Bioengineering Techniques for Streambank Restoration
A Review of Central European Practices

by

Martin Donat

Watershed Restoration Project Report No. 2
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Martin Donat

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This review of bioengineering approaches to streambank and slope stabilization, as applied in Europe, was produced to assist in the development of the Keogh River system (northern Vancouver Island) as a WRP demonstration watershed for the application of rehabilitation techniques including streambank or slope stabilization. The techniques are primarily of application to low gradient smaller streams and gullies typical of those within the coastal low-lands, including urban watersheds in the Georgia Basin, but also many of the more stable small salmonid nursery streams in the interior of British Columbia. Caution should be exercised by seeking local advice on which native vegetative species to use and by monitoring results on pilot sections. Traditional practices of stream bank stabilization in the Pacific Northwest have employed rip-rap revetment designs, and more recently “tree retards” or rip-rap combined with geotextiles and re-vegetation. Also, it is crucial to ensure that stream bank stabilization is coupled with techniques that restore fish-rearing habitat, and this review focuses specifically on erosion control. The B.C. Ministry of Forests’ Land management Handbook No. 18 (1994 edition) provides an instructive chapter (4) on hillslope protection and erosion control including suitable native plant species for grass seeding, wattling and staking. This report has been published within the Watershed Restoration Series as a technical reference (versus a procedural manual), but it is also applicable to habitat rehabilitation projects of the Urban Salmon Habitat Program, Salmonid Enhancement Program, Habitat Conservation Fund, and other related initiatives.

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ABSTRACT


The use of plants for river bank protection and erosion control has a long tradition in Europe. Recently, these old soil conservation and stabilization techniques have been rediscovered and improved. These biotechnical engineering (bioengineering) techniques are summarized here. Developed by a system of trial and error, most of these techniques are based on long-term practical experience. These “soft” engineering practices can provide possibilities to complement, improve or in some cases even replace traditional “hard” river-training constructions, such as placement of gabions or rock. These also offer a more ecologically acceptable way of bank stabilization that still compiles the land use and safety requirements. After a brief introduction to biotechnical engineering, the role of plants in riparian zones, their contributions to bank stability and plant-induced changes to flood run-off are discussed. The main part of this review is a detailed description and discussion of the most important biotechnical construction methods in streambank protection and watershed restoration used in Central Europe. Aspects of maintenance of planted stream banks and an overview on construction and maintenance costs conclude the report.

ACKNOWLEDGEMENTS

The author sincerely thanks Bruce R. Ward and Pat A. Slaney of the B.C. Ministry of Environment, Lands and Parks, Watershed Restoration Program for giving me the opportunity to introduce and discuss bioengineering methods used in stream restoration and enhancement in Central Europe in this report. Additional thanks to Bruce R. Ward and Daiva Zaldokas for their help in the editing process of this review. It intends to offer some new perspectives on the development of river engineering practices in British Columbia.
Bioengineering Techniques for Streambank Restoration:
A Review of Central European Practices

A. INTRODUCTION .................................................................................................................. 1
A-1. Preface ................................................................................................................................ 1
A-2. Biotechnical definitions .................................................................................................... 1

B. THE ROLE OF PLANTS IN RIPARIAN ZONES .................................................................. 4
B-1. Characteristics of riparian vegetation .............................................................................. 4
B-2. Contributions of plants to bank (slope) stability ............................................................. 8
   B-2.1. Mechanical and hydrological aspects of plants – overview ..................................... 8
   B-2.2. Soil reinforcement by plant roots ........................................................................... 9

C. CONSTRUCTION METHODS ............................................................................................. 15
C-1. Brush-mattress construction ........................................................................................ 15
C-2. Biotechnical constructions including geotextiles ........................................................... 16
C-3. Fascines (bush wattles) ............................................................................................... 21
C-4. Wattle (wicker) fences .................................................................................................. 23
C-5. Live slope gratings ....................................................................................................... 25
C-6. Groove and cordon structures ........................................................................................ 26
   C-6.1. Groove (or rut) structures ................................................................................... 26
   C-6.2. Cordon construction ......................................................................................... 27
C-7. Layer structures ............................................................................................................ 28
   C-7.1. Hedge layer construction .................................................................................. 28
   C-7.2. Brush layer construction .................................................................................... 29
   C-7.3. Hedge-brush layer construction ....................................................................... 32
C-8. Placing of cuttings, wall joint plantings, vegetated stone walls and rock piles............. 33
C-9. Crib wall constructions with branch layering .............................................................. 36
C-10. Vegetated gabions .................................................................................................... 38
C-11. Vegetated palisades ................................................................................................... 39
C-12. Branch layers in gullies ............................................................................................ 40
C-13. Transversal structures: Live ground sills, live bush and comb construction ............ 42
C-14. Longitudinal structures ............................................................................................ 45
   C-14.1. Groynes .......................................................................................................... 45
   C-14.2. Log brush barrier and branch packings ............................................................. 52
C-15. Reed structures for bank and shore protection .......................................................... 56
Bioengineering Techniques for Streambank Restoration

A Review of Central European Practices

A. INTRODUCTION

A-1. Preface

The use of plants to secure banks along streams, lakes and beaches has a long tradition. In the Middle Ages banks of canals in France and the Netherlands were stabilized with willows. In rivers of the Alps, structures of timber, rocks and plants have been used over the past centuries. Only in the first half of this century, however, have these old methods been rediscovered and improved with new technical and biological knowledge. Today, there is a variety of biotechnical methods available to suit different situations and requirements. Biotechnical engineering methods have become part of geotechnical and hydraulic engineering and have helped bridge the gap between classical engineering disciplines, land use management, landscape architecture and biological sciences.

In this review of Central European bioengineering practices, the different uses of plants in hydraulic and geotechnical engineering design are presented. A comprehensive overview of biological, ecological and technical considerations for the use of plants in engineering construction is presented in the next five chapters, including: a brief introduction with general definitions and goals of biotechnical construction methods, the ecological role of riparian vegetation, as well as attempts to quantify the impact of plants on stream hydraulics and bank (slope) stability. The core of this review is a comprehensive overview of the most important biotechnical construction methods used in river training and stream enhancement in Central Europe. Methods, construction procedure, and the major advantages and disadvantages of these biotechnical methods are discussed. Suggestions for maintenance and final considerations about construction and maintenance costs conclude this review.

A.2. Biotechnical definitions

Biotechnical engineering techniques rely on biological knowledge to build geotechnical and hydraulic structures and to secure unstable slopes and banks. Whole plants or their parts are used as construction materials to secure unstable sites, in combination with other (dead) construction material. Thus, biotechnical engineering does not replace traditional hydraulic or geotechnical engineering (e.g. geotextiles, or concrete blocks), but complements and improves other technical engineering methods.
The variety of construction methods can be classified according to purpose, material or construction characteristics. However, it is not always easy to distinguish between these different groups of biotechnical methods and strategies. Such a differentiation is often artificial, as similar techniques, with minor changes, are used in both, a classical geotechnical and river engineering context. Biotechnical structures for soil stabilization are either point-by-point systems (structures of single root stocks), linear systems (structures of rows of root stocks) or covering systems (surface-covering mattress of plant webbings). To design with any of these systems requires an understanding of the mechanisms they exploit in the building process itself. The material used and the purpose of the structure allows the techniques to be classified as follows:

1. Surface protection methods (covering methods)
2. Stabilization methods using live materials
3. Methods combining dead and live material
4. Supplementary methods
5. Support structures using non-living material

Covering methods (1) are used primarily to provide quick surface protection for soil conservation. Securing of deeper soil layers are only secondary. By using a large number of plants such as grasses and herbs per unit area, the soil surface is protected against erosion. Structures consisting only of live material (2) can improve slope stability and prevent erosion. Under less favourable conditions, support structures of non-living material may be required to augment constructions made of living materials (3). Under extreme conditions (unfavourable soil, extreme weather, short growing season), or if a site requires stabilization before live plants can be used, materials such as timber, concrete, rocks and dead branches may be used as support constructions. In very wet sites or drainage areas with difficult access, biotechnical methods can support or even replace other methods. Biotechnical drainage systems act by decreasing pore-water pressures, thus avoiding soaking of cohesive soils and prohibiting inner erosion. Supplementary methods (4) are specific and effective methods to facilitate emergence of the climax vegetation (e.g. plantings of single trees or soil improvement techniques). These techniques are costly, and are therefore restricted in use.

A.3. Benefits of biotechnical methods

In comparison with traditional engineering techniques, the non-technical benefits of plants are often stressed along with the usual technical advantages. Four general groups of benefits of biotechnical methods can be outlined:

1. Technical advantages:
   - protection against surface erosion
   - an increase of slope stability by root reinforcement and draining of the soil
   - protection against rock fall and wind
2. Ecological advantages:
- regulation of temperature and humidity close to the surface, thus promoting growth
- improvement of the soil water regime via interception, evapotranspiration and storage
- soil improvement and top soil formation
- improvement of and provision for habitat

3. Economic advantages:
- reduction of construction and maintenance costs
- creation of areas for agricultural and recreational use

4. Aesthetic advantages:
- structures fit into the landscape
- landscape is more appealing

These advantages make biotechnical techniques a worthwhile consideration in stream and bank rehabilitation. In the following chapters, these advantages are discussed in greater detail.
B. THE ROLE OF PLANTS IN RIPARIAN ZONES

B.1. Characteristics of riparian vegetation

Stream ecology requires the viewing of a stream and its surrounding land as a unit. Riparian zones are transitional areas between water and land, ecotones rich with elements of both. Vegetation is a key element in riparian zones that has numerous functions. Briefly, each of these functions are discussed in further detail:

(a) Vegetation regulates the microclimate of streams  
(b) Vegetation secures banks  
(c) Riparian vegetation offers terrestrial habitat  
(d) Vegetation is a food source for aquatic and terrestrial life

(a) Vegetation regulates the microclimate on streams

Trees and bushes shade smaller streams, thus reducing temperature. Stream water temperature of a creek changes with or without alders along throughout the course of a year (Fig. 1). On small creeks, the canopy can reduce sunlight in summer up to 80%.

Fig. 1: Temperature change of a stream with or without alder canopy cover (revised from Niemeyer-Lüllwitz et al 1988)
Trees and bushes not only have an impact on the stream microclimate, but also in neighbouring areas. Dew formation, precipitation and soil moisture increase in their vicinity, while evapotranspiration and wind speed decrease (Fig. 2). Thus, vegetative cover can regulate soil climate, stimulate soil activity through increased biomass production and act as a buffer against fertilizer and pesticide sprays. Trees and bushes slow down surface run off and filter fine material (Rickson and Morgan 1988; Saupe 1992).

**Fig. 2: Effects of tree and bush cordons on microclimate (revised from Wildermuth 1978)**

(b) Vegetation secures banks

Vegetation slows water flow on banks and promotes sedimentation. If bank vegetation is both flexible and a uniform thicket it can act as a flexible wall against flood flow (Fig. 3).

**Fig. 3: Impact of vegetative covers on the distribution of flow velocities (BMLFW 1994)**
Roots of flexible woody plants such as young willows and alders increase bank stabilization, while stiff or single trees may act like levers and cause progressive damage. Bank stabilization properties depend on various aspects such as plant species, age, stream morphology, soil, etc. The increases in slope stability provided by plant roots, as well as the impact of plants on flow characteristics are discussed in section B.2 and the appendices in more detail. (For detailed information on hydraulic calculations of streams with different vegetative covers see Felkel 1960, Scheuerlein 1968, Lindner 1982, Pasche 1984, Rouve 1987, Bertram 1985).

(c) Riparian vegetation as terrestrial habitat

Riparian vegetation provides habitat and can be a food source for both aquatic species and terrestrial wildlife (Fig. 4). This is particularly true for landscapes with intensive land use where streams and small strips of vegetation often act as “ecological refuges”.

Fig. 4: Radius of activity (m) of selected wildlife species from vegetated stream banks in Central Europe (revised from Wildermuth 1978)
(d) Vegetation is a food source for aquatic and terrestrial life

In the upper reaches of a stream the main food source is not in-stream primary production, but leaves and other organic material coming from outside the stream (Fig. 5). In larger, slower moving streams, primary production within the stream becomes increasingly important with stream size, eventually replacing external organic input in the largest streams.

