1 Direct shore stabilisation approaches

Eight stabilisation techniques that directly modify the bank to mitigate erosive forces have been discussed in detail.

1 **Revegetation** — re-establishment of local native vegetation to stabilise bank sediments by generating a network of roots and partially absorbing wave and current forces.

2 **Coir logs** — densely packed and biodegradable coconut fibre tubes anchored to the toe of riverbanks to provide short-term protection while vegetation is established.

3 **Brush mattressing** — logs or branches (or both) placed in an overlapping structure around revegetated sedges and shrubs to stabilise the bank (and provide nutrients) while vegetation is established.

4 **Log walling** — vertical structures constructed from round logs or timber planks attached to vertical piles to protect the toe of the bank and retain a higher elevation of foreshore.

5 **Cut limestone block walling** — low gravity structures (often on reinforced concrete footings) that provide stabilisation while minimising the structure footprint and maintaining a high aesthetic level.

6 **Gabions** — structures formed by a series of wire frame cages filled with rock that are wired together to provide shore or bed scour protection.

7 **Rock revetments** — a system of graded, interlocked, quarried armour stone laid upon a bank to absorb erosive forces and stabilise the adjacent foreshore.

8 **Geotextile revetments** — sand-filled containers placed as relatively flexible revetments to stabilise eroding foreshores.

Detailed information for the eight techniques presented in this section includes the following items (after McCullah and Gray 2005).

- **Description**
  - Advantages and limitations
  - Case studies and examples
- **Purpose and application**
  - Condition where practice applies
  - Complexity and sensitivities
- **Design guidelines**
  - Loading
  - Considerations for detailed design
  - Design life/expected lifetime
  - Materials and equipment
  - Construction/installation
  - Failure mechanisms

- **Monitoring and maintenance**
- **Cost**
- **Technique specific references**

A comparison of the eight techniques is included in Table 1.1. Further information on other techniques is included in Appendix A.

The first stabilisation approach that should be considered for an eroding bank is do nothing/ managed retreat. This is often the least expensive approach with the least adverse environmental impacts. Bank erosion is permitted to continue, which can reduce downdrift erosion and allow the river to migrate. This approach can require fencing, signage and moving infrastructure at risk of damage.

Table 1.1 Comparison of direct shore stabilisation techniques

Technique	PURPOSE	ADVANTAGE	LIMITATIONS	DESIGN LIFE & MAINTENANCE LEVELS	COMBINATION OPPORTUNITIES	Costs[1]
Revegetation	To prevent erosion Improve riverbank ecosystem structure/ function Improve water quality	Re-establishes local native flora Aids bank protection & stabilisation Reduces turbidity Habitat creation Inexpensive	Limited to areas that are protected from active erosive forces & have appropriate slopes Vulnerable to pressures (heavy traffic, river flows & wave action)	Increases in strength & effectiveness with time A long-term option for foreshore stabilisation, providing ongoing monitoring & maintenance	Brush mattressing, erosion control matting, coir logs & bank reshaping Complementary to large woody debris & all 'hard engineering'	Low
Coir logs	Secured along riverbanks to prevent scour & erosion Creates a soft toe armour providing short-term protection & encouragement of revegetation works	Creates habitats & stabilises the bank (with revegetation) Inexpensive, lightweight & easy to install Flexible to curve around banks & vegetation	Not for regions of high flow velocity Susceptible to undercutting & removal May locally enhance wave reflection & scour where wind waves & wake occurs	Effective life of 6–12 years according to site specific environmental conditions, installation methods & maintenance Appropriate storage before use will extend life	Always use with revegetation Combine with brush mattressing, erosion control matting, bank reshaping, large woody debris & rock toe protection	Low/medium

Technique	PURPOSE	ADVANTAGE	LIMITATIONS	DESIGN LIFE & MAINTENANCE LEVELS	COMBINATION OPPORTUNITIES	Costs[1]
Brush mattressing	Temporarily increases the stability of eroding banks while revegetation is established Promotes deposition of sediment, reduces the rate of scour & encourages vegetation growth	Inexpensive Promotes revegetation Effective at sites with fluctuating water levels	Intensive labour required for construction Susceptible to flanking erosion & gullying under the mattress	5–10 years design life while vegetation is established Long-term stability relies on the success of establishing vegetation	Always in combination with revegetation Can be placed above any type of structure that provides sufficient toe protection	**Medium/high**
Log walling	Provides a vertical structure which may retain a low elevation foreshore	Low initial capital costs A more natural look Lightweight, easily installed with limited machinery	Scouring at the tow If placed low on the profile, public access to the beach/bank can be limited Short design life	3–15 years design life depending on how it is applied, the location, quality of the timber, the species durability, the preservative treatment and the structural quality	Rock toe protection in front of the structure Revegetation with sedges	**Medium**
Cut limestone block walling	Provide erosion protection with a high level of amenity to valuable foreshore assets (particularly in areas where there is limited space)	Aids foreshore protection while minimising the structure footprint High level of visual amenity Durable	Wave reflection may exacerbate erosion of the adjacent foreshore Limited capacity to accommodate differential settlement	Components of the structure with limited access (i.e. the footings) should have a design life comparable to that of the structure	Adjacent to other hard structures Revegetation & bioengineering landward of the structure Should be used with renourishment or rock toe protection to reduce undermining	**Medium/high**

Technique	PURPOSE	ADVANTAGE	LIMITATIONS	DESIGN LIFE & MAINTENANCE LEVELS	COMBINATION OPPORTUNITIES	Costs[1]
Gabions	A viable alternative where large armour rock, block work or panel systems are not economically available or aesthetic A hard approach to shore stabilisation For extreme flows or wave conditions	Porous Flexible Designed for a wide range of soil conditions & groundwater flows Can occupy a region of narrow horizontal extent	Relatively expensive Labour intensive (construction) Requires careful management Poor durability	Determined by the capacity of the wire to withstand corrosion, vandalism & abrasion Typical life expectancy of 10–15 years (extended to 25–30 years providing regular maintenance)	Revegetation Renourishment Placed adjacent to any hard structure	**High**
Rock revetments	Absorb erosive forces Protects the adjacent foreshore embankment Applicable for bank stabilisation for the bank profile locations & channel planform locations	High degree of confidence due to detailed design guidelines & examples Absence of earth pressures Ease of maintenance Low wave run-up	Large space required Potential scour of adjacent foreshores High dependence on the skill of the operator placing the armour stone	20 years with a modest degree of maintenance	Adjacent to other hard structures Revegetation & bioengineering landward of the structure Renourishment	**High**
Geotextile revetments	Filtration, drainage, separation & reinforcement Used in revetment applications Prevents the migration of fine soil particles through a structure	Flexibility in application A 'soft' finished product	Vulnerability to puncture during construction & placement Vulnerability to vandalism	10–15 years	Renourishment Bioengineering & revegetation can be incorporated landward of any geofabric sand bag (GSC) project Revegetation can be incorporated with some types of geotextiles	**High**

Note: [1]costs per linear metre: low = < $300/m, medium = $300/m to $1000/m, high = > $1000/m

2 Revegetation

2.1 Description

In these guidelines, the term revegetation refers to the re-establishment of local native sedges, rushes, trees, shrubs and herbs along riverbanks and foreshores. Revegetation may also be described as planting, vegetative stabilisation, landscaping, rehabilitation or restoration of vegetation. Revegetation protects and stabilises banks while providing or improving important environmental elements, including the creation of habitat for native river fauna and reduction of local turbidity.

When used on its own as a stabilisation technique, revegetation is effective only in areas that are protected from active erosive forces and have appropriate slopes. Sites with active erosive forces, steep slopes, banks that are subject to surface flow or drainage, and sites where weeds have been removed require other site stabilisation techniques as well as revegetation (McCullah and Gray 2005).

Vegetation has strength limitations and is vulnerable to pressures such as heavy traffic (pedestrian and animal), river flows and wave action. This is particularly true in the early establishment phase. Revegetation, without other stabilisation techniques, should be applied with caution where there is insufficient setback of high value assets.

Revegetation is relatively inexpensive compared to other methods of foreshore stabilisation. However, it does require regular monitoring and maintenance (infill planting and weed control) to be successful, especially in the early establishment phase. Revegetation projects should be considered to have a three-year construction phase (e.g. three-year capital input) as replacing plants during this initial three-year period should not be seen as 'maintenance'.

When implemented and maintained in appropriate locations, revegetation has the ability to become stronger and more effective over time, thus providing increasing protection to river banks (McCullah and Gray 2005).

2.1.1 Case studies and examples

Successful foreshore revegetation projects are normally the result of strong partnerships between the community and local or state government agencies combined with an ongoing commitment to the maintenance of the project site.

There are many excellent examples of foreshore revegetation works on the Swan and Canning rivers. Several of these examples are in the Canning River Regional Park.

The example described below is located in Ferndale in the Canning River Regional Park near the Greenfield Street Bridge.

In the summer of 2005 a wildfire burnt this site, and some remnant vegetation was damaged. However, the unplanned fire had removed a large weed mass and promoted natural regeneration of the native vegetation, presenting stakeholders with an opportunity to rehabilitate the site.

The Trust and Department of Environment and Conservation (DEC) Community Regional Parks Unit worked in partnership with the South East Regional Centre for Urban Landcare (SERCUL) and Canning River Regional Park Volunteers (CRRPV) to develop a revegetation plan for the site.

An area of nearly one hectare was chosen and an initial budget of approximately $30,000 was allocated for the first year.

The first year of works (2005) involved controlling weeds including *Typha orientalis* (Typha) and *Colocasia esculenta* (Taro), fencing the site, planting 4000 sedges in autumn and spring, planting

8650 shrubs and trees in July, and ongoing weed control through hand removal and chemical control (Figure 2.1).

Through its Riverbank Grants Scheme the Trust provided funding to DEC and CRRPV for ongoing weed control works and extension of the project site.

The photos below show the plant growth during 2005, 2006 and 2007 (Figure 2.1, Figure 2.2 and Figure 2.3).

Source: SERCUL April 2005

Figure 2.1 Initial weed control and sedge planting post-fire near Greenfield Street Bridge

Source: Swan River Trust February 2006

Figure 2.2 Seven-month growth of planting in July 2005 near Greenfield Street Bridge

Source: Swan River Trust, March 2007

Figure 2.3 Twenty-month growth of revegetation near Greenfield Street Bridge

2.2 Purpose and application

Vegetation may be established on riverbanks to prevent erosion, improve ecosystem structure and function and/or improve water quality.

There are four specific ways that vegetation can protect riverbanks (Allen and Leech 1997).

1. Root system helps bind the soil and increases the overall bank stability
2. Exposed vegetation (stalks, stems, branches and foliage) can increase the resistance to flow and reduce the local flow velocities
3. The vegetation acts as a buffer against the abrasive effects of transported materials
4. Dense vegetation can induce sediment deposition (by causing zones of slow velocity and low shear stress near the bank) and deposition of aeolian (wind-blown) sediment in a similar manner.

Revegetation may stabilise banks for the bank profile locations, channel planform locations and type of erosion processes presented in Table 2.1.

Table 2.1 Revegetation applicability

USEFUL FOR EROSION PROCESSES	
Description	**Feasibility**
Toe erosion with upper bank failure	1
Scour of middle and upper banks by currents	
Local scour	
Erosion of local lenses/layers of non-cohesive sediment	
Erosion by overbank runoff	
General bed degradation	
Headcutting	
Piping	
Erosion by navigation waves	1
Erosion by wind waves	1
Erosion by debris gouging	
Bank instability/susceptibility to mass slope failure	
Erosion due to uncontrolled access (either boat launching, human or animal trampling)	2
Erosion due to inappropriate focusing of drainage	
Enhanced erosion due to sedimentation of the channel	
Erosion due to interruption of sediment transport	

PROFILE SPATIAL APPLICATION	
Description	**Feasibility**
Toe	
Midbank	
Top of bank	

HYDROLOGICAL GEOMORPHIC SETTING	
Description	**Feasibility**
Resistive	
Redirective	
Continuous	
Discontinuous	
Outer bends	
Inner bends	
Incision	
Lateral migration	3
Aggradation	

Feasibility method
'White' = feasible
'Grey' = possibly feasible, see table notes
'Black' = not feasible

Note: 1 Can slow the rate of erosion

2 If fencing and paths are also installed

3 Can assist in slowing the rate of bank migration

2.2.1 Condition where practice applies

It is important to understand community use and expectations for an area to establish whether revegetation is an appropriate technique for the location. However, revegetation as a foreshore protection measure can be used from the channel to the upland riparian zone. The success of revegetation in protecting banks depends strongly on the structural protection of the toe of the bank and the ability of the vegetation to establish.

Revegetation alone is suitable across a range of slopes. However, banks steeper than the given rules of thumb for slope, with actively erosive forces will need to be regraded, terraced and/or protected using other stabilisation techniques before revegetation.

The potential erosive force from wave action and boat wash should be considered when planning revegetation works. Studies undertaken by Shafer *et al.* (2003) indicate that wave heights of less than 0.3m can typically be tolerated by established vegetation without causing damage. Wave heights exceeding 0.5m will actively destabilise the vegetation and only broad strips of riparian vegetation can withstand these conditions for sustained periods.

Revegetation works are more sensitive to disturbance during establishment. Hence sites subject to wave action and boat wash are likely to need complementary stabilisation and protection works. This may include short-lived protection measures including coir logs, jute matting or baffles.

2.2.2 Complexity and sensitivities

Factors affecting complexity include soil type and quality (such as contaminated sites and potential acid sulphate soils) access, remnant vegetation, climate/sea level change and weeds.

Sensitivities that should be considered and factored into revegetation plans include:

1 **Slope and erosive processes** — it is critical that revegetation is undertaken in a suitably sloped, and/or a stabilised and protected area. The slope shall be a function of soil type, plant type, hydraulic conditions and the section of foreshore to be revegetated. The following slope constraints should be considered when revegetating different sections of the foreshore:

- slope on an upper bank with no wave action should preferably be flatter than 1V:4H and no steeper than 1V:3H
- slope on a bank exposed to occasional wave action should be preferably flatter than 1V:6H
- slope on a lower bank exposed to regular wave action should be from 1V:12H to 1V:30H, depending on soil type.

Revegetation on steeper slopes may require slope reinforcement measures including techniques such as rock toe protection, brush mattressing, erosion control matting, bank reshaping and terracing. Several of these techniques are outlined in sections four and eight, with additional information in WRC (2001a), McCullah and Gray (2005), WDFW (2003) and USDA (1996). Revegetation works undertaken in actively eroding sites and/or sites steeper than the simple rules above are likely to be ineffective. It is also important to manage drainage over the site to further minimise instability of the revegetation.

2 **Protection from pedestrians, vehicles and animals** — revegetation works, particularly in the early establishment phase, are vulnerable to trampling from humans and animals (including domestic pets, livestock and feral animals). Fencing and signage should be considered to protect vegetation from damage.

Damage and plant predation from vertebrate pests (e.g. pigs and rabbits) may be a consideration in revegetation works, particularly in fluvial areas of the Swan Canning river system. Control of vertebrate pests can be difficult in the semi-urban and urban environment, but may include trapping, baiting and fencing. (Contact the Department of Agriculture and Food for information on policy, management and regulation).

Local native waterfowl (e.g. purple swamphens) can pull out newly planted sedges and rushes. This could be addressed through ongoing monitoring and replacement of plants or, at particularly difficult locations, using larger stock that cannot be removed by birds.

3 **Planting zones** — the ability of vegetation to withstand flooding depends on the amount and distribution of air cells (aerenchyma) present in the roots, rhizomes and stems and physiological attributes (WRC 1999). Appropriate local native plant species should be selected and planted for each riparian zone (WRC 1999): in-stream floodways; lower embankments; upper embankments; floodplains; and upland. (Refer to *Detailed Design* section for more information).

4 **Salinity** — local native plant species selected for revegetation should be tolerant of the site-specific salinity levels. It should be noted that plants grown in nurseries are generally cultivated using freshwater. Some land managers working in brackish and estuarine conditions have seen improved revegetation success by 'hardening' plant stock using saline water prior to planting. This can be achieved by slowly increasing the salinity levels in water applied to the plants while still in the nursery.

5 **Climate change** — should be incorporated into designs according to the most recent Department of Planning and Trust policies, which are based on Intergovernmental Panel on Climate Change (IPCC) predictions. Climate change is generally incorporated solely in terms of elevating design water levels. However, there is potential for increased storminess, flooding and increased wave energy transmission to the banks.

6 **Heat/water** — revegetation works may require watering in the early establishment phases, especially if unusual (hot and dry) seasonal conditions are present.

7 **Soil contamination** — the possibility of site contamination should be considered early in the planning stages, especially if the area to be revegetated had a previous landuse. (For more information on soil contamination refer to DEC 2008b).

