel, palisades protecting reed - site Pichelsdorf


3.1.2.4-2 - Unterhavel, palisades protecting reed - site Schildhorn


3.1.2.4-3 - Unterhavel, palisades protecting reed - site Imchen


3.1.2.5 – Artificial bay habitat – Oder-Havel Canal


3.1.2.6 - Rochemaure, reed belt recreation by palisades


3.1.2.7 - Project fish-friendly sheet pile with various underwater openings


3.1.3.1 - Yanhe River: Shallow behind stone wall and slope protection with vegetated concrete blocks


3.1.3.2 - Teltow Canal, sheet pile protected shallow


3.1.3.3 - Canal Ghent-Bruges, dam protects shallow


3.1.3.4 - Canal Leuven-Dijle, reed plantings between eroded bank and gabion dam


3.1.3.5 Groene Poort, ecol. upgrade, dumping sewer pipes

Fact Files – Average water level changes

Chapter	Impact	Designation
3.2.1.1	low	Redesigned Floodplain in a Canalised river without current - Hemelrijkse Waard in the Maas river
3.2.1.2	low	Branches layers and helophyte fascines - left bank of the Rhône River - Saint-Vallier - France
3.2.2.1	average	Poles and fascines pre-embankment in front of shallow water zone – example Moervaart Canal (B)
3.2.2.2	average	Willow branches in riprap facing – Rhône river - Saint Vallier - France
3.2.2.3	average	Flat profile with sedges and reed bed – right bank of the Rhône River - Péage de Roussillon - France
3.2.2.4	average	Wood barriers, reed plantings, softwood planting – Aller, near Essel, Germany
3.2.3.1	high	Shallow water zone protected by a sheet pile wall with top openings – example urban area, Spree River at Berlin, Germany
3.2.3.2	high	Shallow water zone with reed plantings protected by a wooden palisade – example River Leie (B)

Fact Files – High water level changes

Chapter	Impact	Designation
3.3.1.1	low	Redesigning delta river Floodplains, Heesseltsche Uiterwaarden
3.3.1.2	low	Nature development in a former sand-extraction site – River Waal, Netherlands
3.3.1.3	low	Groyne Field and Slope Stabilization by a Strong Wattle Fence at Gernsheim, Rhine
3.3.2.1	average	Gravel bank stabilization by a parallel dyke and wattle fences at Worms, Rhine
3.3.2.2	average	Wake wash protected shallow water zone – protection by a parallel dam in the German Oder River near Reitwein
3.3.2.3	average	Willow brush mattresses in the German Aller River near Eilte
3.3.3.1	high	Protection technology of soil river bank slope with vetiver grass —Jinjiang River, Changsha
3.3.3.2	high	Compound ecological slope protection for fluctuating zone in Mountainous Reservoir —Xiaojiang River, extreme water level fluctuations
3.3.3.3	high	Pre-cultivated Plant Mats – Rhine, near Worms, Germany

Table 4-8: List and visualisation of all FFs considered in this report with chapter name in Part 2

paragraph Part 2	name measure	relevant (site) boundary conditions																					important design features											
		waterway type			average bank slope			subsoil			ship-induced impact			space availability		surrounding land uses			invasive plant species		water quality		flanking measures			pre-embankment			direct measures			construction components		
		canals and lakes	impounded rivers	free flowing rivers	flat (as inner bank)	normal (≈ 1:3)	steep (as outer bank)	stony, coarse gravel	gravelly - sandy	loamy and silty	negligible to low (H ≤ 0,2 m)	average (H≈ 0,3- 0,4 m)	high (H > 0,5 m)	in the aquatic zone	in the amphibian/terrestrial zone	largely naturalized	extensive land use	intensive urban or agricultural	low extent, introduction or spread	dominate and introduction likely	good physico-chemical quality	major deficits in physico-chemical q	river training measures	speed limits	fairway relocation	far from bank	close to bank	mostly linear	mostly planar (covering)	combined measures	bioengineering (plants)	biotechnical (techn. comp.)	structural engineering	fully conventional
3.1.1.1	Bay of reed flats – Houtribdijk and Trintelzand																																	
3.1.1.2	Reed bed, helophytes and willows protected by a	x	x			x		x	x			x	(x)	x	(x)	(x)	x			(x)	x				x	x	x	x		x			x	x
3.1.1.3	Helophyte plantings on a silty flat – Lac du Lit	x	x		x					x	x													x		x			x		x			
3.1.2.1	Reed Transplant Project Ramspol & Zwartemeer																																	
3.1.2.2	Reed Ecological Revetment Project in Huai'an-Hua	x		(x)		x	x	x		x		x	x	x	x		x	x	x			x	x	x			x			x	x	x	x	
3.1.2.3	Precast-box bank revetment – Danjin-Licao River	x			x	x			(x)	x		x	x	x	(x)		x	x	x		x		x	x			x		x	x	x	x	x	
3.1.2.4	Palisades protecting reed belts and bank slopes in	x	(x)		x	(x)			(x)	x	x			x	x		(x)	x	x		x	(x)		x		x		x		(x)	x	x		
3.1.2.4	Palisades protecting reed belts and bank slopes in	x	(x)			x			(x)	x		x		(x)	x		(x)	x	x		x	(x)		x			x	x		(x)	x	x		
3.1.2.4	Palisades protecting reed belts and bank slopes in	x	(x)			x			(x)	x		x		(x)	x	(x)	(x)	x	x		x	(x)		x			x	x		(x)	x	x		
3.1.2.5	Artificial bay habitat – Oder-Havel Canal, Berlin	x					x		x		x	(x)	(x)	x	x		x		x		x			x			x			x		x	x	
3.1.2.6	Recreation of a helophyte's reed bed on a silty flat	x	x		x					x		x	x											x		x		x	x	x	x	x	x	
3.1.3.1	Shallow water zone behind stone wall and slope p	x		x			x		x	(x)			x		x		x		x			(x)	x	x			x			x			x	
3.1.3.2	Wake wash protected shallow water zone - Examp	x					x		x	x		x		x				x						x			x	x	x	x			x	
3.1.3.3	Shallow water zone protected by parallel dam – ex	x	(x)			x				x		x		x	x		x		x		x			x			x		x	x		x	x	
3.1.3.4	Shallow water zone with reed plantings between	x					x		x	x	x				x			x	x		x	(x)		x			x	x			x	x		
3.2.1.1	Redesigned Floodplain in a Canalised river withou																																	
3.2.1.2	Branches layers and helophyte fascines - left bank	x	x	x		x			x	x	x	x											x	x		x		x		x	x	x	x	
3.2.2.1	Poles and fascines pre-embankment in front of sh	x					x			x	x			x	x		x		x		x			x			x	x				x		
3.2.2.2	Willow branches in riprap facing – Rhône river - Sa		x	x		x	x	x	x				x												x		x			x	x			x
3.2.2.3	Flat profile with sedges and reed bed – right bank			x	x			x	x		x	x											x			x			x	x	x		x	x
3.2.2.4	Wood barriers, reed plantings, softwood planting	x	x	(x)	x	x			x	x	x	x		x	(x)	x	x	x	x		x	(x)	(x)	x		x	x	x	x		x	x		
3.2.3.1	Shallow water zone protected by a sheet pile wall	x	x				x		x	x		x			(x)			x	x	(x)	x	(x)		x			x	(x)	x	x	x		x	
3.2.3.2	Shallow water zone with reed plantings protected	(x)	x		x				x	x		x		x			x		x		x			x			x	x				x	x	
3.3.1.1	Redesigning delta river Floodplains, Heesseltsche																																	
3.3.1.2	Nature development in a former sand-extraction site																																	
3.3.1.3	Groyne Field and Slope Stabilization by a Strong W		(x)	x	x	(x)			x	x	x	x		x	x	(x)	x		x	(x)	x		x		(x)	(x)	x	x			x	x		
3.3.2.1	Gravel bank stabilization by a parallel dyke and wa		(x)	x	x	(x)		x	x		x	x		x	x	(x)	x		x	(x)	x		x		(x)		x	x			x	x		
3.3.2.2	Wake wash protected shallow water zone – protec			x	x				x		x			x		x			x		x		x			(x)	x	x		x			x	
3.3.2.3	Willow brush mattresses in the German Aller River	x	x	x	x	x			x	x	x	x	x		x	x	x	x	x	x									x		x	x		
3.3.3.1	Protection technology of soil river bank slope with			x		x			(x)	x			x	x	x	(x)	(x)		x		(x)		x	x			x			x	x			
3.3.3.2	Compound ecological slope protection for fluctuat	(x)	x			(x)	x	(x)	x		x				x		x	x		x	x		x	x	x		x			x	x	x	(x)	
3.3.3.3	Pre-cultivated Plant Mats – Rhine, near Worms, Ge	x	x	(x)	x	x			x	x	x	x			x	x	x	x	x					(x)					x		x			

Table 4-9: Overview of search criteria concerning BCs and design features – FFs

paragraph Part 2	name measure	(possible) key objectives												(potentially) achieved goals											
		stability demands			economic aims			strived ecological output						technical			economical			achieved ecological output					
		high, because of high risk	average	low as low risk if bank fails	low cost solution needed	expenses ≈ riprap	higher costs acceptable	aquatic habitats	amphibian/terrestrial habitats	vegetation complexity	habitat connectivity	sustainability	ecosystem services	high stability & durability	acceptable local damages	erosion occurs	low cost solution	expenses ≈ riprap	higher costs acceptable	aquatic habitats	amphibian/terrestrial habitats	vegetation complexity	habitat connectivity	sustainability	ecosystem services
3.1.1.1	Bay of reed flats – Houtribdijk and Trintelzand																								
3.1.1.2	Reed bed, helophytes and willows protected by a		x			x	x	x	x		x			x				x	x	x	x	(x)		x	
3.1.1.3	Helophyte plantings on a silty flat – Lac du Lit			x	x			x		x			x		x	x	x			x		x		x	x
3.1.2.1	Reed Transplant Project Ramspol & Zwartemeer																								
3.1.2.2	Reed Ecological Revetment Project in Huai'an-Hua		x			x	x	x	x	x	x	x	x		x			x	x	x	(x)	x	(x)	x	x
3.1.2.3	Precast-box bank revetment – Danjin-Licao River	x			x	x			(x)		x	x	x	x			x	x			(x)		x	x	(x)
3.1.2.4	Palisades protecting reed belts and bank slopes in		x	x	x	(x)		x	x		x	x	x		x		(x)	x		x	x		(x)		(x)
3.1.2.4	Palisades protecting reed belts and bank slopes in		x		x	(x)		x	x		x	x	x		x		(x)	x		x	x	(x)	(x)	(x)	x
3.1.2.4	Palisades protecting reed belts and bank slopes in		x		x	(x)		x	x		x	x	x		x			x		(x)			(x)		(x)
3.1.2.5	Artificial bay habitat – Oder-Havel Canal, Berlin	x				x		x			x		x	(x)	x			x		(x)		x	x	x	x
3.1.2.6	Recreation of a helophyte's reed bed on a silty flat			x	x			x		x	x	x	x			x	x			x		x	x	x	x
3.1.3.1	Shallow water zone behind stone wall and slope p	x	(x)			x	(x)		(x)	(x)		(x)		x				x			x	x		(x)	
3.1.3.2	Wake wash protected shallow water zone - Examp	x				x	(x)	x						x				x	(x)	x				(x)	(x)
3.1.3.3	Shallow water zone protected by parallel dam – ex		x				x	x		x	x			x					x	x		x			
3.1.3.4	Shallow water zone with reed plantings between	x					x	x		x				x					x	x					
3.2.1.1	Redesigned Floodplain in a Canalised river withou																								
3.2.1.2	Branches layers and helophyte fascines - left bank	x			x				x	x	x	x	x		x		x				x	x	x	x	x
3.2.2.1	Poles and fascines pre-embankment in front of sh		x			x		x	x	x					x			x			x	x			
3.2.2.2	Willow branches in riprap facing – Rhône river - Sa	x				x	x				x	x		x				x	x		x		x	x	
3.2.2.3	Flat profile with sedges and reed bed – right bank			x		x		x	x	x	x	x	x		x	x		x	x	x	x	x	x	x	x
3.2.2.4	Wood barriers, reed plantings, softwood planting		x	x		x	(x)	x	x	x	x	x	x	(x)				x	(x)	x	(x)	(x)	(x)	x	(x)
3.2.3.1	Shallow water zone protected by a sheet pile wall	x				x		x	x					x				x		x	x		(x)		x
3.2.3.2	Shallow water zone with reed plantings protected	x				x		x	x							x		x			x	x			
3.3.1.1	Redesigning delta river Floodplains, Heesseltsche																								
3.3.1.2	Nature development in a former sand-extraction site																								
3.3.1.3	Groyne Field and Slope Stabilization by a Strong W		x	x	x	x		(x)	x	x	x	x	x	x			x			(x)	x	(x)	(x)	(x)	x
3.3.2.1	Gravel bank stabilization by a parallel dyke and wa		x	x	x	x		(x)	x	x	x	x	x	x			x			(x)	x	(x)	x	(x)	x
3.3.2.2	Wake wash protected shallow water zone – protec			x			x	x				x		(x)	x				x	x				(x)	
3.3.2.3	Willow brush mattresses in the German Aller Rive		x	x		x			x	x	x	x	x	x	(x)			(x)	x		x	(x)	x	x	x
3.3.3.1	Protection technology of soil river bank slope with			x	x			x	(x)	x	(x)	(x)	(x)	(x)			x			x	(x)	x	x	x	(x)
3.3.3.2	Compound ecological slope protection for fluctuat	x	x			x		x	(x)	x	x	(x)	x	(x)	x			x		(x)	(x)	x	x	(x)	(x)
3.3.3.3	Pre-cultivated Plant Mats – Rhine, near Worms, Ge		(x)	x			x		x	x	x	x	(x)			(x)			x		x	x	(x)	(x)	x

Table 4-10: Overview of search criteria concerning key design objectives and achieved goals – FFs

4.4 Case Studies (CSs)

CSs contain, in general, all the information of the FFs but with comprehensive detail and much more background information. Thus, they are very useful for understanding the recommended detailed design approach shown in Chapter 6; that is, to show users the complex design approach that led to the described measures.

Similar to the BTs and the FFs, the CSs are also characterised concerning the criteria mentioned under Chapter 4.1, as follows:

Case Studies

Chapter	Water level changes	Designation
4.1.1	low	Shallow water zone behind parallel dam on the Brussels-Schelt canal
4.1.2	low	Shallow water zone behind sheet pile wall on Brussels-Schelt canal
4.2.1	moderate	Projected wide shallow water zone behind a sheet pile wall with various adjustable top and underwater openings, Spree-Havel Confluence, Berlin
4.3.1	high	Vegetated riprap, erected 2011 on the right bank of the River Rhine near Worms, Germany
4.3.2	high	Vegetated gabions (reed gabions), erected 2011 on the right bank of the River Rhine near Worms, Germany
4.3.3	high	Living brush mattresses, installed in 2011 on the right bank of the river Rhine close to Worms, Germany

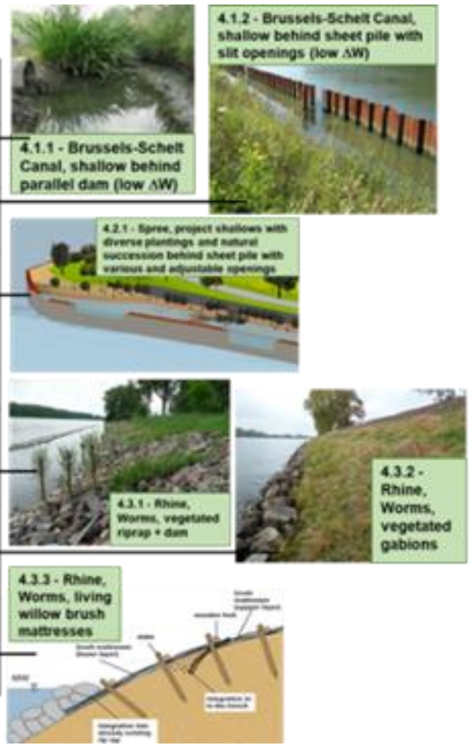


Table 4-11: List and visualisation of all CSs considered in this report with chapter name in Part 2

paragraph Part 2	name measure	relevant (site) boundary conditions: waterway type			average bank slope			subsoil			ship-induced impact			space availability		surrounding land uses			invasive plant species		water quality	
		canals and lakes	impounded rivers	free flowing rivers	flat (as inner bank)	normal (≥1:3)	steep (as outer bank)	stony, coarse gravel	gravelly - sandy	loamy and silty	negligible to low (H ≤ 0.2 m)	average (H≈0.3- 0.4 m)	high (H > 0.5 m)	in the aquatic zone	in the amphibian/terrestrial zone	largely naturalized	extensive land use	intensive urban or agricultural	low extent, introduction or spread	dominate and introduction likely	good physico-chemical quality	major deficits in physico-chemical q
4.1.1	Shallow water zone behind parallel dam on the Br	x	(x)			x				x		x	x	x	x		x			x	(x)	
4.1.2	Shallow water zone behind sheet pile wall on Brus	x	(x)			x				x		x	x	x			x			x	(x)	
4.2.1	Projected shallow water zone with adjustable ope	x	x				x		(x)	x		(x)	x	(x)	(x)			x	x	(x)	x	(x)
4.3.1	Vegetated riprap, erected 2011 on the right bank o	x	x	x	x	x	x	x	x	x	x	x	x		(x)	x	x	x				
4.3.2	Vegetated gabions (reed gabions), erected 2011 or	x	x	(x)	x	x			x	x	x	x			x	x	x	x	x			
4.3.3	Living brush mattresses, installed in 2011 on the ri	x	x	x	x	x			x	x	x	x	(x)		(x)	x	x	x	x	x		

Table 4-12: Overview of search criteria concerning BCs and design features – CSs

paragraph Part 2	name measure	(possible) key objectives												(potentially) achieved goals											
		stability demands			economic aims			strived ecological output						technical			economical			achieved ecological output					
		high, because of high risk	average	low as low risk if bank fails	low cost solution needed	expenses ≈ riprap	higher costs acceptable	aquatic habitats	amphibian/terrestrial habitats	vegetation complexity	habitat connectivity	sustainability	ecosystem services	high stability & durability	acceptable local damages	erosion occurs	low cost solution	expenses ≈ riprap	higher costs acceptable	aquatic habitats	amphibian/terrestrial habitats	vegetation complexity	habitat connectivity	sustainability	ecosystem services
4.1.1	Shallow water zone behind parallel dam on the Br	x					x	x	x	x				x					x	x	x	x			
4.1.2	Shallow water zone behind sheet pile wall on Brus	x					x	x		x					x				x	x					
4.2.1	Projected shallow water zone with adjustable ope	x				(x)	x	x	x	x	(x)	(x)	(x)	x				(x)	x	x	x	x	(x)	(x)	(x)
4.3.1	Vegetated riprap, erected 2011 on the right bank o	x	(x)			(x)	x		x	x	x	(x)	(x)	x					x		x	x	x	x	(x)
4.3.2	Vegetated gabions (reed gabions), erected 2011 o	x	x				x		x	x	x					(x)			x			(x)			
4.3.3	Living brush mattresses, installed in 2011 on the ri		x	x		x			x	x	x	x	x		(x)	(x)		x	x		x	(x)	x	(x)	x

Table 4-13: Overview of search criteria concerning key design objectives and achieved goals – CSs

4.5 Design Case (DC) and New Measure Combinations

The combination of BTs and fitting measures to local conditions in the course of the recommended preselection and detailed design approach will be discussed in Chapter 5.

Assessments concerning possible application ranges to BCs and reachable functionality issues are provided. These assessments were performed by the members of the WG on the basis of their subject-matter-expert knowledge and allow users to design their own measure combinations.

Application examples

Chapter	Water level changes	Designation
5.3.1	moderate	Design Case Example: German Weser River at Stolzenau
5.3.2	high	Analysis Case Example: Willow Brush Mattresses, Rhine, Worms (identical to measure 4.3.3)

Table 4-14: List and visualisation of the Design Case (DC) and a standard Analysis Case (AC) with chapter name in Part 3

4.6 Conclusions Concerning the Preselection of Measures and the Detailed Design

Because of the complex nature and interdependency of the governing processes that determine the applicability of technical-biological measures on a specific site, the preselection approach (including screening) is not deterministic but rather predictive according to well-chosen parameters.

The proposed approach takes practical implementation experiences with measures, both generic basic measures and implemented measures on specific sites, to predict the applicability of these measures on the planned site considered by the user of this report.

An implemented measure that performs well under certain conditions or demands can be presumed to perform comparably well under comparable conditions or demands.

5 PRESELECTION OF APPROPRIATE MEASURES

As outlined already in the executive summary and in the beginning of Chapter 1, the three parts of this report are strongly interrelated. With reference to the corresponding Chapter 5 in Part 3, only the content of this chapter, the basic principles of the recommended preselection approach, and selected application results will be outlined here, which correspond to Chapters 5.1 and 5.2 in Part 3.

This is, because Part 1 focuses on providing basic information only, whereas Part 3 is written for users (that is, practitioners and planners) of the BPA. Also, Chapter 6 provides here only basic information about the corresponding Chapter 6 in Part 3, which guides the user step-by-step through the entire design approach.