Fig. 5: Food web (functional groups) in a small creek (Donat, 1995)
B.2. Contributions of plants to bank (slope) stability

B.2.1. Mechanical and hydrological aspects of plants - overview

The influences of vegetation on slope (bank) stability can be divided into hydrological and mechanical mechanisms:

Hydrological mechanisms:
- interception on foliage (reduces rainfall by adsorption and evaporation)
- infiltration capacity increased due to higher ground surface roughness and permeability
- transpiration of water-uptake by roots lowers pore-water pressure
- desiccation cracking of soil due to transpiration (cracks increase water permeability)

Mechanical mechanisms:
- soil reinforcement by roots increase shear strength
- anchoring of topsoil into firm strata (buttressing and arching)
- increase of surcharge by vegetation weight (increased normal and downhill forces)
- dynamic forces (momentum) caused by wind led into the slope via vegetation (jack effect)
- reduced erosion by dense root webs

Mechanisms beneficial to slope stability clearly outnumber adverse influences. Statistical investigations have shown that, on bare slopes (without vegetation), failures occur more often than in comparable slopes in wooded areas. For geotechnical calculations, increases in slope stability by evapotranspiration and other beneficial hydrological mechanisms have to be neglected, as they do not contribute under extreme, critical conditions (e.g. soil pores saturated with water). For stability calculations, the prime factor is mechanical soil reinforcement by roots. Depending on climatic conditions and special site requirements, appropriate deep-rooting plants are selected (see section B.2.2.1).

The situation of the critical sliding plane determines whether or not reinforcement by roots has an influence on slope stability. There are four general cases for sliding planes parallel to the surface (Fig. 6):

- Type A: A thin surface layer is reinforced, but the roots cannot penetrate the firm rock. The boundary between the two layers is weakest where sliding can occur.

- Type B: Similar to type A, the plants reinforce the surface layer but also anchor it into cracks of the underlying firm strata.
- Type C: A thick surface layer is rooted with a transition zone towards the firm rock layer. By anchoring the top soil to the denser transition zone with higher shear resistance, slope stability increases.

- Type D: Root stocks “swim” on a deep surface layer and hardly contribute to slope stability.

![Fig. 6: Slope classification scheme based on root reinforcement and anchoring (Tsukamoto and Kusakabe, 1984)](image)

B.2.2. Soil reinforcement by plant roots

(a) Root volume characteristics

Growth and quality characteristics of the root system are both genetically fixed and site dependent. One of the handiest and frequently used measures to express the genetically determined soil-binding capacity of a specific plant root system is the root:shoot-volume ratio (Table 1). The ratio between the volume of rooted soil of a specific plant and the volume its shoots require has been found to be roughly constant. This enables us to rank the suitability of plants for a specific site (the higher the ratio the better) and to estimate the contribution of plants to slope stabilization during plant development.
Table 1: Examples for root-shoot-volume ratio for different plant species (Schiechtl, 1973)

<table>
<thead>
<tr>
<th>Plant species</th>
<th>root/shoot volume</th>
<th>Plant species</th>
<th>root/shoot volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salix glabra</td>
<td>2.4</td>
<td>Anus viridis</td>
<td>1.5</td>
</tr>
<tr>
<td>Viburnum lantana</td>
<td>2.3</td>
<td>Fraxinus excelsior</td>
<td>1.5</td>
</tr>
<tr>
<td>Erica carnea</td>
<td>2.0</td>
<td>Acer pseudoplatanus</td>
<td>1.1</td>
</tr>
<tr>
<td>Salix eleagnos</td>
<td>1.8</td>
<td>Populus tremula</td>
<td>1.1</td>
</tr>
<tr>
<td>Salix nigricans</td>
<td>1.8</td>
<td>Salix alba</td>
<td>0.5</td>
</tr>
<tr>
<td>Salix purpurea</td>
<td>1.5</td>
<td>Populus nigra</td>
<td>0.4</td>
</tr>
<tr>
<td>Equisetum arvense</td>
<td>5.5</td>
<td>Festuca ovina</td>
<td>1.1</td>
</tr>
<tr>
<td>Rumex scutatus</td>
<td>5.0</td>
<td>Carex flacca</td>
<td>0.6</td>
</tr>
<tr>
<td>Petasites paradoxus</td>
<td>1.4</td>
<td>Calamagrostis epig.</td>
<td>0.5</td>
</tr>
</tbody>
</table>

(b) Root stocks characteristics

Although the shoot:root-volume ratio is an important biotechnical indicator, it gives no information about the type of the root system (root distribution). According to their genetically fixed root systems, plants can be classified as:

(a) Plants with extensive root systems (extensive-rooters): These plants develop a deep-reaching or/and wide-spreading root system, depending on the availability of water and nutrients (e.g. Salices sp., Petasites paradoxus, Epilobium angustifolium, Lathyrus silvestris, Medicago sp.).

(b) Plants with an intensive root system (intensive-rooters): These plants perforate the soil intensively and form sharply limited, shallow root stocks. (e.g. many copse forming grasses like Achnatherum elatior, Calamagrostis sp., Carex sempervirens, rhizome-forming pioneers and gravel-creeping herbs).

(c) Plants with mixed root system (mixed-rooters): Roots of mixed-rooters are wide-spreading and extensive ranging with an intensive root horizons near the surface (e.g. Saxifraga sp., Bromus sp., other gravel-covering and gravel-creeping herbs).
Although the distinctions between intensive-, mixed and extensive-rooters are general, they are mainly used for herbaceous plants. For trees and bushes, the general distinctions between the different root types is still valid, but needs some adjustment since wood plants have a secondary thickness growth and modifications in their root system. There is a general distinction between three major groups of trees and bushes based on the shape of the root stock:

(a) Tap-rooters: plants with a deep-reaching, strong, perpendicularly expanding root system (e.g. *Juglans regia*, *Pinus silvestris*, *Quercus pubescens*, *Taxus baccata*).

(b) Heart-rooters: plants with an uniform, branched, half-spherical root system that form roots that explore the soil inclined downwards (e.g. *Alnus glutinosa*, *Crategus monogyna*, *Larix decidua*, *Quercus robur*, *Salix eleagnos*, *S. fragilis*, *S. nigricans*, *S. pentandra*, *S. purpurea*, *Tilia cordata*).

(c) Flat-rooters: plants with dominating, sidewards growing, shallow main roots that explore surface soil layers and from which, with increasing age, vertical roots spring off (e.g. *Betula pendula*, *Picea abies*, *Pinus mugo*, *Populus alba*, *Salix alba*, *S. aurita*, *S. caprea*, *S. cinera*, *S. daphnoides*, *S. viminalis*, *Sambucus nigra*, *Sorbus aucuparia*).

Although the type of root system and its basic characteristics are genetically determined, the actual root distribution and some additional characteristics depend on site conditions. External factors with a possible impact on root growth include:

- local soil conditions
- altitude and latitude
- availability of water and nutrients (i.e., reason for chemo- and hydrotropisms)
- climatic factors
- growth-restrictions (dense soil layers, layers with toxic substances)
- seasonal changes (different vegetative cycles of root and shoot development)

The adjustment to local conditions is easier for plants with a phenotypic plasticity. Two examples are:

- Plants with deep-reaching roots on poor, dry sites with adverse conditions root the soil more effectively than when the same species is planted on sites rich in nutrients and moisture.

- In reaction to mechanical stress (caused by soil creep, coverage with gravel, erosion, rockfall, skinning snow) several species develop characteristic root formations (“mechanomorphosis”): anchor roots shaped like hooks or claws and supportive shoot- and root-horizons. Shrubs and bushes such as *Rubus idaeus*, *Tussilago farfara*, *Salices sp.* have the ability to form several root horizons during repeated and frequent covering with gravel.
(c) Root strength parameters

The tensile strength of roots depends on the plants species, root diameter, age, site conditions (e.g. moisture) and season. Root tensile strength usually decreases with increasing diameter. Table 2 lists the range of tensile strengths for different groups of plants.

<table>
<thead>
<tr>
<th>Group of plants</th>
<th>Average tensile strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grasses</td>
<td>5-10 MN/m²</td>
</tr>
<tr>
<td>Herbs</td>
<td>3-60 MN/m²</td>
</tr>
<tr>
<td>Woody plants</td>
<td>10-70 MN/m² (max. 160)</td>
</tr>
</tbody>
</table>

The increase in shear strength of soil with increasing biomass content (weight of dry living roots per soil volume) has been found to be roughly linear (Burkard 1987). After trees and bushes are cut down, the live root mass and the shear resistance decrease rapidly. When a bush layer has re-established itself, the shear resistance returns to about three quarters of the original value (Bourroughs and Thomas 1977).

(d) Other criteria for the selection of plants

The choice of plants for biotechnical structures does not only depend on root strength characteristics but on factors such as:

- ecological amplitude (aspects of plant-sociology and plant-geography)
- succession
- propagation
- growth qualities (speed and patterns of growth, juvenile growth behaviour), and finally
- soil stabilization and anchoring qualities of the root system
- physical and chemical soil characteristics
- climatic aspects
- other biotic aspects (toxicity considerations, etc.)
Considering these general plant characteristics only ensures the suitable vegetation material is selected for a site and a construction method. For example, willows are probably the plant genus most often used for geotechnical structures. There are large differences in characteristics and plant requirements between the various willow species (Fig. 7 and 8). Only suitable plant material guarantees a successful structure. The best reference are natural species and conditions in a specific area.

Fig. 7: Distribution of European willows depending on altitude and soil conditions (Schiechtl and Stern 1994)
Fig. 8: Growth characteristics (height, shape) of mature, wild European tree and bush willows (Schiechtl and Stern 1994)
C. CONSTRUCTION METHODS

In the following section the main types of biotechnical methods using woody or wet land plants or their parts are discussed. Surface covering methods such as seeding, hydroseeding, or rhizome plantings of herbaceous plants, as well as supplementary methods will not be dealt with her (for information see Schwab 1991). Biotechnical methods using willows and other woody plants are especially appropriate for improving existing technical structures. The emphasis of this section paper is on construction of biotechnical structures and their use. The major advantages and disadvantages of each method are summarized.

C-1. Bush-mattress construction

In brush mattress-constructions (Fig. 9), the slope surface is completely covered with a dense layer of long and large, living branches or rods of sprouting material (usually willows)(not shorter than 1.5 m). The mattress of branches and rods is covered with top soil to facilitate rooting. In particular, the bottom end of the thick branches must be covered with soil, and reach the water table of the stream. These bottom ends are secured with fascines, poles, woven fences or rock packings – depending on the characteristics of the steam. Rods and branches are placed perpendicularly or inclined vertically 20°. If the length of the rods or branches is not sufficient to cover the whole slope, rods of the lower layer should overlap with the upper one by at least 50 cm. The matting is fastened to the surface every 3/4 to 1 m with a network of wires, rods, fascines or woven fences.

Fig. 9: Brush-mattress structures (Schiechtl and Stern 1994)
advantages:
- immediately effective after installation
- dense root system and thicket developed
- flexibility in reparation and protection of river banks
- material easily available as structures also serve as a nursery for new plant material

disadvantages:
- high demand on material and labour
- occasional thinning of thicket necessary
- labour intensive

Construction time: Only during dormant season
Costs: 1 to 5 hours/m² (depending on material availability and site conditions)
Use: erosion control of banks and slopes, improvement of (underlying) riprap, bank repair.

C-2. Biotechnical constructions including geotextiles

Geotextiles within a biotechnical context have been used primarily to stabilize loose top soil layers until the roots of planted vegetation can take over (Table 3). It has been found at pioneer sites that geotextiles can also function as a rough supporting and (permanent) reinforcement layer for the root horizont itself. Use of geotextiles for slope and wall structures, supported by life cuttings or branch layers has also become common. These combined geotechnical constructions can replace woven structures, slope gratings, sometimes even rock securing (Fig. 10). They are used if a uniform plane of vegetative covering is desired, particularly when slopes are in danger of erosion and instability (e.g., steepness >45°, easily weathering and falling rock, stream banks). Geotextile widths (webs) are placed with an overlap of only about 30 cm on each side and are fixed with hooks or pegs every m².