8 **Acid sulphate soils** — acid sulphate soils (ASS) are naturally occurring soils and sediments containing iron sulphides, most commonly pyrite. When ASS are exposed to air, the iron sulphides in the soil react with oxygen and water to produce a variety of iron compounds and sulphuric acid. Initially a chemical reaction, the process is accelerated by soil bacteria. The resulting acid can release other substances, including heavy metals, from the soil and to the surrounding environment (DEC 2008a).

Foreshore restoration works in areas of high to moderate ASS risk must be managed appropriately to minimise disturbance and potential damage to the environment. Sites that have already been disturbed through a previous landuse or development may need to be treated appropriately before any revegetation works can occur.

(For a series of fact sheets and guidelines to help with the identification, investigation and management of ASS in Western Australia refer to DEC 2008a).

2.3 Design guidelines

A good plan is an essential aspect for any revegetation project. The plan should outline the objectives for revegetation, works methodology, timing, monitoring and maintenance. This is usually presented in the form of a landscape plan with supporting text.

Components to include in revegetation planning are outlined below.

2.3.1 Loading

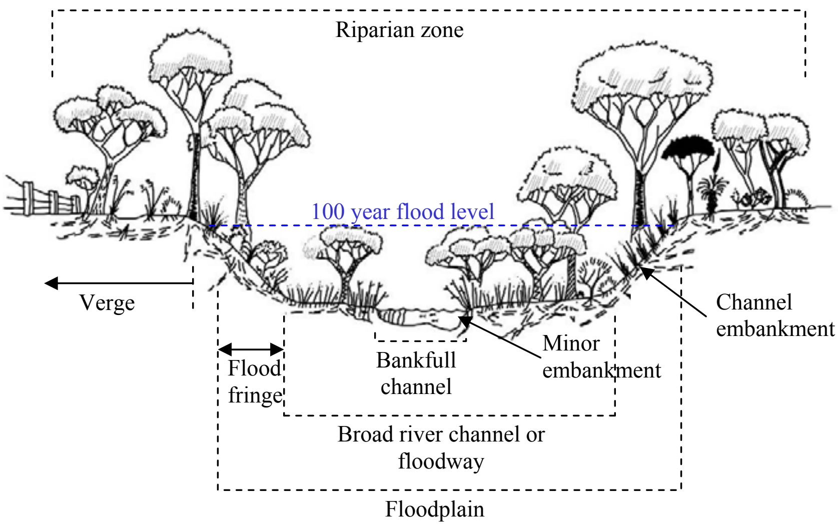
The capacity for revegetation to resist erosive forces from currents and waves is determined largely by the connection between the vegetation and underlying bed material. Resistance increases as the root system becomes fully established and density of foliage increases. Resistance is reduced where the bank is steep, the soil mass has low strength or is lacking in cohesion. Established riparian vegetation can typically withstand waves of less than 0.3m significant wave height without sustaining damage (Shafer *et al.* 2003). Wave heights up to 0.6m height may be experienced with damage, but not total loss of the riparian vegetation.

Assessment of the lower Swan River foreshore suggested that in many cases the greatest stress on riparian vegetation, whether natural or introduced, is caused by vertical movement of the bed in front of the vegetation, causing undercutting (Damara 2007). This is typically developed by changes external to the revegetation works, and should be catered for either through a protective toe at the outer edge of the vegetation (cohesive mud, coarse bedding material or coir logs may be used) or by creating a wide revegetation buffer, subject to regular planting.

2.3.2 Considerations for detailed design

Detailed designs should incorporate the following aspects.

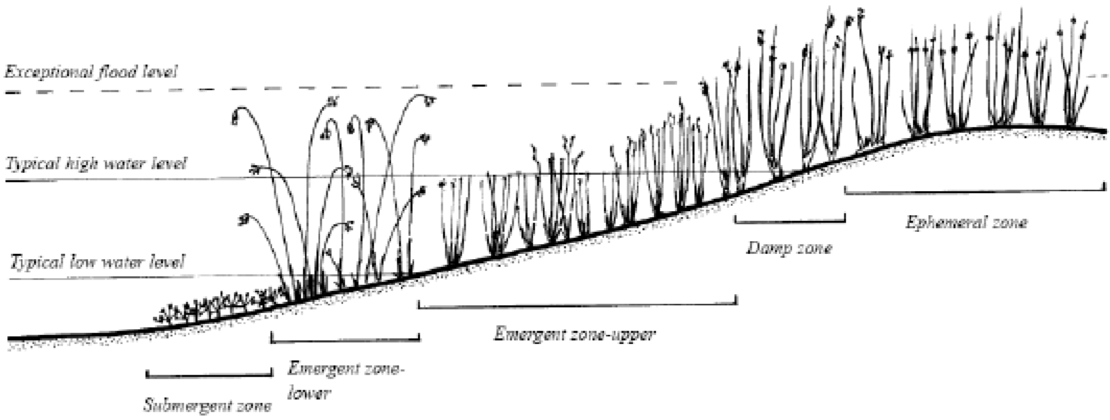
- **A landscape plan** — a landscape plan is usually produced on an aerial map. The plan can be drawn by hand or by using a GIS, CAD or other landscaping computer program. The plan should define the area to be revegetated, identify existing soil types and vegetation, indicate location and definition of high and low water marks and include any other important features. Zones for planting different plant communities/species can also be marked on this plan to assist in planting.
- **Work schedule** — a work schedule should be included specifying appropriate planting times, when site preparation (such as stabilisation and weed control) will fit in with planting and when maintenance (such as weed control) should occur.
- **Site preparation** — the site should be suitably sloped or stabilised (or both) before any revegetation is undertaken. Refer to slope and erosive processes in the *Complexities and sensitivities* section for more information. Erosion control matting is commonly used with revegetation on bank slopes. Matting is used to stabilise the bank and prevent soil loss caused by overland flow in the absence of vegetation cover (WRC 2001a). Details on installation methods are outlined in WRC (2001a, p.24), Donat (1995) and McCullah and Gray (2005, sections on 'turf reinforcement' and 'erosion control blankets'). Weed control should be undertaken before planting and be ongoing after planting. It is important to recognise that some weeds may help stabilise the banks. In this situation it may be appropriate to leave the weeds or manage their growth until the planted vegetation is fully established and protecting the bank. Alternatively, weeds could be removed and banks stabilised before revegetation.
- **Protection of vegetation** — revegetation works may require protection from humans and/or animals. This aspect is discussed further in the *Complexities and sensitivities* section.
- **Species selection** — the type of species selected should be native to the local area. Local native species are adapted to local conditions so avoid contaminating and possibly degrading the gene pool and avoid the possibility of generating new weedy species or variants (WRC 1999). Species local to the area can be determined by using historic references or a local reference site that has good quality remnant vegetation. Species should be selected based on soil maps and hydrological regimes if historic information or reference sites are unavailable.
- **Hydrology and planting zones** — plant species should be selected and planted according to the different zones found across the foreshore (Figure 2.4 and Figure 2.5). Where possible, revegetation works should replicate natural plant communities.



Source: Department of Water & Swan River Trust 2007

Figure 2.4 Foreshore zones

Sedges and rushes have specific hydrological requirements. The areas in which they grow are determined by the minimum and maximum water levels. Although stream and river systems vary considerably, the following zones for rushes, sedges and other aquatic plants can be defined along most water courses: submergent zone; emergent zone; damp zone; and ephemeral zone (Figure 2.5; WRC 2001b).



Source: Water and Rivers Commission 2001b

Figure 2.5 Wetland zones defined in the River Restoration Manual

Zones for different plant communities/species can be marked on the landscape plan to assist in the planting process.

- **Revegetation techniques** — the two main types of revegetation techniques are direct seeding and planting. Direct seeding is best used on floodplains and upland zones and is not recommended for embankments (WRC 1999). Therefore, the focus in this document is on planting. Plant sizes and installation techniques are outlined in *Construction/installation*.

- **Plant size** — the size of stock required will be determined according to the site aspects and revegetation objectives. Areas subject to strong currents, waves or inundation should use strips, blocks/mats or large pots, as small tubes or cells are likely to be washed away.

- **Planting densities** — a general rule of thumb for revegetation densities is 500:50:5 herbs/sedges:shrubs:trees for each 100m^2 (WRC 1999). This rule of thumb applies to riparian zones in south west Western Australia and therefore should be used only as a rough guide to calculate plant numbers. Additional factors, including remnant vegetation, landuse, aesthetics, maintenance of tracks and firebreaks should be factored into the selection of species and densities.

  Foreshore sections to be planted only with sedges and rushes should use the rate of 6-9 tubes or cells per square metre (WRC 2000a). More sedges/rushes per square metre can be used to achieve dense stands faster, if budgets allow.

  For a larger stock size, such as blocks or strips, of sedges/rushes, densities are normally determined by site pressures and budget constraints. The closer the blocks and strips are planted, the quicker they will grow to meet each other and create dense stands.

- **Surface drainage** — surface runoff will follow topographic lines and can be focused on certain locations on the bank, exacerbating erosion. Management of drainage and surface runoff should be included in any revegetation plan. Management options may include installing perforated pipes to rapidly remove water, or kerbing to reduce the amount of surface runoff entering the revegetated area.

- **Monitoring and maintenance** — a monitoring and maintenance plan should be outlined and incorporated into regular works schedules (Section 2.4).

2.3.3 Design life/expected lifetime

Vegetation normally increases in strength and effectiveness with time, providing increasing protection to riverbanks as the vegetation becomes established (McCullah and Gray 2005). With correct application, ongoing monitoring and maintenance (such as infill planting and weed control), revegetation can offer a long-term option for foreshore stabilisation. However, the revegetated bank will continue to retreat if the bank is eroding due to a chronic shortage in sediment supply. Life cycle and potential natural recruitment of different plant species should be taken into account when choosing species for riverbank revegetation.

2.3.4 Materials and equipment

Plants comprise the majority of the materials and equipment required to implement these plans. Plant stock is usually available in a variety of sizes. Trees, shrubs and herbs are grown in cells, tree tubes, 50mm pots and larger pots. Sedges and rushes can be grown in the same containers as well as in strips and blocks/mats. Not all nurseries will provide the full range of sizes, and some stock which require specialised setups such as strip/block sedge (Figure 2.6 and Figure 2.7) are presently grown only by a few local nurseries. The plant size required will be determined by the site aspects and revegetation objectives. Areas subject to strong currents, waves or inundation should use strips, blocks/mats or large pots in revegetation works as small tubes or cells are likely to be washed away.

Figure 5.6 Block sedges

Figure 5.7 Strip sedges

Revegetation stock should be purchased from nurseries that specialise in the propagation of local native species and are fully accredited under the Nursery Industry Accreditation Scheme Australia (NIASA).

Plant orders should be placed at least 10–12 months before the delivery date to ensure the required species and sizes are available. Large stock such as trees in large pots or block sedge will have an even longer lead time. This timeframe should be established early on in the planning phase. Organisations with ongoing or large projects are encouraged to consider propagation contracts with nurseries to ensure that sufficient and good quality stock is available. Refer to Mullan and White (2005) for additional information and advice on seedling quality.

Tree guards can be used to protect newly planted vegetation. In revegetation works the two common types of tree guards are plastic sleeves (solid fill) and plastic mesh. Small tree guards are usually installed with three bamboo stakes and larger mesh tree guards are usually installed with two or three hardwood stakes. Small squares/circles of biodegradable matting can be placed over the soil around the plant, with the tree guards. Tree guards are best used above the high water mark and only when regular maintenance and repairs can be done, as they can be knocked over or moved in flow events.

Mulching can be considered for areas not subject to currents, inundation or flooding. Mulching may help control weeds and retain soil moisture. Avoid using mulch below the high water mark as it is likely to be washed away during high water level events. Mulch should always be clean and weed free.

Watering in stock may be necessary in dry areas or for large tree stock.

Erosion control blankets or matting come in a variety of materials, thicknesses and sizes. One hundred per cent biodegradable products such as jute or coconut fibre are recommended. Products that contain non-biodegradable materials such as plastic mesh should be avoided as these may become a hazard for native fauna and river users. Pins for securing erosion control matting include steel ‘U’ shaped pins or ‘bio’ pins made from 100 per cent biodegradable materials (mainly corn starch).

For more detailed information on erosion control matting products refer to manufacturers’ specifications and WRC (2001a, p.24), Donat (1995) and McCullah and Gray (2005, sections on ‘turf reinforcement mats’ and ‘erosion control blankets’).

The equipment required to undertake works will depend on the stock size being used, and may include the following items:

- hand trowels — for planting smaller stock;
- Hamilton tree planters or pottiputkis and kidney trays (plant carriers) — useful for planting large numbers of smaller stock (ergonomic and efficient);
- long handled spades or post-hole diggers — for planting large stock;
- machine-operated post hole diggers — for planting very large stock;
- rubber mallets — for installing stakes to support guards;
- biodegradable or steel pins — for pinning in large pots, strips, blocks of sedges; and
- stanley knife or strong sharp scissors — for cutting erosion-control matting.

2.3.5 Construction/installation

Site preparation should be planned and undertaken in advance of any planting according to the recommendations in the *Considerations for detailed design* section. Site preparation may involve site stabilisation works, installation of erosion control products (such as coir logs and matting), mulching and weed control.

Trees, shrubs and herbs should be planted into the upland or dryland zones in winter when soil has adequate moisture to promote plant growth (normally June/July).

Rushes and sedges to be planted into permanently wet or moist areas should be planted in spring and summer during their peak growth phase. Seasonally wet areas, including upper banks should be planted in winter to ensure plants have time to establish before the first summer (WRC 2000a).

Planting should follow the revegetation plan and, where possible, reflect the naturally occurring plant communities and layout. In complex sites or where many planting staff are involved, planting zones can be marked (for example with spot marking paint) to make planting easier.

Some basic guidelines to follow when planting are outlined below (Planet Ark, 2008).

- **Dig a hole deeper than the pot** or root and soil mass (depending on stock type and size).
- **Remove the plant gently** from its container; be careful not to tear the leaves or roots. If it's hard to remove, try inverting the pot keeping your fingers securely around the base of the plant and gently squeezing the sides or tapping the bottom of the pot. For seedling trays, use a blunt knife or flat stick to gently lever out the plants.
- **Place the plant gently in the hole**.
- **Fill soil** around the plant without leaving any air gaps.
- **Make sure** the root system is not above the soil surface.
- **Press the soil down** firmly to remove air pockets.
- **If using tree guards** (for areas above the high water mark), place them carefully around the plant. Use three stakes, place two stakes around the plant, use the third stake to stretch the sleeve and ensure a taught triangle.
- **Water the plant**, if possible, to assist in growth and removing air pockets.

The steps above are applicable for planting all stock sizes across the riverbank zones. If using specialised plant sizes or stock such as large block sedge or strips, it is crucial that the vegetation is planted deep into the soil so that the whole root mass and soil is well covered.

Once planted, locks and strips may be pinned into place to prevent plant loss in areas of high wave action and flow. Larger materials such as block sedge will need additional staff and equipment to manoeuvre and install them.

Details on installation methods of erosion control matting are outlined in WRC (2001a, p.24), Donat (1995) and McCullah and Gray (2005) sections on 'turf reinforcement mats' and 'erosion control blankets').

Experienced contractors with specialised safety equipment and training may be required for some projects on sites that are steep or rugged.

2.3.6 Failure mechanisms

Common reasons for failure of revegetation works include: erosion and bank failure; planting at inappropriate times and/or water levels; planting species in inappropriate zones; ineffective weed control; trampling by people or animals; fire; altered soil and water conditions (such as salinity or acidity); insufficient management of surface drainage; and planning trees on steep slopes that can contribute to instability through increased surcharge.

These factors have been discussed throughout this document and should be considered during design, implementation and monitoring.

2.4 Monitoring and maintenance

Regular monitoring and maintenance are required for successful revegetation projects. Monitoring of revegetation projects can involve a number of different techniques such as photo point monitoring, aerial photographic monitoring, measuring plant survival, and growth and surveying of flora and fauna.

A monitoring plan should be established at the beginning of the project and techniques chosen should link back to the project objectives.

It is recommended that the minimum level of monitoring consists of photo points and documentation of observations. This should occur monthly (or at the least quarterly) in the first year of establishment and at least annually thereafter.

General maintenance works should always be factored into the initial budget for the design life of the project, ongoing budgets and work plans. Maintenance works will involve weed control, replacement of any dead or missing plants, repairs to any fencing and replacement or removal of tree guards. Ongoing effective weed control is critical to the success of revegetation and should be a high priority.

Further information on developing a monitoring and evaluation plan can be found in WRC (2002c).

2.5 Cost

Cost estimates are based on 2008 prices from various Western Australian suppliers (Table 2.2). These figures should be used as estimates only and quotes from suppliers should be obtained when producing final budgets.