How the three parts are intercorrelated and which chapter may be useful for different users is shown in Figure 5.1. For example, all chapter numbers in Parts 1 and 3 correspond to one another, whereby Chapters 1-4 are very extensive in Part 1, as they provide basic information, but very brief in Part 3, because they assume background knowledge and prior experience on those topics. The summaries in Part 3 only include information essential for understanding the application of the BPA. By contrast, the following Chapters 5 and 6 are very short – only to understand the approach – but Chapters 5 and 6 in Part 3 are much longer and more comprehensive, so that users can understand and apply all design steps correctly.

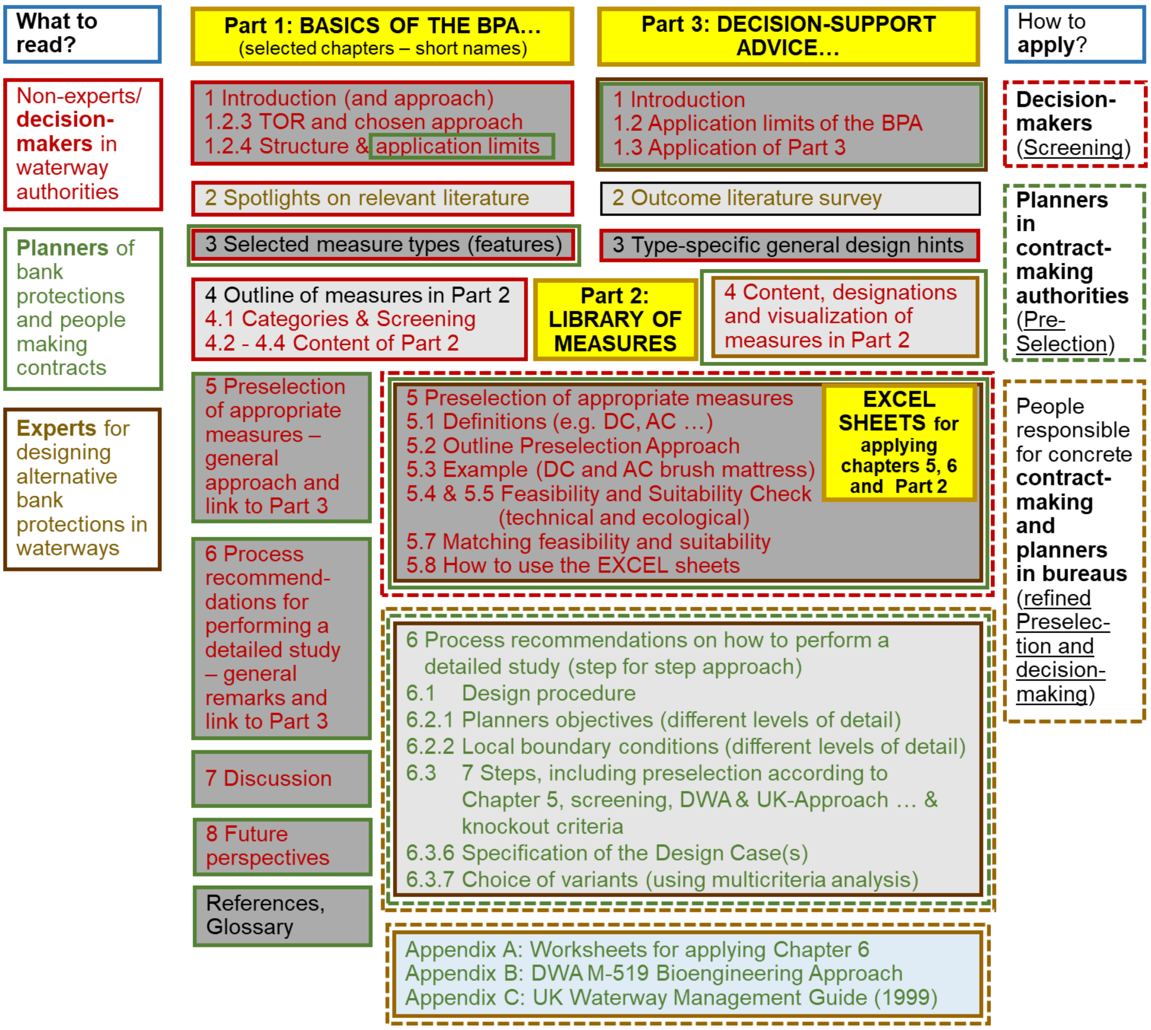


Figure 5.1: Correlations between the three parts of the report

The preselection of measures, which is outlined in the following chapter, is only one of the 7 Steps of the detailed design approach, which is described in the next chapter. Therefore, even if it is generally recommended to follow the entire design approach recommended herein, especially to consider knockout criteria (such as possible discrepancies between budget and costs) – and, thus, to come up with more realistic solutions – the preselection step is nevertheless a very important design step. It allows defining the possible solution space of appropriate, preferably green, measures, and it facilitates the generally recommended approach to the measure descriptions in Part 2 by allowing users to focus only on their preselected measures.

A detailed design study should address all relevant design criteria when selecting appropriate measures as well as the aforementioned knockout criteria, which may number greater than those criteria used for preselection. This approach is necessary to end up in a preferably quantified comparison of selected variants, implemented by using multicriteria approaches on the basis of the analytic hierarchy process (AHP); see next Chapter 6 and the corresponding chapter in Part 3.

Nevertheless, as the recommended design approach, the BPA is still and mainly a *selection* approach for planners, not a tool to determine all construction elements in detail. Even if it goes very far in many cases, including the layout of technical elements if users consult the detailed measure descriptions in Part 2, and may therefore be sufficient for supporting detailed planning, the BPA still remains primarily a selection tool. So, uses may need to, for example, determine the profile and bonding depth of a sheet-pile wall for protecting shallows against wave attack or to design the thickness of greened river mattresses to counteract excess pore water pressure.

The strength of the BPA for selecting and in broad outline designing TBPs, which is outlined here briefly and in Part 3 very comprehensively, lies primarily in the consideration of numerous relevant design criteria to support planners. This strength is especially evident in the report's structured approach, which allows an objective comparison of variants. But even if the number of criteria used for preselection is strongly restricted compared with those used for the AHP in Chapter 6 and the results may thus be called more or less *qualitatively* compared with the detailed design, they may nevertheless be sufficient to convince decision-makers on the possibilities of alternatives to technical solutions. This ability to strongly support the choice of TBP measures is the main purpose of the preselection approach. Finally, the preselection scores for different criteria can be used directly as a first estimate for corresponding AHP scores; see Chapter 6 for more details.

5.1 Scope of the Preselection Approach

The basic idea behind the BPA is that there is a strong link between (1) relevant design criteria, which are grouped here in site-specific BCs and planner's demands concerning functionality and performance, and (2) the properties of implemented measures, which span from natural development up to technical solutions with an ecological upgrade. This link is shown in Figure 5.2.

The BPA is primarily a bottom-up approach, as the BCs and demands point to appropriate measures. A top-down approach, in contrast, would mean to select measures and check whether the properties of those measures and their application ranges fit the BCs of the DC. This top-down approach is included in this report, but it is nevertheless supported by the information provided in Part 2. So, if users already have measures under review, Part 2 allows them to check the fulfilment of the site's BCs using the measure descriptions.

But what does the assumed link between selected criteria and possibly appropriate measures mean more concretely – especially if significant differences exist between the BCs or the objectives of the planners at the DC site and those where such measures were already implemented (that is, the ACs)?

This comparison is shown in Figure 5.3, where the main BCs and objectives of the DC example (a bank area on the impounded Weser River that shall be ecologically upgraded using bioengineering methods and possibly also by supporting shallow water zones), are compared with those of the predominantly used AC, a bank protection using willow-brush mattresses on the free-flowing River Rhine near Worms, Germany. The problem is, of course, that especially the ΔW and the ship-induced impacts (average at DC, high at AC) differ, but the planner's aims also differ, as the focus is on protecting the bank slope at the AC site but on the support of shallow water zones – besides the stabilisation – at the DC site.

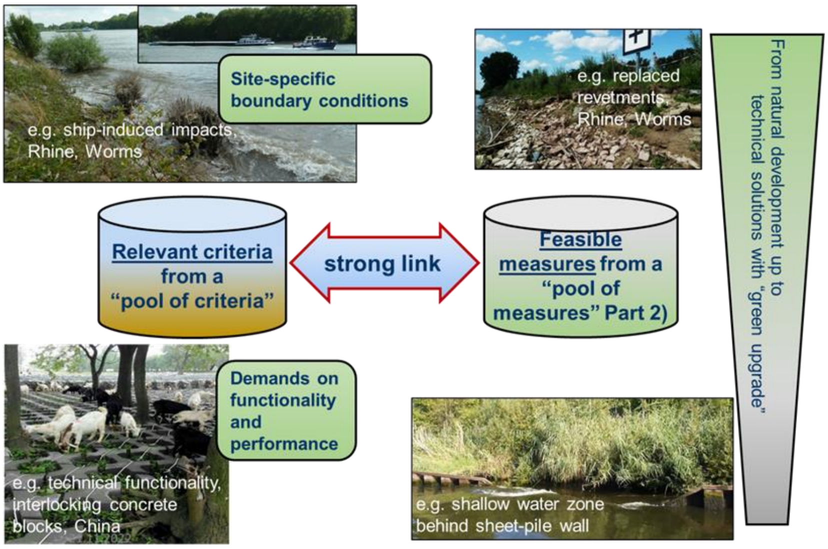


Figure 5.2: Basic ideas behind the BPA

The BCs do not fit optimally between the DC and AC sites in this example comparison, leading to the following questions: how substantial are the differences, and is the AC measure nevertheless feasible at the DC site since the DC BCs are milder than at the AC site? These questions will be answered by the preselection tools' feasibility check, which compares the BCs of the DC and AC and which is outlined in this chapter and covered comprehensively in Chapter 5 of Part 3.

Whether the planner's demands at the DC site will be fulfilled by the properties and thus the offered functionality of the AC measures is considered by the suitability check. This check compares the demands and corresponding properties of the potentially suitable measure.

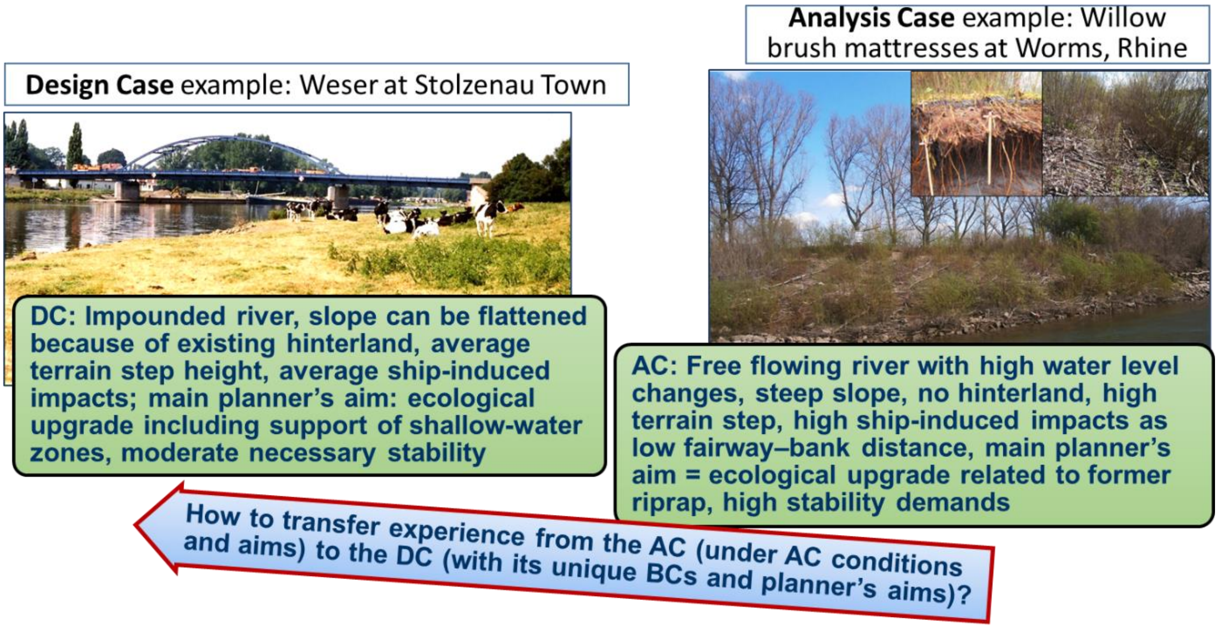


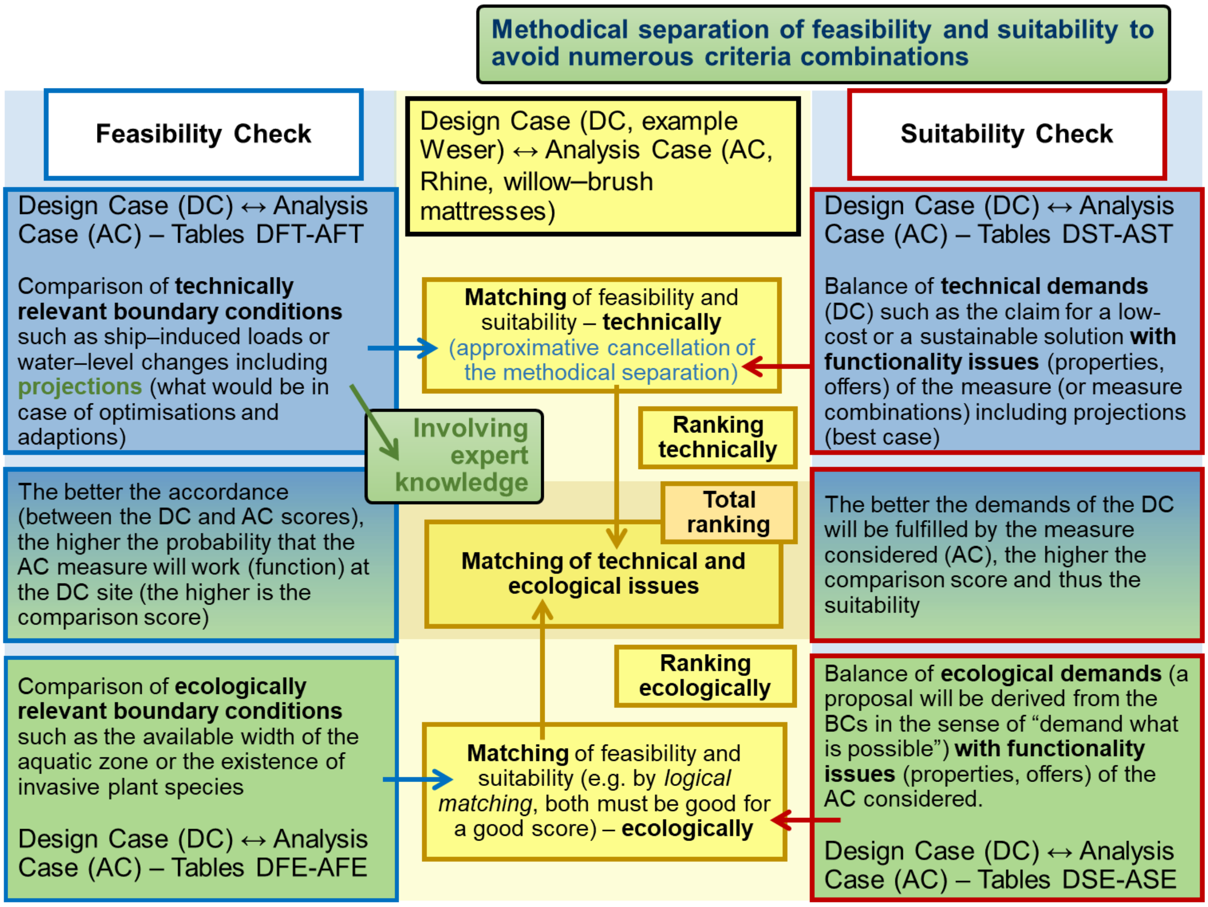
Figure 5.3: Transfer of experience from the chosen AC example: willow-brush mattresses at the free-flowing River Rhine at Worms to a possible application at the DC site example (impounded Weser at Stolzenau)

5.2 Outline and Application Steps

But how do these comparisons work in detail, considering there are several relevant BCs and demands, not only the aforementioned ΔW and ship-induced loads and the demand for using preferably only plants to achieve the desired functionality of bank protection? For example, ice effects such as frost heaving or ice drift may represent other decisive BCs needing consideration. Local conditions related to erosion resistance are also important; for example, the grain sizes of the bank substrates or the bank's ability to support natural vegetation, which helps to stabilise the bank. Concerning possibly relevant demands, a preferably short initial phase may be an important issue too, especially in the case of high traffic density and necessary restrictions to navigation during this phase, or the enabling of good access to the bank area to facilitate maintenance measures.

There may be hundreds of criteria to be considered, depending especially on the various site conditions, which would be far beyond the scope of the BPA, so the WG instead selected generally *decisive* criteria for preselection purposes. Nevertheless, the full extent of possible criteria will be discussed using the process recommendations in Chapter 6, where necessary.

But even restricting the number of criteria, this report still uses, in total, 44 criteria, requiring a structured, multicriteria analysis as shown in Figure 5.4. It shows a flow chart of the preselection approach with a focus on the categorisation of criteria and the matching procedure for different results. The principles applied and associated with this approach are outlined in the following section.



Abbreviations: DFT = Design Case, feasibility check, technical aspects), DFE = Design Case, feasibility, check, ecological aspects, DST = Design Case, suitability check, technical aspects, DSE = Design Case, suitability check, ecological aspects. AFT, AFE, AST, ASE = the same as above, but concerning the Analysis Case

Figure 5.4: Flow chart of the preselection approach with a focus on the categorisation of criteria, the corresponding tables in the Excel files, and the matching procedure for different results

Selection and Categorisation:

As outlined above, only *generally decisive criteria* according to the experiences of the WG 128 members were selected – and they were reasonably categorised and grouped into technical and ecological issues as well as into those related to BCs (for the feasibility check) and demands versus properties (suitability check). The criteria for each group are collected in corresponding tables (or *TABs*), which are indicated in Figure 5.4. and the following list:

For performing the feasibility check (comparing BCs, *left column* in Figure 5.4):

- Technical issues Technical issues (*upper*, *blue-coloured* part of Figure 5.4, Table DFT – DC, feasibility, technical):
  - Stability-related BCs – Ship-induced impacts, average slope, erodibility, excess pore water pressure, and hinterland properties.
  - Issues regarding water-level fluctuations ΔW – Degree of ΔW or categorisation, such as canals or still water, impounded rivers, and free-flowing rivers.
  - Climate-related BCs – Vegetation growth conditions (technical) and icy conditions (frost heaving, ice uplift, ice drift).

- Ecologically relevant BCs (*lower*, *green-coloured* part of Figure 5.4):
  - Space availability (aquatic, terrestrial), surrounding land users, hydrodynamic environment and vessel impact, bank substrates, water quality as well as influence of invasive plant species.

For considering functionality issues in the suitability check (reconciliation of demands and properties, *right column* in Figure 5.4):

- Technical issues:
  - Stability-related functionalities – Erosion resistance, stability and durability of construction elements, duration of initial phase, sustainability related to local conditions and materials used.
  - Effort-related issues – Administrative support, access, investment, and maintenance costs.
- Ecological demands and functionalities:
  - Taxa-related issues – Effects on macrophytes, riparian vegetation, arthropods, benthic invertebrates, fish fauna, and birds.
  - Habitat-related – Impact on the ecological quality of channel bed and banks, the quality of the riparian zone, and the habitat connectivity.

Quantification:

To compare the aforementioned BCs and functionality issues requires making them *measurable*. For this purpose, all relevant design criteria are substantiated (concretised, quantified) by specific technical statements (attributes) – for example, concerning the magnitude of ship-induced loads or on the growth conditions for plants – whereby always two limiting attributes will be offered; for example, *low hydraulic loads* such as in large water bodies without significant navigational impact and *very large ship-induced loads* such as in a canal with a small fairway–bank distance.

The degree of fulfilment of these attributes must be assigned a score (*degree-of-fulfilment score*) between one (1.0), which is generally assigned to *mild* conditions (in the example with low loads) and zero (0.0) (high vessel-induced loads) assigned to *severe* conditions. So, users of the BPA must assign an appropriate score for all of the aforementioned 44 criteria.

For assessing the very important score for ship-induced loads, a large number of tools are made available in Appendix B in Part 3, using correlations between wave heights and *macroscopic parameters* such as the waterway class (CEMT class) or the fairway–bank distance. So, users uncertain about choosing the ship-impact score will be supported in many ways, without being forced to make measurements or calculations.

Additional comprehensive support for scoring will be provided by numerous explanations in Chapters 5.4 (feasibility check) and 5.5 (suitability check) in Part 3 and – of course – by the Excel tools, which explain the scoring just ahead of each criterion and which perform all the comparisons that result from the scoring automatically.