Geotextiles used for biotechnical constructions are typically made of biodegradable materials such as jute, kokos, wood-wool, reed, flax, or synthetic fibres such as cellulose. They only last until sufficient rooting is established. Geotextiles for long-term reinforcement are usually made of UV-stabilized polypropylen or polyethylen, polyester or polyamids (nylon). All geotextiles used close to the surface need sufficient resistance against ultraviolet radiation.

Design criteria for, as well as functions of geotextiles are summarized in the tables below (Table 4 to 7). They must meet the conflicting requirements of plants (porous, fine-meshed) and of geotechnics (filter-criteria). Plant growth and the penetration of these textiles by roots or shoots depend on:
- characteristics of the geotextile (pore diameter, thickness, structure, etc.),
- site conditions (climate, altitude, exposure, precipitation, moisture, nutrients),
- plants characteristics.

Following these plant-specific requirements and other general site characteristics, the following parameters may determine the choice of geotextiles:

- slope of area to be secured
- soil characteristics
- weathering factors until overgrowth occurs
- type of vegetation
- time of planting
- the duration until the development of a root-system occurs
- drag-force of water (for hydrotechnical use)

Table 3: Geotextiles used for different biotechnical methods

<table>
<thead>
<tr>
<th>type of geotextile</th>
<th>biotechnical method used</th>
</tr>
</thead>
<tbody>
<tr>
<td>coarse mesh textile (mesh diameter &gt;5 mm)</td>
<td>conventional surface seeding</td>
</tr>
<tr>
<td>structure mattress (coarse or fine)</td>
<td>seeding, hydroseeding</td>
</tr>
<tr>
<td></td>
<td>planting of cuttings</td>
</tr>
<tr>
<td>fine mesh textile (mesh diameter ca. 2-5 mm)</td>
<td>hydroseeding</td>
</tr>
<tr>
<td></td>
<td>planting of cuttings</td>
</tr>
<tr>
<td>special geotextiles (effective mesh size 0.5-1 mm)</td>
<td>hydroseeding</td>
</tr>
<tr>
<td>standard fleece (effective mesh size 0.08-0.5 mm)</td>
<td>hydroseeding restricted (pre-tests necessary)</td>
</tr>
</tbody>
</table>

Structure mattresses are three-dimensional webbings of welded synthetic threads (e.g. nylon, mattress thickness: ca. 5-30 mm) which can be filled with (top) soil material or grit (eventually combined with bitumen). Plants root in or penetrate through such mattresses easily. Immediate vegetation is necessary for wide mesh systems to ensure a sufficient filter effect and protection against surface erosion.
Table 4: Choice of geotextiles according to its use

<table>
<thead>
<tr>
<th>use of geotextile</th>
<th>usual type of geotextile</th>
</tr>
</thead>
<tbody>
<tr>
<td>reinforcement of top soil and root network</td>
<td>textile, other lattice-like webbings structure mattress</td>
</tr>
<tr>
<td>protection against erosion</td>
<td>fleece (with textiles), structure mattress</td>
</tr>
<tr>
<td>vegetating (standard seeding, hydro-seeding)</td>
<td>textile, structure mattress (use of thick, fine-porous geotextiles limited)</td>
</tr>
</tbody>
</table>

Table 5: Wear requirements for geotextiles

<table>
<thead>
<tr>
<th>Resistance to wear by ...</th>
<th>max. reduction in tensile strength (%)</th>
<th>Case 1</th>
<th>Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>uv-radiation</td>
<td></td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>biological influences</td>
<td></td>
<td>25</td>
<td>5</td>
</tr>
<tr>
<td>(microorganisms)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>chemical influences:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>acids</td>
<td></td>
<td>25</td>
<td>5</td>
</tr>
<tr>
<td>bases</td>
<td></td>
<td>25</td>
<td>25</td>
</tr>
</tbody>
</table>

Case 1: geotextiles for short-term support of roots and protection of the soil against erosion until plants take over
Case 2: geotextiles for long-term support and erosion control
### Table 6: Requirements for slopes endangered by erosion due to water or wind

<table>
<thead>
<tr>
<th>soil type</th>
<th>slope angle (°)</th>
<th>max. efficient pore diameter of textile for hydroseeding</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>immediately</td>
<td>t &lt; 2 months</td>
<td>t &gt; 2 months</td>
</tr>
<tr>
<td>cohesive</td>
<td>&lt; 40</td>
<td>(-)</td>
<td>(-)</td>
<td>(-)</td>
</tr>
<tr>
<td></td>
<td>&gt; 40</td>
<td>(-)</td>
<td>4*d$_{85}$</td>
<td>2*d$_{85}$</td>
</tr>
<tr>
<td>non-cohesive</td>
<td>&lt; 35</td>
<td>8*d$_{85}^a$</td>
<td>4*d$_{85}$</td>
<td>2*d$_{85}$</td>
</tr>
<tr>
<td></td>
<td>&gt; 35</td>
<td>4*d$_{85}$</td>
<td>2*d$_{85}$</td>
<td>1*d$_{85}$</td>
</tr>
</tbody>
</table>

(-) no instruction regarding mesh diameter

*a time until hydroseeding or until sprouting of sod at standard seeding on the surface respectively

d$_{85}$ … sieve diameter passed by 85% of the soil material

### Table 7: Mechanical criteria for geotextiles

<table>
<thead>
<tr>
<th>Use of geotextiles</th>
<th>criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>erosion control only</td>
<td>tensile strength r$\geq$6.0 kN/m (no punctual fixation)</td>
</tr>
<tr>
<td>soil stabilization</td>
<td>tensile strength r$\geq$10.0 kN/m, expansion under tension r$\geq$20 %</td>
</tr>
<tr>
<td>for all uses</td>
<td>minimum permeability k$\geq$10$^{-4}$ m/s (at normal pressure of 20 kN/m$^2$)</td>
</tr>
</tbody>
</table>
advantages:
- immediately effectiveness
- standardized material and calculation
- can be combined with other techniques

disadvantages:
- costly (material, labour)
- use limited (restrictions for soil material, slope angle, wear, penetration)
- limited height of geotextile constructions

Construction time: during dormant season if living branches are introduced; seeding or planting of rooted material usually done in growing season; living pegs can also be driven in also after completion of constructions.
Costs: usually cheaper than other combined biotechnical methods
Use: surface protection (long or short term), wall constructions.
C-3. Fascines (bush wattles)

Fascines of sprouting material are placed in ditches (depth: 0.3-0.5 m; width: 0.3-0.5 m). The fascine should consist of at least 5 rods, each with a diameter of at least 1 cm. Fascines used along water courses are usually much thicker, as not all rods are bedded in soil or are able to sprout there. Similarly, fascines used for drainage purposes are thicker and placed straight down a slope. Slope fascines need not be bound as tightly (only every 3/4 m) as fascines used in waterway constructions. The fascines are fixed with pegs (min. length 1/2 m of wood or steel, about 3/4 m apart, perpendicular to the surface). Rather than placing the pegs below the fascine (construction by Hoffmann), they now penetrate the fascine (construction by Käbel), thus saving on fixations. Finally, the ditches are refilled. Most of the fascines, but especially their ends should be covered with soil.

Fig. 11: Manufacturing of fascines with or without rock core (Lange and Lecher 1993)

Fig. 12: Fascines for slope stabilization (construction pattern see also Fig. 16) (Schiechtl and Stern 1992)
Fig. 13: Fascine variations for securing bank toes (Donat 1995; Schiechtl and Stern 1994)

Fig. 14: Fascines for drainage purposes (Schiechtl and Stern 1992)
advantages:
- fast and simple construction
- little soil movements
- useful for wet slopes or zones
- little reparations
- promotes development towards climax

disadvantages:
- flexible branches and rods necessary
- susceptible to rockfall and shearing
- little securing of deeper soil layers
- labour intensive

Construction time: only possible during dormancy
Costs: for geotechnical use: 0.5-1 hours/m; drainage river engineering structures: 1-3 hours/m.
Use: Stabilization of top soil layers, slopes of fine material or bank toes, drainage of wet zones; securing of other brush layers (e.g. in sills, layer constructions, branch packings).

C-4. Wattle (wicker) fences

Wooden poles (1 = 100 cm; d = 3-10 cm) or steel pegs are driven into the soil 1 m apart. Between these pegs and poles, shorter (70 cm) poles of living material are driven in, and flexible strong rods of sprouting material are woven around them. The ends of the woven rods are struck into the soil. Each pair of rods must be pressed down after being woven. Three to seven rods are placed together. Alternatively, prefabricated rods or woven structures fixed on pegs can be used. At least 2/3 of the length of the pegs would be in the soil and their top ends should not stick out more than 5 cm over the woven portion. The fences are partially covered with soil to enable at least the bottom rod to root. Fences bedded totally in soil root are better than constructions above the surface. These fences can be placed as continuous horizontal rows or as diagonal fences in the shape of a rhombus. Wattle fences are used for securing dams and slope cuttings. They secure the top layer until the area in between is fixed by grasses, forbs, planted trees or bushes that root in deeper layers.
advantages:
- rooted fences retain and stop moving soil, and establish terraces
- a flexible and rapid step towards a climax-like vegetation
- easily combined with other methods

disadvantages:
- high labour and material costs, and continuous control required
- securing effect is small
- large quantities of flexible branches are required (potential lack of local material)
- easily damaged, thus not sufficient for persistent rockfall
- frequently washed out when placed on creeks
Construction time: Only fences made during the dormant season sprout.
Costs: 0.75 - 1.5 hours/meter
While used extensively in the past, they are rarely constructed any longer because of their high labour costs and the danger of erosion of fine material from behind the fence along water courses.
Use: Stabilization of top soil layers, slopes of fine material or bank toes, drainage of wet zones; securing of other brush layers (e.g. in sills, layer constructions, branch packings).

C-5. Live slope gratings

Gratings of wooden, metal, plastic or concrete poles (1.5 x 1.5 to 2.0 x 2.0 m) are fixed to the slope surface with living pegs or poles. These sprouting fixations and additional revegetation (by seeding or cuttings) in the grating-fields guarantees a long-term securing of the slope or slippage. Gratings may be built as three-dimensional double gratings: two gratings (as described above) form box-like compartments that are filled with layers of living material and porous soil. Live slope gratings are used on extremely steep slopes or small slides, endangered by on-going erosion, where conventional revegetation methods fail.

Fig. 17: Single and double live slope gratings (Donat 1995)
advantages:
- fixation of top soil at extreme sites and makes revegetation possible
- many variations and combinations possible
- immediately effective on the surface and deeper
- little maintenance

disadvantages:
- high labour costs, and high material use (double gratings)
- deep-reaching effect only occurs after rooting
- usually used for smaller sites (max. height: 15-20 m)

Construction time: during dormant season, if livings material used; seeding is necessary during growth season
Costs: 2-5 hours/m²
Use: for vegetating and securing extremely steep surfaces (due to slides or side cutting)

C-6. Groove and cordon structures

C-6.1. Groove (or rut) structures

On the front edge of shallow ditches (width: 30-60 cm; depth of a spade), thin fascines of living material are fixed with pegs every meter (cf. slope fascine constructions). Behind these fascines 1-2 small rooted trees or bushes are placed every meter. Then the ditch is refilled with material dug out of the upper terrace and mixed with top soil, compost or a mixture of both (ca. 50 l/m). To avoid slope failure by increased water retention, the ditches are not drawn horizontally but inclined 10-30°, often z-shaped or in a herring-bone pattern. Groove structures should not be used on marl and clay soil.

Fig. 18: Groove (rut) constructions with and without additional securing (Donat 1995)
advantages:
- good combination of water retention and drainage (depending on inclination)
- initial and climax vegetation can be combined
- moderate maintenance requirements
- for reforestation of dry slopes and erosion control

disadvantages:
- large amount of top soil required
- high labour costs
- not suitable for rocky and/or steep slopes

Construction time: only during dormant season
Costs: 1-3 hours/meter
Use: for plane, wet slopes with good growth conditions

C-6.2. Cordon construction

On a 0.5-1.5 m wide terrace, long poles of dead material are planted diagonally and covered with branches of conifers. This bedding is covered with about 10 cm of soil. Next, live cuttings are placed on the terrace (2 to 3 cm apart, diagonally) and afterwards covered with soil. Work starts at the bottom of a slope and makes its way up as the material dug out for the next ditch fills up the lower terrace.