Note that many of the products below may be discounted if buying in bulk.

It is recommended that budgets include maintenance and monitoring costs, with funding requirements determined on a site-by-site basis. As a rule of thumb, for the first three years, planning costs for maintenance can be 25 per cent of the cost from the first year, with 10 per cent per year thereafter.

Table 2.2 Costs estimates for key elements to implement revegetation works

ITEM	APPROXIMATE COST
Plants	
Tree tubes	$1 – $2 each
Cells	$0.5 – $1 each
Strips sedge	$10 – $12 each
Block sedge (per m^2)	$100 – $120 each
Large stock	Varies depending on species and size. For example $6 for a 13cm pot, $160 for a 100L pot
Tree guards	$1 – $20/tree
Sediment fill	$5 – $15/tonne
Soil	$25 – $65/$m^3$
Mulch	$60 – $70/$m^2$ (plus $130-$150 mobilisation/ demobilisation cost)
Erosion control matting	
Biodegradable matting (e.g. jute or coconut fibre)	$160/50$m^2$ roll
Biodegradable pins	$380 – $470/box (two styles/lengths available, box size varies, contact suppliers for quotes)
Steel pins (various lengths)	$0.2 – $0.4/pin
Labour for installation	$40 – $80/hour
Soil compactor	$90 – $120/day

Note: Costs sourced from Rawlinsons (2008) and various WA suppliers (2008)

2.6 References

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3 Coir logs

3.1 Description

Coir logs, also known as coir rolls and coconut fibre rolls, are densely packed coconut fibre tubes bound together with coir netting. The coconut fibre is biodegradable, gradually breaking apart through exposure to water movements and weather. Coir logs are anchored along the toe of riverbanks to provide short-term protection for establishing vegetation. Because coir logs do not provide long-term bank stabilisation, they should be used only in situations where revegetation will provide all necessary long-term bank strength (WDFW 2003). When used with revegetation, coir logs stabilise banks and provide or improve several important environmental elements, including the creation of habitat for native river fauna.

Coir logs are relatively inexpensive compared to other techniques, lightweight and easily installed by hand. They are flexible, curve easily around banks and existing vegetation and can be used as a single row or to create terraces.

Coir logs are not recommended with revegetation in areas with high water velocities or in actively incising reaches. In these situations they need to be used with other stabilisation techniques.

Coir logs may locally enhance wave reflection and scour in areas susceptible to wind waves and boat wakes as they have limited porosity. Coir logs placed in high wave conditions are susceptible to undercutting and removal.

3.1.1 Case studies and examples

In September 2008 coir logs were installed using best management practice at Sir James Mitchell Park in South Perth (Figure 3.1) as a small part of a large foreshore renovation project. The coir log work was undertaken near the car park at the eastern end of the South Perth Esplanade. The works involved bank reshaping, installing erosion control matting and coir logs, planting local native sedges and placement of loose rock.

Source: Swan River Trust

Figure 3.1 Coir logs installed according to best management practice at Sir James Mitchell Park

3.2 Purpose and application

Coir logs are secured along riverbanks to help prevent scour and erosion. They create a soft toe armour that provides short-term protection and encourages revegetation landward of the log. Vegetation established landward of the log increases surface roughness, slows water velocity, causes sediment to drop out and aids accretion at the toe (McCullah and Gray 2005).

Coir logs may locally enhance wave reflection and scour and can be subject to undercutting in areas susceptible to wind waves and boat wakes.

Coir logs may be used to stabilise banks for the bank profile locations, channel planform locations and the types of erosion processes presented in Table 3.1.

Table 3.1 Coir log applicability

USEFUL FOR EROSION PROCESSES	
Description	**Feasibility**
Toe erosion with upper bank failure	
Scour of middle and upper banks by currents	
Local scour	
Erosion of local lenses/layers of non-cohesive sediment	
Erosion by overbank runoff	
General bed degradation	
Headcutting	
Piping	
Erosion by navigation waves	
Erosion by wind waves	
Erosion by debris gouging	
Bank instability/susceptibility to mass slope failure	
Erosion due to uncontrolled access (either boat launching, human or animal trampling)	
Erosion due to inappropriate focusing of drainage	
Enhance erosion due to sedimentation of the channel	
Erosion due to interruption of sediment transport	

PROFILE SPATIAL APPLICATION	
Description	**Feasibility**
Toe	
Midbank	
Top of bank	

HYDROLOGICAL GEOMORPHIC SETTING	
Description	**Feasibility**
Resistive	
Redirective	
Continuous	
Discontinuous	
Outer bends	
Inner bends	
Incision	
Lateral migration	1
Aggradation	

Feasibility method

'White' = feasible

'Grey' = possibly feasible, see table notes

'Black' = not feasible

Note: 1 Can slow the progress of bank retreat

3.2.1 Condition where practice applies

Coir logs are most suited to relatively shallow, low-energy areas with low water velocities and wave heights. In higher energy situations it is recommended that they be used in combination with other stabilisation techniques (WDFW 2003).

Coir logs should be used only in situations where sand accretion and revegetation are desirable and where vegetation will provide all necessary long-term bank strength.

3.2.2 Complexity and sensitivities

The design and construction of coir logs is not complex. Coir logs are lightweight and easy to install.

The following sensitivities should be considered and factored into planning and implementation.

- **Securing** — successful implementation requires that coir logs are secured properly. Poor installation will lead to reduced life or failure or both. A common mistake is staking through the centre of a coir log rather than on either side. Some examples of common mistakes made when securing coir logs are provided in Figure 3.2 and Figure 3.3. Refer to Section 3.3 for design guidelines and installation methods.1

Figure 3.2 Stakes too short

Figure 3.3 Stakes too long and pushed through centre of log instead of either side

- **Placement on the bank profile** — coir logs are normally placed at the toe of the bank in a trench that is dug slightly lower than the bed level (WDFW 2003). Refer to diagram in Figure 3.5. Coir logs may also be placed in front of existing revegetation. In this situation it is recommended that logs be placed at or above the lower limit of vegetation (WDFW 2003). When using a hard toe protection method (such as rock) with coir logs they should be placed above the toe protection works.
- **Heavy when wet** — once wet, coir logs can become very heavy and difficult to manoeuvre. It is best to prepare the site, organise materials and place coir logs before they are to be secured.
- **Planting into coir logs** — some references discuss planting into the coir log itself. This is not always possible due to the water-holding capacity of the log. It is recommended that planting efforts be focused landward of the coir log.
- **Storage** — unsuitable storage can reduce the productive life of coir logs. It is recommended that coir logs are stored in an environment where the biodegradation process is slowed, such as in a dry shed away from sunlight.
- **Availability** — coir logs should be ordered in advance to ensure that stock is available in time for implementation, as there are only a few suppliers in Perth.
- **Non biodegradable products** — it is recommended that only 100 per cent biodegradable coir logs be used in environmental restoration projects. Some references discuss using coir logs made with biodegradable coir and a non-biodegradable synthetic netting. The internal coir of these logs will break down over time, leaving the synthetic netting, which could become a hazard for native fauna and river users.
- **Materials for securing logs to stakes** — coir rope, rubber tree ties or wire are commonly used to secure coir logs to stakes. The material chosen to secure the log should be considered carefully. If a non-biodegradable product (e.g. wire) is used, the project manager should commit to returning and removing it once the erosion control works have finished. Metal strapping should never be used to secure coir logs.
- **Securing ends** — the upstream and downstream ends of the continuous length of coir logs tend to be weak spots and should be buried laterally in the bank to protect against erosive forces (WDFW 2003). However, this may not always be possible, especially if the bank is unstable and digging would promote erosion. In this situation, coir log ends should be rotated toward the bank, secured well with stakes, monitored and re-staked if required.
- **Terracing coir logs** — coir logs can be installed at intervals up a sloping bank to create steps or terraces to control surface erosion and assist revegetation (WDFW 2003). Coir logs can also be installed at two different water levels (low tide and high tide) in estuarine areas with a height differential across the lower bank.
- **Stacking coir logs** — coir logs can also be stacked on each other to form a taller face. In this situation the second log should be placed above and slightly back from the first log. All logs should be laced together and well secured to prevent any separation (WDFW 2003).

3.3 Design guidelines

Coir logs should be used in appropriate locations and secured properly to ensure their success as a stabilisation technique.

A conceptual design taken from McCullah and Gray (2005) is provided in Figure 3.5.

3.3.1 Loading

Loading on coir logs is produced by waves and currents moving water across the logs, resulting in pressure or suction on the log, depending on relative motion. The effective load on the log is reduced when it is aligned parallel with the flow. As a simple approximation for the loads on a log, the equations P = 6.9 H sin(a) and P = 6.0 U^2 sin^2(a) may be used to calculate loads provided by the waves and currents respectively, where P is pressure in kPa, H is wave height in m, U is velocity in m/s and 'a' is the difference between the flow angle and the log.

As coir logs have a low buoyant weight, they are not stable on their own, requiring stakes to anchor them in place. The resistance is dependent on the bedding material, the length and the thickness of the stakes. In sand, 0.025m thickness stakes have a tug resistance of approximately 0.2kN when embedded 0.5m and 0.4 kN when embedded 0.75m. For conditions with a wave height of more than 0.75m or a velocity of more than 0.5m/s, coir logs are impractical.

Due to the relatively small diameter of coir logs, a significant source of their failure is brought about through vertical movement of the bed on either side of the coir log. This can be resisted in part by placing the coir log on a foundation of cohesive or coarse bedding material, or by integrating buried filter cloth with the coir log system.

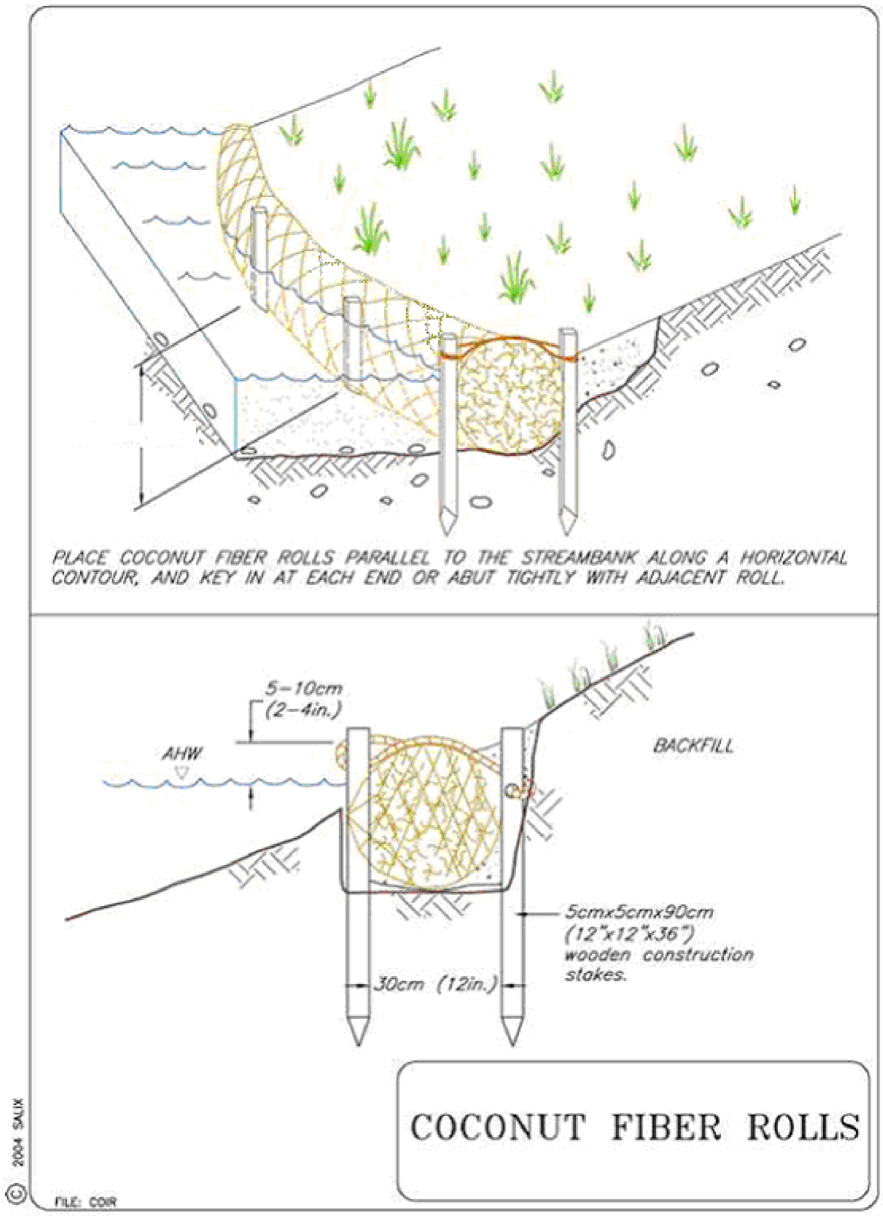
3.3.2 Considerations for detailed design

Designs should also indicate appropriate placement of coir logs on the riverbank (see *Construction/ installation*) and detail the correct securing method. Revegetation works should be included in detailed designs for coir logs. Further information on revegetation is contained in Section 2. It is likely that several years of infill planting will be required after the initial works are undertaken.

Detailed designs should consider whether additional stabilisation and protection works are required (other than coir logs). These may include hard toe protection, bank reshaping and erosion control matting. Refer to the relevant sections in this document and associated references for additional information on these techniques.

Climate change should be incorporated into designs as outlined in the most recent Department of Planning and Swan River Trust policies, based on Intergovernmental Panel on Climate Change (IPCC) predictions. Climate change is generally incorporated solely in terms of elevating design water levels. However, there is potential for increased storminess, flooding and increased wave energy transmission to the banks.

Works should be undertaken at low tides and during the optimum planting times to allow for revegetation to be conducted directly after coir logs are installed. Normally this would be in spring or summer to allow for sedges, rushes and other aquatic plants (growing below the ephemeral zone) to be planted at the same time. Planting trees, shrubs and herbs on the upland area would occur the following winter. Planting details are discussed in Section 2.



Source: McCullah & Gray (2005)

Figure 3.5 Conceptual design of coir logs

3.3.3 Design life/expected lifetime

Coir logs have an estimated effective life of six to 12 years (McCullah and Gray 2005; WDFW 2003). However, this will vary according to site specific environmental conditions, installation methods and maintenance. Historical evidence suggests that coir logs used in estuarine conditions on the Swan Canning river system have an actual life of approximately two to three years. This should be factored into project planning and some sites may need several sets of coir logs installed over the years until vegetation is established.

Appropriate storage of coir logs before use will extend their product life. It is recommended that coir logs be stored in an environment where the biodegradation process is slowed, such as in a dry shed away from sunlight.

3.3.4 Materials and equipment

The following materials and equipment are required for a coir log project.

- **Coir logs** — available in several sizes, the most common is 30cm diameter and 3m in length. Note that it is important, when measuring the length of foreshore to determine the number of coir logs, to factor in securing the ends into the bank.
- **Hardwood stakes** — recommended size is 5cm x 5cm x 90cm. Stake length and width may need to vary slightly depending on the ground conditions. However, where possible stakes should be at least two-thirds below the ground and one-third above.
- **Rubber tree ties, coir twine/rope or wire** — to secure logs to stakes. Refer to the information on 'materials for securing logs to stakes' in *Complexities and sensitivities*.
- **Coir twine** — to secure logs to each other.
- **Spade** — for digging trench.
- **Drill** — for making holes in stakes.
- **Mallet or post driver** — for installing stakes.
- **Plants** — normally sedges and rushes are used directly behind the logs. Trees, shrubs, herbs can be used on the bank and into the upland zone as desired. Refer to *Materials and equipment* in the *Revegetation* section for additional information.
- **An excavator and clean fill** — may be required if bank reshaping is conducted.
- **Biodegradable erosion control matting and pins** — may be needed to provide additional bank protection behind the coir logs. Additional information and links to references on this technique are outlined in the *Revegetation* section.

3.3.5 Construction/installation

The following recommended construction procedure has been adapted from McCullah and Gray (2005) and WDFW (2003).

1 Dig a shallow trench wide enough for the log and at a depth slightly below the channel grade. Refer to *Sensitivities and complexities* for information on placement.

2 Lay coir logs in the trench and lace ends together. They may also be laced together on dry ground before placement in the trench.

3 Bend the upstream and downstream ends towards the bank and bury in the bank if possible.

4 Secure the coir log in the trench by driving the stakes in the ground on either side of the log. Netting should be held open and stakes driven through the netting on either side of the logs, not through the centre of the log. Pairs of stakes (one on either side) should be installed at approximately one metre intervals. Stakes should be flush with the top of the log when completed.