The expert-rated scores for all ACs, meaning for all measures described in Part 2, can also be found in Part 3 and are stored in the Excel file. This data centralization allows the quantitative comparison between BCs for the feasibility check and the reconciliation of demands versus functionalities for assessing the suitability for all ACs together automatically. User must only specify the DC.

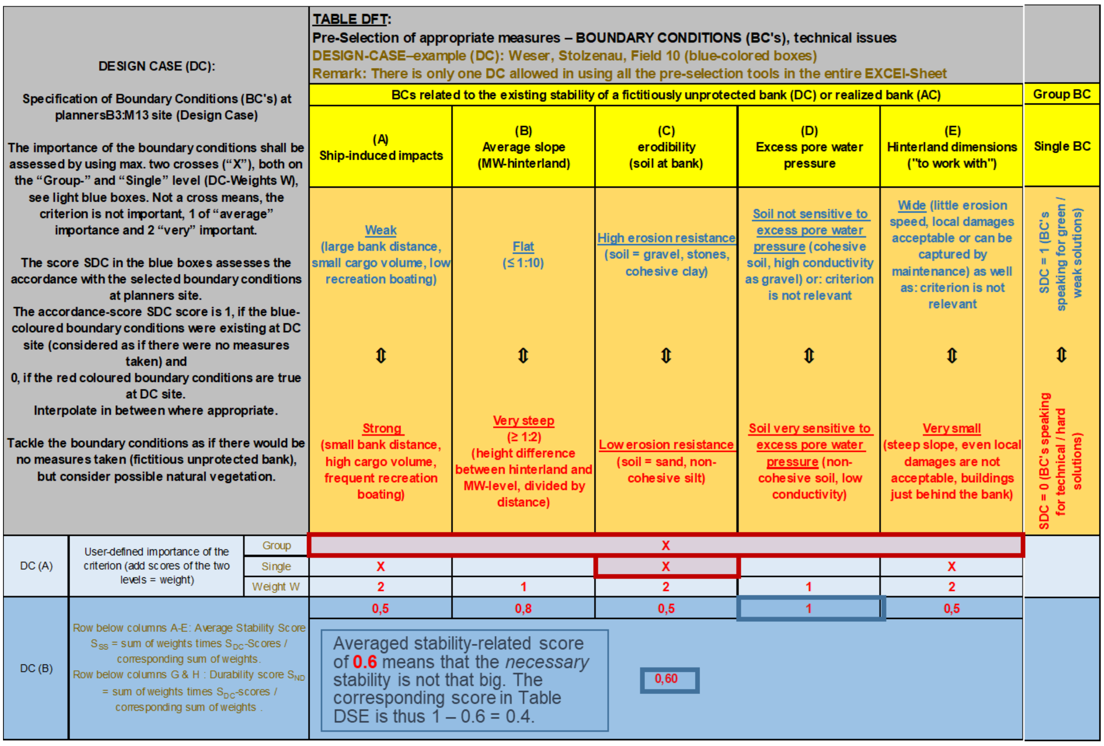
The aforementioned specification and quantification of criteria also include the assessment of the *significance* (importance, weight) of each criterion, especially considering the site BCs. In the DC example, especially the BCs related to ΔW and the demand to restrict maintenance efforts were assessed to be very important at the Weser site; treating technical issues and the space availability in the aquatic zone, which is necessary to support shallows or the vitality of water-bound vegetation, were assessed to be very significant concerning ecological aspects.

For quantifying the importance, *X*s will be used. No *X* means the criterion is not important (weight = 0). One *X* means the criterion has *some* influence, two an *important* influence, three a *very important* influence, and four a *decisive* influence on the results.

To end up with comprehensive scores between 0 and 1, which facilitates the comparison and interpretation of these scores, the single scores (or differences between DC and AC scores) will be multiplied by the number of Xs and then divided by the total sum of Xs, separately for all criteria categories. These weighted averages allow quantitative comparisons and matching these comprehensive scores to further comprehensive scores.

Figure 5.5 presents an example on how the weights and scores have to be filled in the Excel file. It shows an extract of Table (*TAB* in the Excel file) DFT (DC, feasibility check, technical issues) concerning the stability-related aspects:

- To show the quantification of the importance, the importance Xs of the erodibility criterion (column C) are marked by a *purple frame* in the *middle* of Figure 5.5. The number is two (2) Xs out of a maximum four (4), meaning the criterion has an *important* influence on the results.
- A *blue frame* marks the score of the excess pore water pressure (column D) criterion. The score is 1 because the gravelly bank substrates are not sensitive to excess pore water pressure, meaning there is no danger of bank slides due to quick water-level drawdown from navigation at the DC site, so that no surface weight on the bank slope is necessary and therefore bioengineering methods are suitable to counteract erosion.



DESIGN CASE (DC): Specification of Boundary Conditions (BC's) at plannersB3:M13 site (Design Case)	TABLE DFT: Pre-Selection of appropriate measures – BOUNDARY CONDITIONS (BC's), technical issues. DESIGN-CASE–example (DC): Weser, Stolzenau, Field 10 (blue-colored boxes). Remark: There is only one DC allowed in using all the pre-selection tools in the entire EXCEl-Sheet					
	BCs related to the existing stability of a fictitiously unprotected bank (DC) or realized bank (AC)					Group BC
	(A) Ship-induced impacts	(B) Average slope (MW-hinterland)	(C) erodibility (soil at bank)	(D) Excess pore water pressure	(E) Hinterland dimensions ("to work with")	Single BC
The importance of the boundary conditions shall be assessed by using max. two crosses ("X"), both on the "Group-" and "Single" level (DC-Weights W), see light blue boxes. Not a cross means, the criterion is not important, 1 of "average" importance and 2 "very" important. The score SDC in the blue boxes assesses the accordance with the selected boundary conditions at planners site. The accordance-score SDC score is 1, if the blue-coloured boundary conditions were existing at DC site (considered as if there were no measures taken) and 0, if the red coloured boundary conditions are true at DC site. Interpolate in between where appropriate. Tackle the boundary conditions as if there would be no measures taken (fictitious unprotected bank), but consider possible natural vegetation.	Weak (large bank distance, small cargo volume, low recreation boating) ⇕ Strong (small bank distance, high cargo volume, frequent recreation boating)	Flat (≤ 1:10) ⇕ Very steep (≥ 1:2) (height difference between hinterland and MW-level, divided by distance)	High erosion resistance (soil = gravel, stones, cohesive clay) ⇕ Low erosion resistance (soil = sand, non-cohesive silt)	Soil not sensitive to excess pore water pressure (cohesive soil, high conductivity as gravel) or: criterion is not relevant ⇕ Soil very sensitive to excess pore water pressure (non-cohesive soil, low conductivity)	Wide (little erosion speed, local damages acceptable or can be captured by maintenance) as well as: criterion is not relevant ⇕ Very small (steep slope, even local damages are not acceptable, buildings just behind the bank)	SDC = 1 (BC's speaking for green / weak solutions) ⇕ SDC = 0 (BC's speaking for technical / hard solutions)
DC (A) User-defined importance of the criterion (add scores of the two levels = weight) – Group			X			
DC (A) – Single	X		X		X	
DC (A) – Weight W	2	1	2	1	2	
DC (B)	0,5	0,8	0,5	1	0,5	
Row below columns A-E: Average Stability Score S_{SS} = sum of weights times S_{DC}-Scores / corresponding sum of weights. Row below columns G & H : Durability score S_{ND} = sum of weights times S_{DC}-scores / corresponding sum of weights .	Averaged stability-related score of **0.6** means that the *necessary* stability is not that big. The corresponding score in Table DSE is thus 1 – 0.6 = 0.4.		0,60			

Figure 5.5: Extract (first five columns, related to stability) from the Excel table DFT (DC, feasibility check, technical issues). The degree of fulfilment scores concerning the excess pore water pressure (column D) and the weight-averaged score of all stability-related criteria are marked by a blue frame.

Comparative analysis:

To quantify the feasibility of an AC measure at the DC site, the degree of fulfilment scores of the DC and AC are always compared with one another, criterion after criterion, both for technical and ecological issues. The smaller the difference between two scores of one criterion, the greater the associated comparison score, whereby a total agreement results in a score of +1. If there is no agreement at all (for example, the AC score is 1, but the DC score 0) the comparison score equals −1. This scoring rule will be used for all comparisons.

Weighted averages of these comparison scores lead to *comprehensive* feasibility scores, both for technical and ecological issues. The better the accordance (between the DC and AC scores), the higher the probability that the AC measure will work (function) at the DC site (the higher the comparison score).

According to the scoring rules of all the single scores, the comprehensive scores can be interpreted as follows: a score of +1 means that the probability is very high that the AC measure will work (function) at the DC site too. This assumption of functionality comes from the practical implementation experience and subject-matter expertise of the experts in WG 128, which shows that a positive score corresponds to suitability. A comprehensive score of up to 0 may thus be associated with the wording *adequate*. That is, the AC measure is a fit but perhaps not the most suitable fit. Only negative numbers on the comprehensive feasibility scores raise doubts about the feasibility of the AC measure under DC conditions.

At the same time, the suitability of the measure is evaluated by comparing the functionalities, formulated as requirements (demands) for the DC with the functionalities actually achieved. The better the requirements are met by the AC measure, the higher the suitability. Phrased more concretely:

- If a special property of the measure (for example, its stability) is demanded and entirely fulfilled, the score is +1, but if not, the score is −1.
- If there is no demand to fulfil a special criterion, but it is nevertheless fulfilled, the score will be 0.5.

More information is provided in Part 3. In the end, a score greater than or equal to 0 but less than 1 means that the AC measure suits the demands – not optimally, but adequately. But the higher this number, the better.

Evaluation of the feasibility and suitability check:

All the comprehensive comparison scores of the aforementioned checks, both for technical and ecological issues and of course for all AC measures in Part 2, will be evaluated in several ways in the Excel files. The most important way to present results is the creation of ranking lists of the best measures – meaning those with the highest weighted averaged comparison scores. In the end, users receive such lists for all four categories (technical and ecological feasibility and suitability) of criteria shown in Figure 5.4.

Results for the standard DC are shown in Figure 5.6. The ranking lists show little accordance, but measures using pre-embankment constructions are in the majority, both for the feasibility and suitability checks. This outcome is the logical consequence of the strongly weighted criteria related to ΔW – as the lower ΔW makes wave-breaking constructions reasonable – and the demand to enhance shallow water zones at the DC site – as pre-embankment solutions support the creation of shallows in general. But the technically oriented measures differ especially in their extent compared with those focusing on ecological issues. Therefore, the preselection tools, which focus on the *type* of measure, whereby its *extent* and, thus, its *costs*, is only one of several criteria, is not that important. For this reason, the preselection results must be checked again, among other things by reviewing possible knockout criteria, as it is, for example, obvious that an ecologically very suitable measure may not be possible if the DC site lacks the physical space for implementation. This limitation will be accounted for in the 7 steps of the detailed design recommendations in Chapter 6.

Matching of feasibility and suitability results is nevertheless essentially to facilitate the selection of appropriate measures, as it is obvious that, for example, AC measures fitting the DC BCs may be feasible but not be suitable because they would not fulfil all the DC's demands – and not all technically optimal measures will satisfy the ecological demands too. Nevertheless, the ranking lists of all four categories are very informative, depending on users' priorities.

Consideration of the methodological separation between feasibility and suitability:

The two design aspects, feasibility and suitability, are closely linked. For example, the stability of a measure can be better guaranteed if the water-level fluctuations in canals or impounded rivers are smaller than in free-flowing waters. But the methodological separation of both design aspects was necessary to avoid an overly complex criteria matrix. Combining the eight technical BCs with the nine technical demands would result in an 8 × 9 grid of criteria combinations – totally unmanageable. Therefore, results of the feasibility and suitability checks must be matched in some way.

Nevertheless, the influence of different BCs on the suitability of measures under DC conditions must be considered, because even the best-matching procedure cannot account for the aforementioned strong link between BCs and achieved functionality. This problem is resolved by applying the AHP approach; see the last point of the 7 Steps, explained in the next chapter.

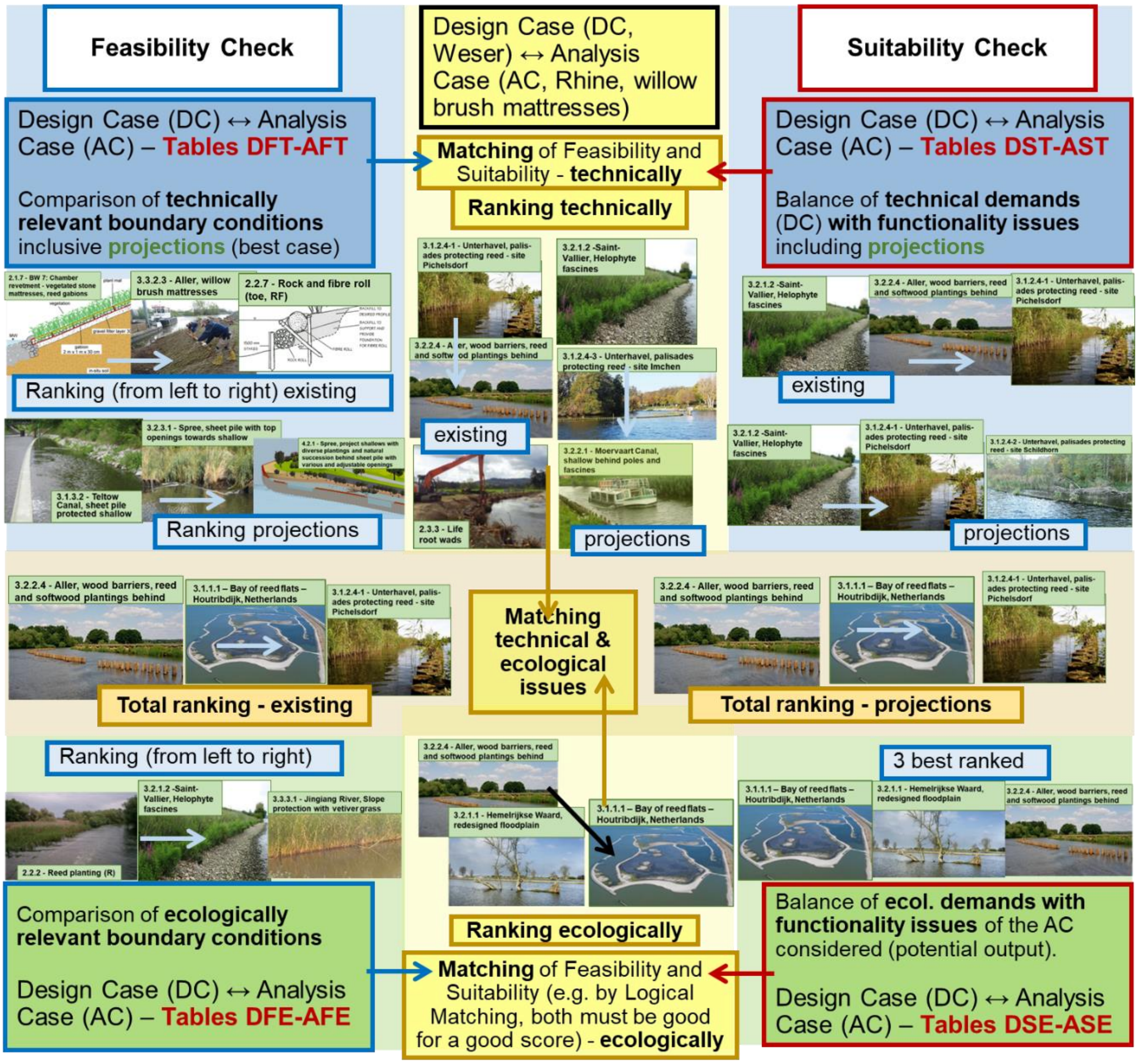


Figure 5.6: Visualisation of ranking lists (first-named three measures each) of all four categories (left and right columns) and corresponding matched results (middle column) for the standard DC (Weser, Stolzenau, Germany)

Matching of feasibility and suitability:

The preselection tools, available in the big Excel file, offer several ways to match the comprehensive scores from the feasibility and suitability checks. One is the weighted averaging and another the (arithmetical) *logical matching* method. The latter ensures that both design aspects must be fulfilled for a high score (see Chapter 5.2 in Part 3). But the method ensures also that the score of measures, whose BCs at the site of realisation are very different to those at DC site, is not too bad to be sorted out too early, if the suitability is still good (preference of suitability over feasibility in case of large differences of the BCs).

The results of the matching procedures are summarizing scores for both technical and ecological aspects processed, as with the separate results, with Excel support into ranking lists of suitable measures; see Figure 5.6. It visualises the first three ranked measures for technical aspects in the *middle* of the *upper third* of the graph and ecological issues in the *middle* with a *light-green* background colour.

The ranking lists, as already mentioned for the separate lists addressing feasibility and suitability and technical and ecological issues, are still very different, so that matching of technical and ecological issues is important too.

Matching of technical and ecological issues:

Analogous matching algorithms can be used to account for both technical and ecological issues. The Excel sheet offers several algorithms for this purpose, e.g. the usual weighted arithmetic averaging. But, as ranking lists of technical and ecological aspects usually have only a few measures in common, the chosen matching algorithm has a very big influence on the results. Thus, it should be done in in a 'logical way' as the recommended 'geometrical logical matching'. It is basing on the geometrical mean (or a weighted geometrical mean) of increased technical and ecological scores (to make sure that they are larger than zero). This approach is different to the 'arithmetical logical matching procedure' with its preference of suitability issues in extreme cases, because *both* design criteria, technical *and* ecological functionality, have to be fulfilled to end-up with a good score. If, for example, the score of one of both criteria, is -1, the final score should be -1 too. This ensures the adapted geometrical matching procedure.

Using this method (without weighting) leads to the results shown in the *middle* part of Figure 5.6.

Again, pre-embankment solutions dominate the results, whereby measures using palisades to protect the bank area against strong impacts are ranked higher than, for example, measures using more technical elements to achieve the protection, such as permeable sheet-pile walks. This result is because the potential ecological output, which was quantified by the experts in the WG through corresponding AC scores, was assessed to be better, using as few as possible technical elements and, if unavoidable, at least using those of wooden materials.

But these results are unique for the DC considered, with all its special local BCs and planner's demands. So, applying the preselection tools will lead to very different results depending on the user-specified BCs and demands, corresponding weights, and also the selection of matching tools. Therefore, before making a final decision on preferred measures, users should perform *sensitivity tests* by adjusting the weights and scores of main influencing parameters in reasonable ranges and then comparing the results.

Projections:

To make the subject-matter-expert knowledge in the WG even more available for practitioners, two states (conditions) are considered for the technical aspects. First, all AC measures were evaluated (by scoring) with regard to the implemented state (called *existing measures*) but second also for an ideal (fictitious) state, if, for example, adaptions to account for the local BCs and optimisations were to be implemented. These assessments, called *projections*, significantly increase the informative value of the preselection methods and lead to further rankings.

Both results (for existing measures and projections), with more concrete extracts from the corresponding ranking lists, are shown in Figure 5.6 in the *upper third* of the diagram. The results of the feasibility check especially are very different. In the example DC, this result means that, direct measures predominate in its existing state, but pre-embankment measures, which may be possible if, for example, the bank geometry will be adapted, got a better rank in the projections.

The ecological analysis does not use such projections. First, because the *potential ecological output* will be assessed (not the existing one), as the majority of measures are not in an optimal state but could be with a few adaptions, and second, because in most cases, no long-term experience or concrete monitoring results for the measures under consideration exist.

Nevertheless, because of the matching of technical and ecological issues, final ranking lists will be offered both for (potentially) existing – see results on the *left middle* of Figure 5.6 – and projected states – on the *right middle* of Figure 5.6. The results are almost identical, supporting the chosen preselection strategy.

Consistent methodical procedure:

Because of the large number of influencing parameters, the locally very different BCs and requirements, and, of course, the numerous parameters to be selected by the user (for example, concerning the matching procedures and the absence of possible knockout criteria such as the aforementioned space availability), the selection and design of a planned measure will always require individual case studies, as shown in the next chapter, even if the preselection process is a very important design step. It is therefore all the more important to formulate *process recommendations* for how the complex design task can best and most efficiently be handled methodologically.

In the following chapter, these process recommendations will be outlined. More information is available in the corresponding chapter in Part 3.

6 PROCESS RECOMMENDATIONS FOR DETAILED DESIGN

All the design steps outlined in this chapter are demonstrated by the DC example at the impounded Weser River in Stolzenau, Germany. This example was already used to demonstrate the application of the preselection approach; see previous chapter.

With reference to Figure 5.1, showing the connections between Parts 1 and 3 of the report, this chapter provides only basic principles of the recommended detailed design approach and some results from the corresponding Chapter 6 in Part 3. The titles of subchapters are the same in both parts to facilitate getting more information from Part 3.

Considering the outcome of the previous chapter, which may stand alone as mentioned above for decision-makers, it is nevertheless recommended to follow all the steps outlined in this chapter. Following the steps in this chapter is especially important for practitioners and planners, as the preselection approach addresses the measures more or less *qualitatively*, meaning, for example, that measure types will be selected – which of course must then be adapted *quantitatively* to the site BCs; for example, by considering the available space or available budget.