Fig. 19: Cordon construction (revised from Schiechtl and Stern 1992)
advantages:
- use of machinery in shallow or moderately steep areas
- good water retention capacity in dry climates
- high sliding resistance
- root aeration improved by branch layer
- useful for steep and wet slopes of clay, also in limestone

disadvantages:
- higher water infiltration undesirable on unstable slopes
- high labour and material costs
- sometimes reparation and fertilization necessary

Construction time: only during dormant season
Costs: 3-4 hours/meter (most expensive method)
Use: stabilization of instable slopes of cohesive and wet material

C-7. Layer structures

Layer structures are mainly used in side cuttings. Their construction is in principle more or less the same: 0.5-2 m wide berms or terraces (in steep terrain about 0.5 m deep ditches) are built, starting from the bottom of a slope working its way up. Each of these terraces should be inclined with 5-10° towards the slope. The terrace lines are either horizontal or inclined up to 60° to drain surface water. The berms are 1-3 m apart, depending on the slope and machinery used.

C-7.1. Hedge layer construction

On 0.5-0.75 m wide terraces rooted plants are placed side by side such that after refilling two thirds of their length will be covered with soil and the last third is above the surface. The plants are covered with a thin layer of straw, bark compost or top soil to ameliorate poor or dry sites. For refilling, the material dug out from the next higher berm is used. Plant material for hedge layers are deciduous woody plants that can be buried and develop adventive roots, and preferably 2 to 4 years old. For fast growing species (e.g. Alnus spp.) 2 year old seedlings are often preferred. The sprout-to-root-ratio as an indicator of soil stabilization capacity strongly influences the choice of plant material.
advantages:
- development towards forest climax accelerated
- stabilization occurs immediately after construction

disadvantages:
- large amounts of plant material required
- high costs
- mainly used at favourable locations (loess, gravel soils, sandy and clay soils in favourable climates) and where willows are not available

Construction time: spring and fall
Costs: 1-3 hours/meter
Use: slope revegetation and stabilization of fertile soils or where willows cannot be used or are not available

C-7.2. Brush layer construction

Starting at the slope bottom working upwards, 0.5-2 m wide terraces are dug out. On the inclined (ca 10°) planum branches are placed cross-wise (not parallel) such that only 1/4 m reaches above the surface. That way as much of the branches as possible are covered by soil for rooting, and a mixture of species and root horizons is achieved. The excavation material from the next higher terrace fills up the lower one.
Brush layers can also be built also during dam construction. The branches placed cross-wise are longer (2-5 m) and covered with several soil layers till a new packing of plants is brought in. These branch layers provide a deep-reaching slope stabilization that cannot be provided by any other biotechnical construction. At wet side cuttings terraces are inclined at 15 to 90 degrees to provide better drainage. The brush layers should be more than 1.5 m (usually 2-3) apart to avoid local slope failures.

Variation:

To avoid erosion furrows and to reinforce the edge of the planum, about 1/4 m wide strips of geotextiles, roofing felt, boards or plastic foliage are placed below the branches. As this type of construction is more sensitive to rock-fall, it is built starting from the top of the slope working its way down. Other than that the construction is the same as before.

Fig. 21: Brush layer constructions (on existing slopes and during dam construction) (Donat 1995; Schiechtl and Stern 1992)
advantages:
- simple and fast construction with the deepest reaching maximal stabilization effect of all construction methods (except hedge-brush layers)
- all parts of a plant are used for construction
- machinery use make construction simpler and less expensive
- fast stabilization of cuts and fills at extreme sites
- thick, high bush climax develops
- used as a nursery for new plant material at the same time

disadvantages:
- not suitable for retaining top soil (except variation method)
- difficult to construct in existing slopes
- most plant material must be dormant during construction
- maintenance costs for pruning bushes
- not to be used for slopes with deep top soil cover

Construction time: during dormant season
Costs: 0.75-2  hours/meter
Use: securing of side cuts and soil movements, revegetation of near-surface slides, especially used in torrent control and watershed restoration
C-7.3. Hedge-brush layer construction

The construction system is the same as for brush layers. However, to diversify the plant material used and improve the success of the construction, some rooted, healthy plants (several years old shoots) are used in addition to the brush material and placed 0.5 to 1.0 m. apart on the terraces. Like the brushes, these rooted plants will be covered three quarters of their length with soil after refilling of the terraces. The adventive root system that develops along the whole length of the covered sprout parts provides additional fixation of soil material. Similar to brush-layer constructions, irrigation or the addition of top soil is not required, although they may promote growth. Hedge-brush-layers with or without longitudinal reinforcement strips are primarily used to secure side cutting slopes, local small slides and landfills.

advantages:
- same as for brush layers
- two stages of re-vegetation by rooted and unrooted material
- more technically effective

disadvantages:
- not suitable for retaining top soil (except reinforcement variation)
- maintenance costs (cutting out of branches)
- more difficult to establish on existing slopes
Construction time: during dormant season
Costs: 0.75-2.5 hours/m
Use: like brush layer construction, but rooted material allows wider use

**C-8. Placing of cuttings, wall joint plantings, vegetated stone walls and rock piles**

Two to ten healthy, cuttings per square meter (one to several years old, length: 0.5-1 m, diameter: 1-5 cm) are driven into the soil perpendicular to the surface up to three quarters of their length. Injuries to the bark of these cuttings during construction stimulates root-formation. For joint plantings, cuttings are placed in dry stone walls or rock-pavings after construction. The plant loss is about 30 to 50%. For vegetated stone walls and rock piles the sprouting material is brought in during the construction. The diameter and length of the cuttings is much bigger than of the plant material used for simple placement cuttings.

![Cuttings](image1)

**Fig. 23: Cuttings (Donat 1995)**

![Planting of slope drainage constructions](image2)

**Fig. 24: Planting of slope drainage constructions (revised from Schiechtl and stern 1992)**
Fig. 25: Joint planting of rock pavements and groynes (revised from Schiechtl and Stern 1994)
Fig. 26: Planting of riprap (Donat 1995; Schiechtl and Stern 1994)

**advantages:**
- inexpensive and fast method
- excellent stabilization and aesthetic effect
- used to improve existing structures
- almost no maintenance
- a method of planting in moist slopes for controlling wind, water and avalanches erosion
- plant material for vegetated stone walls and rock piles has less requirements regarding shape of cuttings than other plantings
- wall constructions are flexible and can be reused possible if it fails
disadvantages:
- stabilization occurs only after rooting
- construction only possible during dormancy
- planting of completed constructions (walls, stone packings, etc.) is often difficult
- growth is restricted to certain species
- height of wall structures is limited
- wall structures labour intensive (other placements are not!)

Construction time: during dormant season
Costs: 0.05-0.1 hours/cutting, planting of cuttings: 5-7 m²/hour, joint plantings: 2-4m²/hour (including additional work and harvest of cuttings)
Use: Vegetation of bare slopes; revegetation of technical structures, support method to drainage constructions.

C-9. Crib wall constructions with branch layering

Longitudinal elements and cross beams of wood, concrete, steel or plastic material (diameter: 10-25 cm) are placed on each other alternately and joined to form a single or double, box-like crib wall (width: 1-1.5 m). The structure is filled with gravel and soil material, with layers of living branches in between at an angle of 10°. The ends of the branches reach about 1/4 m out of the crib wall and stick into the native soil material on the other end. The living material offers additional anchoring, long lasting fixation of soil material and a water pumping effect of the foliage by evapotranspiration.

Fig. 27: Vegetated crib walls for slope stabilization (revised from Schiechtl and Stern 1992)
Fig. 28: Vegetated crib wall for bank protection and restoration (also used for sill structures) (revised from Schiechtl and Stern 1994)

Fig. 29: Vegetated crib walls from dam-like structures in streams and tributaries (revised from Schiechtl and Stern 1994)

**Advantages:**
- short construction time, fast stabilization
- simple foundation (slope of foundation important for concrete crib walls)
- “elastic” and effective structure for critical points
- if planted, aesthetically appealing

**Disadvantages:**
- high material costs, especially for prefabricated crib walls (except for wooden crib walls)
- durability of lumber limited
- choice of filling material is a trade-off between filter criteria and plant requirements
- limited construction height
Construction time: during dormant season
Costs: comparable to dry stone walls (except wooden crib walls!)
Use: Slope and bank stabilization (toes, side cuts), dam-like structures for slowing down sediment transport in tributaries

C-10. Vegetated gabions

Gabions are rather stiff boxes or flexible rolls of close-meshed wire filled with coarse gravel. Between gabion boxes and within them, living branches are introduced to root in both the gabion and the surrounding soil. If gabions could be displaced by mechanical forces, they are fixed with deep-reaching metal poles. Combinations of gabions of different shape and dimensions are easily possible. Similar to other structures, the decision which soil material should be used is always a trade-off between filter criteria and requirements of the vegetation.

![Vegetated gabions](image)

**Fig. 30: Vegetated gabions (revised from Schiechtl and Stern 1992)**

**advantages:**
- fast, simple and common construction method
- elastic structure with multi-purpose use, can be combined with other structures
- used for unstable slopes endangered by erosion, especially along streams or in debris areas
- no danger of water impoundment, used also for wet sites with fine soil material
disadvantages:
- gravel and rocks necessary (trade-off between plant-and filter requirements)
- vegetating after construction of the gabion is difficult
- height restriction
- gabions without vegetation or relatively smooth surfaces act as “guide-rails for water” if used for securing of stream banks

Construction time: during dormant season (later vegetating hardly possible)
Costs: inexpensive
Use: like crib walls (C-9), especially where debris available

C-11. Vegetated palisades

Living, uniform stakes of live material are driven into the soil (one third of their length) side by side to form a palisade. The top ends are cut plane and tied to a horizontal (living or dead) pole that ties in the ground at both sides of the gully. Pallisades are used to promote deposition in V-shaped gullies and rehabilitation in fine soils (clay, sand, loess, loam).

Fig. 31: Vegetated palisades (Schiechtl and Stern 1992)
advantages:
- quickly and easily built
- immediately effective, usually grows well
- filter effect
- evapotranspiration reduces pore water pressure

disadvantages:
- limited width (about 6m) and length (2-4 m)
- availability of material restricted (long, straight poles)
- only for restricted water and debris flow

Construction time: during dormant season
Costs: cheap if material at site is available
Use: reduce slope in gullies and tributaries, encourage deposition of sediments especially in fine soils

C-12. Branch layers in gullies

Live branches are placed in gullies in a fish-bone pattern with their tops up. When living branches are lacking, conifer branches can be used (which will not sprout). This branch mattress is fixed every 2 m with horizontal cross-pieces (poles) that bind in on both sides of the gully. The branches are covered by soil material to encourage sprouting. Branch layers are used for rehabilitation of gullies to stop progressive erosion. These ditches with or without permanent run-off may be up to 8 m wide and a maximum of 3 m deep.

Fig. 32: Branch layers in gullies (Donat 1995)
advantages:
- continued effectiveness (live plants)
- usually no maintenance
- succession easily introduced
- particularly suitable for shallow gullies

disadvantages:
- construction with live material slightly more expensive than dead branches
- not suitable for severe bed movement (only for moderate and/or periodic transport)

Construction time: only during dormant season
Costs: relatively cheap if branches are at hand
Use: up to 3 m deep gullies with permanent or intermittent water flow and sediment transport; against progressive erosion
C-13. Transversal structures: Live ground sills, live brush and comb construction

For live bush ground sills cuttings are placed in the fugues of a ground ramp. If these cuttings are planted only in the stream bed they are called live brush and comb constructions. For another variation, shallow ditches (1/4 to 1/2 m deep) are dug out, living brushes (1 to 1.5 m long) are placed crosswise, in flow direction with their thicker end in the ditch. The branches form a dense brush without any gaps to avoid local erosion later on. The branches are covered with some fine material to promote rooting and are secured by rocks or pegs (live brush ground sills), live or rock-filled fascines (live fascine ground sills) or gabions (live gabion ground sills). Then the branches are covered 1/2 or 2/3 of their length with bed material.