5 Strap together stake pairs (next to each other) to hold the coir log in place and prevent lifting. Holes can be predrilled in stakes or drilled onsite. Coir twine, plastic tree ties or similar are used to tie one stake to the other.

6 Fill and shape behind the logs if required. Additional techniques such as jute matting or brush mattressing can also be used at this stage.

7 Plants should be planted behind the coir logs and up the bank as desired. Refer to Section 2 for additional information.

3.3.6 Failure mechanisms

There are several key factors that contribute to the failure of coir logs, including: poor installation; lack of monitoring and maintenance; inappropriate site selection (e.g. erosive forces are too strong for the logs); inappropriate placement across the profile; and failed revegetation works with no subsequent replanting undertaken.

These factors have been discussed throughout this document and should be considered during design, implementation and monitoring.

3.4 Monitoring and maintenance

Regular maintenance and monitoring are required for successful coir log and revegetation works.

Monitoring of works can involve several different techniques, such as photo point monitoring, aerial photographic monitoring, measuring plant survival and growth, and flora and fauna surveying. A monitoring plan should be established at the beginning of the project and techniques chosen should link back to the project objectives.

It is recommended that the minimum level of monitoring consist of photo points and documenting observations. Regular monitoring will allow early detection of maintenance required.

It is recommended that coir logs be inspected and maintained as required after each high flow (one in one year water level) and storm events for the first few years. Field inspections should focus on weak points of coir logs, stakes, twine or wire, and joins between logs and at the ends of the works. General maintenance works should always be factored into the initial budget for the design life of the project, into ongoing budgets and work plans. Maintenance may involve resecuring logs, replacing logs and repairing breaks in the netting.

Any non-biodegradable or potentially hazardous materials should be removed once works have reached the end of their life, particularly at heavily accessed sites. An example of this is hardwood stakes that have outlived coir logs posing a hazard for people accessing the foreshore.

Maintenance works for the revegetation will include weed control, replacement of any dead or missing plants, repairs to any fencing and replacing or removing tree guards (if used). Ongoing effective weed control is critical to the success of revegetation and should be a maintenance priority.

Further information on developing a monitoring and evaluation plan can be found in WRC (2002c).

3.5 Cost

Cost estimates are based on 2008 prices from various Western Australian suppliers (Table 3.2). These figures should be used as estimates only and quotes from suppliers should be obtained when producing final budgets.

Note that many of the products below may be discounted if buying in bulk.

In addition, costing should be included for maintenance and monitoring. Monitoring should include (at a minimum) annual or biannual engineering inspection, including a site visit and report. The monetary requirements for maintenance and monitoring should be determined on a site-by-site basis. For budgeting purposes, an approximate cost of maintenance and monitoring coir logs is 10 per cent of total initial capital costs per year (with potentially higher costs for the first three years due to replanting requirements).

Table 3.2 Cost estimates for key elements to implement coir log protection

ITEM	APPROXIMATE COST (EX GST)
Coir logs (sizes vary)	$100 – $150 each depending on size
Hardwood stakes (sizes vary)	$2 – $5 each depending on size
Sediment fill	$15 – $30/tonne
Erosion control matting	
Biodegradable matting (e.g. jute or coconut fibre)	$3 – $5/m^2
Synthetic erosion control matting	$6 – $12/m^2
Plants	
Tree tubes	$1 – $2 each
Cells	$0.5 – $1 each
Strips sedge	$10 – $12 each
Block sedge (per m^2)	$100 – $120 each
Large stock	Varies depending on species and size e.g. $6 for a 13cm pot, $160 for a 100L pot
Labour for installation	$40 – $80/hour
Soil compactor	$90 – $120/day
Excavator	$90 – $140/hour

Note: Costs sourced from Rawlinsons (2008) and various WA suppliers (2008)

A figure of $85 per square metre has been estimated for coir log works. This is based on coir logs used with erosion control matting and tubestock sedge planting. This includes labour but does not include any site preparation such as bank reshaping and weed control.

3.6 References

McCullah, J & Gray, D 2005, 'Coconut Fibre Rolls', *Environmentally Sensitive Channel- and Bank-Protection Measures*, National Cooperative Highway Research Program – Transportation Research Board, Report no. 544, Washington, DC, USA.

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Water and Rivers Commission (WRC) 2002c, *Monitoring and evaluating river restoration works*, Water and Rivers Commission, Report no. WN28, Water Notes, Perth, Western Australia.

4 Brush mattressing

4.1 Description

Brush mattressing is a bioengineering bank stabilisation technique, developed and extensively implemented in Europe and America during the past 100 years. This ‘soft engineering’ technique is often a practical and cheaper alternative to conventional engineering works, such as hard walling. Brush mattressing typically consists of several layers of logs and brush placed on jute or coconut fibre matting with extensive/dense planting of endemic rushes and sedges. The organic material needs to be wired down for stability.

Logs and branches are placed as a mattress surrounding planted sedges and shrubs to stabilise sediments (and provide nutrients) while vegetation is established. Brush mattressing is also referred to as brush matting or log mattressing or log brush mattressing (where logs form the main material in the mattress, overlaid by branches). Brushing, bundling and brush layering all refer to a similar type of bioengineering technique where logs or branches are placed horizontally on an eroding bank. For stability, these structures need to be secured with wire and rocks or limestone spalls.

Typically in the Swan and Canning rivers, cut logs or branches are placed as a mattress surrounding planted sedges and shrubs to stabilise sediments (and provide nutrients) while vegetation is established. The branches can be placed along the bank, across the bank or a combination of both.

In America and Europe live branches of sprouting woody plants are often placed against an inclined bank as an anchored mattress. The branches sprout and stabilise the bank through a network of roots and plant stems. In WA, we refer to this as ‘live brush mattressing’. It is not applicable in the Swan Canning river system as there are no locally native sprouting trees or shrubs that can provide appropriate live branches.

Brush mattressing can be relatively inexpensive to implement compared to hard structures, provided the materials are readily available and if there is low-cost labour at hand. The technique promotes revegetation by providing flexible surface protection, increasing the scour resistance (if anchored well) and increasing the potential for trapping native seeds (USDA 1996; McCullah and Gray 2005). Brush mattressing can assist in rebuilding banks as the brush reduces local flows during high current events, leading to suspended sediment being deposited. It can be effective at sites with fluctuating water levels (USDA 1996).

The main disadvantage of brush mattressing is the intensive labour required for construction, particularly locally as the plants must be placed in the mattress. The mattress will generally require toe protection and an anchoring system. It is susceptible to flanking erosion and gullying under the mattress (CBBEL 1999; McCullah and Gray 2005). Bank protection is provided for the life of the brushing material only, as the logs will decompose. Revegetation is required for long-term bank stability. Insufficient anchoring or unsecured brushing could result in branches washing downstream, causing blockages or damage to structures such as bridges or weirs (BCC 2004).

4.1.1 Case studies and examples

Brush mattressing has been applied more frequently in the last five years in the Swan Canning river system to promote riverbank revegetation. Anchored brush mattressing examples include Mounts Bay Road in 2002 (Figure 4.1), Banks Reserve in 2007 (Figure 4.2) and at Point Fraser from 2003 to 2005 as a primary technique (Figure 4.3) and to stabilise an upper bank above hard walling (Figure 4.4). These three sites incorporate logs and branches placed as an interlocked mattress surrounding planted sedges and shrubs. The mattress stabilised sediments and provided nutrients while vegetation was established. Some limestone rocks were placed as anchors on the mattress, with additional rock placed as toe protection. Reticulation systems or watering trucks were used to irrigate in the first summer to improve plant response. Nonetheless, watering will be minimal or not required at all once plants are established at sufficient density.

Brush mattressing has been effective in revegetating the banks at these sites under existing environmental conditions. The placement method has successfully maintained the mattress integrity. However, smaller limestone rocks placed on the mattress as anchors can move during higher energy conditions. Heavier rocks would be appropriate on steeper sites susceptible to higher energy wave conditions. Rocks 300mm in diameter are recommended.

The steepness (approximately 1V:2.5 to 3H) of the brush mattress at Mounts Bay Road resulted in an increased potential for:

- loss of sediment from under the structure (slope steeper than the natural repose of most sediments)
- rocks and branch units to be mobilised
- undermining of the toe (due to increased scour).

The Mounts Bay Road site (Figure 4.1) is susceptible to a range of water levels and strong southerly wind waves, with additional hydraulic stress due to the adjacent hard walling. Rocks were placed along the toe of the structure and between the walling and brush mattress to improve mattress stability. Many of the smaller stones have been moved from the site since 2004. However, vegetation has established at the site. The mattressing has effectively promoted vegetation growth between two hard structures, with increased maintenance required due to the site's steepness.

Source: A) Syrinx (2003); B and C) Swan River Trust & Damara (January 2004)

Figure 4.1 Brush mattressing at Mounts Bay Road

Banks Reserve (Figure 4.2) had brush mattressing applied in 2007 across a relatively long foreshore length (180m) at a slope of 1H:4V. The site is susceptible to tidal currents, river currents and boat wakes and is inundated in high water level conditions in winter (surge and river flow). Banks Reserve was eroding with a visible bankface of coal slag (deposited during operation of the East Perth Power Station). It can be inferred that vegetation should establish more easily at this site due to the reduced slope and smaller design wave heights than Mounts Bay Road. However, Banks Reserve is susceptible to longer period ferry wake, with the uprush in certain water level conditions potentially resulting in enhanced buoyancy of the logs and rocks.

Source: A) Oceanica & Swan River Trust (February 2007); B and C) Swan River Trust (July 2007)

Figure 4.2 Brush mattressing at Banks Reserve

A small section (approx. 80m) of mattressing was placed at Point Fraser (Figure 4.3) at a slope of approximately 1H:6V, and above an inclined limestone block wall with a limestone rock toe between the coping and toe of the mattress (Figure 4.4).

The mattress was applied directly to the riverbank, with a limestone rock toe, upstream of the walling. This site has historic rubble lower on the slope and the bank has been modified from its original alignment.

The mattress upstream of the walling is inundated regularly (surge plus tide) and experiences significant south-westerly wind waves, resulting in less effective bank stabilisation than other applications. It is likely that larger toe protection and increased anchoring will increase the life of the mattress.

Source: Swan River Trust & Damara (January 2005)

Figure 4.3 Brush mattressing at Point Fraser with limestone toe

The local approach of log brush mattressing appears to be a successful modification to the traditional American and European approach of using live cuttings, provided sufficient anchoring is incorporated. The mattress reduces the rate of bank erosion while vegetation is established. Brush mattressing is most effective when the guidelines for bank slope in the *Revegetation* section (Section 2) are followed. Steeper slopes can be stabilised in the short-term, before the branches degrade or stress on the anchoring is exceeded.

Insufficient toe protection and achoring are the most common faults resulting in the failure of brush mattressing in the Swan and Canning rivers. It results in the mattress being mobilised or undermined. Sediment is lost from under the structure, threatening plants' root systems. Other faults could occur if the works had: inadequate surface flow diversion over the bank; inadequate structure elevation; insufficient funding to continue maintenance planting (important for the first three years); or too steep a slope. In some locations, vandals may move branch units or anchor rocks, decreasing the mattress' stability. Increased monitoring would be required in locations susceptible to vandalism.

It is also important to ensure the log brush mattressing is appropriately orientated in relation to waves, storm surge, water flow at high tide, and orientation of the water body in front of the structure. For example, towards the northern end of Banks Reserve it was necessary to change the orientation of the mattress structure from directly east to north east due to the increase in width of the water body towards Maylands Yacht Club. This reorientation work was recently (December 2008) completed.

Source: A) Swan River Trust & Damara (January 2004); B) Swan River Trust & Damara (January 2005)

Figure 4.4 Brush mattressing at Point Fraser above walling

4.2 Purpose and application

Brush mattressing temporarily stabilises eroding banks while revegetation is established. The mattress promotes sediment deposition, reduces the rate of scour, and encourages vegetation growth by reducing pressure on the root system. The technique is applicable for banks with low-level erosion (scour/undercutting) that are susceptible to low to medium flow velocities and low to medium wave heights (generally short period to minimise buoyancy of material). It can also be applied to heavily eroded banks if the area is accessible for machinery to regrade and compact the soil.

Sufficient anchoring is required in narrow navigable regions where the brush mattressing could mobilise during floods, damaging bridges or boats downstream (BCC 2004). Correct anchoring must include stakes, wiring and spalls or rocks.

Brush mattresses may be used to stabilise banks for the bank profile locations, channel planform locations and type of erosion processes presented in Table 4.1.

Table 4.1 Brush mattressing applicability

USEFUL FOR EROSION PROCESSES	
Description	**Feasibility**
Toe erosion with upper bank failure	
Scour of middle and upper banks by currents	
Local scour	
Erosion of local lenses/layers of non-cohesive sediment	
Erosion by overbank runoff	
General bed degradation	
Headcutting	
Piping	
Erosion by navigation waves	1
Erosion by wind waves	2
Erosion by debris gouging	
Bank instability/susceptibility to mass slope failure	
Erosion due to uncontrolled access (either boat launching, human or animal trampling)	
Erosion due to inappropriate focusing of drainage	
Enhance erosion due to sedimentation of the channel	
Erosion due to interruption of sediment transport	

PROFILE SPATIAL APPLICATION	
Description	**Feasibility**
Toe	
Midbank	
Top of bank	
HYDROLOGICAL GEOMORPHIC SETTING	
Description	**Feasibility**
Resistive	
Redirective	
Continuous	
Discontinuous	
Outer bends	3
Inner bends	
Incision	
Lateral migration	
Aggradation	

Feasibility method

‘White’ = feasible

‘Grey’ = possibly feasible, see table notes

‘Black’ = not feasible

Note: 1 If anchored and in low frequency of passage

2 If anchored

3 If bank steepness is not exceeded

4.2.1 Condition where practice applies

Brush mattressing can be applied where revegetation is desired on banks experiencing scour or undermining that are subject to low to medium flow velocities (as a general rule, velocity <2.7m^{s-1} using staked method without toe protection (Allen and Fischenich 2001)) and low to medium wave heights (<0.3m, though up to 0.5m is possible (Shafer *et al.* 2003)). The mattress provides immediate surface protection by reducing the water velocity, absorbing water and wave energy, and wave forces acting directly onto the banks. In high-velocity conditions, the anchoring and interlocking is likely to be insufficient to resist the buoyant and uplift forces acting on the submerged branches. Once certain velocities are experienced the mattress will move. Rock toe protection will be required in any areas susceptible to waves. In the Swan River between Balbuck Way and Sandalford Winery the influence of ferry wakes makes additional protection necessary. Longer-period ferry wake (due to the increased boat length) has a drawdown and initial uprush which has a greater capacity to mobilise sediment. Rock riprap and toe protection should be used and additional rocks or spalls placed on the mattress to add weight (spalls 300 to 500mm in diameter are preferable).

Brush mattressing is reported to be viable at a maximum slope of 1V:3H. Ideally slopes of 1V:4H to 1V:6H are preferred. The most effective mattressing will be installed at or below the angle of repose of the underlying sediments. On sites susceptible to occasional waves and currents, slopes of 1V:4H to 1V:6H are ideal. The project will require a wider bank area as the slope decreases. This technique can also be used to reduce erosion at the toe of a steeper eroding bank, if used in combination with toe protection.

Brush mattressing is not suitable where there is: a bank steeper than 1V:3H (following resloping); beach or lower bank access is required; narrow navigable areas where brush could mobilise, causing debris damage to bridges or to boats (BCC 2004); adjacent medium or high-economic value assets and no maintenance funding available; and a long-term low-maintenance stabilisation solution is required. This technique should not be applied if the main erosion mechanism is subsurface drainage through the bank (e.g. piping) or in combination with overbank drainage (e.g. gullying). Significant drainage management would be required before installing brush mattressing, making the cost prohibitive.

Brush mattressing has a high aesthetic value as it only takes two to three years for the vegetation to increase in density and hide the branches.

4.2.2 Complexity and sensitivities

The complexity in designing brush mattressing is related mainly to anchoring and ensuring sufficient anchoring is provided to restrict the buoyant movement of the woody debris. In addition, grade is also very important and is always difficult to achieve due to limited space. The following sensitivities should be considered when designing or planning for brush mattressing.

1 **Type of wood for the brush mattress or brushing** — a wood of known density enables design and anchoring parameters to be calculated. Local native plants should be used for brush mattressing. Local weed species that could re-establish from the branches should not be used. The Trust has favoured using Melaleuca brushing, as the branches bearing seed will release the seed to the soil, encouraging seedling germination and growth (WRC 2001a). Log material should be of about 150 to 200mm diameter and placed reasonably upright and straight. The material should be placed flat on the ground for best absorption of water and energy and to reduce potential movement.