6.1 Design Procedure

Chapter 6 in Part 3 forms the central switching point for the application of this report, as it guides the user, step-by-step, through the entire planning process. While mainly written for experts following all relevant design steps, this report's different levels of comprehensiveness still meet multiple users' needs for waterway-relevant design aspects and different user profiles.

How Parts 1 and 3 in general and the corresponding Chapters 5 and 6 specifically are linked together, and which chapters may be relevant for different users of the report, is shown in Figure 5.1. The following figure (Figure 6.1) shows how results from the preselection are used for performing the detailed design.

On the *left* of the figure, the different points of the preselection approach are visualised according to their correlations among each other; for example, how the results from the feasibility and suitability checks for technical and ecological results are matched. Also, the designations of the corresponding TABs (that is, tables) in the Excel file are mentioned. The *arrows* between the boxes indicate the workflow; for example, on how the scores from preselection are linked to the chapters and issues for the detailed design, which are shown on the *right* in Figure 6.1.

One can see that, among other things, the ranking lists of appropriate measures run into Step 3 of the 7 Steps for design, which includes the aforementioned preselection tools. Also, the scores of the preselection will be used as proposals for the final scores of the detailed variant comparison in Step 7 (Chapter 6.7 of Part 3); see *brown arrow* from the *lower-left yellow box* pointing to Chapter 6.7.

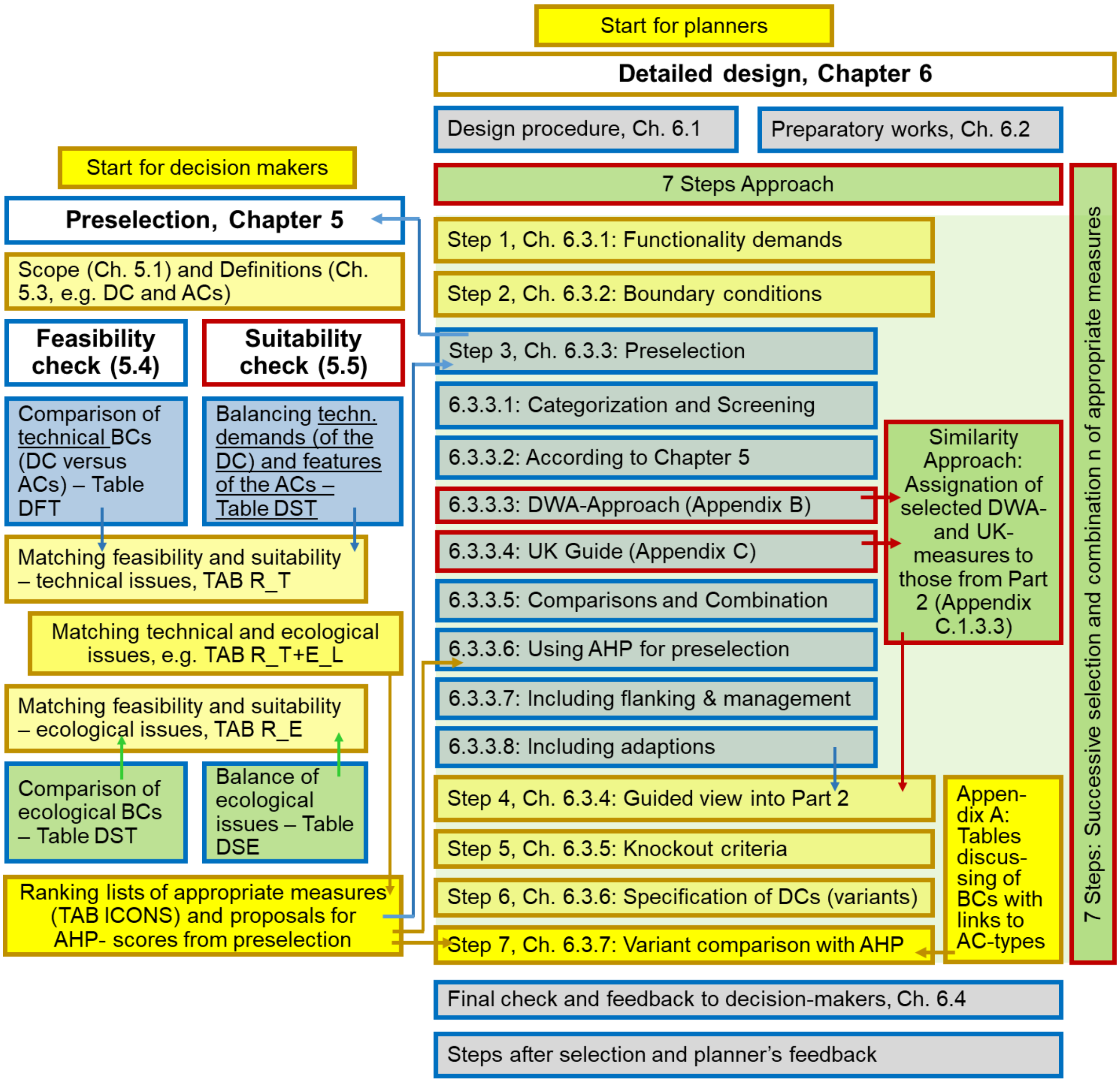
The *left* of Figure 6.1 is headed by *Start for decision-makers* according to the main purpose of the preselection tools to show the general applicability of TBPs, while the *right* of the figure is reserved for planners and shows all the points to be considered for performing a detailed design study. Users should read and apply all the recommended 7 design steps, which are outlined as follows:

Step 1. Discuss and specify the planner's aims.

Step 2. Discuss the relevant local BCs. The user of the design approach is always forced to specify the boundary conditions and demands *verbally* (textualization) in order to reduce the number of relevant design criteria as far as possible. The report offers numerous tables with guidance on how the criteria will affect the design (also Appendix A in Part 3).

Step 3. Apply all the preselection tools (screening and comprehensive preselection according to Chapter 5, DWA-M 519, and UK Guide using AHP weighting) to develop ranked lists of appropriate measures. Step 3 also includes the discussion of measure combinations and the role of flanking measures as well as management strategies. Step 3 results in a large number of possible solutions, depending on the focus of the user, which must be sorted out in the next steps.

Step 4. Practitioners should now consult Part 2 in greater detail, focusing on the measures from the preselection step. Practitioners must review the construction details, possible improvements to account for planner's aims, and possible adaptations to relevant BCs. This initial review of measure details will provide a preliminary sorting of the potential measures.



The acronyms R_T, R_T+E_L, R_E and ICONS are designations of the corresponding tables (TABs) in the corresponding Excel worksheet. The Chapter names refer to Part 3.

Figure 6.1: Simplified application steps of the preselection scheme (left) and the detailed design (right)

Step 5. Practitioners and planners should next review the knockout criteria, such as ice effects in Northern Europe or excess pore water pressure, which occurs if the drawdown speed of a passing vessel overtops the permeability and which requires ballasting the bank slope (for example, with rip rap or gabions). This important step may further reduce the number of potential measures.

Step 6. Practitioners and planners must now perform a final selection of measures from the resulting list (that is, *variants*). Users must specify these variants (DCs) as far as possible using the descriptions in Part 2 – preferably not only the construction details and corresponding numbers – because it helps to concentrate on really important features. These variants will be considered for adaptation to the DC site so as to adapt the corresponding functionality issues (and the corresponding suitability scores). Therefore, the preselection scores can be used, but only in the sense of proposals.

Step 7. Finally, practitioners and planners should *compare* the selected variants in a structured way using the AHP. This standardized multicriteria evaluation method uses three criteria groups, as mentioned above:

- Technical issues (subgroups feasibility, stability and sustainability, restriction of effort)
- Social aspects (human concerns, landscape, law, and acceptance)
- Ecology (feasibility and adaptability, selected target organisms and habitats)

Its structure and its cross linking to the preselection tools is shown in Figure 6.2. Here, too, assistance is provided on the importance and quantification of the individual criteria using the preselection scores and corresponding Excel tables, which allow, for example, a combination of measure properties and accounting for the influence of BCs on the functionality.

By the end of Step 7, practitioners will be supported in a rational and objectified way towards choosing an appropriate variant optimally fitted to the DC site with its unique BCs. This optimal variant selection is achieved by applying comparative analysis techniques (as all measures and variants are assessed the same way), by addressing generally relevant design criteria, and by leveraging the knowledge and experience of the experts in WG 128 in the form of the predefined scores for all measures in Part 2.

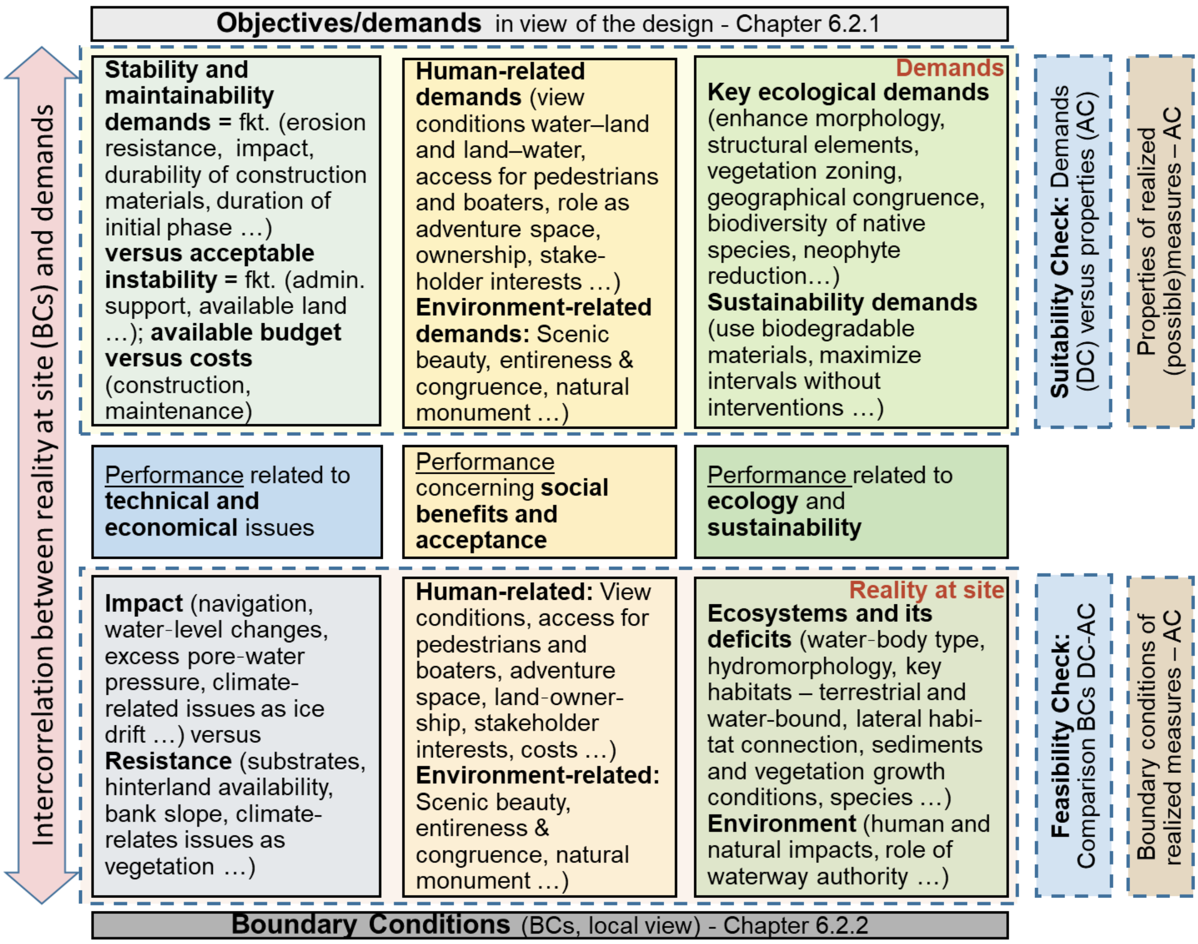


Figure 6.2: Overview on the recommended detailed design approach – aspects and criteria groups

Even with good process recommendations on how to perform a detailed design study, every DC is unique and maybe very complex too, especially concerning the consideration of local BCs, stakeholder interests, and numerous corresponding relevant criteria. Thus, every DC demands its own approach, and the following recommended BPA must therefore be adapted accordingly.

Nevertheless, using the numerous criteria mentioned in the following section for guidance will help ensure the inclusion of design-relevant aspects that might otherwise be forgotten or overlooked. Thus, the process recommendations, which are outlined in the following section in more detail, do not assert claims on completeness, but they will help users structure decision-making, with the aim of ending up with reasonable decisions on appropriate measures.

6.2 Preparatory Works

Before starting with the aforementioned 7 Steps, users should review Appendix A of Part 3. It contains worksheets for specifying the design and discusses numerous planner's aims and possibly relevant BCs. These aims and BCs were taken from different sources; for example, the DWA-M 519 or the UK approach and will be discussed in Step 7 to check the overall suitability of selected variants. Appendix A of Part 3 also provides users with design guidance; for example, concerning the type (for example, pre-embankment or direct measures) and features (for example, necessary stability and durability) of measures suited to the BCs discussed.

An extract of one of these tables is shown in Figure 6.3. It addresses screening criteria, here the subsoil type and space availability in the aquatic zone (Table A.2-1 in Part 3). Some key messages are highlighted in *red*, such as the guidance on how to select appropriate plant species using, for example, the catalogue of species in the DWA guideline (Appendix B in Part 3), or under which conditions management strategies may be acceptable (with reference to the UK approach in Appendix C, Part 3).

The tables in Appendix A in Part 3 also allow users to mark the importance of the criteria, which may then be used in applying the preselection approaches and AHP; see *left column* in Figure 6.3.

Using the generally applicable information from Appendix A in Part 3, users should now select and specify relevant planner's demands for the DC considered, adding, where appropriate, comments on why these demands may be relevant (in *blue* in Part 3 and the following figures) and how important they are. One example is shown in Figure 6.4, focusing on stability-related issues.

With the same level of detail, users should also select and discuss the BCs listed in Appendix A in Part 3. Again, an example is shown in Figure 6.5, focusing on the technical BCs used for preselection.

In the end, users should be able to identify the *decisive* planner's objectives and local BCs, which may be used for performing the next steps.

With reference to Figure 1.1, which shows the contribution of this report to the planning process, Chapter 6.2 in Part 3 offers also some more information about things to do before the planning process goes into greater detail, such as to check whether the existing data basis is appropriate or should be upgraded (with guidance, such as which dates are generally relevant and which qualities are necessary) or whether mitigation (for example, by restrictions to navigation, maybe only temporarily) or the possibilities of flanking measures (for example, upgrade of river-engineering measures) have been exhausted to support weak bank protections.

While a large number of possible planning aspects are addressed, this report nevertheless does not claim to include all possible planning aspects. As mentioned several times before, every DC is unique, but nevertheless the guidance this report provides will help users, especially those who are not as familiar with possibly relevant criteria.

For example, the planned final shutdown of nuclear power plants in Germany may it make necessary to account for ice effects again, which were not really important during the last few decades because of waste heat from the plants warming the waters. This aspect became less relevant while planning renaturation measures during this time, but the criteria lists make clear its potential relevance in the future.

So, users should consider the numerous planning aids in Chapter 6.2, and of course generally in this report. Even if experienced planners may find them less useful, these planning aids still serve as reminders of possibly relevant design aspects. That is, this section first widens the view, and then the next section, the 7 Steps, narrows the view to concentrate on decisive issues and the most feasible and suitable solutions for the specific DC considered.

Criteria	Implication on design	Design hints
BCs group – technical issues **Subsoil** (& erodibility, mainly technical view) Importance (maybe split into existing and artificially coarsened granulometry to increase erosion resistance) = …………………	The type and granulometry of the subsoil in the bank area defines both the erosion resistance and (together with the water-level fluctuations and the nutrient conditions), the vitality of vegetation. The erosion resistance is minor for non-cohesive sediments such as sand or silt and increases with the proportion of coarse components (gravel, stones). Thus, the necessary erosion protections will be the more technical, the lower the erosion resistance. Even a small proportion (say >10%) of grains with a sieve diameter of D ≥ 60 mm can form an armour layer and increase the erosion resistance significantly. Also the content of cohesive components up to a stiff clay increases the erosion resistance, but is counterproductive for many near-water growing plants such as willows. Non-erosive flow velocities for different bank materials can be found for example in in PIANC (1999) or the UK Waterway Management Guide (1999), both for different materials without and with vegetation. In Appendix C.1 of Part 3, these numbers can be transferred to wave heights and related to impact scores used for Table DFT. Type and grain sizes of the subsoil define also the sensitivity to excess pore-water pressure due to quick drawdown of a passing vessel, which may lead to hydrodynamic soil displacement (washout of fine materials) up to bank failures by slides. Very critical are non-cohesive, fine-grained soils with low permeability. Resistant against pore-water pressure are coarse-grained, non-cohesive sols with high permeability and soils with significant cohesion such as clays.	Think about adapting the granulometry where appropriate, for example by covering the bank surface with a small layer of coarse gravel and stones. Consider filter laws where necessary, so that the fine sediments below the cover will not be washed out. Consult a plant expert concerning natural succession under altered granulometric conditions. **Select the species used for plantings preferably according to the soil, see inter alia advice given in (DWA, 2016) or the UK-Waterway Management Guide (1999, here in Appendix C.1).** **Consult a local plant specialist where necessary, such as the choice of the species often defines success or failure of bioengineering measures.** **Example of advices concerning measure properties**
BCs group – ecological issues **Space availability in the aquatic zone** Assess the importance for the Design Case considered here, maybe in form of a number between 0 (not important) and 1 (very important): Importance = …………………	The dimensions (width, water depth) of the aquatic zone in front of the bank zone to be protected defines both the strength of the ship-induced impacts and the possibilities of taking pre-embankment measures from the technical point of view. **Also the ecological potential for improving the aquatic zone depends on the size. If the space is large, say more than about 50 m, which is a rule of thumb for decreasing drawdown-induced impact such as excess pore-water pressure, flanking measures such as river training are generally applicable, together with other pre-embankment measures to further reduce ship impacts or simply to create areas with low flow velocities for example to support fish spawning. By contrast, if the available space is small, direct measures are the first choice, maybe complemented by small dams or berms on the bank slope to support shallow-water zones.** As a general rule, planners should always think about supporting or extending the aquatic zone where possible, e.g. by fairway relocation.	Often, actual soundings and velocity measurements as well as hydrodynamic model data exist only in the area of the fairway and not in sufficient quality in the shallows: But they are very important especially to plan pre-embankment measures, for example palisades or parallel dams, which make sense especially if the water depth is not too large in order to restrict costs. Thus, the planners should insist on receiving a good data basis also for the shallows. **If the width of the aquatic zone is large, management strategies may be sufficient, see for example Appendix C.1.3.1.**

Figure 6.3: Extract from Table A.2-1 in Part 3: Discussion of local BCs and its implications on design – BCs used for screening

Planners' objectives and demands (and sources of more information)	Brief remarks about in which cases the objectives may be relevant with links to appropriate measures	Importance
General stability demands (e.g. Table 6.2 in Part 3) or necessary erosion resistance (e.g. from Appendix A.4.1 in Part 3)	The necessary stability strongly depends on the boundary conditions as ship-induced impacts, bank stability or available hinterland space as well as the consequences of a bank failure (see also Tables A.2-1 – A.2-3). The higher the stability demands, the more technical elements and the more direct measures (on the bank slope) are necessary for protection. **Note that the erosion resistance can be increased by adapting the granulometry of the bank substrates or by flattening the slope.** Think also if loads in the upper part of the bank, e.g. because of infrastructure measures, can be reduced. **The ship-induced impacts are moderate to strong, because the fairway–bank distance is small and because it affects the bank stability almost permanently there is a strong need to ensure sufficient bank stability for the Weser example, but not over the entire bank area, as the second terrain step is far away from the fairway.**	……… (XX)
Necessary stability and durability of construction elements	The worse the access and the monitoring, the more expensive maintenance and the worse the climate conditions, the better should the stability and durability of construction elements be. For the Weser DC, very high stability and durability standards were required.	……… (XXXX)

Figure 6.4: Extract from Table 6-2 in Part 3 – Collection of technical demands related to stability

Boundary conditions (and sources of more information)	Brief remarks about in which cases the objectives may be relevant with links to appropriate measures	Importance
Waterway Type and water level fluctuations (e.g. Table 6-7 or Appendix A.4.2 in Part 3)	The waterway type is mostly associated with water-level fluctuations ΔW (especially between HSW - highest shipping level - and MW (lowest level for plant growth) and the magnitude of ship-induced impacts. **ΔW also determines the efficiency of pre-embankment measures to reduce ship-induced impacts.** The waterway type is thus one of the most important BCs, see e.g. Appendix B.1. **At the Weser DC, the water level fluctuations between MW and the first hinterland level, which are relevant for design, are moderate, so that pre-embankment measures to break waves may be a good option.**	….. (XXXX)
Average bank slope	The average bank slope, here calculated from the lateral and vertical differences between the MW water line and the first terrain level of the hinterland or rather the slope in the bank zone to be protected, determines the available space to take measures and the resistance against erosion or against negative effects from excess pore-water pressure as well as the possibilities and limitations to implement a natural zoning of the bank vegetation, to mention just some slope-related aspects. Check, whether the slope can be flattened. Check always, whether the slope can be flattened as in case of the Weser DC.	….. (X)
Erodibility of bank substrates	The larger the grain sizes and the more cohesive they are, the higher the erosion resistance is and the lower the effect of excess pore-water pressure is. Note that the erodibility is adaptable e.g. by dumping course gravel on the bank slope, which is not necessary at the Weser DC.	….. (XX)

Figure 6.5: Extract from Table 6-7 in Part 3 – Collection of technical BCs for preselection

6.3 7 Steps Approach

Step 1: Concretise Planner's Objectives for the DC Considered (Chapter 6.3.1 in Part 3)

This section discusses the 7 Steps in a very concrete way for the DC considered and the relevant planner's objectives. Most importantly, user should always put these demands – and of course the relevant BCs – into written descriptions. Especially during the often very controversial discussions between ecologists and engineers, writing down and describing the main issues helps all stakeholders because a successful planning process requires all relevant stakeholders to declare what they really want. Considering the local BCs makes it simpler to evaluate what is realistically workable; for example, by considering the existing space or budget. The outcome of this evaluation for the Weser DC shows the list in Figure 6.6. Practitioners and planners should always refer back to this list while following the other steps, as it is very important to have the most important functionality demands always in mind.