The sill construction (especially the live fascines) extends at least 1.0-1.5 m on each side into the stream banks and is secured there. The root of the sill in the banks is planted in addition to technical reinforcement with cuttings. The downstream side needs extra securing with large rocks and live branches that brake the energy of the water in case of an overflow. Single or double fascine constructions are common and can be packed with additional rock and branch material, then reinforced with pegs (every 0.5 m) and steel ropes, if necessary. Fascines sills are more stable than regular brush sills. A combination of woven fences and fascines or fences and brushes is also possible, although they are not very persistent. Immediately downstreams of sills banks must be secured with dense brush mattresses (wired down).

Fig. 33: Different types of sills (revised from Schiechtl and Stern 1994)
Fig. 34: Fascine sills (Donat 1995)

Fig. 35: Block-brush sill (revised from Schiechtl and Stern 1994)
Fig. 36: Crib wall ramp (revised from Schiechtl and Stern 1994)

advantages:
- simple, fast, and rather cheap construction
- many variations and combinations of sills with other methods possible
- provides structuring of stream bed, especially water line
- promotes sedimentation
- resistant (up to 150 N/M²), recovers after damage
- maintenance simple

disadvantages:
- limited to smaller gullies and ditches with flush floods
- not to be used in torrents with heavy bed load
- reinforcement is necessary (depending on the flow characteristics)
- not very stable (only for low land streams and upper tributaries to torrents)
- usually in streams or vadis not wider than 5 m

Construction time: during dormant season at low water flow
Costs: cheap construction technique
Use: slow down sediment flow in tributaries to torrents, stabilize bed of small creeks
C-14. Longitudinal structures

Longitudinal construction methods encompass single or a sequence of local structure along stream banks (e.g. groynes, structures for repairing local bank failures), and secondly linear (or longitudinal) structures. This second group of methods uses mainly grass species (e.g. Carex, Phragmites, Phalaris, Typha) instead of the willows normally used for biotechnical constructions.

C-14.1. Groynes

Groynes are transversal structures extending from the stream banks into the stream to secure the banks by redirecting the flow and transforming flow energy. While linear longitudinal structures secure banks on the whole length, groynes only limit stream courses (wider than 10 m) locally. They are either built inclined (repelling), declined (attracting) or rectangular (deflecting) to the flow, and vary considerably with stream characteristics and the material used.

Fig. 37: Construction principles of groynes (Ehrengruber 1989, revised)

Fig. 38: Basic groyne patterns (Ehrengruber 1989, revised)
Declined (attracting) groynes (pointing in flow direction; $\beta = \text{ca. } 45^\circ$) are rare, because they act like sills when subjected to overflow during floods and can cause damage on the banks. Inclined (repelling) groynes point against the flow direction (angle $\alpha = \text{usually } 60-85^\circ$), directing the flow towards the middle of the stream (even during floods) and thus acting like weirs. If groynes are built on both sides of a stream, their heads (tips) are placed opposite each other, otherwise the flow swings in the areas between the groynes.

![Fig. 39: Impacts of groynes on stream bed morphology (Kern 1994, revised)](image)

The length of groynes depends on stream width, required hydraulic capacity, the available material, and the purpose of the structure. Short groynes require smaller distances in between than longer ones. If they are too short, other continuous, longitudinal structures or bank protections are cheaper and more effective. For diversifying stream habitat, a length of up to $1/3$ of the stream width has proven useful. For bank protection, the correlation between the length of, and distance between groynes are discussed below.

![Fig. 40: Flow characteristics between groynes (Lange and Lecher 1993, revised)](image)
Groynes that reach above water level at medium or low flow cause two types of eddies that promote the formation of potholes near the head and deposition of fine material in the interface. The separation beam runs at an angle \( \beta \) of about 6°-15° into the area between groynes (Langer and Lecher 1989, Aulitzky 1990). Similar to length considerations, estimates of the distance between groynes depends on their purpose and overall structural concept:

a. sequence of singular groynes:

If groynes function on a one by one basis, the separation beam should hit the next groyne in the middle of its length. The distance \( d \) of these groynes can be estimated as

\[
d = f \times l \times \sin(\alpha - \beta)
\]

where:
- \( d \) is the distance between groynes,
- \( l \) is the length of groynes,
- \( \alpha \) is the angle of groyne,
- \( \beta \) is the angle of separation beam (6°-15°),
- \( f \) is the factor.

For bank securing: 4.5 to 4.78 (commonly used estimates)
1 to 2 (Duhm 1946)
2.5 (for redirecting flow)

\( f \times l = 0.25 \) to 1 times stream width
In bends, on outside: \( f \times l \) up to 0.5 times stream width

For restructuring: 5 to 7 times medium stream width (Wesche 1985)
5 to 10 times medium stream width (Frauendorfer 1985)

![Diagram of groyne arrangement](image)

Fig. 41: Flow characteristics between groynes (Lange and Lecher 1993, revised)

b. sequence of interdependent groynes:

If a sequence of groynes should act as composite structure instead of a sequence of single structures, they should be positioned at such a distance so that the main flow (beam) does not hit the next groyne, but rather the back flow of its eddy. In such sequences the potholes behind the
first groyne is deeper than behind the following ones. Thus, the first groyne needs extra securing. Estimates are done for the bed forming water flow.

Fig. 42: Graphical estimation of bed forming water level of streams (Lange and Lecher 1993, revised)

The groyne head needs special securing: in riprap groynes the largest single rock must be placed at the tip and be founded in the natural pavement of the stream bottom. The level of the crest of groynes depends on their function: If groynes are built to regulate low water flow, the crest is at the low water mark. For bank protection purposes, the crest is usually at medium water level or at the level of the bed-forming flow (see above). Higher groynes are used to restructure banks. The crest should be secured to avoid damages during floods.

Groynes are sloped upstream 1:2 to 1:3 and downstream 1:3 to 1:4. The slope of their head towards the middle of the stream varies (usually between 1:4 to 1:10). The crest is sloped towards the banks (1:10 to 1:100) and the structure secured there wide and deep enough.

Groynes can be made of sheet walls (steel, steel-concrete, wood), gabions, pallisades, fascines (with or without rock fillings), rock packings, concrete elements (e.g. tripods), crib wall structures or a combination of these. The actual choice of material and structural design depends mainly on the kind of material available at the specific site. Biotechnical engineering introduces plants in these structures above the mid-water level. In addition, cuttings are introduced between the blocks. If potholes are to be prevented, additional live brush, cuttings or reed are placed on the downstream side beneath the mid-water level to help brake the flow. The interface between the groynes can be filled with comb-structures made of live brushes or cuttings to promote sedimentation.

Two main types of groynes are commonly used: box-shaped and riprap. Box-shaped groynes are cribwall-like structures of timber or steel, rock and live plant material. Geotextiles are to
keep fine material in place to enable plants to sprout. Rocks for riprap groynes can be either tipped or placed. Placed riprap reduces the amount of rock needed and forms a more reliable static structure.

Groynes reduce both the cross-sectional area of a stream and the hydraulic capacity, as well as slow down the mean flow. The Manning-Strickler coefficient $k_{st}$ is reduced in average by 5-15% (Bechteler and Vollmers 1988). As groynes direct the main flow into the middle of a stream, they reduce bank erosion and promote sedimentation (especially hook- or T-shaped groynes). They are used to stabilize or restore banks and redirect the flow to diversify stream habitats.

Fig. 43: Riprap groynes (Lowe 1992)
Fig. 44: Hook groyne, paved (riprap type) (Ehrengrubler 1989)

Fig. 45: Brush traverse structure (vegetated riprap or fascine groyne) (Schiechtl and Stern 1994)
Fig. 46: Wooden (box) groyne (Waltl 1948)

**advantages:**
- simple, traditional, very resistant, and immediately effective construction
- directs flow, diversifies choriotos of a stream and promotes habitat heterogeneity
- requires little maintenance
- reinforcement and later changes are possible
- numerous variations and combinations with other structures are possible

**disadvantages:**
- can be constructed only during dormancy
- minimum width of streams is 10 m (in narrow streams only for diversification of alignment)
- not all variations are suitable for mountain creeks (reinforcement necessary)
- cross-sectional flow and eddies can’t cause bank damage during overflow (cf. declined groynes)

Construction time: during low flow, usually during dormant season
Costs: cheaper than continuous riprap
Use: securing of banks, redirecting water flow, encourage diversification of stream morphology
C-14.2. Log brush barrier and branch packings

Log brush barriers combine several biotechnical methods to restore more severe bank damage. Beginning at the top and proceeding in the flow direction, a log brush barrier is erected. Then, the future water line is marked with wooden stakes (2-3 m apart). In both, the area marked by the stakes and the present bank, big dead branches and small trees are laid perpendicular to the flow direction, with their thick ends towards the banks. Their tips are to reach 1/2 to 3/4 m over the stake line into the stream. The thickness of this bottom layer depends on the water depth at the site.

Next shorter live branches are set into the stream bed, inclined towards the middle of the stream. For stability reasons, the branches should form a very dense and deep reaching brush near the stakes. This branch mattress is weighted down with bigger rocks every 1 to 1.5 m. Perpendicular to these first branches and parallel to the future shore line live branches (inclined in flow direction) form a second layer. If there is a lack of live material, the branches can form rows with dead branches or bed material in between. This second brush layer is secured with rocks like the first. The first part of the structure (where the bank failures starts) must be carefully secured with rocks. Both brush layers together should reach about 1 m above the low water level. The remainder of the damaged banks should be covered with a brush mattress to prevent further erosion.

Larger bank failures do not need to be filled with log brush barriers completely. It is sufficient to secure the first quarter with this construction and encourage sedimentation in the rest with brush sills every 4 m with brush-comb structures occurring in between.

Fig. 47: Log brush barriers for large bank failures (Schiechtl and Stern 1994)
Fig. 48: Construction of a log brush barrier (Schiechtl and Stern 1994)

Branch packings are simpler construction than log brush layers, where mattresses of live branches and gravel layers are placed on top of each other. Unlike log brush layers, stakes mark not only the future shore line, but also cover the entire area with a network of stakes that are 1 m apart. These stakes (1 m long) are drive 1/2 to 2/3 of their length into the ground. Between them, a thick layer of live branches are wired down with their tips on shore and their thick ends reaching into the water (the opposite of log brush layers). Driving in the stakes with the wire network further presses down branches to a 10 cm thick mattress. Soil poured on top of this mattress fills up the gaps between the branches, and finally rocks weigh it down. This procedure is repeated until the whole bank failure is filled up. The result is a sandwich of live mattresses and rock/gravel layers.

These sandwich layers need not be horizontal, as packings are also made on slopes (cf. a sequence of brush mattresses). Live fascines (with or without rock core), rock fascines or other structures can reinforce particularly larger branch packings. If there is not enough live material, the mattresses below the mid-water level can be made up of up to 75% dead branches.
Fig. 49: Branch packings (BMLFW 1993; Donat 1995; Schiechtl and Stern 1994, revised)
advantages:
- immediately effective restoration of bank failures with increasing effectiveness over time
- prevents progressive erosion, promotes siltation and restructures water and shore line
- used in fast running streams with variable flow of water and bed load
- aesthetically appealing
- can be combined with other methods

disadvantages:
- higher labour costs
- large amounts of live material needed
- only up to 3m water depth
- built only during dormancy

Construction time: during dormant season
Costs: medium, about 25-50% of the costs for hard methods (e.g. riprap)
For branch packings: 5-10 hours/m (1 m high, 4 m wide)
Use: restoration of bank failures
C-15. Reed structures for bank and shore protection

C-15.1. Reed chump planting, reed rhizome and shoot planting

For reed structures, ditches or holes are dug out. Reed mace, reed, and rushes should be placed a bit (10 to 15 cm) below the mid-water mark in summer, with sedges and other swamp plants a bit above that level. These ditches or holes can also be spared in existing riprap or other bank protection structures. Root chumps of reed, their rhizomes or shoots (Phragmites communis) and other swamp plants are placed in a ditch or holes along the stream banks or lake shore. For shoot plantings, 3 to 5 shoots are stuck into the ground every 0.25 to 0.5 m using a drill. The shoots are introduced shallow enough that the top ends remain close to the surface and adventive roots can form at the joints.