2 **Timing** — brush mattressing should be installed at a time of year where there is optimal growth for the revegetation and germination of any seeds. Revegetation works may require watering in the early establishment phases. Tidal levels and salinity levels also need to be factored into the timing. In the Swan and Canning rivers, October to December is the best time, but is a relatively small window of opportunity. Often works will have to be implemented through to March. However, salinity can be an issue at this time.

3 **Method of anchoring** — the method of anchoring should be selected to ensure the type of mattress is dynamically stable under the hydraulic stresses at the site. The type of mattress could be horizontally placed brush, vertically placed brush or interlocked. The forces acting on the anchors should be considered when choosing whether to use rocks, stakes or cross-layered branches. These anchors are used to stabilise a tying material such as wire or steel cables (for brushing). These materials can be placed perpendicular to the upper layer of the branches in the mattress or as a diamond network. The breaking strength of each strand of wire, rope and cord should be considered when selecting the tying material. Poor anchoring will lead to reduced life or failure or both. If a non-biodegradable product (e.g. wire) is used to secure the branches to the anchors, the project manager should be committed to removing the product at the end of the project life.

4 **Design parameters** — the design should consider the appropriate slope, method of anchoring, crest elevation and depth the toe protection is embedded. The parameters should be selected

based on consideration of the force balance between the hydraulic loading (including consideration of the properties of the brush itself) and strength of the anchoring system. Wave velocity, wave height, area of water body in front, wind direction with the potential biggest impact, and survey data to -1m AHD are also required in the design consideration.

5 **Toe protection** — toe protection should be included in all areas and the volume of rock used should depend on the susceptibly to waves (boat wake or wind waves or both) which undermine the mattress or brushing.

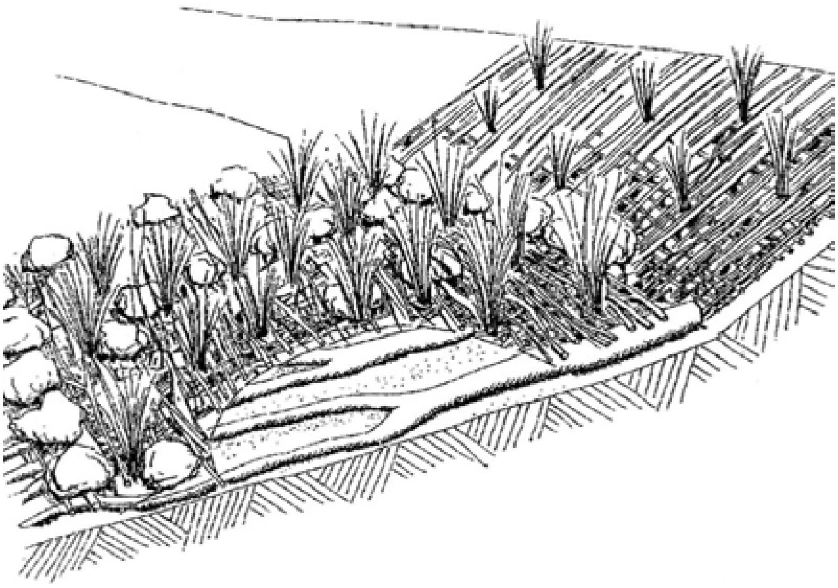
6 **Drainage management** — drainage management is required to minimise sediment loss from under the structure. This can be achieved using a series of gravel-lined trenches to divert surface (and groundwater) flow from the mattress. Drainage management would need to be carefully designed in areas where the main erosion mechanisms are piping and gullying.

7 **Adjacent foreshore** — uplift and undermining will occur at the up and down-stream ends of the mattress if it is not adequately tied to the adjacent banks. This is most significant next to structures. The most common technique used is placing rock spall at the ends of the mattress to increase stability and foster sediment accretion in summer.

In addition, plants selected for revegetation should consider the planting zones, salinity and presence of soil contamination or acid sulphate soils (Section 2.1).

4.3 Design guidelines

The local approach to brush mattressing is shown in Figure 4.5. The concept of brushing (horizontal log/ large branch placement) is shown in Figure 4.6. The live brush mattressing technique (demonstrating another method of anchoring and the need for rock toe protection such as is used at Point Fraser) is demonstrated in Figure 4.7. The general design consists of branches and logs anchored to the bank in a way that sediment can be placed with revegetation.



Source: Syrinx

Figure 4.5 Brush mattressing

The following steps are typically undertaken to implement brush mattressing.

- Prepare ground with a grade of 1V:4H to 1V:6H.
- Install jute or coconut matting, pinned down with six to eight pins/m^2 and installed perpendicular to the water flow direction.
- Place logs (150 to 200mm diameter), about 500mm apart and at a width of restoration area

(often 3 to 4m). Note, narrow sections of log brush mattressing often suffer from instability and additional rock placement is required. Logs should be flush with the grade of the embankment and placed at right angles to the shoreline.

- Plant densely (6 to 8 plants/m). Plant height must be 300 to 450mm. Plants propagated in larger pots increase the chance of plant survival and speed the process of plant establishment and soil stabilisation.
- Three layers of brush are cross layered on top of the logs, placed in a dense arrangement, each layer approximately 50mm thick once compacted and secured (using wire). The first and final layer must be perpendicular to the shoreline (brush material must be free of seeds).
- Use galvanised wire and predrilled stakes to secure the mattress. Each pegged section of brush mattressing should be approximately 1.5 to 3m long (parallel to the shoreline) and 2 to 3m wide.
- Place limestone spalls (300mm) along the base and randomly on top of the entire barrier.

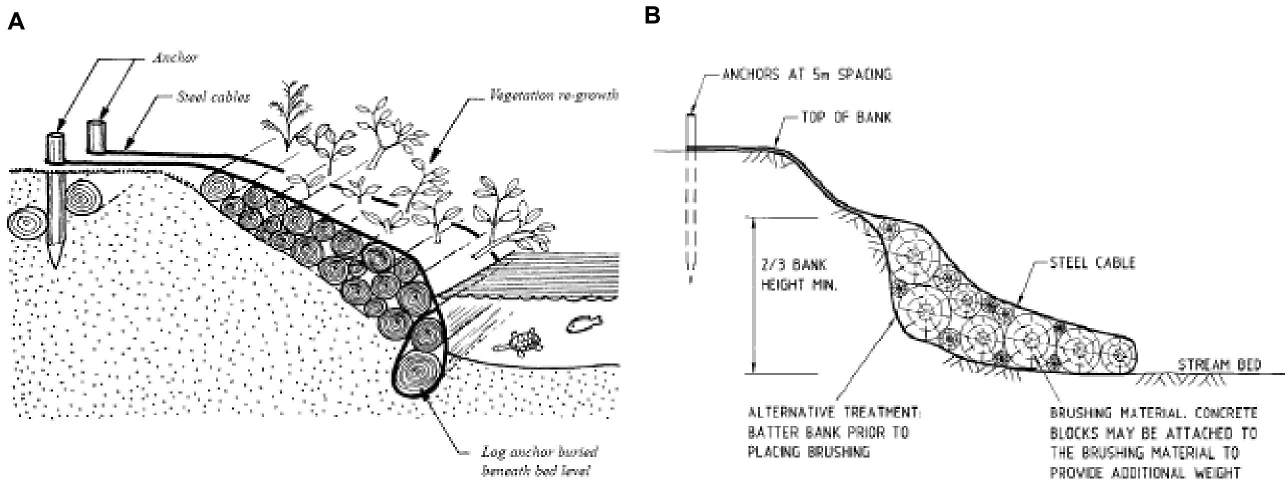
There is a lack of general principles and standards for the design of brush mattressing. There are some general rules for the maximum slope, mattress thickness and elevation for the live brush mattress to ensure vegetation will grow (e.g. Allen and Fischenisch 2001; McCullah and Gray 2005). However, the technique generally relies on past experience.

The design specifications for brush mattressing should include the following.

- **Optimal slope** — brush mattressing will have best performance if the slope follows the guidelines for applying revegetation to different sections of the foreshore in Section 2 – *Revegetation*.
  - Slope on an upper bank with no wave action should preferably be flatter than 1V:4H and no steeper than 1V:3H
  - Slope on a bank exposed to occasional wave action should be preferably flatter than 1V:6H (1V:4H may be appropriate in some areas)
  - Slope on a lower bank exposed to regular wave action should be from 1V:12H to 1V:30H, depending on soil type
  - Slightly steeper slopes can be achieved using brush mattressing with toe protection.
- **Crest elevation** — the crest elevation should be calculated using standard methods to minimise overtopping and inundation for a sloped structure based on design water levels, currents and waves (USACE 2006 for waves). If using traditional revetment calculations, a significantly increased porosity should be used compared to rock revetments. The recommended crest elevation in current-dominated reaches for hard structures should be set as a level equal to the design flow level plus a margin for freeboard. The level of acceptable overtopping and inundation depends on what is on the bank landward of the mattress. Overtopping is less of a concern if the bank is vegetated landward of the mattress. Multiple rows of branches can be incorporated for higher elevations.
- **Toe embedment/protection** — the toe of the brush mattress should be located at least 0.2m below mean sea level, with toe protection placed according to Section 3 – *Coir logs* or Section 8 – *Rock revetments*. The size and slope of the armour units for the toe protection should be calculated according to Hudson's formula for reaches susceptible to waves (Sections 5 and 8). Armour unit size and slope in reaches susceptible to currents should follow the approach in Biedernharn *et al.* (1997), Pilarczyk and Breteler (1998) and BAW (2005). If a thin layer of rock armour is used, an additional safety factor should be incorporated to minimise likelihood of uplift. The design guidelines should include the unit size (mass and diameter), slope and elevation range of the toe protection.
- **Plan for diversion of surface flow** — drainage management should be incorporated as discussed in the *Complexities and sensitivities* section. Drainage management should follow the natural bank topography where possible and be in accordance with Trust drainage management policies and requirements.

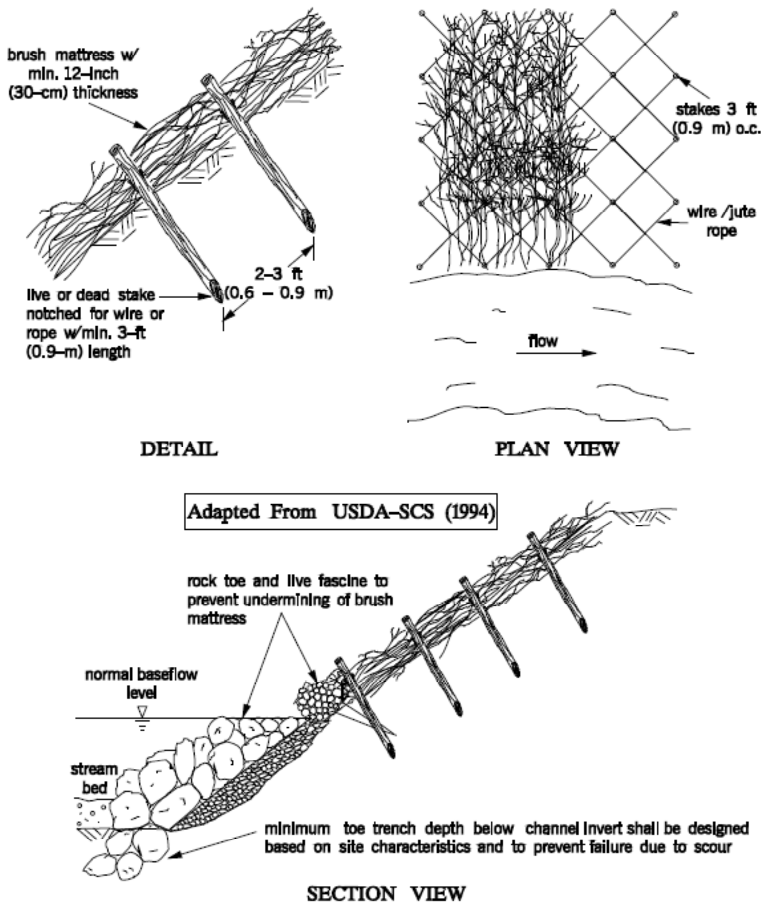
- **Anchoring system** — the method, type and density of the anchoring system's placement should be included in the design guidelines. The anchoring system should be demonstrated to be able to sustain the uplift forces due to the buoyant nature of wood, waves and currents (see *Loading*). Details should be included on the breaking strength of a strand of the tying material, staking and anchors, and density of placement.

The revegetation plan should follow the design requirements in Section 2 – *Revegetation*, including a landscape plan (with densities), species selection and what to plant in the various hydrology and planting zones. High planting densities are best: 8 to 10 plants/m^2 are preferable but no less than six plants/m^2 if possible.



Source: A) WRC (2001a) and B) BCC (2004)

Figure 4.6 Horizontal log/large branch placement method



Source: after MDoEWMA (2000 MGWC 2.8)

Figure 4.7 Live brush mattressing applied in America and Europe

4.3.1 Loading

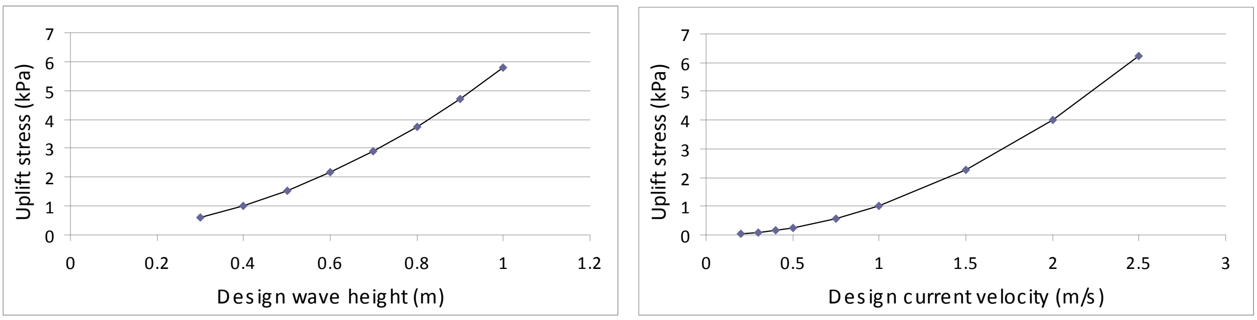
The hydraulic loads that should be considered in the design of a brush mattress include design waves (wind and boat wakes), water levels and current speeds. Wave velocity studies should be undertaken locally. If possible, include winter and summer conditions and public holidays when boating traffic will be increased. In non-navigable areas of the upper river, currents associated with winter rainfall will be the principal design loads. This hydraulic forcing can be responsible for sediment transport under or through the structure, or could mobilise the brushing and break the anchoring.

Consider a force balance approach to determine the stability of the brush mattressing. The net buoyancy and potential horizontal movement of the brush should not exceed the breaking strength of the anchoring system, or the brush will move. The buoyancy should consider the hydraulic loading, weight of the brush units, immersed weight of the brush units, interlocking strength of the anchor system, additional weight provided by trapped sediment, and any additional weight provided by rock anchors. A stronger anchoring system is required if the relative buoyancy of the brush suggests branch uplift is likely. Net horizontal movement will occur if the horizontal drag forces exceed the frictional force at the base of the brush and the horizontal breaking strength of the anchor system. The method for calculating these force balances can be adapted from D'Aoust and Millar (2000) and Shields *et al.* (2004), which were developed for large woody debris.

A quick method (for concept designs only) of calculating the uplift forces acting on the anchoring and check if the anchoring system is sufficient, is to sum the uplift pressures due to waves and currents and compare this to the weight of the brush mattress. The uplift from waves and currents is demonstrated in Figure 4.8. The uplift stress (in kPa) from the brush mattress is calculated by:

$$\text{Uplift stress} = (\rho w - \rho wood) \times g$$

Where ρw is the density of water (1,025 kgm^{-3} for mixed areas of the estuary, with a range of 1,010–1,030 kgm^{-3}), ρwood is the density of the brush mattress (*in-situ* density for living trees is approximately 800-1,000 kgm^{-3} depending on species, assume 900 kgm^{-3}) and g is the acceleration due to gravity ($g=9.81ms^{-2}$).



A B

Figure 4.8 Uplift stress due to (A) waves and (B) currents

The thickness of wire/rope/cord required to ensure the mattressing can sustain the design wave and current conditions can be approximated quickly using the following approach (for concept designs only):

$$Diameter = \sqrt{\frac{(FS \times Strand\ capacity)}{Strand\ strength}} \times 1000$$

Where the diameter is calculated in millimetres, FS is a safety factor to account for inconsistencies in the strand quality (assume 1.5 should be sufficient), the strand capacity (kN) is calculated using the total uplift stress (calculated above in kPA) multiplied by the cross-sectional area between the anchor units, and the strand strength provided by the manufacturer (kPa). This formula allows for manipulation of the spacing between the anchor units.