Step 1, Ch. 6.3.1, Table 6-9 in Part 3:
Decisive functionality demands of the DC (Weser)

Textualization of all relevant issues recommended!

Category	AHP-Criterion	Most important demands - shortened
Technical demands	1.2: Stability and sustainability	High sustainability needed concerning stability and durability of construction materials as well as to avoid maintenance efforts. Moderate erosion stability needed as impacts are restricted. Reduce the discrepancy between available und necessary space by flattening the slope as far as possible ....
	1.3: Avoiding efforts	Choose cost-effective solutions, both for construction and maintenance ...
Social and legal demands	2.1: Human	Enable view from water side towards the hinterland and backwards ...
	2.2: Landsape and preservation issues	Increase scenic beauty, ensure the legal demands of navigation (safety and ease) ...
	2.3: Legal issuers and acceptance	Respect the demands of various stakeholders, for example of private owners.
Ecological demands	3.2: Taxa	Enhance the water-bound habitats, especially for corresponding macrophytes and fish. Enhance also the habitats of riparian vegetation.
	3.3: Habitat	Create shallow-water zones with varying water depth's, grain sizes and structural elements. Improve plant zonation and vegetation complexity as far as possible ...

Figure 6.6: Table 6-9 in Part 3, listing most important, design-relevant demands for the Weser DC

Step 2: Concretise Decisive BCs for the DC Considered (Chapter 6.3.2 in Part 3)

The second design step is to sort out and consider design-relevant BCs in the context of the decisive demands defined in the previous chapter. See Figure 6.8, which shows an extract of this very long list. Again, practitioners and planners should always refer back to this list while following the other steps, as it is very important to have the most important functionality demands always in mind.

Step 2, Ch. 6.3.2, Table 6-10 in Part 3: Extract of decisive BCs for the DC Weser

Category	AHP-Criterion	Most important boundary conditions – shortened
Technical boundary conditions, e.g. related to stability and maintainability	1.1: To be discussed according to the degree of fit to site conditions	The waterway type is an impounded river, which allows to some extent to install effective wave breakers. The bank zone is of moderate erodibility because of the bank substrates and moderate ship-induced impacts. Thus a moderate erosion speed of the unprotected bank will occur, which may allow to some extent and over restricted time management strategies ...
Ecological boundary conditions e.g. related to achievable ecological upgrade	3.1: To be discussed according to the degree of fit to site conditions	There is an average space availability in the aquatic zone, but a small one in the terrestrial zone. The vessel impact on plant growth and recovery and other species is moderate, also from private boating as the bank zone is not that interesting for touristic or recreational use ... The land use behind the bank is restricted to e.g. grazing cattle. The human impact is low ... The budget for construction and maintenance is low, as a cheap and sustainable solution is demanded for ... The existing habitat quality is low and should be improved.

Figure 6.7: Extract from Table 6-10 in Part 3, listing most important BCs for the DC Weser

Step 3: Preselection (Chapter 6.3.3 in Part 3)

The third design step helps identify generally appropriate measure types by using numerous preselection tools – in a qualitative way, as mentioned in Chapter 5.2.

For this purpose, user should first review Table 3.1 in Part 3, where measures are categorized according to main construction issues such as the use of pre-embankment structures or the extent of technical elements used. The table also offers links to the most important BCs, such as the magnitude of water-level fluctuations or the influence of excess pore water pressure, which generally define the main features of possible measures. Concerning the example DC, it follows that pre-embankment structures may be appropriate to protect the bank area against too large impacts.

Next, apply the screening approach as outlined in Chapter 4.1 (and more comprehensively in Chapter 6.3.3.1 in Part 3). The latter uses more, but still a very restricted number of, criteria to point toward possible measures, not only *measure types* but also *concrete measures* from the catalogue in Part 2. Again, measures that use pre-embankment structures are in the majority.

Then apply the preselection approach from Chapter 5, whereby all the considerations about relevant BCs and their importance from Steps 1 and 2 can be used. Selected results are shown, together with other preselection tools, in Figure 6.8 (*upper right*, five best-ranked measures).

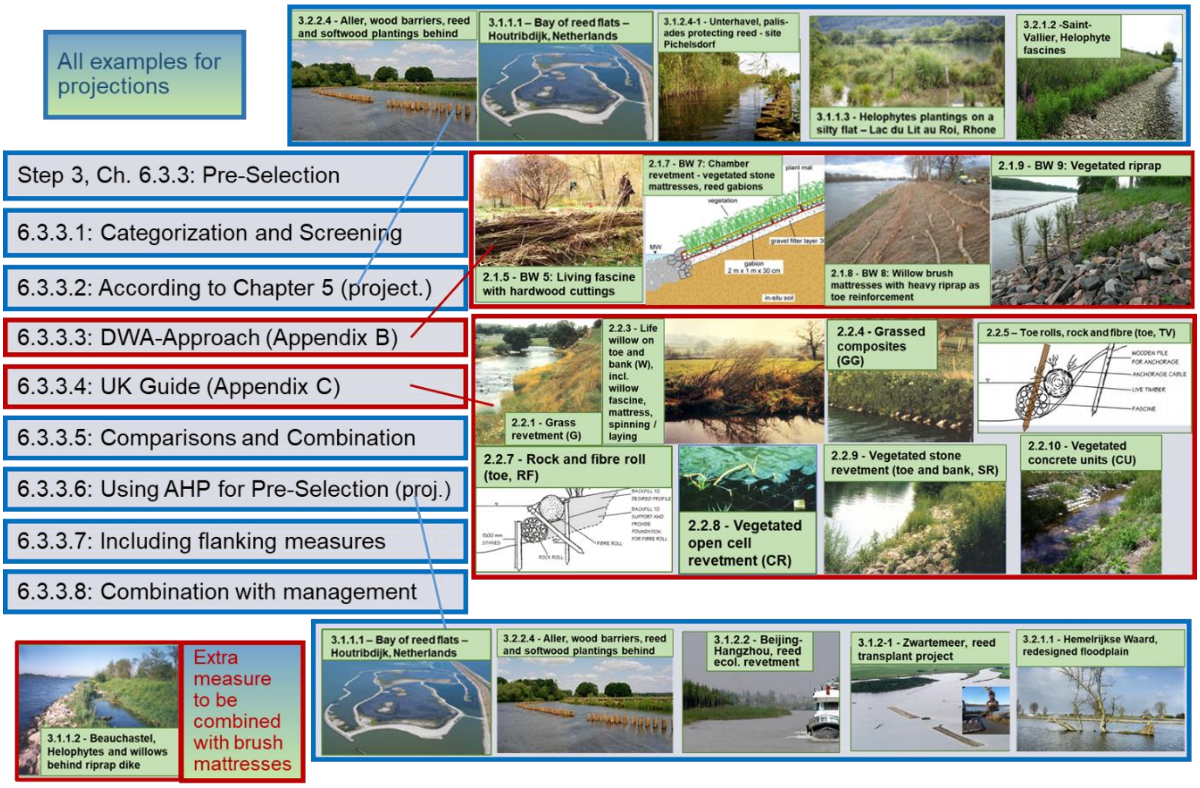


Figure 6.8: Selected results from preselection tools, applied to the Weser DC (ranked from left to right)

For comparisons, use both the DWA-M 519 bioengineering approach (Appendix B in Part 3) and the comprehensive design rules from the UK Waterway Management Guide (Appendix C in Part 3), which include management strategies (see *middle right* of Figure 6.8), and for getting scoring support, use the DWA's approach concerning ship-induced loads. One result addressing bioengineering methods, derived from the UK approach, is shown in Figure 6.9. Results concerning the example DC are marked in *blue boxes* (for example, *grass revetment* or *live willow*). Both alternative design rules address only direct measures, which may not be optimal for the example DC considered here, but they offer numerous design advices in the corresponding descriptions in Part 2, which can be used, for example, to specify variants or variant combinations for Step 6.

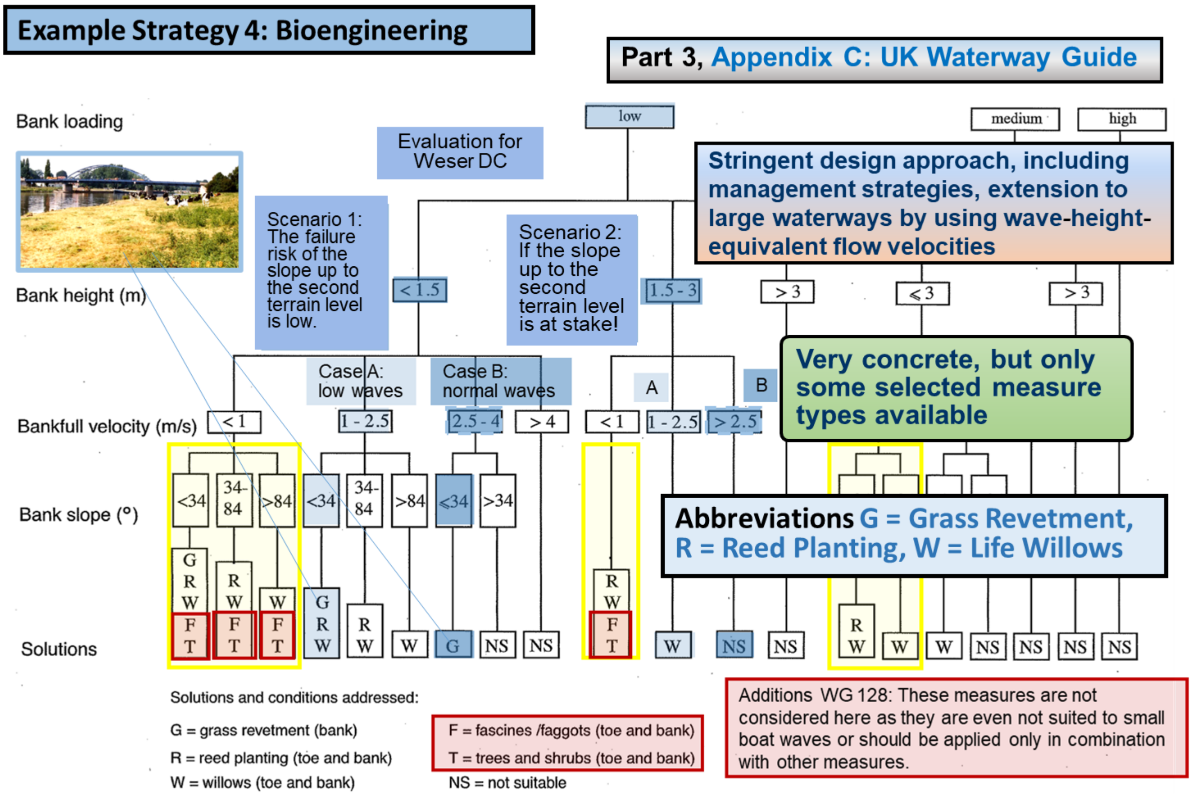


Figure 6.9: Example of the numerous design charts in the UK-Guide – here concerning bioengineering methods

The last preselection results shown in Figure 6.8 are generated by applying the AHP to scores from preselection, here for projections. How the preselection components and tables are linked to the proposals for the AHP scores is shown in Figure 6.10.

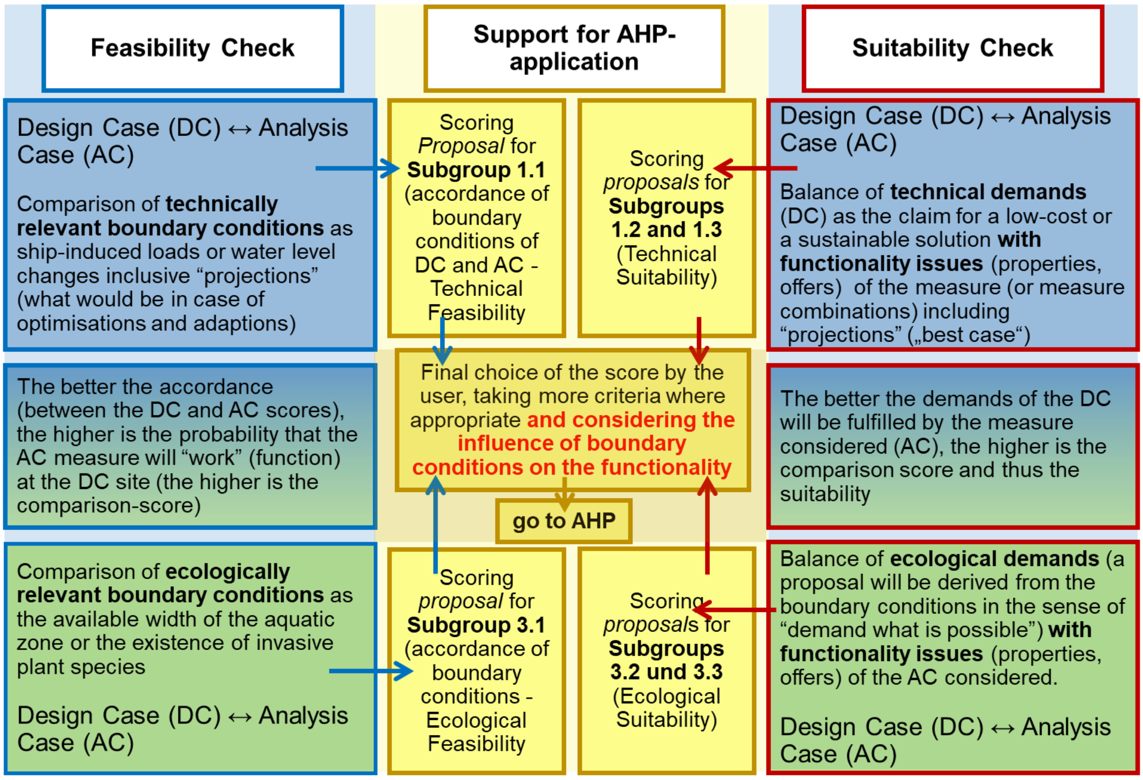


Figure 6.10: Links between preselection and proposals for AHP scores – here used as preselection tool

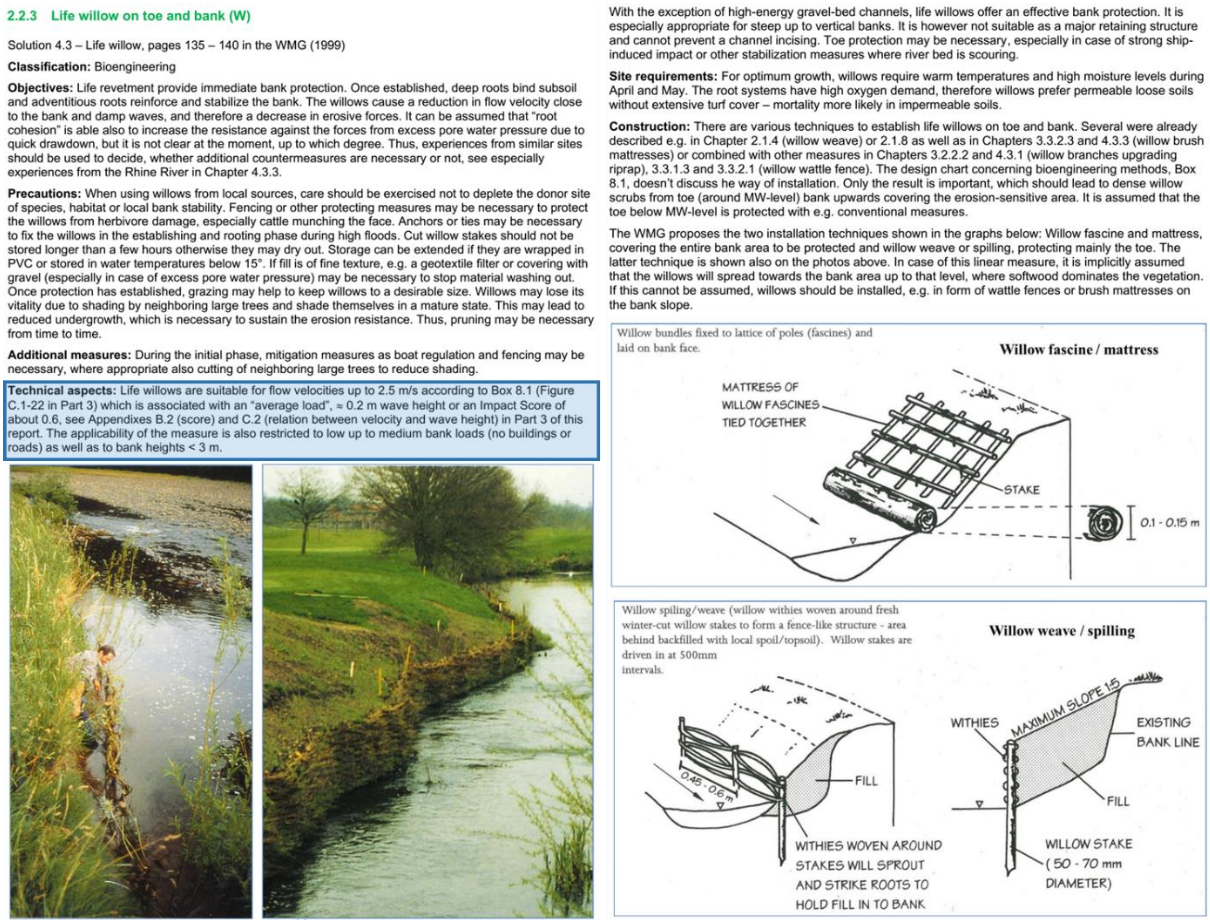
The majority of the best-ranked measures are comprehensive measure combinations, including pre-embankment structures. Because of this result and having the restricted available space of the example DC in mind, a measure on the River Rhône at Beachastel, France, which is shown at *lower left* in Figure 6.8, was added even though it is not as highly ranked as the other measures.

Practitioners and planners should next review flanking measures, which may be combined with other measures such as speed limits or fairway replacement, especially in the initial phase. These are comprehensively discussed in Appendix C in Part 3 or – concerning the example DC, in Chapter 6.3.3.7 in Part 3, including flanking measures and management strategies, which may replace – even only temporarily – engineering measures.

Step 4: Guided view into the Collection of Measures in Part 2 (Chapter 6.3.4 in Part 3)

Even if the study of all the measure descriptions in Part 2 is generally recommended, especially to recognise all the different construction details and the application limits, users needing concrete design recommendations may focus instead only on those recommended measures from preselection.

To give an example, Figure 6.11 shows an extract of the measure 2.2.3 *Live willow at toe and bank*. Application remarks are in the *blue box* and reflect the application charts of bioengineering methods in Figure 6.9.



2.2.3 Life willow on toe and bank (W)

Solution 4.3 – Life willow, pages 135 – 140 in the WMG (1999)

Classification: Bioengineering

Objectives: Life revetment provide immediate bank protection. Once established, deep roots bind subsoil and adventitious roots reinforce and stabilize the bank. The willows cause a reduction in flow velocity close to the bank and damp waves, and therefore a decrease in erosive forces. It can be assumed that "root cohesion" is able also to increase the resistance against the forces from excess pore water pressure due to quick drawdown, but it is not clear at the moment, up to which degree. Thus, experiences from similar sites should be used to decide, whether additional countermeasures are necessary or not, see especially experiences from the Rhine River in Chapter 4.3.3.

Precautions: When using willows from local sources, care should be exercised not to deplete the donor site of species, habitat or local bank stability. Fencing or other protecting measures may be necessary to protect the willows from herbivore damage, especially cattle munching the face. Anchors or ties may be necessary to fix the willows in the establishing and rooting phase during high floods. Cut willow stakes should not be stored longer than a few hours otherwise they may dry out. Storage can be extended if they are wrapped in PVC or stored in water temperatures below 15°. If fill is of fine texture, e.g. a geotextile filter or covering with gravel (especially in case of excess pore water pressure) may be necessary to stop material washing out. Once protection has established, grazing may help to keep willows to a desirable size. Willows may lose its vitality due to shading by neighboring large trees and shade themselves in a mature state. This may lead to reduced undergrowth, which is necessary to sustain the erosion resistance. Thus, pruning may be necessary from time to time.