For rhizome and chump constructions, at least 30x30x30 cm big roots stocks or rhizome bundles are dug out. Roots (rhizomes) and surrounding soil are wrapped in decomposable textiles (e.g. jute) and the young shoots are protected against damage during transport. The chumps in the textiles are placed side by side about 0.5 m from the water line. The planted shoots or the placed chumps are covered with gravel and sand, then secured with a few rocks. The roots must reach fertile soil for the rhizomes to spread. In riprap structures sand, soil and fine gravel must be filled in the prefabricated ditches or holes to enable sprouting. Young, healthy reed haulms, about 1 m long (with only leaves) are cut off close to the surface. The vulnerable haulms are transported bundled and wrapped in textiles to the construction site.

Fig. 50: Reed constructions along shores and banks of slow flowing streams (Schiechtl and Stern 1994, revised)
advantages:
- simple and cheap construction
- propagation easy in silty-sandy soil
- tolerant species (except in shadow)
- natural feature on lakes, ponds, canals and streams with slow flow

disadvantages:
- construction possible only during a short time of the year
- transportation costs (weight)
- no immediate protection; not for sites with direct wave impacts
- difficult to control growth
- intolerant of shady sites

Construction time: root stocks and rhizomes usually during dormancy, before sprouting in spring (March/April); for fast replanting all year long;
Shoot plantings only beginning of May until mid June
Costs: 1-3 hour/m²
Use: revegetation and protection of shores of lakes and slow flowing streams

C-15.2. Reed roll constructions (swamp sod rolls)

Stakes (1-1.5 m long, 1-1.5 m apart) are driven into the ground along the mid-water mark in summer, until only 30 cm reach above the water. Behind this line, a ditch (0.5 m deep, 0.5 m wide) is dug out and secured with boards, if necessary. In this slot about 1.5 m wide mesh wire is placed for the roll. The gap between the roll and the ditch wall is plugged by the material falling through the mesh during filling. The fill is a mixture of medium and coarse gravel with rests of reed chumps. If the mesh is covered with branches first, the bottom fifth can be filled with material dug out earlier. The top fifth consists of reed chumps. After filling the mesh wire it is pulled together to form a roll. The boards on the walls of the ditch are removed, the gaps refilled and the stakes are driven in to match the crest of the roll. The completed roll should stick 5-10 cm out of the water. For bigger bank failures gravel fascines or riprap with additional brush layers can act as a foundation of reed rolls.
Fig. 51: Reed roll constructions (Donat 1995; Schiechtl and Stern 1994, revised)
advantages:
- most stable reed construction
- almost no maintenance
- immediate protection after construction
- resistant to water pollution

disadvantages:
- higher costs (labour!) than simple reed plantings
- possible construction time limited

Construction time: during dormant season; especially early spring
Costs: 4-6 hours/m
Use: revegetation and protection of banks of lakes or slow flowing streams
D. MAINTAINANCE OF STREAM BANKS

D-1. Introduction

In cultivated landscapes, streams and their tributaries are remainders of former natural systems. However, even such an apparently natural water course is usually altered by changes in land use in its immediate vicinity, as well as in the entire watershed. Streams in a cultivated landscape require care and maintenance. This is particularly true for streams re-structured and restored from channels formerly degraded by land use requirements and designed following only technical standards. Important aspects for the structural quality of natural reaches of streams include

- the unity of the stream and riparian zone
- linking of different biotops, reaches and corridors
- stream bed dynamics (dynamics of water flow and sediment transportation)
- diversity of substrates, choriotops, structures and vegetation
- unique patterns of (land) use in different watersheds.

River training works, as technical answers to land use conflicts, often restrict streams to a certain (modified) channel. That reduces potential stream development and cuts down on morphological and structural stream quality. Ecological improvement of such altered reaches are often restricted to measures on the waterline or in the immediate riparian zone. Biotechnical methods are examples for more biologically sensitive approaches to stream bank protection and design, where these methods are also acceptable from an engineering point of view. Nevertheless, they are methods to help secure banks and technical structures and, with some variations, maintain a certain “status quo”.

While the principal goal of maintenance in such altered stream systems is usually to maintain certain technical conditions, it can also be a tool to influence and improve the ecological quality of reaches and diversify habitats. Thus, maintenance plays a key role in the development of diverse, semi-natural systems in an increasingly cultivated landscape.

Maintenance measures often try compromises between technical and safety requirements and the long-term need to guarantee a certain minimum of “ecological functioning” of streams. Non-recurring and recurring measures to meet technical, economic and ecological goals in specific areas or on specific reaches are prescribed stream maintenance plans. Type, technique, timing, frequency, and duration of specific measures to reach a certain set quality goal are discussed and listed in these reports.
Overly detailed maintenance plans have proven not to be practical and incur high costs. Short prescriptions and a regular training of the people doing the maintenance work are commonly regarded to be most effective. The following section discusses some of the considerations regarding maintenance of riparian vegetation only. Although a distinction between stream bed, riparian zone and adjacent land is not always clear, nor even always useful, the main focus of the following section is on maintenance measures in connection with the biotechnical methods discussed earlier.

If stream bank management or other maintenance measure are at stake, then in all situations the prime question to be asked is: “Is a certain measure in this specific situation really necessary?” This question is probably the best and single most economically efficient guide to help decide which methods should be used, where, and to what extend. This question should be in our minds when reading through the following and all other sections.

D-2. General maintenance requirements

River training constructions, with or without plants, need maintenance. Maintenance of plants in general and biotechnical methods specifically depend not only on technical requirements, but include biological aspects of plant development and ecological considerations of plant stand as habitats for wildlife. Biotechnical structures usually contribute little to slope (bank) stability immediately after construction, but increasingly does so as plants develop. Maintenance supports and facilitates this development, and is most important when site conditions are most extreme. Three periods of care and maintenance can be distinguished according to varying intensities of care and changing needs of the plants:

- initial care (during and immediately after construction) which gives plant development a good start
- care and maintenance during development (2-5 vegetation periods)
- long-term maintenance.
D-3. Initial care

Care during and immediately after construction depends on the goals of initial plant development. Standards for different types of plantings have been developed and the requirements are briefly listed below. Fertilization, irrigation, soil cultivation and soil improvement (see discussion in D-4) can help meet these standards.

Table 8: General contract requirements for completed plantings (after DIN 18918)

<table>
<thead>
<tr>
<th>Type of planting</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>seeding and seed mats (herbaceous plants)</td>
<td>uniform stand of grass and herbs with 50% average covering rate</td>
</tr>
<tr>
<td>seeding of woody plants</td>
<td>uniform distribution of swelled seeds and mulch material</td>
</tr>
<tr>
<td>sods, mulch material</td>
<td>uniform already rooted turf layer (cannot be lifted up)</td>
</tr>
<tr>
<td>plantings of trees and bushes</td>
<td>drop-out rate &lt; 30%, construction goal has still to be met</td>
</tr>
<tr>
<td>living parts of plants (branches, rods, root stocks, rhizomes)</td>
<td>fascines, brush layers, hedge and hedge-brush layers, wattling: 5 sprouts/m in average, but at least 2 sprout/m bush mattresses: 10 sprouts/m² in average, but at least 5 sprouts/m² cuttings: at least 2/3 sprouting (uniformly distributed)</td>
</tr>
</tbody>
</table>

D-4. Care and maintenance during plant development

Biotechnical structures tend to accelerate plant succession, thereby establishing some sort of climax vegetation in a short period of time. This explains why biotechnical methods require more care and maintenance in their early stages than later on. How much work they require depends on the type of vegetation to be established and the construction method used. Care and maintenance during plant development typically includes activities such as:
(a) Fertilization

Sites where biotechnical structures are used are often poor in plant nutrients and top soil. To promote plant development, fertilization has repeatedly proven successful, especially on raw soil. On pioneer stands it promotes a much faster closing of the plant cover, which in return reduces the risk of erosion. Mineralized fertilizers, manure, compost and cuttings are commonly used. The amount, combination and timing of fertilizers is plant, site and time specific, and should be detailed in a fertilization plan.

(b) Irrigation

In moderate climatic zones irrigation should only be used to sludge the root stocks of new plantings, or to assist during droughts. Overly intensive irrigation jeopardizes the development of a wide-spreading root-system. On the other hand, in arid zones, or areas with very dry summers, may require irrigation to ensure successful growth.

(c) Soil cultivation and soil improvement

Loosening of soil and (mechanical) weed control promote plant development, particularly at the beginning. A 10-20 cm thick mulch layer of rotting material (especially litter, straw, grass and weed cuttings) can regulate temperature and humidity close to the soil surface, and improve soil activity. In areas with rodent problems the litter layer must be removed before winter starts.

(d) Mowing

Mowing is not necessary, but if it is done once a year it stimulates the growth of sprouts and roots and accelerates the arrival of low grasses and herbs. Long-term strategies of mowing are discussed in section D-5.1.

(e) Care for trees and bushes

Woody plants may require cutting in the first 2 years to improve their health and shape. Bushes with a single main stem are cut to produce several main shoots. High stem trees and single woody shoots may require support by fastening them to pegs for the first 3-5 years.

(f) Plant protection and pest control

Protection of plants against plant pests (fungi) and animal pests (insects) should be done without chemicals. Damage by wildlife may require chemical and mechanical protection (fences, wiring).
Table 9: Timetable for care and maintenance during plant development (Schiechtl and Stern 1994)

<table>
<thead>
<tr>
<th>Type of maintenance</th>
<th>Timing</th>
</tr>
</thead>
<tbody>
<tr>
<td>repairing of lawn</td>
<td>March – June</td>
</tr>
<tr>
<td>irrigation, soil cultivation, fertilization, mowing, mechanical pest control, mulching, fences, fastening to pegs</td>
<td>May – September</td>
</tr>
<tr>
<td>protection against mechanical damage by wildlife</td>
<td>September – December</td>
</tr>
<tr>
<td>re-planting of dead-loss</td>
<td>October – April</td>
</tr>
<tr>
<td>cut-back of trees and bushes to rejuvenate them and to reduce pioneer vegetation, reducing undergrowth</td>
<td>December – March</td>
</tr>
<tr>
<td>removing undesired natural growth (bushes, trees)</td>
<td>all year around</td>
</tr>
</tbody>
</table>

D-5. Long-term maintenance

While biotechnical structures require intensive care during early development, maintenance remains extensive later on. In general, herbaceous plants require more care than woody vegetation. Methods and timing of maintenance depend on the technical, ecological and aesthetic goals to be met. Other goals to be considered are the further use of these plant communities as plantations to obtain more live material for new biotechnical structures, and the diversification of plant-monocultures. A technically and ecologically sensitive maintenance of grass and shrub covers, and the care of woody vegetation are the primary aspects discussed in the following subsections.

D-5.1. Mowing of dams and banks

The maintenance of grass and shrub covers is the most costly and intensive on banks and dams in moderate climates. Aside from ecological aspects, such as species diversity, purely technical reasons justify mowing stream banks. These technical arguments include:
Mowing helps maintain the required hydraulic capacity for flood events. Banks with no maintenance narrow the profile by favouring bush and tree growth.

Woody vegetation not only narrows the profile by its shoots, but also promotes sedimentation, particularly at the bottom of banks.

Frequent mowing strengthens the root system, increases the density of growth and resistance to erosion by water and ice. Lack of maintenance increases erosion by thinning the herbaceous undergrowth cover.

Lack of maintenance creates favourable conditions for rodents.

Ecological values are often in contrast with these technical requirements. An exception is perhaps the argument that specific mowing promotes and later ensures meadows rich in species, an element of ecological diversification in a cultivated landscape. The following list summarizes measures and timing of mowing to meet certain ecological goals (Table 10). These strategies are the first steps towards changing dull grass-covered banks and dams into more diverse ecological habitats without jeopardizing technical requirements.