The wave and current loading operating on the rocks placed at the toe and to tie the mattress adjacent banks should also be considered. Estimating design rock sizes using Hudson's equation for wave dominated conditions is discussed in more detail in Sections 5 and 8. An additional safety factor is required for free-standing rocks placed as anchors, as there is no interlocking.

The maximum loading brush mattressing can sustain is variable, depending on many factors including (for example): brush characteristics; type of placement; bank slope; method of anchoring; breaking strength of the anchoring material; type of toe protection; and density of planting in the mattress. Allen and Fischenich (2001) suggest a 20 per cent increase in maximum design velocities can be sustained if a rock toe is present for live brush mattressing (from $2.7 ms^{-1}$ to $3.4 ms^{-1}$).

4.3.2 Considerations for detailed design

Considerations for detailed design are largely addressed in the *Design guidelines*, *Loading and complexities*, and *Sensitivities* sections.

The development of clear specifications and plans for the site slope, placing the mattress, revegetation, anchoring, drainage management, toe protection and tying to adjacent banks is critical to ensure the mattress is constructed as required. The type of wood to be used in the brushing should be stressed, as different species have different densities, which will influence the success of the anchoring system.

Climate change should be incorporated in designs according to the most recent Department of Planning and Trust policies, which are based on Intergovernmental Panel on Climate Change (IPCC) predictions. Climate change is generally incorporated solely in terms of elevating design water levels. However, there is potential for increased storminess, flooding and increased wave energy transmission to the banks.

Funding and plans for a monitoring and maintenance plan should be included in any detailed designs.

4.3.3 Design life/expected lifetime

Brush mattressing has an expected effective life of five to 10 years while vegetation is established, before the anchoring fails and wood degrades. Toe protection would ensure a minimum of five years effective life, if sufficient anchoring is incorporated, drainage is managed and maintenance is conducted (revegetation and anchoring). Long-term stability relies on the success of establishing vegetation. If the cause of erosion is not addressed, retreat will occur and design life may be reduced. Another viable option involves keeping the toe protection intact as part of the maintenance program.

The design life of five years is appropriate for brush mattressing stabilised with wire due to corrosion. However, brush mattressing is unlikely to withstand any significant flood event due to the increased uplift forces.

4.3.4 Materials and equipment

The following materials and equipment are required for a brush mattressing/brushing project (CBBEL 1999; Bentrup and Hoag 1998; Allen and Fischenich 2001; Muhlberg and Moore 2005a; McCullah and Gray 2005).

Materials

- brush material – logs or branches (with seed and without leaves)
- topsoil (can be a mix of yellow sand, clay and silt or typical landscape topsoil mix)

- jute or coconut matting for stabilising regraded and disturbed soil, use pins (metal or starch) to secure
- plants for revegetation
- gravel fill for trenches for surface and subsurface drainage management
- steel cable for anchoring brushing
- logs/timber piles for brushing anchors and concrete blocks for brushing weights (BCC 2004)
- limestone rock for anchoring and toe protection (coir logs may also be used as toe protection, see Section 4.2 for details)
- polyethylene or jute rope (coir bristled twine machine spun with thickness of 5–6mm), clothesline cord or wire (2.8–3.5mm annealed) for securing brush mattressing
- construction stakes at least one metre long (if using stakes to anchor the mattress)
- seed of native grasses to assist in the reduction of topsoil loss (optional).

Equipment

- excavator – useful for large-scale brushing (BCC 2004)
- pile driver (or hammer attachment for excavator) – useful for placing anchors for brushing (BCC 2004)
- backhoe or shovel
- chainsaw or loppers to harvest brush material
- mallet or sledgehammer for driving in stakes
- temporary irrigation system if deemed necessary or the use of watering trucks.

With regards to the seasonal conditions, late spring to mid-summer is favoured, particularly during times of low tide and low wind velocities. The work must be completed in a single campaign due to the potential impact of rainfall or storm surges. Checking weather forecasts and tidal levels at the nearest recorded location is advised.

4.3.5 Construction/installation

Different techniques are required to install brushing, brush mattressing and staked brush mattressing (Figure 4.5, Figure 4.6 and Figure 4.7). All three approaches require the bank to be cleared and resloped (to design slope). The construction plant should be operated from the top of the bank to minimise bank disturbance. The bank should be excavated for resloping, rather than encroaching on the river channel. Soil compaction should not exceed 85 per cent of its maximum compaction to ensure roots can penetrate the soil. The site preparation should also include a trench at the toe of the streambank along the length of the project if coir logs are to be installed.

The construction method for brushing is presented in BCC (2004) and WRC (2001a). If any geotextile or jute matting is required under the structure it should be placed before any brushing. The brushing is secured with steel cabling between anchors at the top of the bank and may include buried weights at the toe of the bank (Figure 4.6). Firstly anchors need to be located (or constructed) at the top of the bank. Constructed anchors could include buried logs or driven timber piles. The brushing can be secured to the anchor using cabling with anchors at the toe, or with sufficient length of cable to return to the anchor after the brushing has been placed. Brushing should be placed approximately horizontally with the bank with the butts facing slightly downstream. Alternatively, the branches can be placed across the bank with the butts facing the upper bank. Brushing is more effective if toe protection is incorporated. Toe protection may need to be installed before placing the brushing.

The live brush mattressing technique has been modified for local conditions (due to the absence of live brushing) using cabling and stakes from the methods presented in Bentrup and Hoag (1998), Allen and Fischenich (2001) and CBBEL (1999). Once the site has been prepared (with a trench), the base of the cuttings are placed in the trench and laid along the face of the slope one to two branches thick (5–10cm). Gaps should be created in the mattress to plant sedge and small shrubs.

The anchoring technique requires creating a network of rope or wire secured with stakes (Figure 4.7). A grid of wedge stakes, approximately 0.6–1m long, (diagonally split wooden stakes are effective) should be constructed at a density to ensure anchor stability (approximately one metre). Longer stakes will be required in less cohesive (sandy) soils. The stakes should be hammered in leaving at least 10cm above the mattress, as they will be hammered in further once the rope or wire is attached. The brush is secured by tying (using clove-hitch knots) rope or wire in horizontal runs and diagonally between each row of stakes. The rope or wire should be at least 5–10cm from the top of the stake. Once the network is secure, the stakes should be driven further to compress the mattress tightly against the bank.

The final stages require placing a coir log or small rock revetment at the toe of the brush mattress for stabilisation. The remainder of the site can be backfilled using material excavated from the trench, with soil worked into the branches near the new plants. Broadcasting native grass seed is optional. A temporary irrigation system may also need to be installed during this stage of the construction.

The local brush mattressing approach has been developed by Syrinx Environmental Pty Ltd, adapted from techniques used in Europe (Schwarten, T. pers. comm.; Figure 4.5). The logs and branches should have most of the leaves stripped before installation (this applies to logs only, do not remove leaf material from *Melaleuca* or *Kunzea* species as leaf material is required for energy absorption). Once the bank has been prepared, place large logs 500mm apart across the bank with the base at the toe of the bank. The smaller branches are layered horizontally along the bank. Three layers of brush should be cross-layered on top of the logs, placed in a dense arrangement. Each layer should be approximately 50mm thick once compacted and secured (using wire). The first and final layer must be perpendicular to the shoreline. The brush material must be free of seeds.

In locations susceptible to higher stresses, some of the branches can be drilled and bolted to the underlying logs to improve stability. A second layer of branches is applied across the bank, with either all butts placed up the bank, or alternating top to toe. The branches can be shifted slightly to make space for planting sedges and small shrubs. Following planting, the mattress can be anchored using a combination of wire or rope weighed down with rocks. Stakes improve stability. Use galvanised wire and pre-drilled stakes to secure the mattress. Each pegged section of brush mattressing should be approximately 1.5–3m long (parallel to the shoreline) and 2–3m wide. This technique relies on a rock toe to stabilise the mattress.

All techniques require keying in to adjacent banks and toe protection to prevent river currents and waves removing sediment from behind and under the mattress. The most common method for tying into adjacent banks is using a small quantity of rock riprap that is sufficient mass to withstand the uplift forces.

4.3.6 Failure mechanisms

The main failure mechanisms are:

- loss of sediment through, under or at the ends of the brush mattress. This could be due to insufficient drainage management, inadequate or absent toe protection, flanking erosion or not having sufficient elevation of works (minimum of one in one year water level)
- grades too steep
- failure of anchoring due to insufficient design or inadequate maintenance
- instability due to inappropriate site selection (e.g. a bank where subsurface drainage is the main erosion mechanism)

- failed revegetation with no subsequent replanting and vegetation is not established before the end of the design life of the brush mattressing.

Factors that could reduce the likelihood of failure are discussed above in relation to design and construction and below in relation to maintenance.

4.4 Monitoring and maintenance

Monitoring and maintenance will extend the life of brush mattressing and increase the likelihood of successful bank revegetation. General approaches to developing a monitoring and evaluation plan can be found in WRC (2002c). Monitoring of brush mattressing should include visual inspection and photographs of:

- plant health and density (supplementary planting for 2 to 3 years if needed)
- integrity of anchor system (presence and state of anchor stakes/rocks, tension and presence of wires/cord), check quarterly or as needed, if traffic is high monthly inspections are required
- any missing or moved branches (due to natural forcing or human interference)
- presence of weeds
- state of toe protection and where mattress is tied into adjacent banks
- locations where there is any washout of material due to subsurface drainage, surface drainage or undermining
- incorporate refuse removal (be aware of sharp items).

The works should be inspected regularly (a minimum of three inspections during winter and one in summer) for the first three years when the majority of the maintenance would be required (Donat 1995; McCullah and Gray 2005). New plants may need watering for the first year. After the first three years, the mattressing should be inspected at the end of each winter or following any exceedance of the one-in-10 year water levels.

Most maintenance required for brush mattressing is anticipated in the first three years (Donat 1995). Maintenance should be conducted as required to replace plants, remove weeds, repairs to any reticulation, reanchor (securing stakes, replacing wire/cord/twine), and replace any missing or moved branches. Additional maintenance may be required where sediment is lost from under the mattress or at the up and down-stream ends of the structures. The maintenance works may require sediment replacement and additional rocks.

Funding for maintenance and monitoring should be included in any life-cycle planning for brush mattressing.

4.5 Cost

Cost estimates are based on 2008 prices from various Western Australian suppliers (Table 4.2). These figures should be used as estimates only and quotes from suppliers should be obtained when producing final budgets.

The project budget should also include design, localised wave velocity studies and site survey costs, along with the need for monitoring and maintenance. All revegetation projects require replanting due to some losses in the initial three years. Additional costs will be incurred due to reanchoring requirements. Donat (1995) suggests the initial maintenance costs for brush mattressing (first three years) would be approximately 50 per cent of the total maintenance budget. Costs for planning and supervision are likely to be 10–20 per cent of the total project cost (Donat 1995). When constructing a budget, Donat (1995) suggests construction time could be in the order of 3–4 hours/m^2 depending on the technique used.

Table 4.2 Cost estimates for key elements to implement log/brush mattressing protection

ITEM	APPROXIMATE COST (EX GST)
Logs 1) 0.4m diameter logs 2) 0.2m diameter logs	 Approx $4.00 each Approx $2.50 each
Long branch cuttings	$43/bundle (1 bundle covers 1m^2 with three layers
Hardwood stakes	$1 each (approx 9 per m^2)
Limestone rocks	$140/tonne
Filter size rocks (limestone, density of 1.8tonne/m^3) 1) 0.1-0.3m diameter (2 – 15kg) 2) 0.3-0.6m diameter (50 – 225kg)	 $30 – $50/tonne $40 – $70/tonne
Sediment fill	$29 – $38/m^3 pending volume delivered to site
Crushed stone	$25 – $40/m^3
Gravel fill	$45/m^3
Erosion control matting	
Biodegradable matting (e.g. jute or coconut fibre)	$160/50m^2 roll
Biodegradable pins	$380 - $470/box (two styles/lengths available, box size varies, contact suppliers for quotes)
Steel pins (various lengths)	$0.2 – $0.4/pin
Plants	
Tree tubes	$1 – $2 each
Cells	$0.5 – $1 each
Strips sedge	$10 – $12 each
Labour for installation	$85/hour
Site supervisor	$140/hour
Chainsaw hire	$100/day
Circular saw (9 inch blade)	$40/day
Soil compactor	$90 – $120/day
Excavator	$90 – $140/hour
Truck and transport costs	$80 – $90/hour

Note: Costs sourced from Rawlinsons (2008) and various WA suppliers (2008)

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5 Gabions

5.1 Description

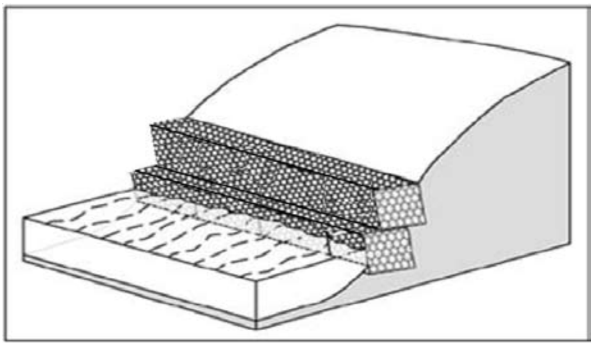
A gabion is a structural unit consisting of a wire frame cage filled with rocks. They are used to build structures such as river walling. This technique commonly uses a set of gabion 'blocks' or 'baskets' wired together. A rock 'mattress' is a relatively thin cage with comparatively large surface area, laid on the grade of the bank or bed. Gabion blocks and mattresses are often used in combination; the blocks provide the vertical gravity walling and the mattresses are placed below the blocks to provide scour protection. However, they may be installed separately, as block walls and mattress systems respectively (Figure 5.1; Figure 5.2). Gabions are also widely used in weir and stormwater drainage structures.

The first industrial manufacture of gabions began in 1894 (Chaychuk 2005). Gabion units are known under several names. The systems most widely used in Western Australia are associated with Maccaferri, who use the terms Terramesh gabions and Reno mattresses. Other gabion brands include Rhinomesh and Terrastop. Gabion blocks are typically 2-4m long, 2-4m wide and 0.5-1m thick. Gabion mattresses are typically 3-6m long, 1-2m wide and from 0.15-0.5m thick.

Modern gabion units use internal cells and bracing to provide additional stiffening. Some manufacturers provide preformed standardised bracing wires specific to each gabion unit. This improves the effectiveness of the installed gabion units.

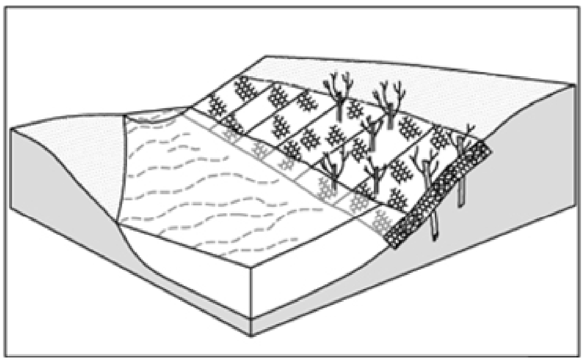
In certain situations it can be possible to establish local native riparian plant species into or on top of the gabions. For this reason they are occasionally proposed as environmentally sensitive alternatives to concrete panel walls or rock pitching.

The use of willow switches to initiate growth is widely documented in North America; however, an equivalent for the Swan Canning Riverpark does not exist and non-native species should not be used in foreshore stabilisation projects in these areas.



Source: Modified from McCullah & Gray (2005)

Figure 5.1 Schematic diagram of gabion walling



Source: McCullah & Gray (2005)

Figure 5.2 Schematic diagram of vegetated rock mattresses

5.1.1 Case studies and examples

The performance of gabion systems has varied in the Swan Canning Riverpark. Mattresses placed as 'back-stops' underneath variable estuary beaches have performed adequately along Lucky Bay, Applecross and near Point Waylen, west of Applecross Jetty. In general, gabion mattresses placed at grades flatter than one in three have performed effectively.

Figure 5.3 Gabion mattresses west of the Narrows, with failure of lower units requiring maintenance

Figure 5.3 shows a section of rock mattress nearing the end of its structural life. In this case rock loss around the mean water level has resulted in failure of the lower units. This highlights the importance of continued maintenance of rock mattresses and gabions. Significant advances in wire technology have occurred since these mattresses were installed.

Vertical gabions exposed to large wave loads on the Swan River have not performed as well. The vertical gabion wall adjacent to the Swan Brewery Development (Figure 5.4) has failed in some sections. This section of walling is scheduled for replacement with a limestone block wall in 2010. There are several examples of vertical gabion walls around the Swan River that have performed adequately but now require maintenance or replacement.