Additional measures: During the initial phase, mitigation measures as boat regulation and fencing may be necessary, where appropriate also cutting of neighboring large trees to reduce shading.

Technical aspects: Life willows are suitable for flow velocities up to 2.5 m/s according to Box 8.1 (Figure C.1-22 in Part 3) which is associated with an "average load", ≈ 0.2 m wave height or an Impact Score of about 0.6, see Appendixes B.2 (score) and C.2 (relation between velocity and wave height) in Part 3 of this report. The applicability of the measure is also restricted to low up to medium bank loads (no buildings or roads) as well as to bank heights < 3 m.

With the exception of high-energy gravel-bed channels, life willows offer an effective bank protection. It is especially appropriate for steep up to vertical banks. It is however not suitable as a major retaining structure and cannot prevent a channel incising. Toe protection may be necessary, especially in case of strong ship-induced impact or other stabilization measures where river bed is scouring.

Site requirements: For optimum growth, willows require warm temperatures and high moisture levels during April and May. The root systems have high oxygen demand, therefore willows prefer permeable loose soils without extensive turf cover – mortality more likely in impermeable soils.

Construction: There are various techniques to establish life willows on toe and bank. Several were already described e.g. in Chapter 2.1.4 (willow weave) or 2.1.8 as well as in Chapters 3.3.2.3 and 4.3.3 (willow brush mattresses) or combined with other measures in Chapters 3.2.2.2 and 4.3.1 (willow branches upgrading riprap), 3.3.1.3 and 3.3.2.1 (willow wattle fence). The design chart concerning bioengineering methods, Box 8.1, doesn't discuss he way of installation. Only the result is important, which should lead to dense willow scrubs from toe (around MW-level) bank upwards covering the erosion-sensitive area. It is assumed that the toe below MW-level is protected with e.g. conventional measures.

The WMG proposes the two installation techniques shown in the graphs below: Willow fascine and mattress, covering the entire bank area to be protected and willow weave or spilling, protecting mainly the toe. The latter technique is shown also on the photos above. In case of this linear measure, it is implicitly assumed that the willows will spread towards the bank area up to that level, where softwood dominates the vegetation. If this cannot be assumed, willows should be installed, e.g. in form of wattle fences or brush mattresses on the bank slope.

Figure 6.11: Extract from Part 2 concerning the BT Live willow at toe and bank

What can be learnt from the descriptions concerning the example DC is that, for example, it is not that important how the growth of vital willow bushes is initiated (for example, by constructing a wattle fence or by brush mattresses) because the result is about the same once mature: dense willow bushes able to withstand forces from the flow field and to some extent also ship-induced currents. More details can be found in Parts 2 and 3.

After reviewing the measure descriptions, users should have a deeper insight into the main issues associated with the preselected measures. This insight is especially – having the tables of decisive demands and BCs in mind – to recognize the preselected measures' possible drawbacks, which are discussed in the next step.

Step 5: Consideration of Knock-out Criteria (Chapter 6.3.5 in Part 3)

To narrow the set of potential measures even further, sort out measures that obviously contradict with important design criteria, the *knockout criteria*, or those measures where the risk of failure is too great. Thus, Step 5 may also be called *risk analysis*.

Most criteria were already considered while applying the preselection tools, but while using weighted averages of numerous scores and matching tools, some originally decisive criteria lost their significance for design. Thus, these criteria must be considered separately.

For example, ice effects generally demand heavy, technical construction components. So, the majority of bioengineering methods are in such cases simply not reasonable.

For this purpose, as for all design aspects discussed previously, the report offers a large list of relevant criteria, which should be checked by the user so as not to miss any potentially relevant criteria. Of course, experienced planners are unlikely to miss any, but it nevertheless makes sense to check them all again and mark (in Part 3 in *blue letters*) whether they are relevant and which of the preselected measures have to be sorted out, whereby Part 2 offers information to aid this process.

Some knockout criteria with such comments are shown in Figure 6.12 for the example DC. Reviewing the measures in Part 2 reveals that especially large and comprehensive measures may not be appropriate simply because of the discrepancy between available space and budget.

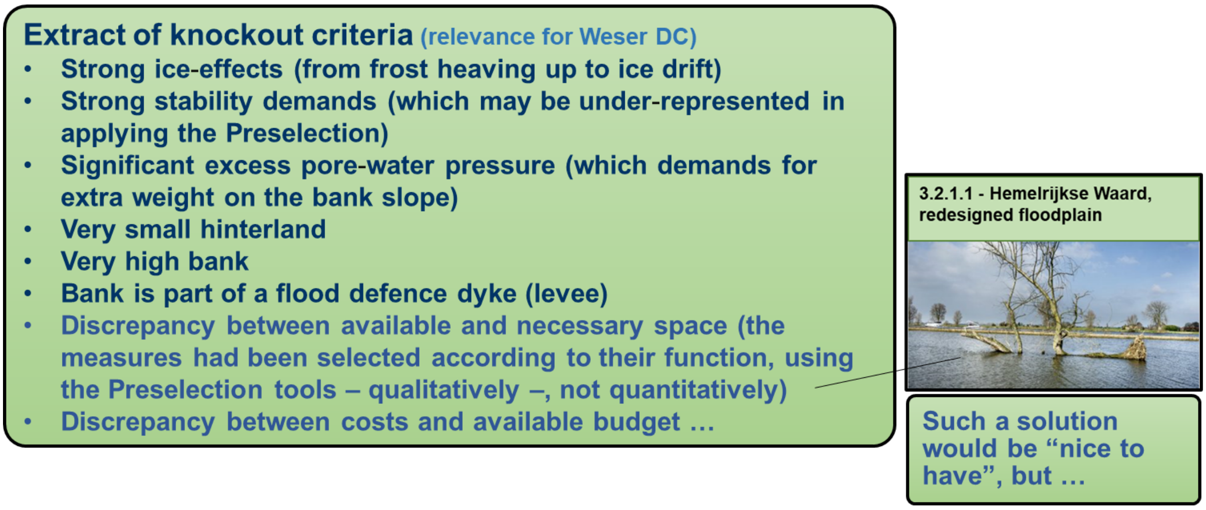


Figure 6.12: Extract from the large list of knockout criteria (relevance for Weser DC marked in blue letters)

Step 6: Definition and Specification of Variants to be Considered in Detail (Chapter 6.3.6 in Part 3)

By the end of Step 5, users should be able to extract realistically feasible measures from all the preselected measures. Looking into the variant description of Part 2 again, users should also be able to adapt and specify these measures for their DC's purposes too. These measures are called *variants* – and because of their origin, they are also called *ACs behind the variants*. This indication is necessary to use all the preselection scores as the basis for applying the AHP.

If a selected variant is a combination of two or more ACs, the Excel sheets offer several combining tools of variant properties, so that corresponding preselection scores can be assessed. Of course, users can modify these scores where appropriate.

If, for example, ecological deficits of a preferred AC shall be upgraded, construction elements of another measure can be combined with the preferred solution. For example, the standard AC example of willow-brush mattresses, protecting the bank slope above MW level (measure 4.3.3), may be upgraded by building a small dam on the rip rap-covered bank in water depths below MW to create a shallow water zone as in the River Rhône close to Beauchastel (measure 3.1.1.2). This combination is surely a good solution for the DC at the impounded Weser River.

The variants shown in Figure 6.13 were therefore chosen for demonstrating the final selection step using the AHP.

Again, as for all previous steps, users must specify all relevant issues, in this case especially the construction details and of course the adaptions made to the ACs behind the variants.

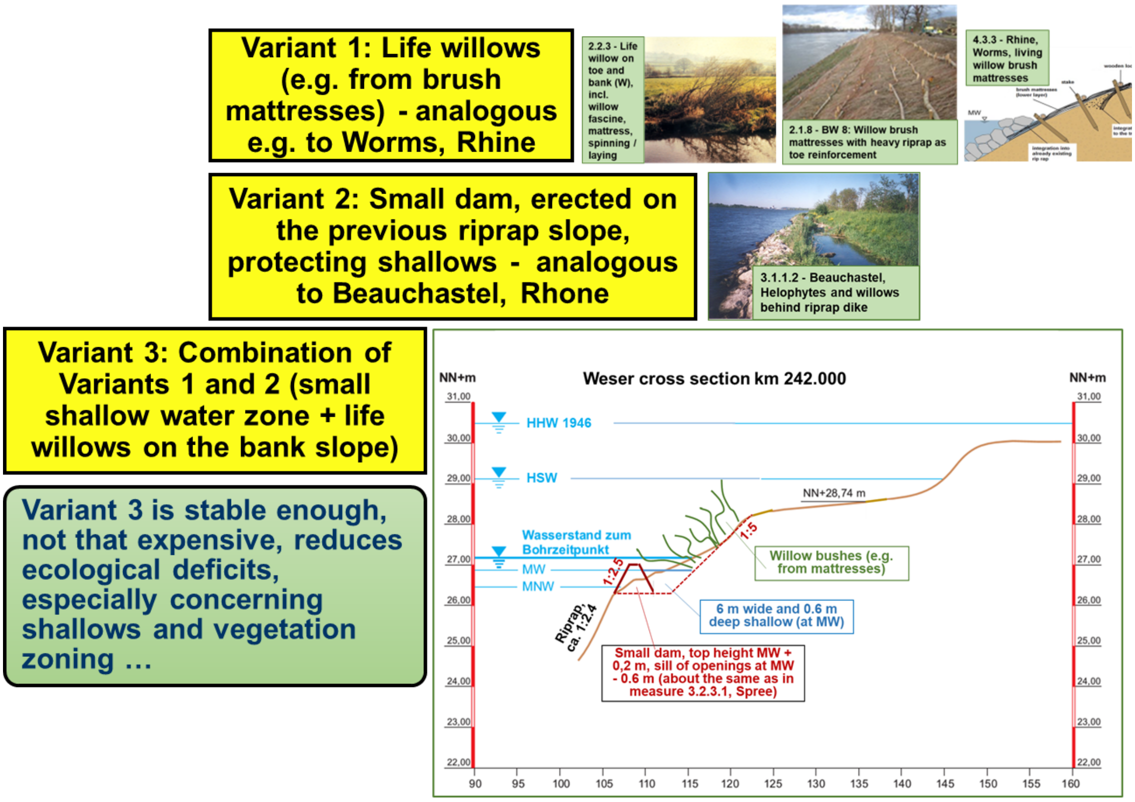


Figure 6.13: Examples (variants) chosen to explain the design approach in the report

Step 7: Choice of the Best Variant (Chapter 6.3.7 in Part 3)

As already outlined in Chapter 6.1, the report and the corresponding Excel sheet offers a standard multicriteria analysis tool, the AHP, which was adapted by the WG members for the special purpose of selecting TBPs. The application of this tool is of course only a *proposal* for performing the multicriteria analysis, not a requirement, but it is a problem-adapted way to resolve with several, partly contradicting, issues.

With reference to Chapter 6.3.7 in Part 3 and the brief description of the AHP in Chapter 6.1 with Figure 6.2 showing the criteria categories and Figure 6.10 the cross links between preselection and AHP scoring, some features of this approach are highlighted as follows:

- The AHP multicriteria approach uses, as the preselection tools in Chapter 5 do, a weighted average of several scores that quantify the importance (by the weight) and the degree of fulfilment (by a score) of the different criteria, leading to a final score, which is used to compare selected variants. The main difference to the preselection approach is the restriction to only a few comprehensive criteria and the use of strongly focused weights, avoiding to smudge the final score through too many less important criteria.
- The AHP uses for this purpose hierarchically structured criteria. Here, three criteria groups were chosen that are related to technical, social, and ecological issues; see Figure 6.2 and the following Table 6.1. Each group contains three subgroups, which include in principle a

large number of single criteria, but they will be addressed when applying the AHP as one comprehensive sub-criterion only.

- The subgroups of the technical and ecological issues describe the accordance of different aspects with BCs and the assessed degree of fulfilment of functionality demands; for example, stability and economy in the technical group or selected taxa and habitats in the ecological group (see Table 6.1).
- The main purpose of the mathematical background of the AHP is to ensure the weighting of the scoring remains *objective*. This objectivity is achieved through pairwise comparisons of the importance of one criterion related to the other and supported by written specifications such as 'The first criterion is three times more important than the second one'. That is, mathematically the weight of Criterion 1 should be three times greater than the weight of Criterion 2. Together with the reasonable rule that the sum of weights should be one (1.0), these criteria pairings result in an overdetermined equation system for evaluating the weights that is solved by the AHP algorithms. The advantage of this approach is that the most important criteria are carved out so that the final weighted-average result is not diluted as if users assessed the weights directly.

But even if the applier of the WG 128 approach gets assistance to objectify the weights, he is generally not an expert and needs at least assistance for scoring. Besides the numerous tables offering scoring guidance for all relevant criteria, the report also offers the ability to use results from the comprehensive preselection tools described in Chapter 5; see Figure 6.10, showing this feature.

To that end, users can get a *first proposal* for the technical and ecological scores for the ACs and ACs behind the variants. For these proposals, either *implemented* measures (measures as they are at the AC site) or *projections* (measures as they could be if adapted and optimised) can be used. More realistic – as the AC shall of course be adapted to the DC site – is to use the projections option, but it is nevertheless recommended to use the implemented scores (marked in *red* in Table 6.1) as the basis for this first proposal of the final scores. Using these scores is better because the preselection scores address only a small number of criteria and because the projections consider *generally possible* adaptions and optimisations, not *specific* adaptions and optimisations for the variants considered. Users should thus use the projection scores only for comparison.

In choosing the final score, also the strong relation between boundary conditions and functionality issues has to be considered, which was neglected while using the preselection tools from practical reasons and replaced approximatively by the numerous matching procedures. Thus, the applier of the AHP is demanded always to answer the following two questions in choosing the final score:

- What would be (how would the score change), if the AC (behind the variant) would have been adapted to DC conditions (consider the AC as to be already realized at DC site), and
- how can the AC measure be further upgraded (for example, ecologically)?

To consider these questions, scoring guidance is offered in Chapter 6.3.7 of Part 3 and the corresponding Excel sheets. Two of such fillable tables are shown in the following: Table 6-2 guides the user to obtain a reasonable $S_{1.1}$ score, quantifying the *degree of fit to site and adaptability* in the *technical performance* group. Table 6-3 provides assistance to quantify the $S_{3.3}$ score, concerning *performance related to selected habitats* in the *ecological performance* group. Both are simplified versions of the corresponding tables in Part 3, presenting only the selected very important criteria (the others are hidden). Even though the two tables are largely self explaining, some remarks will be provided in the following:

Concerning the $S_{1.1}$ score (Table 6-2):

First, the *relevance* of the numerous criteria for the variant considered (here Variant 1) has to be chosen. The latter is marked by a 'X' in column 3. As mentioned earlier, 'decisive' criteria are marked with a blue background. Note that the 'relevance-markings' should be generally the same for all variants, because all variants will be realised at the same place, the DC-site. Nevertheless, the relevance may be different if the measure types are totally different, e.g. if they use wave breakers or not, so that e.g. the relevance of strong ship-induced waves is different.

The *importance* of the criteria should then be chosen. According to Table DFT, max. 4 importance-marks can be used. Note that these marks should be exactly the same for all variants as they reflect the local conditions at DC site only. They should also be in accordance with those from preselection.

The $S_{1.1}$-Score from preselection quantifies mainly the *difference* between BCs of AC- and DC-site. The larger the difference, the lower the probability that the AC will 'work' also under DC conditions. But the AC (behind the variant) may also 'work' at conditions closer to those at DC-site. This is accounted for here by correcting the $S_{1.1}$ from preselection (of realised measures) by an adequate $\Delta S_{1.1}$. For this purpose, single $\Delta S_{1.1}$ are assessed for all selected criteria by checking, up to what extent the boundary conditions at DC site are better or worse than at AC-site and what it means for the functionality of the variant considered.

The user is prompted for this purpose to simply consider predefined objective messages (states) in columns 4-10 as 'DC better, function somewhat better' (2nd best situation) or 'DC worse, function decisively worse' (worst condition) and mark those states, which apply best by 'X'. For example, if the slope at DC site is very much smaller than at AC site, several aspects of the functionality, for example the stability, are decisively better at DC site that at the site of realisation. Then, the 'X-mark' of the criterion 'average bank slope' should be placed in column 4 with the highest positive $\Delta S_{1.1}$ of 0,4.

As all these objective messages are assigned to corresponding $\Delta S_{1.1}$, the quantification of the corrections are simply realised by the X-markings. This approach facilitates the scoring strongly and seems to be appropriate as the corrections $\Delta S_{1.1}$, are generally small.

Note that the BCs should be tackled in the same way as for preselection. This means more specifically: Consider an unprotected bank, but with natural vegetation. This holds true for all BCs considered in the tables.

At the end of the table, a comprehensive $\Delta S_{1.1}$ is calculated by weighted averages of all the assigned single corrections $\Delta S_{1.1}$, (in row 4 below columns 4-10) by multiplying the single scores with the number of importance-crosses (from column 2) from those criteria, which are marked to be relevant in column 3 and divided by the sum of relevant importance marks. These are added to $S_{1.1}$ from preselection of realised measures and compared to the numbers from projections from preselection.

The final choice of the $S_{1.1}$-score to be filled in Table 6-14 (column 5, line 2, marked in blue colour) may be used in between the numbers of realised scores plus corrections and those from projections from preselection. This choice is indicated in Table 6.2 in the box called 'final choice' below right. Here, 2/3 of the corrected preselection number was chosen plus 1/3 of the score for projections. The same approach is used in the Excel file.

Concerning the $S_{3.3}$ score (Table 6-3):

By contrast to the $S_{1.1}$ score (just as the $S_{3.1}$ score for ecological aspects), which tackles *BCs* and its *indirect* effects on functionality, the $S_{3.3}$-Score (just like the $S_{2.1}$ – $S_{2.3}$ and $S_{3.2}$ scores) quantifies the *suitability* of the measures, but now under *direct* consideration of the BCs at DC site. More concrete, the $S_{3.3}$ score quantifies, up to which degree the planner's demands concerning ecological benefits of selected habitats will be fulfilled by the selected measure (here willow brush mattresses at Weser site).

For obtaining these $\Delta S_{3.3}$, assess, whether and to what extent the AC measure may be reasonably adapted and optimised to fulfil the demands better than at the AC, tackling criteria analogous to those in Tables DSE and ASE (demands versus 'offers') and how the different BCs at DC site speak for an improved functionality.

For this purpose, mark again first the importance of the criterion by max. 2 'X' in column 2 (use the same importance for all variants). If the criterion is relevant for the variant, mark it by an 'X' in column 3. Reduce the relevant criteria where appropriate to those, which are really decisive and which allow differences in the variants to be worked out as well as the ACs behind the variants.

Mark finally the applicable objective message (state, wording) in the columns 4-10 of the table by an 'X' for relevant criteria. Example: If the available space for potential riparian vegetation at DC site is very much larger than at AC site or if it is reasonable and possible to increase the existing space strongly compared to the conditions at AC, the conditions at DC site are far better than at the AC and thus the suitability score would be better, if the AC measure would be realised at DC site, leading to $\Delta S_{3.2}$ = + 0.4.

Again, as in Table 6.2, all the single $\Delta S_{3.3}$ will be combined by a weighted averaging to a comprehensive $\Delta S_{3.3}$, which increases the $S_{3.3}$ from preselection and may be the final choice to be implemented (here) in Table 6-1.