**Table 10: Mowing of dams and banks – measures and timing to meet specific ecological goals**

<table>
<thead>
<tr>
<th>Goal</th>
<th>Measures</th>
<th>Timing</th>
</tr>
</thead>
<tbody>
<tr>
<td>promotion and maintenance of flowers on poor site</td>
<td>mowing 1-2 times/year; material has to be removed</td>
<td>end of June till September/ October (^{(1)})</td>
</tr>
<tr>
<td>promotion of specific plant species (e.g. orchids)</td>
<td>mowing 1-2 times/year; material has to be removed</td>
<td>only after seeds are ripe</td>
</tr>
<tr>
<td>promotion and maintenance of flowers and securing biotops for birds, small mammals and insects in summer</td>
<td>1/3 of the meadows remain untreated over the summer, mowing once a year, material has to be removed</td>
<td>mowing at the end of September/ October</td>
</tr>
<tr>
<td>Activity</td>
<td>Action</td>
<td>Time Frame</td>
</tr>
<tr>
<td>----------</td>
<td>--------</td>
<td>------------</td>
</tr>
<tr>
<td>Promotion and maintenance of flowers and securing food for birds, small mammals, and insects in winter</td>
<td>1/3 of the meadows remain uncut over winter, mowing once a year, material has to be removed</td>
<td>Mowing in early spring</td>
</tr>
<tr>
<td>Removing of undesired plant species</td>
<td>Mowing of patches, if necessary</td>
<td>During flowering, material has to be removed and placed separately</td>
</tr>
<tr>
<td>Establishing a riparian zone of reed and sedges</td>
<td>* Reed blade plantings: 3-5 reed blades (1=1m) planted every 0.25-0.5 m up to half of their length into the ground</td>
<td>Beginning of May until mid June</td>
</tr>
<tr>
<td></td>
<td>* Root bale plantings: reed or sedge chumps bigger than 30/30/30 cm dug out and replanted</td>
<td>During dormant season before sprouting; when transported carefully until mid or end of April</td>
</tr>
<tr>
<td>Minimizing impact on water fowl (breeding), insects, and fish (especially cyprinids) and diversifying flora</td>
<td>Selective mowing of reaches or only parts of the cross section</td>
<td>In fall (usually before mid September)</td>
</tr>
<tr>
<td>Bank protection by reed; reed habitat for water fowl, insects, and fish</td>
<td>Usually no mowing or selective mowing</td>
<td>If at all before mid September</td>
</tr>
<tr>
<td>Promotion and maintenance of perennials and shrub edges</td>
<td>Mowing reach by reach every 2 years, half of the area should be left untouched; material has to be removed</td>
<td>In fall (end of September until end of October)</td>
</tr>
<tr>
<td>Promotion and maintenance of herbaceous stream edges</td>
<td>Mowing reach by reach every 2 to 3 years, 2/3 of the area should be left untouched every time; material has to be removed</td>
<td>In fall (end of September until end of October) or spring (March)</td>
</tr>
</tbody>
</table>
re-establishing a dense grass cover; closing local failures by seeding or sods; on water-facing dam shoulder mowing one to several times a year, on the land-facing shoulder occasionally during growth season

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(1) … Mowing frequency depends on growth conditions (usually twice a year between June and October).

(2) … The less used areas of the profile above the reed zone often have a diverse flora and do not need to be always mowed, nor everywhere. If hydraulic considerations require earlier mowing, reaches of 10 to 100 m should be left untouched, or mowing should occur only on one side. These “isles” enable plants to produce seeds, spare nesting areas and stands of rare plants. This compromise should not cause hydraulic difficulties. If at all, mowing should be done in fall to minimize the impact on water fowl (breeding), insects and fish (especially cyprinides).

(3) … Bank protection and ecological considerations argue against mowing of reeds. If hydraulic reasons require cutting on creeks wider than 2 m, it should not be done before mid-September so as to maintain important habitat for water fowl, insects, and fish. On smaller creeks short reaches or even one side of the profile should remain unmowed.

In side channels, flood retention and retardation basins, sand and gravel catchments, and channel enlargements, hydraulic engineering considerations hardly require mowing. In areas with woody plants no mowing is necessary. The primary reasons why mowed grass should be removed from the banks include:

* to avoid matting of grass (which would favour rodents)
* mowed grass can impair water flow and causes oxygen reduction in the water
* to avoid fertilization of poor sites that are habitats for rare plants species.

The mowed grass can be spread in wooded reaches, where it improves soil conditions and cannot be swept away.

Mowing machines with beaters or suction devices should be avoided, as they decimate small animals and make it difficult to transport the material off the site. Extensive grazing of sheep...
on flat banks, on dams or in forelands has been found to be successful for the maintenance of grass covers under certain conditions:

* where there are no more than 10 sheep per hectare
* grazing only occurs on very flat dams or banks.

Extensive grazing removes grass, makes the new growth stronger, disturbs moles, and makes economic sense. Sheep grazing can be restricted to areas above the reed zone if bird breeding and plant seed selection is not jeopardized. Grazing by cattle must always be avoided, as their weight destroys the grass sods and induces progressive erosion.
D-5.2. Maintenance of trees and bushes

Trees and bushes are the dominant elements of natural riparian zones. They secure banks, provide shadow, protect against wind, reduce summer temperature increases of and oxygen decreases in the stream water, reduce the growth of algae and other submerged plants, provide shelter for wildlife, and are the dominant elements of landscape aesthetics especially in cultivated areas. These functions describe the different ecological aspects that should be included in management plans of woody riparian vegetation. Ecological demands must be reconciled with technical and safety requirements. Some aspects have been addressed in D-5.1. General rules of thumb on how to deal with woody vegetation are:

* Trees and bushes (or parts of them) that are unstable or an obstacle to run-off must be removed.

* Gaps in the belt of trees and bushes must be closed by new plantings (danger of gap erosion and pot-hole formation).

* Where hydraulic considerations restrict woody vegetation, certain tree and bush species (e.g. willows, alders) must be cut back every 5-15 years to enable them to sprout again.

Planting trees and bushes on dams have been, and, to a lesser extent, still are a source of conflict between engineers and biologists. Larger plants can be able to reduce dam stability by mechanically loosening dam layers, penetrating parts of the core and increasing water permeability in their root zone. However, previous experience generally encourages planting of bushes, sometimes also trees on dams under certain conditions:

* On the land-facing shoulder of dams, plantings with bushes and trees are only possible if the covering depth is large enough that roots remain outside the core or the effective static zone of the dam and do not harm them. Oversized dams can bear woody plants, but usually not others. If necessary, the static filling of a dam must be complemented by a design filling.

* On the land-facing shoulder of the dam there should not be single trees, but rather thickets (groups of younger trees and bushes). A thicket of woody plants is less endangered by wind than single tree (lever effect). While strict general maintenance rules of dams require a protection strip (2-5 m) on the toe of the dam which should be mowed several times in summer, the more moderate approach above is founded on practical experience. Even under conservative consideration, woody plants are acceptable in certain reaches, if the depth of the dam cover layer is deep enough to bear roots and the short reaches of the dam crest are elevated to avoid overflow during floods.
* On the dam shoulder facing water woody plants are particularly applicable on berms and flatter parts of the shoulder outside the minimum cross sectional profile. Small trees with restricted rooting radius are acceptable at the toe, and, proceeding up the dam, immediately followed by bushes. A strip of woody plants at foreland and the toe of the dam must not create a secondary flow channel behind it that increases erosion of the dam toe. The height of bushes should gradually decrease going up the slope and give place to a zone of herbaceous plants. A strip of grass (ca. 1 m) should run on each side of the dam crest road.

* Old, singular trees, undercut root stocks, branches that endanger service roads and other hazards must be removed.

**Table 11: Measures and timing of maintenance for woody vegetation**

<table>
<thead>
<tr>
<th>Type of woody vegetation</th>
<th>Measures</th>
<th>Timing</th>
</tr>
</thead>
<tbody>
<tr>
<td>new plantings</td>
<td>planting</td>
<td>in frost-free periods of the dormant season (November till May)</td>
</tr>
<tr>
<td></td>
<td>mulching with straw and pieces of tree bark</td>
<td>during planting in dormant season</td>
</tr>
<tr>
<td></td>
<td>mowing and other maintenance</td>
<td>June till August</td>
</tr>
<tr>
<td>juvenile stand</td>
<td>mowing around them once a year</td>
<td>March</td>
</tr>
<tr>
<td>stable trees and bushes</td>
<td>cutting to a trunk that sprouts again, depending on species composition and flood run-off reach by reach every 5-15 years</td>
<td>winter</td>
</tr>
</tbody>
</table>
D-5.3. Removing of (other) hydraulic obstacles

Other than dredging, removal of woody debris, broken-down trees and other obstacles can improve hydraulic conditions of a reach. These obstacles are deposited by floods and should be removed from the stream profile. Woody plants that impede water flow should be cut back (see D-5.2). Proactively, trees that are in danger of falling, stranded root stocks or dead wood should be removed from the banks where dam (bank) safety is at stake. Otherwise the ecological functions of dead wood for species in the water and onshore should prevail and debris should remain, despite certain aesthetic objections.

Formation of potholes, undercutting of banks and damage by rodents are the most frequent reasons for local bank failures that frequently become apparent after flood events. If bed load regime, adjacent land use and position of technical structures (e.g. roads, bridges, houses) are not relevant, these damages should be left untouched, thus creating new zones so plant succession can start all over again. Otherwise, these local failures must be repaired immediately. In many cases repairing with biotechnical methods can be a sufficient remedy.

D-5.5. Rodent control

Muskrats and other rodents dig tunnels and holes into stream banks and are responsible for the heavy damage that occurs during flood events. Damage caused by rats and mice tends to occur particularly in heavily polluted streams and when mowed grass remains on the banks. When such damage is spotted, the holes are dug up and carefully refilled. When legal, the rodents are often hunted.

The first steps of rodent control are to maintain good water quality and remove mowed grass. Planting of bushes and trees has also been found to be helpful. The shadow provided by a closed canopy of woody plants reduces the growth of submerged plants, which in turn reduces the food source for muskrats.
E. CONSTRUCTION AND MAINTENANCE COSTS OF BIOTECHNICAL STRUCTURES

E-1. Introduction

Although construction of biotechnical structures more work, the overall building and maintenance costs of reaches secured by methods using woody vegetation have proven to be cheaper than comparable conventional standard profile constructions (Anselm 1976; Schiechtl 1982; Tönsemann 1983; Dahl 1984; Anselm 1984). Unfortunately, outlining absolute prices of various biotechnical structures and their maintenance will not be helpful here for several reasons: (1) most of the reported work on costs is about 10 years old, and so prices do not include inflation or changes of wages since then; (2) more recent reports only cover some financial aspects that, all in all, paint no different picture; (3) absolute prices would neglect the different wage and price systems in Central Europe and Western Canada. To avoid these problems with absolute prices, the following references are offered:

* average construction time required for different methods: the single largest cost of a biotechnical structure is construction time, so this point should be addressed first. Costs for planning and supervision, material used and machinery vary with availability, size of a project, and region.

* average maintenance costs are offered in average percentages of the overall maintenance costs. Although changes in efficiency and wages may have occurred over time, this brief summary offers some initial references.

Ecological, social and other costs or benefits are not included in this review. These aspects, however, must be part of an overall assessment and evaluation of river training works and stream management strategies.
E-2. Planning and construction costs

Costs for planning and supervision of the construction (including surveying, negotiations with land owners, etc.) are usually 10-20% of the overall costs:

- **7 – 15%** planning phase (first concepts, alternatives, evaluation, final concept)
- **3 – 7%** approval phase (until the final completion of the maps)
- **3 – 7%** realization phase (invitation for tenders, supervision of construction, accounting)

Construction costs vary. For comparisons the average required construction times for different biotechnical structures are listed in Table 12. They include the time necessary to obtain the live material and prefabricate elements (e.g. fascines). Knowing the appropriate wages, as well as the costs for machinery and materials, buildings costs of different methods in various regions can be estimated.