Figure 5.4 Gabion walling adjacent to Swan Brewery development

5.2 Purpose and application

Gabion units may provide a viable alternative where large armour rock, block work or panel systems are not economically available or aesthetically suitable, or where there is geotechnical instability. Properly connected gabion units act as a monolithic structure, increasing their resistance to hydraulic and wave loadings. Another significant advantage of the gabion system is they are porous, reducing the effect of hydrostatic pressure loading. Further, because they contain relatively smaller rocks, the number of filter layers required to provide hydraulic stability for the bed or bank material may be reduced. As such, they are commonly considered advantageous where there is limited space to construct a conventional rock armour revetment with filters.

Gabion systems are free-draining and may be designed to cater for a wide range of soil conditions, extreme flow or wave conditions and groundwater flows.

Gabion units may be used to stabilise banks for the bank profile locations, channel planform locations and type of erosion processes presented in Table 5.1.

Table 5.1 Gabion unit applicability

USEFUL FOR EROSION PROCESSES	
Description	**Feasibility**
Toe erosion with upper bank failure	
Scour of middle and upper banks by currents	
Local scour	
Erosion of local lenses/layers of non-cohesive sediment	
Erosion by overbank runoff	
General bed degradation	
Headcutting	
Piping	
Erosion by navigation waves	
Erosion by wind waves	
Erosion by debris gouging	
Bank instability/susceptibility to mass slope failure	
Erosion due to uncontrolled access (either boat launching, human or animal trampling)	
Erosion due to inappropriate focusing of drainage	
Enhance erosion due to sedimentation of the channel	
Erosion due to interruption of sediment transport	

PROFILE SPATIAL APPLICATION	
Description	**Feasibility**
Toe	
Midbank	
Top of bank	

HYDROLOGICAL GEOMORPHIC SETTING	
Description	**Feasibility**
Resistive	
Redirective	
Continuous	
Discontinuous	1
Outer bends	2
Inner bends	
Incision	
Lateral migration	2
Aggradation	

Feasibility method

'White' = feasible

'Grey' = possibly feasible, see table notes

'Black' = unfeasible

Notes: 1 Difficult to achieve transitions

2 Requires greater consideration of the embedment depth

5.2.1 Conditions where practice applies

Gabions are suitable for use in high stress environments, or where protection of high value foreshore infrastructure is required. Gabion units may also be suited to areas where geotechnical investigations have found the ground to be unstable.

The mass of the entire basket is able to resist wave action and its porous nature helps reduce groundwater pressures. Gabion blocks are typically up to three tonnes in mass or approximately 1.8 tonnes per m^3. This allows a single unit to resist up to 1m waves, and therefore gabions are suited to relatively energetic locations. Connected as a system, gabions may in theory withstand wave action up to 2m, although their performance under such conditions is limited by how well they are joined. The gabion system must also cover the entire area exposed to wave stresses capable of mobilising sediment, which may be exaggerated through wave reflection.

Like vertical block gravity walls, gabion block systems can only be used economically for a limited vertical extent. Because they are gravity systems, their thickness increases approximately proportional to their height, making the cost increase dramatically for systems higher than 3m. Improvements in bracing means geogrids can be used with gabion units. These geogrids are commonly used for high panel walling or sheet piling and improve the overall stability of the wall. The effective height may be extended through tiered gabion walls, connected with gabion mattresses.

5.2.2 Complexity and sensitivities

The most common problems associated with gabion wall systems are typically due to inappropriate design, specification or construction. Some complexities and sensitivities associated with design and construction are outlined below.

Foundation materials

As a gravity wall, the overall stability of gabion block structures is strongly linked to the underlying foundation materials. Where clays or mud are located next to or underneath the proposed structure, advice should be obtained from a specialist geotechnical engineer regarding the effects of the gabion wall system for bearing and overall stability against rotation.

Integration with rigid systems

The mobility of gabion units is influenced by the quality of rock, bracing and its packing. However, gabions typically experience gradual deformation over time. As a result, integration of gabion units with rigid systems such as concrete coping is typically a source of ongoing maintenance and repairs which left unattended can create a hazard. An example of this was the gabion wall and coping along Mounts Bay Road from 1991-2010 (Figure 5.4). By the end of 2010, this structure will have been replaced by limestone block walling.

Rock selection

Considerable care must be undertaken in selecting and installing rock into the cages. The *Australian Standard AS2758.4 – 2000 Aggregate for gabion baskets and wire mattresses* provides a basis for specifying requirements for aggregates intended for use in gabion structures. This standard should be used throughout the design and construction process. Poor rock quality, or failure to fill the cages completely, results in increased abrasion and rock breakage, amplifying deformation and damage to cage wiring. Limestone should be avoided in areas with strong erosive forces. Ideally, igneous or metamorphic river rocks should be used, as they are less susceptible to breakage and have few sharp edges. However, it is acknowledged that supply of these materials is limited in the Perth metropolitan region with the exception of a few quarries such as Gosnells.

Packing rock into blocks/mattresses

Particular attention should be paid to the rock placement process to ensure rocks are hand packed tightly. This is an integral part of the gabion function.

Keying in/wall return

Careful consideration should be given to 'keying' the end of gabion walls into the riverbank to protect the end of the wall from scour. This is done by extending the end of the wall at right angles into the riverbank. This is also known as a 'wall return'.

Vandalism

Vandalism can be a significant problem for gabion systems with people cutting the wire mesh to access rock. Gabion mattresses can also be cut open by fisherman retrieving lost fishing tackle. Consequently, gabion structures in easily accessible locations and/or exposed to fishing activities should be inspected for damage on a regular basis.

5.3 Design guidelines

Some general design approaches are outlined below. However, detailed designs are required and should be prepared by a professional engineer with experience in gabion design and installation in river and/or coastal environments.

A basic gabion wall system comprises a set of gabion blocks, a gabion mattress as a scour blanket, a filter cloth, rock filter and loose rock sublayer (Figure 5.5).

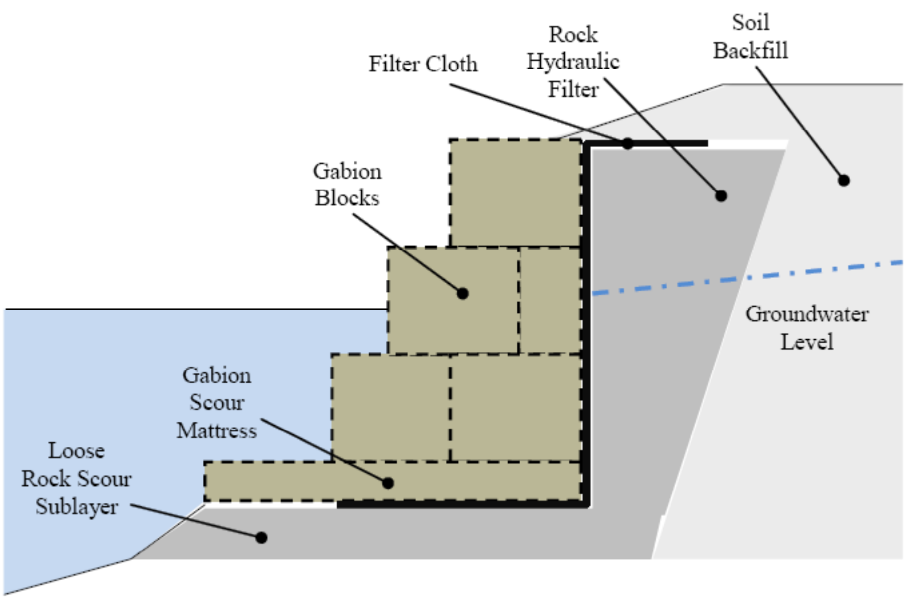


Figure 5.6 Schematic diagram of gabion walling

Gabion walls are generally analysed as gravity retaining walls with a range of design guidelines available (MGS 2004). However, design of a foreshore protection gabion system requires consideration of the following by an experienced engineer:

- wave loading
- current loading
- corrosion and abrasion resistance of cage wiring
- sliding and uplift relative to under-layer material
- internal stability of rock fill
- hydraulic stability for the fill underneath
- earth loads & surcharges (geotechnical stability for overturning and sliding)
- integration with adjacent foreshore treatment.

Gabion walls should consider the general principles outlined in *Australian Standard AS4678-(2002) Earth retaining structures*, subject to design criteria meeting the *Australian Standard AS4997 (2005) Guidelines for the design of maritime structures*. However, neither of these standards contain specific design principles for gabions, as such, professional engineering support is required throughout all elements of gabion design and installation.

The initial design check for a gabion system should consider the stability of an individual unit in the design conditions. A 0.5m³ unit can withstand approximately 1m waves, and a 2m³ unit can withstand approximately 1.8 m waves, although the capacity varies significantly according to the rock specific gravity and packing density.

Gabions placed as walls require a stagger or inclination of greater than one in 10 (horizontal to vertical) to cater for deformation, regardless of surcharge and earth loads.

For a gabion mattress, the ability for underscour to cause blanket flexure should be reduced by placing a loose rock foundation, and possibly a double gabion mattress toe.

Rock selection

As mentioned previously A*ustralian Standard AS2758.4 – 2000 Aggregate for gabion baskets and wire mattresses* provides a basis for specifying requirements for aggregates intended for use in gabion structures. This standard should be used throughout the design and construction process.

Baskets

Structural performance of the baskets is enhanced by PVC wire coating, double wiring, galvanised wiring and double meshing on the exposed face. In the estuarine environment PVC coating and galfan wiring are recommended.

Significant improvements in wire coating technology have improved the durability of the wire cages, particularly in marine environments with high corrosion potential. Many gabion manufacturers use zinc/5% aluminium coatings such as Galfan, which comply with the recommendations of *Australian New Zealand Standard AS/NZS4534-2006 zinc and zinc/aluminium-alloy coatings on steel wire*. These zinc/5% aluminium coatings offer from two to about three times greater protection than standard zinc coatings.

Geofabric filters

Gabions are almost always installed with geofabric filters on their rear side or underneath an intermediate rock filter. The geotextile material must be robust, sufficiently permeable and abrasive-resistant in hydraulic applications. The geotextile will not perform its function if it is damaged. Site supervisors must ensure the contractor takes due care to minimise damage to the geotextile during installation.

Revegetation

Vegetation growth on top of rock mattresses can be promoted by brushing native soil into the voids between the rocks. A layer of jute matting can also be placed on the soil prior to closure of the mattress to hold soil in place and increase the effectiveness of growth.

5.3.1 Loading

Design loads for gabions require consideration by an experienced engineer. Gabions are susceptible to loading by waves, currents, sliding and uplift, hydrostatic pressures, earth loads and surcharges. Design of a gabion system requires each of these loads to be calculated in conjunction with the overall stability of the structure in relation to the bed. General rules of thumb for the wave loading gabions can sustain are described in Section 5.2.1.

5.3.2 Considerations for detailed design

When placed as a near vertical wall, the effect of earth loads and surcharges must be considered across the full range of water levels. Gross stability against overturning and sliding should be evaluated and careful design is required to evaluate pivot points for overturning. Buoyancy effects must be incorporated into the effective design density, as this is a significant factor in the ratio of disturbing to resisting forces. Tieback systems including deadmen or geogrids may also be a design option.

Undercutting, overtopping, bypassing or soil loss through the gabion system invariably increases the rate of structural degradation and should therefore be addressed throughout the design process.

Climate change should be incorporated into designs according to the most recent Department of Planning and Trust policies, which are based on Intergovernmental Panel on Climate Change (IPCC) predictions. Climate change is generally incorporated solely in terms of elevating design water levels. However, there is potential for increased storminess, flooding and wave energy transmission to the banks.

5.3.3 Design life/expected lifetime

The structural life of gabion units is generally determined by the wire's capacity to withstand corrosion, vandalism and abrasion from the rocks contained within.

Typically a structural life of 10-15 years may be achieved with minimal maintenance, although the life may be extended to 25-30 years with regular maintenance. This includes annually wiring up any holes, topping up rock every three-five years and replacing an outer layer of mesh every five-10 years on the exposed side of the cages. Where an extended life is desired, constructing a rock filter between the gabion and underlying material is advised in preference to solely relying on the geofabric filter to provide hydraulic stability beneath the gabion units.

5.3.4 Materials and equipment

The following materials and equipment are required for the construction of gabions (Australian Standard, AS2758-2000):

- gabion baskets
- rocks to fill gabion baskets
- geofabric filter
- pneumatic lacing tool
- stainless steel rings
- preformed braces
- pins to secure geofabric
- filter size rock
- loader or excavator
- crane or excavator with rig
- soil fill
- drainage material (perforated pipes)
- any materials required to tie in with adjacent foreshores landward of the gabions (including sediment if nourishment is required).

Technical data sheets on gabions systems can be obtained from the manufacturer. These data sheets provide guidance on standard basket sizes, lacing operations and recommended installation tools.

5.3.5 Construction/installation

Constructing gabion foreshore protection is labour intensive, but also requires dedicated heavy lifting equipment and a supply of suitable rock fill. Construction of gabion units typically requires a large laydown area to enable rock stockpiling and cage assembly.

The order in which the rock filter and geofabric filter are laid depends on the site conditions. For a gabion mattress, the foreshore embankment is typically battered near to its angle of repose. A geofabric filter is laid over the slope and pinned in place. Rock filter layers are then placed over the geofabric. For a gabion wall, it is not unusual for the bottom level of gabion blocks to be placed first. The geofabric may then be draped over the back of the first layer of units, with rock filter placed and compacted in layers. The remaining gabion layers are completed in a similar fashion.

Gabions are supplied as pre-manufactured cages, which are assembled manually onsite. The gabion units are typically filled in place (if possible) to avoid unnecessary handling of filled cages. Wood or steel formwork is used to support the cages during filling operations. The gabions are partially filled using a loader or excavator (Figure 5.6).

Figure 5.6 Partial filling of gabion units with a hydraulic excavator

Rocks are then placed by hand along the exposed faces (Figure 5.7) and preformed bracing wires installed.

Figure 5.7 Hand placing rock in partially filled gabion unit

The gabion units are then completely filled with rocks, which are placed by hand to ensure the cages are fully filled and tightly packed. As outlined in Section 5.2.2 this is an integral part of the gabion function.

The gabions are then manually connected to adjacent units using wire twists.

5.3.6 Failure mechanisms

The following failure modes have been identified with gabion systems (Klein Breteler & Pilarczyk 1998).

- Overall stability — sliding or overturning of the gabion system associated with earth loads, hydraulic loading, groundwater loads and surcharges.
- Interface stability — sliding or deformation of the gabion system relative to the fill underneath.
- Internal stability — including durability of the mesh and rock fill.
- Under-layer stability — loss of fill through hydraulic instability, overtopping or under-scour.

These failure modes should be considered by an experienced engineer during the design process.

5.4 Monitoring and maintenance

Like any marine structure, maintenance is required throughout the life of a gabion wall or mattress. Maintenance is typically labour-intensive and subject to tide and weather restrictions.

Due to the potential for vandalism (usually involving people cutting the baskets to access rock or to retrieve lost fishing tackle), exposed gabion structures should be inspected regularly to determine if wiring has been damaged. Where rocks fracture or wear on the outer face is apparent, a subsequent layer of mesh may be placed over the outer face. However, care must be taken to repack any voids, to avoid subsequent motion and breakage of the rock fill.

Shotcrete has regularly been applied to gabions along South Perth foreshore to prevent vandalism and extend the effective life of the gabions by two to five years. However, shotcreting has limited effectiveness, as once cracking begins, it delaminates rapidly due to high water pressures. In addition, shotcreting reduces the drainage capacity of the gabion systems, which may be an integral function when there is overtopping of the wall by waves. Horizontal pinning has been used along the Swan River near Barrack Square to improve the performance of gabion blocks by providing a tieback into the wall. A similar approach is suggested by Donat (1995) to improve the lateral stability of gabions.

5.5 Cost

Cost estimates are based on 2008 prices from various Western Australian suppliers (Table 5.2). Gabion blocks are typically supplied and installed by a contractor from \$280-\$320 per m^3. Rock mattresses are typically supplied and installed by a contractor from \$60-\$80 per m^2. These figures should be used as estimates only and quotes from suppliers should be obtained when producing final budgets.

In addition, costing should be included for maintenance and monitoring. Monitoring should include (at a minimum) annual or biannual engineering inspection, including a site visit and report. Budget requirements for maintenance and monitoring should be determined on a site-by-site basis. However, in the interest of approximating costs for budgeting, estimates for gabions are approximately 5 per cent of total initial capital costs per year (accrued until maintenance is about 25 per cent of initial capital cost).