(1) Group	(2) Group weight	(3) Single (subgroup) criterion and *references to scoring guidance*	(4) Weight related to single criterion (subgroup)	(5) Single (subgroup) score	(6) Remarks concerning scoring	(7) Weighted group score	(8) Final score
1: Technical performance	W_1 (0.47)	Degree of fit to site and adaptability	$W_{1.1}$ (0.48)	$S_{1.1}$ (0.37) (0.17)	The score scales *differences* in BCs between the DC site and AC sites (where the example variant was already implemented) – analogous to the scoring in Tables DFT and AFT, which should form the basis of this score.	Technical performance score: S_1 = $W_{1.1} \cdot S_{1.1}$ + $W_{1.2} \cdot S_{1.2}$ + $W_{1.3} \cdot S_{1.3}$ = 0.31	Overall performance score S_{AHP} = $W_1 \cdot S_1$ + $W_2 \cdot S_2$ + $W_3 \cdot S_3$ = 0.17
		Performance concerning stability and sustainability	$W_{1.2}$ (0.41)	$S_{1.2}$ (0.23) (0.02)	The score assesses to what degree the DC's demands will be fulfilled by the variant – analogous to the scoring in Tables DST and AST (criteria C–G), which should form the basis of this score.		
		Performance related to avoiding technical efforts	$W_{1.3}$ (0.11)	$S_{1.3}$ (0.36) (0.22)	The score assesses to what degree the DC's demands will be fulfilled by the variant – analogous to the scoring in Tables DST and AST (criteria A,B, H, I), which should form the basis of this score.		
2: Social and legal performance	W_2 (0.06)	Fulfilment of human demands	$W_{2.1}$ (0.09)	$S_{2.1}$ (−0.05)	The score must be assessed by the user directly, judging to what degree the DC's demands will be fulfilled by the variant.	Social and legal performance score: S_1 =	

		Performance concerning landscape and preservation issues	$W_{2.2}$ (0.45)	$S_{2.2}$ (0.08)	The score must be assessed by the user directly, judging to what degree the DC's demands will be fulfilled by the variant.	$W_{2.1} \cdot S_{2.1}$ + $W_{2.2} \cdot S_{2.2}$ + $W_{2.3} \cdot S_{2.3}$ = 0.18	
		Fulfilment of legal demands and acceptance	$W_{2.3}$ (0.45)	$S_{2.3}$ (0.34)	The score must be assessed by the user directly, judging to what degree the DC's demands will be fulfilled by the variant.		
3: Ecological performance	W_3 (0.47)	Degree of fit to site conditions and adaptability	$W_{3.1}$ (0.47)	$S_{3.1}$ (0.15) (0.10)	The score scales *differences* in BCs between the DC and AC sites (where the example variant was already implemented) – analogous to the scoring in Tables DFE and AFE, which should form the basis of this score.	Ecological performance score: S_1 = $W_{3.1} \cdot S_{3.1}$ + $W_{3.2} \cdot S_{3.2}$ + $W_{3.3} \cdot S_{3.3}$ = 0.01	
		Performance related to selected taxa	$W_{3.2}$ (0.07)	$S_{3.2}$ −0.05 (−0.11)	The score assesses to what degree the DC's demands will be fulfilled by the variant – analogous to the scoring in Tables DSE and ASE, which should form the basis of this score.		
		Performance related to selected habitats	$W_{3.3}$ (0.47)	$S_{3.3}$ −0.11 (−0.19)	The score assesses to what degree the DC's demands will be fulfilled by the variant – analogous to the scoring in Tables DSE and ASE, which should form the basis for this score.		

Table 6-1: Weighting and scoring for the AHP with scoring guidance (values are for the Weser DC and the AC example of willow-brush mattresses – measure 4.3.3), here called Variant 1 (red numbers come from preselection) for the implemented measure at the AC site). The weights of the criteria in each subgroup and those between groups are assessed through pairwise comparisons of the importance of the one criterion related to the other using the AHP algorithm.

For the AC example, willow-brush mattresses, which should be implemented at the Weser DC site, the results are shown in Table 6.1. It turned out that the milder BCs at the DC site result in a relatively high score concerning the fit to BCs, a lower but still good score concerning stability and sustainability, and an even higher score concerning effort-related issues (especially to avoid costs), as the chosen planner's demands to find a possibly low-cost solution could satisfactory be fulfilled. The final technical score (0.3-0.4) is good but could be better.

The score concerning human demands is negative, the one concerning landscape and preservation is still low but at least positive, and the score concerning the fulfilment of legal aspects is good, resulting in a low but still positive overall score concerning social aspects. This result is not surprising given human demands such as access to the waterline are strongly hindered by dense willow bushes.

It is also not surprising that the ecological functionality scores are low because the demand to enhance the shallows is not fulfilled. Of course, if the chosen demands in this DC example were different, then the ecological score might then be higher.

The final score is adequate (0,17 is at least larger than zero) meaning that the AC measure is feasible and that it fulfils most of the planner's demands. Variant 3 (not presented here) got a better score (0,24), showing that measures that create a shallow ahead of the bank slope may be more appropriate for this example DC site's chosen demands, which were formulated previously; see Figure 6.6. However, because this example only selected three variants from the overall list of possible measures, Variant 3's score here does not mean it is, in fact, the optimal variant for the DC considered. When using the AHP to assign final scores, users should first select as many variants as appropriate for their specific DC.

Name of Variant: Willow brush mattresses according to measure 4.3.3 – Variant 1

Criteria and scoring rules for **adapting the $S_{1.1}$ – Score from preselection** (Tables DFT and AFT, considering the **accordance with boundary conditions and adaptability** to DC conditions in the **Technical Functionality Group**, see also Tables A.4-1 – A.4-3), **based on 'realised' measures.**

Have a look at Table DFT concerning chosen BCs. Consider the importance of these BCs in applying this table. Have a look also at Table 6-8 in Part 3, where all 'decisive' BCs are collected and mark their relevance accordingly.

Column 1	2	3	4	5	6	7	8	9	10
The $S_{1.1}$-Score quantifies the difference between BCs of AC- and DC-site. The larger the difference, the lower the probability that the AC will 'work' also under DC conditions. But the AC (behind the variant) may also 'work' at conditions closer to those at DC-site. This is accounted for here by correcting $S_{1.1}$ by adequate $\Delta S_{1.1}$. For obtaining $\Delta S_{1.1}$, assess, to what extent the following BCs at DC site are better or worse than at AC-site and what it means for the functionality of the variant considered. • **Mark the importance of the boundary conditions by max. 4 'X' in column 2 (use the same importance for all variants), showing at DC site.** • **If the BC is relevant for the variant, mark it by an 'X' in column 3.** • Use as far as possible the same relevance-marks for all variants. • Reduce the relevant criteria where appropriate to those which are really decisive (look e.g. at Table 6-10) for all variants (not for the DC only as in Table 6-10) and which allow differences in the variants to be worked out as well as the ACs behind the variants. • **Mark the applicable wording in the columns 4-10 of the table by an 'X' for relevant BCs.** Example: If the slope at DC site is very much smaller than at AC site, several aspects of the functionality, for example the stability, are decisively better. The 'X-mark' of the criterion 'average bank slope' should be placed in column 4. The 'projection'-option of the preselection tools makes generally the same, but only for selected BCs. Nevertheless, use the projected $S_{1.1}$ for comparisons.	Importance of the criterion	Relevance for the DC considered	DC far better, function decisively better	DC better, function somewhat better	DC better, function at least the same	0 = DC about the same	DC worse, function about the same	DC worse, function somewhat worse	DC worse, function decisively worse
$\Delta S_{1.1}$ – categories			+0.4	+0.2	+0.1	0	-0.1	-0.2	-0.4
Colouring: BCs at DC better than AC ('mild site') and vice versa ('worse site')			BCs at DC are better than at AC				BCs at DC are worse than at AC		
Renewed Consideration of selected BCs from Table DFT & AFT to account for better scores on the 'mild side' (see remarks below the table) (proposal: choose the same number of importance-'X' as in Table DFT for relevant criteria)									
(A) Ship-induced impacts	XX	X				X	$\Delta S_{1.1}$ already adequately considered by Pre-Selection		
(B) Average Bank Slope (smaller at DC and can be further flattened)	X	X		X					
(E) Hinterland space ('to work with') (larger at DC site)	XX	X	X						
(F) Water level fluctuations (waterway type) (much lower at DC compared to AC)	XXXX	X	X						
Additional BCs from Table A.4-1 (DWA-M 519) – see Appendix B									
Waterway Class of largest single-sailing vessel (n. I.1.1 in Tab. I.1 in Appendix B) (lower at DC)	XX	X		X					
Midship-bank distance of large commercial vessels (Tab. I.1 in Appendix B)	XX	X		X					
Speed limit for large commercial vessels (no. I.1.4 in Tab.I.1 of Appendix B) (existing at DC)	X	X			X				
Traffic volume of large vessels (no. I.1.5 in Tab. I.1) (very much lower at DC)	X	X		X					
Additional BCs from Table A.4-2 (UK Waterway Management Guide) - Appendix C									
Channel status (sedimentological view), see Fig. C.1-9 (erosion at AC, DC stable)	X	X			X				
Consequences of bank erosion, see Fig. C.1-10 (very much more severe at AC)	X	X		X					
Issues to be addressed (wildlife, fishing, grazing access, recreational access, mooring access, prevention of property, navigation, flood defence, structures nearby (e.g. weirs, river regulation measures, bridges, roads, buildings, mooring facilities), various stakeholder's interests (e.g. waterway authorities, local government, private ownership), vandalism etc., see Fig. C.1-14 & C.1-15 – mark and select relevant issues (issues are more relevant at DC compared to AC)	XX	X					X		
BCs related to allow management strategies, see Figures C.1-14 & C.1-15	X	X				X			
BCs related to boat regulation, see Figures C.1-20 & C.1-21	X	X			X				

BCs related to tree management - for selecting non-engineering measures	X	X							X	
Bank loading (above and on bank slope), see Figures C.1-22 & C.1-23	X	X	X							
Bank height for selecting engineering measures, see Figures C.1-22 & C.1-23	XX	X		X						
Bankfull flow velocity without navigation, see Fig. C.1-22 & C.1-23 in Appendix C.2	X	X		X						
Selected additional BCs from Table A.4-3 (Student Research Project, TU-Darmstadt										
Floating foreign matter (relevant for variants 2 and 3 – garbage deposits at AC)	XXXX									
Extreme dry and inundation periods	XX	X	X							
Wind wave impact (relevant for Variants 2 and 3 – highest impact at AC Rhone)	XX									
Potential erosion amount and/or speed (unprotected bank)	XX	X		X						
Sunlight exposure, influencing vegetation	X	X					X			
Dimension of the bank area supporting vegetation zoning	X	X					X			
Risk of bank failure (unprotected bank) or consequences of erosion	XX	X		X						
Possibilities of pre-embankment measures	X	X		X						
Land use behind the bank	XX	X		X						
Budget versus construction costs (low-cost solution demanded at DC)	XX	X					X			
Budget versus maintenance costs (low-cost solution demanded at DC)	XX	X					X			
Numerical evaluation: Multiply the number of importance crosses with the assigned $\Delta S_{1.1}$ for all relevant criteria (mark 'X' in column 3), sum the products up and divide by the total number of importance crosses for all relevant criteria.	$\Delta S_{1.1}$= 0.15									
Preselection Score $S_{1.1}$ (realized measure) = 0.17 / Pre-Sel. $S_{1.1}$ for projections = 0.47	$S_{1.1} + \Delta S_{1.1}$ = 0.32									
Final choice e.g. 2/3*($S_{31,realized}$+ΔS_{31}) + 1/3*$S_{31,projections}$	Final choice $S_{1.1}$ = **0.37**									

Table 6-2: Guidance for determining the S1.1 score (degree of fit to site and adaptability) when applying the AHP to Variant 1 – criteria not used hidden (complies with Table 6-15 in Part 3, decisive criteria for all 3 variants are marked by a X with dark-blue background)

For completion, it should be noted that Part 3 offers also tools for *direct* variant comparisons, basing again on AHP, which is used in this case not only for calculating the weights, but also for scoring. The comparisons may then be applied to all 9 criteria-groups defined above (to end-up with corresponding scores $S_{1.1}$ – $S_{3.3}$) and then combined again by using the above mentioned AHP-weights.

These direct variant comparisons seem to be easier to apply for many users, especially for non-experts, but the results are of course stronger influenced by personal preferences, because the numerous results from preselection are not used. Also, the comparisons and thus the scores are variant-specific, so that every new variant combination will lead to different scores.

Therefore, it seems appropriate that at least two (better more) appliers should make the same comparisons to explore the 'human factor' on the results of the direct variant comparisons. But, as the 'human factor' cannot be neglected also in using the recommended selection schemes presented above, a general recommendation is that the approaches should be applied generally by several users, maybe divided into engineers for the technical and biologists for the ecological aspects, but both groups of appliers should perform the steps for all relevant variants altogether.

Name of Variant: Willow brush mattresses according to AC measure 4.3.3									
Criteria and scoring rules for **adapting the $S_{3.3}$ – Score from preselection** (Tables DSE and ASE, considering **potential ecological benefits of selected habitats** in the **Ecological Performance Group** see also Table A.4-8), **based on 'realised' measures.** Have a look at Table DSE concerning chosen demands. Consider the importance of these demands in applying this table. Have a look also in Table 6-23 in Part 3, where all 'decisive' demands are collected and mark their relevance accordingly.									
Column 1	2	3	4	5	6	7	8	9	10
The $S_{3.3}$-Score quantifies the, *up to which degree the planner's demands concerning ecological benefits of selected habitats will be fulfilled by the measure*. This is called 'suitability' in the preselection scheme. The better the demands will be fulfilled, the higher is the suitability score (total fulfilment: $S_{3.3}$= 1, no fulfilment at all: $S_{3.3}$ = -1). The preselection score of realised measures considers the measure as it is and under AC conditions and for a few selected criteria only. **The question is, what would be, if the AC (behind the variant) was adapted and realised under DC conditions and how would the scores change if other criteria will be added.** This is made here by correcting $S_{3.3}$ by adequate $\Delta S_{3.3}$ For obtaining $\Delta S_{3.3}$, **assess** • **whether and to what extent the AC measure may be reasonably adapted and optimised to fulfil the demands better than at the AC,** tackling criteria analogous to those in Tables DSE and ASE (demands versus 'offers') **and** • **how the different BCs at DC site speak for an improved functionality.** For this purpose, • **mark the importance of the criterion by max. 2 'X' in column 2 (use the same importance for all variants).** • **If the criterion is relevant for the variant, mark it by an 'X' in column 3.** • **Reduce the relevant criteria where appropriate to those, which are really decisive and which allow differences in the variants to be worked out as well as the ACs behind the variants.** • **Mark the applicable wording in the columns 4-10 of the table by an 'X' for relevant criteria.** Example: If the available space for potential riparian vegetation at DC site is very much larger than at AC site or if it is reasonable and possible to increase the existing space strongly compared to the conditions at AC, the conditions at DC site are far better than at the AC and thus the suitability score would be better, if the AC measure would be realised at DC site, leading to $\Delta S_{3.2}$ = + 0.4. For assessing suitability issues, consider the variant to be realised at DC-site.	Importance of the criterion	Relevance for the DC considered	DC far better, function decisively better	DC better, function somewhat better	DC better, function at least the same	0 = DC about the same	DC worse, function about the same	DC worse, function somewhat worse	DC worse, function decisively worse
$\Delta S_{3.3}$ - categories			+0.4	+0.2	+0.1	0	-0.1	-0.2	-0.4
Colouring: BCs at DC better than AC ('mild site') and vice versa ('worse site')			At DC better or better adapta b-le as at AC				At DC worse or worse adaptab-le as at AC		
Renewed consideration of taxa-related preselection criteria (demands/offers) from Tab. DSE & ASE (proposal: choose the same number of importance 'X' as in Table DFT for relevant criteria)									
(7) Habitats of bed and banks (aquatic zone, wet reed zone, up to & around MW)	XX	X		X					
(8) Habitats of riparian zone and floodplains (amphibian and terrestrial zone - bank area around and above MW)	XX	X			X				
(9) Habitats connectivity	X	X			X				
Additional criteria from Table A.4-8 (Student Research Project, TU-Darmstadt)									
Status dead matter in relevant aquatic habitats (rip rap, groynes, deadwood)	X	X				X			
Status dead matter in relevant terrestrial habitats (remaining technical protections)	X	X				X			
Avail. & potential development of terrestrial habitats (soft- and hardwood zone)	X	X			X				
Vegetation zoning and its lateral extension (better as smaller slope at DC site)	XX	X		X					
Geographical congruence of habitats	X	X				X			
Deficits between target and possible vegetation	XX	X				X			

Reducing construction and maintenance efforts due to creating aimed habitats	XX	X			X				
Consideration of selected boundary conditions, related to benefits for selected habitats									
(A) Space availability in the aquatic zone	*XX*	*X*			*X*				
(B) Space availability in the terrestrial/amphibian zone	*XX*	*X*					*X*		
(C) Surrounding land uses	*X*	*X*		*X*					
(D) Hydrodynamic Environment	*XX*	*X*		*X*					
(E) Vessel impact (ecological view, e.g. impact on plants, disturbance frequency)	*XX*	*X*		*X*					
(F) Bank substrate (ecological view, e.g. ability to support vegetation)	*X*	*X*			*X*				
Waterway (channel) type and water level fluctuations	*XX*	*X*		*X*					
Average bank slope	*X*	*X*		*X*					
Issues to be addressed (wildlife, fishing, grazing access, recreational access, mooring access, prevention of property, navigation, flood defence, structures nearby (e.g. weirs, river regulation measures, bridges, roads, buildings, mooring facilities), various stakeholder's interests (e.g. waterway authorities, local government, private ownership), vandalism etc., see Fig. C.1-14 & C.1-15 – mark and select relevant issues	*XX*	*X*				*X*			
Existing hinterland space, see Fig. C.1-17	*X*	*X*			*X*				
Possibilities and limitations of constraints to navigation, Fig. C.1-20 & C.1-21	*X*	*X*	*X*						
BCs related to tree management	*XX*	*X*				*X*			
Flow velocity in bank zone without navigation, see Fig. C.1-22 & C.1-23 in C.2	*X*	*X*			*X*				
Floating foreign matter (relevant for variants 2 and 3 – garbage deposits at AC)	*XX*								
Extreme dry and inundation periods	*XX*	*X*	*X*						
Wind impact (dry out, wind wave impact, relevant for Variants 2 and 3)	*XX*								
Ice-effects (from frost heaving, ice lift up to ice drift)	*X*	*X*				*X*			
Influence of river training	*X*	*X*			*X*				
Sunlight exposure and shading, influencing vegetation	*XX*	*X*				*X*			
Plant regeneration ability on unprotected bank	*X*	*X*		*X*					
Dimension of the bank area supporting vegetation zoning	*XX*	*X*				*X*			
Stabilization by natural plant growth	*X*	*X*				*X*			
Possibilities of pre-embankment measures (also for ecological upgrade only)	*X*	*X*	*X*						
Possibilities and limitations of intensive maintenance measures	*XX*	*X*						*X*	
Available space and land use behind the bank	*X*	*X*		*X*					
Sensitivity to changing conditions, e.g. water levels or climate	*X*	*X*		*X*					
Budget versus construction costs	*X*	*X*					*X*		
Budget versus maintenance costs	*XX*	*X*						*X*	
Aquatic habitat quality	*XX*	*X*			*X*				
Terrestrial habitat quality	*XX*	*X*			*X*				
Numerical evaluation: Multiply the number of importance crosses with the assigned $\Delta S_{3.3}$ for all relevant criteria (mark 'X' in column 3), sum the products up and divide by the total number of importance crosses for all relevant (marked) criteria.	$\Delta S_{3.3}$ = + 0.08								
Preselection Score $S_{3.3}$ (realised measure) = - 0.19	$S_{3.3} + \Delta S_{3.3}$ = - 0.11								
Use e.g. a rounded number – here 2 decimals were used.	Final choice $S_{3.3}$ = **- 0.11**								

Table 6-3: Weighting Scoring guidance for S3.3 score (performance related to selected habitats) when applying the AHP to Variant 1 — criteria not used hidden (complies with Table 6-23 in Part 3, decisive criteria for all 3 variants are marked by a X with dark-blue background)

6.4 Steps after Selection

As mentioned in Chapter 1, almost all design processes, including the BPA should be a looped approach – meaning always provide feedback to the decision-making bodies, contract-making authorities, and other stakeholders. Presenting and justifying the selection will generally end with questioning the basics of the measure's design.

During this looped-feedback process, nature-protection authorities may express disappointment or frustration that the selected measure will not provide enough ecological benefit. By contrast, waterway authorities may express fear or doubt that the selected measure will not provide enough bank stability. Thus, discussions held with these stakeholders will often lead to modified planner's demands and thus additional loops of the BPA.

This looped approach to the BPA often requires patience and compromise, but the end result – a TBP measure that fulfils as many demands as the DC site's BCs allow – is well worth this additional effort.

7 DISCUSSION OF THE BEST-PRACTICE APPROACH'S (BPA) LIMITS

This report has broadly examined the topic of TBPs for inland waterways. However, the report does not seek to examine all facets of blended TBPs in all potential use cases. For instance, navigable waterways serve as the primary focus, which implies a focus on rivers large enough to support navigation where ship-induced impacts are the dominant forces in bank-erosion processes. The report also focuses on actions in the near-bank environment rather than river training or watershed management. The approach described here is restricted to the typical objectives of an engineering study of bank protection, and management decisions at larger temporal and spatial scales (for example, land-use zoning) are beyond this report's scope. Chapter 1.2.3 (and Chapter 1.2 in Part 3) summarises the major scoping decisions guiding this report and can be revisited through the lens of limitations in the application of the BPA.

The WG reviewed TBPs using an empirical approach that bases on examples presented in agency reports, peer-reviewed literature, and other available documents. Examples were only included if detailed studies supported their development or monitoring data were collected. Best practices should be developed from detailed accounts of project success and failure, and project databases are valuable tools to collect examples and lessons learned. Comparable databases have been developed for other areas of engineering practice and could serve as models, such as the international stormwater best-management-practice database (**https://bmpdatabase.org/**). For bank stabilisation, a database would need to be flexibly structured to adapt to the rapidly growing breadth of actions and associated combinations of actions. Similarly, the database should include projects with varying levels of monitoring, from simple compliance to long-term performance [van Rees et al., 2022].