Table 12: Average construction time required for different biotechnical structures

<table>
<thead>
<tr>
<th>Structure</th>
<th>average time required</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brush-mattress</td>
<td>1-5 hrs/m²</td>
</tr>
<tr>
<td>Geotextile structures</td>
<td>(?) cheaper than other combined biotechnical methods</td>
</tr>
<tr>
<td>Fascines (bush wattles):</td>
<td></td>
</tr>
<tr>
<td>geotechnical fascines</td>
<td>0.5-1 hr/m</td>
</tr>
<tr>
<td>drainage or river engineering fascines</td>
<td>1-3 hrs/m</td>
</tr>
<tr>
<td>Wattle (wicker) fences</td>
<td>0.75-1.5 hrs/m</td>
</tr>
<tr>
<td>Live slope gratings</td>
<td>2-5 hrs/m²</td>
</tr>
<tr>
<td>Groove and cordon structures:</td>
<td></td>
</tr>
<tr>
<td>Groove (or rut)</td>
<td>1-3 hrs/m</td>
</tr>
<tr>
<td>Cordon</td>
<td>3-4 hrs/m</td>
</tr>
</tbody>
</table>
### Layer structures:
- **Hedge layer**: 1-3 hrs/m
- **Brush layer**: 0.75-2 hrs/m
- **Hedge-brush layer**: 0.75-2.5 hrs/m

### Cuttings:
- **Planting of cuttings**: 0.05-0.1 hr/cutting
- **Joint plantings**: 5-7 m²/hr

### Crib wall with branch layering
- (?) comparable to dry stone wall

### Vegetated gabions
- (?) inexpensive

### Vegetated palisades
- (?) cheap if material is available

### Branch layering in gullies
- (?) relatively cheap if branches are at hand

### Transversal structures (live ground sills, live bush sills, comb constructions)
- (?) cheap construction technique

### Longitudinal structures:
- **Groynes**: (?) cheaper than continuous riprap
- **Log brush barrier and branch packing**: (?) about 25-50% of the costs of hard methods (e.g. riprap)

### Reed structures for bank and shore protection:
- **Reed chumps / Reed rhizome / reed shoot plantings**: 1-3 hrs/m²
- **Reed roll constructions**: 4-6 hrs/m

An increase in construction costs are typically incurred when:

* the necessary land is either expensive or unavailable
* physical constraints (e.g. buildings, roads) require expensive securing
* recreational considerations must be made (profile design, hiking and biking paths, stair cases, etc)
* technical buildings have to be included in the overall design
E-3. Maintenance costs

The initial maintenance costs of biotechnical structures are much higher (ca. 50% during the first 3 years) than those of conventional structures (Wolf 1977; Dahl and Schlüter 1983), but they become much lower, and also more steady later on. Maintenance of wood vegetation depends on:

* maintenance frequency (see Fig. 52)
* age of the riparian thicket, density of growth
* successional stage (pioneer stage up to climax)
* accessibility and width of growth
* species (willows are more effective in bank securing but need more care)
* water quality (increase of submerse plants when water quality drops)
* size of the stream
* density of stream network (see Fig. 52)
* stream region (upper, medium and lower reaches) (see Fig. 52)
* debris and sediment transport

Fig. 52: Average expenditures for maintenance of the second order streams in Lower Saxonia/Germany (revised from Anselm 1976)

The following diagram summarizes average relative maintenance costs for different methods of river training based on 357 streams over a total length of more than 4000 km (Anselm 1976). In general, absolute costs of maintenance (not in Fig. 53) favour structures with fascines or
woody vegetation in general over other (including conventional) bank protection methods. More recent investigations of some of these aspects support the general rule that, if hydraulic and safety requirements are met, natural and semi-natural stream management approaches are altogether cheaper than purely technical river training work.

* “mowing” = mowing and removing of submerse plants
* “pest control”
* “dredging”
* “cut-back thicket” = cutting of trees and bushes back to stock, thinning
* “flood damages” = repairing of damages after floods
* “others” = transporting material and debris off-site, maintenance of buildings

Fig. 53: Average relative maintenance costs for different bank structures (revised from Anselm 1976)
E.4. Summary

Changes in stream alignment and profile usually have a major impact on construction costs. Costs of the land and groundworks, eventually combined with costs for recreational facilities drive prices up for construction streams. If streams are kept semi-natural, measures against erosion on the banks and lowering of the stream bed incur the highest costs. The cheapest solution is to give a stream enough space within set-back dikes. Land use requirements often favour the second cheapest solution: a combination of bed stabilization and longitudinal bank protection methods. Riprap combined with reed and bush structures are the preferred, and cheapest, heavy-duty construction methods to secure banks when necessary. Costs of plants can be reduced by building up plantations for the plant material needed. Not all areas need to be seeded, but can be left to natural succession, especially if construction timing follows the ripening cycles of naturally distributed seeds.

However, the main point remains to secure only those areas that are endangered by erosion (e.g. the outside bank in bends) with appropriate structures, and not the entire reach. The more conventional or biotechnical bank securing that is planned, the more expensive the project will be. Reducing costly structures and starting restoration work in the watersheds (e.g. retarding of run-off, erosion control) may free the money necessary to buy up land along streams and provide space for a semi-natural system.
F. REFERENCES


Appendix

“COMPOUND STRENGTH” OF ROOTED SOIL

The soil stabilization effect of plant roots is based on two components: (1) by friction between the soil particles that transfer shear stresses from the soil to the root reinforcement system, and (2) by soil arches that build up between cylindrical soil units that are reinforced by roots (root stock-soil elements) and stabilize areas that are not rooted. Shear increase in rooted soil is based on the model of a “compound strength” of a material that consists of fibres of relatively high strength and adhesion to a matrix of lower tensile strength. Most geotechnical models express the increase in shear strength of rooted soil as an increase in cohesion exclusively based on the anchoring effect of plant roots. Rarely do such models take into account an increase of the angle of inner friction due to biologically changed soil properties.

Biotechnical reinforcement occurs in relatively shallow soil layers. The rooting depths of herbaceous plants is less than 0.5 m, that of trees and bushes less than 3-5 m. Therefore, normal stress is small and an increase in surcharge (surface load of the vegetative cover and the stored water) is almost negligible. In this range of normal stress the Coulomb approximation of the shear curve differs considerably from the Mohr envelope curve, and the angle of internal friction changes quickly (Fig. 55).

![Mohr and Coulomb shear curve](image)

**Fig. 55: Mohr and Coulomb shear curve**
The Mohr curve should therefore be used for quantifications of plant root effects on soil shear resistance, since it is more accurate than the Coulomb curve in the range of small normal stresses. There are two ways to describe the Mohr curve: (1) approximations (curve or polygon) that best fits with the test results, or (2) analytical approaches such as the following equation (Pregl 1986):

\[ \phi = a + b \log\left(\frac{e_0}{e}\right) + c \log\left(\frac{\sigma}{\sigma_b}\right) \]  

\( \phi \) … shear angle = angle between x-axis and the line from point zero of the coordinate system to the point on the shear curve. It is not the angle of internal friction (rad)

\( e \) … present void ratio

\( e_0 \) … initial void ratio = reference void ratio

\( \sigma \) … present normal stress (kN.m\(^{-2}\))

\( \sigma_b \) … reference normal stress (freely chosen: 10 kN.m\(^{-2}\))

\( a, b, c \) … material specific constants

For soils without true cohesion (no particle cementation by pore water pressure) “a” is zero, for rock material “a” is greater than zero. The shear strength \( \tau \) at a certain normal stress \( \sigma \) is calculated as:

\[ \tan \phi = \frac{\tau}{\sigma} \]  

(Equ. 2)

\[ \tau = \sigma \cdot \tan \phi \]  

(Equ. 3)

The increase in shear strength by roots “\( \Delta \tau \)” is the plant- and soil-specific vertical displacement of the Mohr curve (Fig. 56).

Fig. 56: Shear curves with and without plant root reinforcement
“Δτ” is not constant, but decreases with depth, and is zero in soil horizons without root reinforcement. An increase in cohesion due to soil suction under unsaturated soil water conditions is only temporary and should not be considered. The modified equation for shear resistance of a soil with root reinforcement is:

$$\tau = \Delta \tau + \sigma \tan \phi$$  (Equ. 4)

$$\tau$$ … shear strength (kN.m$^{-2}$)
$$\Delta \tau$$ … root reinforcement effect (kN.m$^{-2}$)
$$\sigma$$ … normal stress (kN.m$^{-2}$)
$$\phi$$ … shear angle (°)

$\phi$ is the shear angle, and not the angle of internal friction $\Phi$(See Fig. 57)

<table>
<thead>
<tr>
<th>$$\sigma$$</th>
<th>normal stress (kN.m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$$\tau$$</td>
<td>shear stress (kN.m$^{-2}$)</td>
</tr>
<tr>
<td>$$\phi$$</td>
<td>shear angle (°)</td>
</tr>
<tr>
<td>$\Phi$</td>
<td>angle of internal friction (°)</td>
</tr>
</tbody>
</table>

Fig. 57: Shear angle and angle of inner friction

“Δτ” depends on:

- the tensile strength of the roots
- the soil material
- the friction between root surface and soil material

To obtain the final Mohr curve for rooted soil, “Δτ” has to be calculated for a several depths (normal stresses) with the prevailing angle of internal friction and root ratio.
Theoretical model for shear strength increases due to plant roots

Roots that contribute to an increase of shear strength must cross the sliding plan. By displacement of the soil within the shear zone, tensile stress is mobilized in the roots. The roots act like anchors. Root stress components tangential to the sliding plane are shear forces. Stress components in a right angle to the shear surface increase the normal stress in the sliding plane. It is assumed that the roots are anchored sufficiently on both sides of the sliding plane so that failure is caused by rupture of the root and not by pulling them out from the soil. Further assumptions are: (1) the root is in a right angle to the sliding plane before shearing, (2) the tensile strength is completey mobilized, (3) the roots do not change the angle of internal friction of the soil. Under these conditions, the increase in shear strength (as an increase of cohesion $c$) is:

$$\Delta \tau_r = t_r^*(\cos \theta \tan \Phi + \sin \theta) \quad \text{(Equ. 5)}$$

$$t_r = T_r^*(A_r/A) = \sum ((T_{r,i}^*n_i^*a_i)/A) \quad \text{(Equ. 6)}$$

- $t_r$ ... tensile strength of the roots per unit area of the sliding plane (kN.m$^{-2}$)
- $T_r$ ... average tensile strength of the roots (kN.m$^{-2}$)
- $A_r/A$ ... area ratio occupied by roots (m$^2$.m$^{-2}$)
- $T_{r,i}$ ... average tensile strength of the roots of the diameter class $i$ (kN.m$^{-2}$)
- $n_i$ ... average number of roots of the diameter class $i$ per unit area
- $a_i$ ... average cross section area of roots of the diameter class $i$ (m$^2$)
- $A$ ... cross section area (m$^2$)
- $\theta$ ... angle of shear distortion ($^\circ$)

The distortion angle $\theta$ depends on the thickness of the shear zone and the shear displacement when approaching the maximum shear strength ($\theta$ usually between 40$^\circ$ to 70$^\circ$). As $\Phi$ is between 25$^\circ$ and 40$^\circ$, the term $(\cos \theta \tan \Phi + \sin \theta)$ is in the range from 1.0 to 1.3 (most probably 1.15).

$$\Delta \tau_r = 1.15 \times t_r \quad \text{(Equ. 7)}$$

To be able to attribute the shear failure to root rupture, the minimum anchoring length of the roots on both sides of the sliding plane has to be

$$L_{\text{min}} > (T_r*d_r)/(2*\tau'_r) \quad \text{(Equ. 8)}$$

- $L_{\text{min}}$ ... minimum anchoring length (m)
- $T_r$ ... tensile strength of the roots (kN)
- $d_r$ ... diameter of the roots (m)
- $\tau'_r$ ... shear strength between root and surrounding soil (kN.m$^{-2}$)
  $\quad = $ maximum bond stress or pull-out resistance between root and soil.
This simple estimation bases the increase in shear strength on the average tensile strength $T_r$ of the roots and the area ration $A_r/A$. To be on the safe side, despite of assumptions such as constant root properties or a full mobilization of the shear strength of different root diameters at the same extension, the tensile strength is usually assumed sufficiently low. While the contribution of roots to shear strength increases should vary with their angle to the shear plane, experimental results have shown that purely random positioned fibres produce approximately the same increase in shear strength as fibres perpendicular to the shear plane do (Gray and Ohashi, 1983). Therefore, the simple, theoretical model based on perpendicular roots (fibres) is sufficiently accurate.