A major limitation of the BPA as presented here is the breadth and diversity of ecological and engineering contexts. For instance, the same bank-stabilization measure could perform very differently short distances away if the planted vegetation varied or an ecological barrier to recruitment or dispersal existed. The specification of ecological BCs proved to be a limitation of the transferability of some seemingly comparable measures and sites.

An additional challenge this WG encountered was somewhat fundamental differences between ecological and engineering design approaches and levels of risk tolerance. Success from an engineering viewpoint often focuses on concepts of predictability, reliability, and static performance, whereas ecological success may rely on ideas of recovery, diversity, and self-organization. These challenges led to the WG developing a set of methods and tools that are largely comparative, rather than deterministic. For instance, the analysis methods shown in this report could provide useful metrics of the relative success of two potential actions at a given site or the relative merits of two nearby sites, but the values of the assessments may not be rigorously comparable across diverse regions. The analysis methods should be applied with this scope in mind (that is, largely restricted to planning decisions), and some design decisions may require additional process-oriented models.

Importantly, the WG found that alternative methods for bank stabilisation are widely used, viable in many contexts, and particularly appropriate for sites with multiple objectives. The analysis tools offered here can inform planning-level decisions for bank-stabilisation projects, but engineering judgement and analysis will still be needed at the detailed design scale (for example: material selection and sizing).

8 THE FUTURE OF RESPONSIBLE INTEGRATED DESIGN OF NATURE-FRIENDLY BANK-PROTECTION METHODS AND THE USE OF THE DECISION MODEL

The intention is that the report of WG 128 forms the basis for a responsible decision about the most suitable nature-friendly bank along inland waterways and rivers. The choice model also presented herein is intended as a decision-support system.

The decision-support system will therefore always have to be followed by a design phase based on the local circumstances using the outcomes of the system. It is important when using natural bank systems that variation is guaranteed.

This built-in variation is also in line with the more holistic approach to design that takes into account specific wishes and requirements of the environment, both in a human and an ecological sense.

This holistic approach to environmental management normally produces a broadly supported design, because the chance of vandalism or opposition to the plan must be included during the planning phase.

It is therefore very important to have a good idea of both the ecological score and the possibilities of shared recreational use in advance so that the planning scope is clear and the design can be modified on that basis.

While compiling this report, the WG found the differences in standardisation of hydraulic engineering works and the possibilities to score the ecological performance between engineering bureaus, waterway authorities, and other planning agencies particularly difficult to reconcile.

The WG has therefore already considered using the methods of ecological key factors used by the Dutch water authorities, which are based on the EU's WFD and referred to as *good ecological potential* (GEP).

For proper integration of nature-friendly banks, practitioners must obtain a picture of this ecological performance by means of extensive monitoring so that it is clear how the bank performs ecologically.

This discussion between technology and ecology, together with the COVID-19 pandemic (2020-2022), has led to a significant delay in work, although all members of the WG continued with their tasks and activities during this difficult time to complete the report in a dignified manner.

These special circumstances have generated a great deal of team spirit among the WG, whose members are therefore open to constructive comments and expect that readers will benefit greatly from the guidance they have provided here.

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APPENDIX A: ABBREVIATIONS AND GLOSSARY

A.1 ABBREVIATIONS

Abbreviation	Definition
AC	Analysis Case
AFE	Analysis Case, feasibility check, ecological aspects
AFT	Analysis Case, feasibility check, technical aspects
AHP	Analytical Hierarchy Process
ASE	Analysis Case, suitability check, ecological aspects
Asl	Above Sea Level
AST	Analysis case, Suitability check, Technical aspects
BAW	German Federal Waterways Engineering and Research Institute
BC	Boundary Condition
BfG	German Federal Institute of Hydrology
BPA	Best Practice Approach
BT	Basic Type
CEMT	European Waterway Classification
CETMEF	Centre d'Etudes Maritimes Et Fluviales
CoCom	International Co-Operation Commission of PIANC
CS	Case Study
CR	Vegetated Open Cell Revetment (from WMG)
CV	Vegetated Concrete Units Revetment (from WMG)
DC	Design Case
DDR	German Former Eastern State
DFE	DC, feasibility check, ecological aspects
DFT	DC, feasibility check, technical aspects
DSE	DC, suitability check, ecological aspects
DST	DC, suitability check, technical aspects
DWD	German Weather Forecast Service
DWA-M 519	German Code of Practice for Designing TBPs (DWA 2016)
EnviCom	Environmental Commission of PIANC
ES	Ecosystem Services
FD	Functionality Demands
FF	Fact File

G	Grass Revetment (from WMG)
GEP	Good Ecological Potential (from EU WFD)
GG	Grass and Geotextiles (from WMG)
HHW	Highest Observed Water Level
GBB	German Code of Practice for Designing Bank Protections (Software GBBSoft+)
HSW	Highest Shipping Level
HW	High Water
InCom	Inland Navigation Commission of PIANC
LUBW	State Institute for the Environment Baden-Württemberg
MarCom	Maritime Navigation Commission of PIANC
MHW	Mean High Water Level
MNW	Mean Low Water Level
MW	Mean Water Level
NN	German Abbreviation of *Normal Null*, Meaning *Sea Level*
OSC	Overall suitability check
PIANC	The World Association for Waterborne Transport Infrastructure
PS	Preselection
RF	Rock and Fiber Roll (from WMG)
SGW	Ship generated wave
SR	Vegetated Stone Revetment (from WMG)
TAB	Table (in particular in attached Excel tables)
TBP	Technical-Biological Bank Protection
TG	Toe Geotextile (from WMG)
TV	Timer and Vegetation (from WMG)
Qx	Discharge with x Years Recurrence
ToR	Terms of Reference
W	Life Willow at Toe and Bank (from WMG)
WFD	European Union Water Framework Directive
WG	Working Group
WMG	UK Waterway Management Guide (UK 1999)
WSA	German Waterways and Shipping Office
WTI	Waterborne Transport Infrastructure
ΔW	Water level fluctuation

A.2 GLOSSARY

7 Steps. Seven-step process for selecting a bank-protection measure for a Design Case.

Analysis Case (AC). Generally, the AC is a bank-protection measure from the catalogue of measures in Part 2. It was already implemented at AC-site under its unique conditions at the site of realisation. The AC may also be a Basic Type. See also ***Basic Type*** and ***Design Case***.

Analysis Case behind the variant. Measure from an Analysis Case adapted to the specific boundary conditions of a Design Case. See also ***variant***.

Bank protection. Management actions designed with the primary intent of reducing or minimising erosion of streambanks.

Bank protection (biological). Bank-protection actions designed using largely or wholly natural materials such as tree plantings, fibre matting, and other green materials.

Bank protection (technical). Bank-protection actions designed using conventional engineering approaches, typically using concrete, steel, rip rap, and other forms of grey materials.

Bank protection (technical-biological). Bank-protection actions designed with a combination of green and grey materials in a hybrid format, also known as *bioengineering methods*.

Basic Type. Bank-protection measure compiled from existing guidance and synthesised into 23 common categories. It is generally not correlated with a specific Analysis Case, but it's 'typical boundary conditions at possible realisation sites' are nevertheless given. Thus, it can be treated here in the same way as an Analysis Case AC. See also ***Analysis Case, Fact File*** and ***Case Study***.

Bioengineering methods. Technical-biological bank protection achieved predominantly through plants, preferably living plants. See also ***bank protection (biological)***.

Biohut. Artificial fish nursery meant to equip port infrastructures such as docks, pontoons, or dykes.

Biotechnical engineering. Measure using technical elements, but the protection function is still achieved predominantly through living plants. See also ***bank protection (technical-biological)***.

Blocking effect of vegetation. Reduced flow velocity towards the ground because the flow passes through dense vegetation; wake wash will also be damped.

Boundary condition. Site-specific limiting criterion for a Design Case; examples include magnitude of water-level changes and subsoil type. See also ***demand*** and ***functionality***.

Case Study. Bank-protection measure correlated with a specific Analysis Case that also includes additional background information, monitoring and maintenance data, or other comprehensive details. See also ***Basic Type*** and ***Fact File***.

Combined measures. Measures combining direct and indirect measures or those using technical elements and living plants.

Connectivity. "The transfer of matter, energy, and/or organisms between elements of the hydrologic cycle" [Pringle, 2001], specifically hydrologic connectivity with dimensions along the channel profile (longitudinal); across the channel–floodplain continuum (lateral); and between the groundwater, hyporheic, and channel zones (vertical).

Demand. Required functionality for a Design Case; can be technical, ecological, social, legal, or economic. See also ***boundary condition*** and ***functionality***.

Design Case (DC). A planned measure to be realized at a special site with its unique boundary conditions. The Design Case includes user-defined demands, properties and the unique site conditions at the site of planned realization. Generally, the measure to be realised at DC-site is taken here from the catalogue of measures in Part 2, but it is generally adapted to DC-site conditions and corresponding planner's demands. This modified measure is called **variant**. So, the properties of the variant are often different to the corresponding ACs. Thus, the corresponding AC will often be called more precisely 'Analysis Case behind the variant'. See also ***Analysis Case (AC)*** and ***Analysis Case behind the variant***.

Direct measures. Measures constructed directly on the (surface of the) bank slope.

Drawdown. Water-level decline during a vessel's passage; quick drawdown can induce excess pore water pressure, which destabilises the bank.

Ecosystem services. "The benefits people obtain from ecosystems" [Millennium Assessment, 2005].

Ecological upgrade. Measures not necessary to protect the bank but that improve the bank's ecology.

Engineering measures. Measures achieving bank-protection function predominantly through constructed structures; generally accompanied by plantings or other measures to upgrade the ecology.

Entomofauna. Insects.

Erosion protection. Measures that protect the bank from erosion or at least reduce erosion speed. See also ***bank protection***.

Fact File. Bank-protection measure correlated with a specific Analysis Case but lacking the additional background information and comprehensive detail of a Case Study. See also ***Basic Type*** and ***Case Study***.

Feasibility check. Part of the preselection process to compare the boundary conditions of a Design Case with the boundary conditions of an Analysis Case to determine whether a measure is technically and ecologically feasible for the Design Case; greater similarity between the Analysis Case and Design Case means the measure is more likely to be suitable for the Design Case. See also ***suitability check***.

Filter stability. Filter, usually placed between the bank protection (for example, rip rap) and the soil, to prevent soil washout through the revetment.

Flanking measures. Measures that reduce impacts or enhance the local environment; almost all bank-protection measures also have flanking measures.

Functionality. Effect a measure can produce; can be technical, ecological, social, legal, or economic. See also ***demand***.

Gabions. Wire baskets, often vegetated, that contain rocks or soil placed as a technical-biological bank-protection measure.

Hinterland. Floodplain or upland ecosystem upslope from the stream bank.

Hydrodynamic soil displacement. Soil mobilized by excess pore water pressure.

Hydraulic conveyance. Discharge capacity of a river.

Indirect measures. Bank-protection measures, generally dams or palisades, that repel or reduce impacts.

Knockout criteria. Site-specific criteria for a Design Case that make a measure unsuitable for that Design Case. See also ***screening***.

Linear measures. Measures protecting only a small part of the bank or the bank zone linear and parallel to the water line; generally used at low water-level changes.

Mesophilic. Growing or thriving best in an intermediate environment (as in one of moderate temperature).

Management strategies. Strategies for the ongoing management, maintenance, and monitoring of a measure that generally accompany all measures, including engineering measures; a special management strategy is natural succession. Management strategies may replace engineering measures, at least temporarily, in some cases.

Measures. Management actions intended to achieve an engineering objective, usually bank-protection features in the context of this report.

Mitigation measures. Measures that reduce streambank erosion or reduce impacts.

Natural succession. Management strategy that allows a bank to evolve through the natural processes of erosion, sediment transport, deposition, and revegetation; if conditions allow, natural succession is always ecologically preferable.

Planar (or bank-slope-covering) measures. Measures providing full-surface protection, especially in cases of large water-level fluctuations, where the impact zone varies over the entire bank slope.

Planner. Person (generally a project engineer) or organization (for example an engineering or landscape planning bureau or a waterway authority), responsible for performing all the steps from surveying, setting objectives, designing the measure, budget planning up to construction supervision)

Pleaching. Interwoven tree branches (special bioengineering method from WMG).

Preselection. Process to develop a list of measures that fit the boundary conditions, demands, and required functionalities of a Design Case. See also ***screening*** and ***knockout criteria***.

Projections. In the context of this report, an ideal state of a measure produced by applying adaptations and optimisations (as opposed to the measure's real state as implemented at a site) that increases that measure's applicability, feasibility, or suitability for a Design Case; used during the feasibility and suitability checks. The corresponding extended BCs and functionalities of ACs had been assessed by the WG's experts.

River-training works. Management alternatives used in the main channel to alter river morphology, typically in the interest of maintaining a navigable channel.

Root cohesion. Ability of plant roots to strengthen the soil so that it is able to withstand tensile stress as in the case of cohesive soil.

Score. In the context of this report, a number assigned to quantify an attribute (BC, demand, level of functionality) to allow suitability comparison between measures for a Design Case.

Screening. Simplified preselection tool, using a strongly reduced number of criteria.

Spiling. Willow spiling is a traditional soft engineering technique used to stabilise eroding banks consisting of weaving live willow rods between live willow stakes set into the affected bank at regular intervals and filling the space behind the willow wall to the existing bank with soil to provide an area for the willow roots to grow.

Spur dyke (or groyne). River-training measure that deflects the flow from the bank zone and concentrates the flow in the middle of the river.

Stream bank. The bank of a navigable river defined from the base of the main channel to the top of the bank (a geomorphic change in slope) and the beginning of the floodplain or upland ecosystem. Also referred to as *embankment* or *bank slope*.

Suitability check. Part of the preselection process to compare the demands of a Design Case with the achieved functionalities of an Analysis Case to determine whether a measure is technically and ecologically suitable for a Design Case; greater similarity between the Analysis Case and Design Case means the measure is more likely to be suitable for the Design Case. See also ***feasibility check***.

Variant. Measure from an Analysis Case adapted to the specific boundary conditions of a Design Case. See also ***Analysis Case behind the variant.***

Vegetated structural engineering. Measure that achieves its bank-protection function predominantly through technical elements such as gabions, concrete mats, or rip rap but that offers at least some ecological upgrade.

APPENDIX B: WG 128 TERMS OF REFERENCE - TOR

Terms of reference Working Group 128 InCom

Alternative Technical-Biological Bank-Protection Methods for Inland Waterways

The PIANC INCOM WG 128 was established in 2009. Because of several personnel problems the group met only three times in different composition. It is planned to reactivate the working group. Because the knowledge on the design and maintenance of technical-biological bank protections increased since 2009, for example because there is a German Guideline available, the former TOR will be updated as follows:

1 Background

Since the mid 1980's, considerable interest has grown in the use of softer forms of bank protection to reduce costs, increase environmental benefits and more recently to demonstrate sustainable construction. In 1987, PIANC produced guidelines on the design and use of such techniques which were well received and used to create industry standards.

In 2007, PIANC InCom WG 27 reported that an increasing number of alternative bank protection measures are being implemented across the world in navigation channels, for example:

- Bio-engineering as reed planting or live willow fascine,
- Bio-technical engineering as grass composite, vegetated pocket fabric, geotextiles, rock and fibre rolls, planted coir pallets, and
- Structural engineering as timber revetments, wattle hurdles and timber piling.

However, there is still limited published guidance based on actual experiences with existing alternative bank protection methods that identifies effective alternatives that can be used under specific project boundary conditions. Some of these documents were used in the WG 27 report 'Considerations to Reduce Environmental Impacts of Vessels' to select adequate mitigation measures. Further work has recently been undertaken by other PIANC Working Groups, namely MarCom 56 ('Application of Geo-Textiles in Waterfront Protection') and CoCom 2 ('Best Practices for Shoreline Stabilisation Methods'), to consider the use of geo-textiles in a coastal environment.

Whilst there is limited existing knowledge, there is an increasing pressure for those involved in channel design and maintenance to adopt new techniques on the assumption that these will better meet the following requirements:

- Engineering,
- Ecological,
- Economic,

rather than the use of traditional engineering solutions such as rip rap or sheet piling. Consequently, there is a need for collecting and assessing existing experiences with alternative bank protection methods in a sense of a best practice approach to form a basis for an objective decision-making tool for waterway improvement and management.

2 Objective

The objective of the new InCom Working Group is to understand, evaluate and report on the effectiveness of best practice examples of innovative (alternative) bank protection measures, as related to different impact influences and boundary conditions, to fulfil the technical purposes and additionally to improve the ecological conditions. To formulate recommendations based on results obtained from assessments of physically implemented schemes.

From the European perspective, the mandate of the Water Framework Directive and other initiatives has created a requirement for results that should be available as soon as possible. Therefore, restrictions on the range and extent of the field of inquiry are necessary. To create an even more finite scope of activity by the Working Group, bank protection in lakes should be viewed as extraneous to the report.

Maintenance costs and details of ecological monitoring for selected alternatives must be available for a point in time at least one year after installation and must be included in the report.

Project details should include water body type (e.g. free-flowing and dammed rivers, canals), climate, water level variation, flow velocity (both fast and slow), substrate of the banks, bank slope, distance to fairway, ship types and hydraulic impacts from shipping.

Information should be collected on successful and, to the fullest extent possible, on unsuccessful applications looking back over the last twenty years. It is felt that this is an appropriate timescale commensurate with the development of these techniques and will allow a full review to be undertaken to see how vegetative protection techniques have matured or not!

3 Earlier Reports to be Reviewed

Besides the report of InCom WG 27, the following papers give an overview on existing guide codes:

- Doyle, P.F. (1992): "Performance of Alternative Methods of Bank Protection", Canadian Journal of Civil Engineering.
- PIANC (1996): "Bank Protection Utilising Geo-Textiles and Vegetation".
- Cranfield University/UK on behalf of British Waterways (1999): "Waterway Bank Protection: A Guide to Erosion Assessment and Management".
- Fischenich, Craig (2001): "Stability Thresholds for Stream Restoration Materials", ERDC, USACE.
- "Guide de protection des berges", Comité Zone d'intervention Prioritaire (ZIP) des Seigneuries, [Online], Available: **http://www.ville.repentigny.qc.ca/viecitoyenne/environnement/guide-de-protection-des-berges.html**.
- Numerous reports of the German research project on 'technicalbiological bank protections', including field tests, see **http://ufersicherung.baw.de/de/index.html**.
- DWA-M 519 (2015): "Technisch-biologische Ufersicherungen an großen und schiffbaren Binnengewässern *(Translation: "Technical-biological bank protections in large and navigable inland waters")*, Guideline of the German Association for Water, Wastewater and Waste.

These guides, however, do not clearly state how effective these bank protection techniques have proven to be in operation, they only list a few examples based on results soon after installation. Presently there is not enough information available to avoid repeating mistakes of inappropriate installation of innovative bank protection!

4 Scope

Because of the public and legal pressure to realise environmental-friendly bank protections and because of the elapsed time setting up the existing WG 128, the scope of work should focus on the collection and evaluation of existing guidelines and of both positive and negative experiences with realised alternative bank protections measures, leading to a list of measures with as variable as possible local boundary conditions. This list of evaluated measures can be used in terms of a best practice approach, meaning that the planner of an alternative measure compares his local boundary conditions to the latter in the list of existing measures to decide, whether listed measures could be successful or not.

Additional to the general boundary conditions related to one listed project, specific characteristic parameters shall be added, which come e.g. from the German DWA design rules, especially concerning the influence of wave impact, bank slope or subsoil, because it turned out that only a few parameters are decisive for design. These relevant parameters can thus be used additionally to facilitate the selection process.

5 Intended Product

As mentioned earlier, the product is a best practice document, basing on existing design guidance and experiences. Because of the dominant influence on local boundary conditions, as e.g. the natural site conditions of plants, the intended result cannot be a straightforward design rule, but it nevertheless will support planners with very helpful information as existing design codes and the a.m. list of reference projects, together with guidance on the data needed to apply existing guidelines and the recommended best practice approach.

6 Recommended Members

The members of WG 128 may be by profession civil or environmental engineers or landscape architects to mention just three professional groups working in the field of bank protections in waterways in general, especially with environmental-friendly solutions. The members could come from public or private organisations, especially waterway administrations and engineering bureaus or organisations representing stakeholders in the inland waterways system. But most important is that the working group members should have own experiences with existing alternative bank protection measures as well as with the application of corresponding national design rules.

Because PIANC provides international guidelines and because local boundaries as types and properties of plants used for environmental-friendly solutions may be very different from country to country and waterway to waterway, the working group members should come not only from countries lying in the temperate climate zones as in North Europe or America, they should come from other climate zones, if possible, too, if there are experiences available. This is especially important for possible application of the future best practice approach to Countries in Transition and concerning climate change effects.

7 Relevance for Countries in Transition

The benefits of promoting the development and use of bio-engineering techniques are considered vital in both Countries in Transition, and developing countries, in protecting against the pressures associated with increasing economic development and growth.

8 Climate Change

Climate change may affect bank protection measures in many ways, especially those using plants, because of longer periods with low water and thus poor water supply for the vegetation cover. This may force to e.g. use other plant species. For this reason, it is important to involve members from countries with generally higher average temperatures into the group.

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http://www.pianc.org | VAT BE 408-287-945 | ISBN 978-2-87223-035-8