Table 5.2 Cost estimates for key elements to implement gabion protection

ITEM	APPROXIMATE COST (EX GST)
Gabion baskets	\$75 – \$140 each
Gabion mattress baskets	\$210 – \$240 each
Rock fill for baskets (ideally igneous or metamorphic)	\$30 – \$85/tonne
Geotextile filter cloth	\$2 – \$5/m²
Filter size rocks (limestone, density of 1.8 tonne/m³) 1) 0.1 – 0.3m diameter (2 – 15kg) 2) 0.3 – 0.6m diameter (50 – 225kg)	 \$30 – \$50/tonne \$40 – \$70/tonne
Sediment fill	\$5 – \$15/tonne
Crushed stone	\$15 – \$30/tonne
Gravel fill	\$50 – \$100/tonne
Labour for installation	\$40 – \$80/hour
Site supervisor	\$110 – \$150/hour
Soil compactor	\$95/day
Drainage	\$65 – \$250 each
Excavator	\$90 – \$140/hour

Note: Costs sourced from Rawlinsons (2008) and various WA suppliers (2008)

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6 Log walling

6.1 Description

Log walls are vertical structures constructed from round logs or timber planks placed horizontally and attached to vertical piles. Log walling can also be referred to as timber walling, timber retaining walling and timber bulkheads. Log walling is generally intended to protect the toe of the bank and retain a higher foreshore elevation. On the Swan Canning river system, log walling has often been used to hold bank material in place where tree roots are exposed.

The advantages of log walling are the modest footprint of the vertical structure, relatively low initial capital costs and more natural look of wood rather than limestone, gabions or steel. Timber is also easily handled due to its low weight relative to other vertical structure materials.

Log walling, as a vertical structure, can result in strong wave reflection, which can cause scouring (lowering of the bed elevation) in front of the structure and downdrift erosion as the structure does not reduce wave heights or flow velocities. If the walling is placed low on the profile it can limit public access to the beach or bank below. Log walling can have a shorter design life than other vertical structures (approximately 15 years) due to lower unit strength and the susceptibility of timber to degradation. Regular maintenance is required to extend the design life. Such maintenance may include adding new or replacing old filter cloths behind the structure. This is a common procedure, as filter cloths were not always used in the 1970s and 1980s when log walling was a popular foreshore protection measure in the Swan Canning river system.

6.1.1 Case studies and examples

Log walling was a popular low-elevation structure in the Swan Canning river system in the 1970s and 1980s, used mainly in areas subjected to low-energy waves. Most log walling is located between the Maylands Peninsula and Middle Swan Bridge on the Swan River.

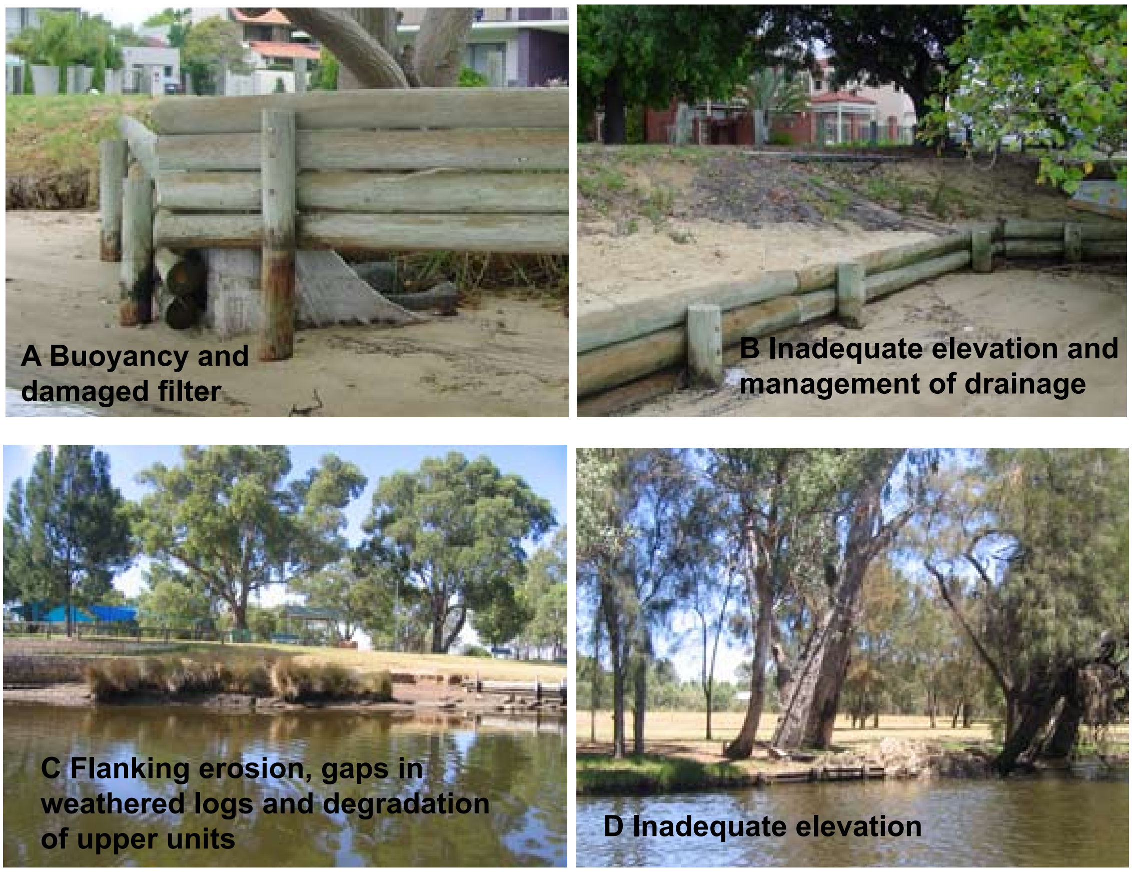
Specific locations where log walling has been installed include: Police Academy (Maylands Peninsula); Maylands Yacht Club; Tranby House; Ron Courtney Island; Garvey Park; West Midland Pool (Marshall Park); Middle Swan Bridge; and Canning Rowing Club. Log walling was also present downstream of Tranby House, at Success Hill and Fishmarket Reserve, but has now been removed. In many instances, the failure of log walling projects was due to the lack of ongoing maintenance. Where filter cloth has been added subsequently, walls have survived for longer.

The majority of the walling has surpassed its design life and requires removal with potential placement of new structural solutions. The most successful use of log walling in the Swan Canning river system occurred where low elevation structures (less than 1m) were used to mitigate mild erosion on low elevation banks. An example is at Garvey Park immediately downstream of the kayak club. Sedges have been planted in front of the walling and some maintenance has been conducted (Figure 6.1). At present, the log walling at this location only requires periodic sediment infill and filter cloth replacement behind the structure. The most successful applications of log walling are those constructed higher on the bank profile, on low-grade banks without any surcharge loading from trees or infrastructure.

Figure 6.1 Garvey Park log walling immediately downstream of the Kayak Club

Log walling has been less successful when the walling was used to stabilise an eroding reclaimed foreshore, such as on the Maylands Peninsula and Ron Courtney Island. Walling on reclaimed foreshores requires more maintenance, due to increased pressures acting on the wall and the increased downdrift erosion on adjacent non-walled foreshores.

The main failure mechanism of log walling observed in the Swan Canning river system was loss of bank material through the structure due to insufficient maintenance. Sediment was lost through the structure due to damaged filter cloth, gaps in weathered logs and degradation of the uppermost log units (Figure 6.2). Other failure mechanisms included: loss of sediment behind the structure, due to inadequate structure elevation (caused by wave overtopping) or inadequate management of drainage behind the structure; flanking erosion extending behind the structure; and not accounting for buoyancy in design and construction, resulting in sediment lost from underneath the structure (Figure 6.2).



Source: A) and B) Damara & Swan River Trust (February 2004) in Applecross, C) Oceanica & Swan River Trust (February 2007) in Garvey Park, D) Oceanica & Swan River Trust (February 2007) at Reg Bond Reserve

Figure 6.2 Photos of failed log walling

6.2 Purpose and application

The main purpose of log walling is to provide a vertical structure which may retain a low elevation foreshore with a relatively low initial cost compared to other walling materials. This technique is applicable for banks where toe erosion or undercutting is occurring. It cannot be constructed on hard riverbeds due to the nature of the piled structure in sediment.

Log walling may stabilise banks for the bank profile locations, channel planform locations and type of erosion processes presented in Table 6.1.

Table 6.1 Log walling applicability

USEFUL FOR EROSION PROCESSES	
Description	**Feasibility**
Toe erosion with upper bank failure	
Scour of middle and upper banks by currents	
Local scour	
Erosion of local lenses/layers of non-cohesive sediment	
Erosion by overbank runoff	
General bed degradation	
Headcutting	
Piping	
Erosion by navigation waves	
Erosion by wind waves	
Erosion by debris gouging	
Bank instability/susceptibility to mass slope failure	
Erosion due to uncontrolled access (either boat launching, human or animal trampling)	
Erosion due to inappropriate focusing of drainage	
Enhance erosion due to sedimentation of the channel	
Erosion due to interruption of sediment transport	

PROFILE SPATIAL APPLICATION	
Description	**Feasibility**
Toe	
Midbank	
Top of bank	

HYDROLOGICAL GEOMORPHIC SETTING	
Description	**Feasibility**
Resistive	
Redirective	
Continuous	
Discontinuous	1
Outer bends	2
Inner bends	
Incision	
Lateral migration	
Aggradation	

Feasibility method

'White' = feasible

'Grey' = possibly feasible, see table notes

'Black' = not feasible

Note: 1 Possible if wanting to create embayments in between

2 Limited long-term effectiveness

6.2.1 Condition where practice applies

Log walls are applicable in areas with low economic-value assets, such as trees, which require erosion mitigation from toe erosion or undercutting. The vertical nature of the structure is useful when there is limited foreshore area because part of the bank is normally excavated to minimise channel confinement. The piled walling is also ideal when a bank is used intensively for boating operations and mooring, such as near yacht clubs and jetties. An example in the Swan River is at Maylands Yacht Club. Log walls should only be applied as low-elevation structures (generally <1m) when there are low surcharge and earth pressure loads and low wave heights (generally <0.3m). Large wave heights would result in overtopping and continued bank erosion, along with excessive scour in front of the structure and undermining (USDA 1996).

Log walling is not suitable where there is a hard bed, large changes in bed elevation, or a steep eroding scarp or bank landward of the structure. This technique should also be avoided when there are adjacent high-value assets and no maintenance funding is available. Like any vertical structure, log walling eliminates riparian habitat, and should be avoided if the timber treatment chemicals could affect adjacent aquatic habitats.

Timber has a higher aesthetic value than other types of vertical structures but is considered less appealing than a vegetated bank.

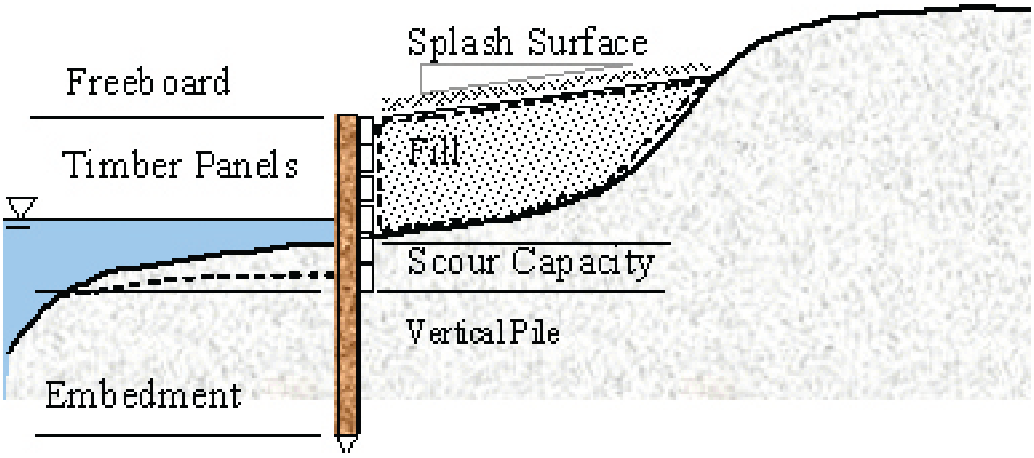
6.2.2 Complexity and sensitivities

The complexity in designing log walling is relatively low compared to other vertical structures. There are a number of sensitivities that should be considered when designing or planning log walling.

- **Maintenance** — maintenance funding is required to extend the functional life of the structure as failure of log walling can occur rapidly following damage. Once gaps form between the logs this increases the likelihood of damage to the geotextile lining. Material loss will be rapid once waves and high water levels breach the gaps.
- **Adjacent foreshore** — any vertical structure placed on an eroding bank will result in exacerbated erosion of the adjacent foreshores. This is due to a combination of: lowering the bed elevation in front of the structure (due to wave reflection); reduced sediment supply for the downdrift foreshore due to stabilisation of the bank; and no attenuation of current velocities and wave heights provided to adjacent banks by vertical structures. A design for log walling should incorporate plans to manage and mitigate erosion of adjacent banks.
- **Design specifications** — the design should consider the appropriate location on the profile, depth of the toe (accounting for scour in front of the structure), crest elevation, length of the structure, selection of appropriate geotextile filter and filter layers. In addition, the need for tiebacks to accommodate the earth and surcharge loads should be considered.
- **Site access** — log walling should only be constructed if there is sufficient site access for construction.
- **Boating and debris** — debris (such as logs) and boats could damage the log walling. Additional protection to the piles should be considered in areas of high boat traffic where loading and unloading of passengers may occur. The influence of reflected boat wakes on opposite banks should be considered if the opposite bank is also being eroded. Reflected waves may also affect the navigation safety for recreational users.
- **Drainage** — drainage of the backfill is recommended to prevent buildup of hydrostatic pressure and to reduce the quantity of backfill washed away during surface runoff and overtopping. Drainage can be achieved using perforated pipes or a series of granular filters. Reducing the upper slope behind the structure can also reduce the amount of backfill lost due to surface runoff.
- **Buoyancy** — buoyancy effects must be considered in the design to minimise uplift of the timber piles.
- **Using timber** — timber requires treatment with chemicals to protect against marine borer attack. In addition it is important to pre-dry the wood before placement to minimise warping and gaps in the logs. Further information on considerations in using timber as a material is included in Section 6.3.

6.3 Design guidelines

Typical drawings of log walling (without tiebacks) are illustrated in Figure 6.3 and Figure 6.4, comprising round logs or timber planks placed horizontally and attached to vertical piles, with sediment fill and geotextile filter located behind the structure.



Source: Damara (2007)

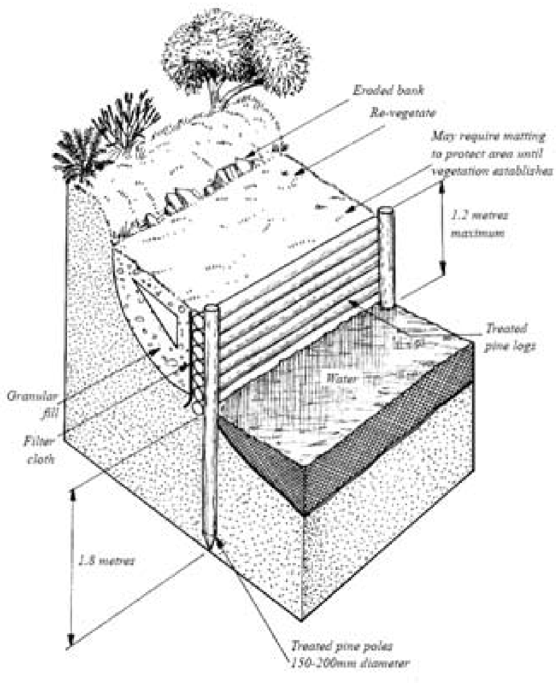
Figure 6.3 Log wall structure

The general principles behind the design of vertical walling should follow the *Australian Standard AS4678 (2002) Earth retaining structures* and *Australian Standard AS4997 (2005) Guidelines for the Design of Maritime Structures*, including methods of calculating loading, crest elevation and the durability of timber. Further information is included in NAVFAC (1988). This is additional to the sensitivities noted above (maintenance, drainage, adjacent foreshore treatments, site access, drainage, buoyancy, use of timber and specific design specifications).

The design specifications should include:

- location on the profile
- depth of the toe and level of embedment of the piles
- crest elevation (freeboard)
- length of the structure
- selection of appropriate geotextile filter, backfill and drainage
- whether tiebacks are required.

There are no standards for determining the depth of the toe and crest elevation for log walling. Crest elevations should be calculated using standard methods to minimise overtopping and inundation. A concept diagram illustrating log walling in Western Australia suggests a maximum elevation of the structure of 1.2m above the bed, with an embedment depth of 1.8m (WRC 2001a; Figure 6.4). These specifications would not apply for all sites and site-specific assessments of loading on the structure must be undertaken. The structure should be embedded deep enough to account for buoyancy of the piles and scour in front of the wall.



Source: Water and Rivers Commission (2001a)

Figure 6.4 Concept diagram of log walling construction

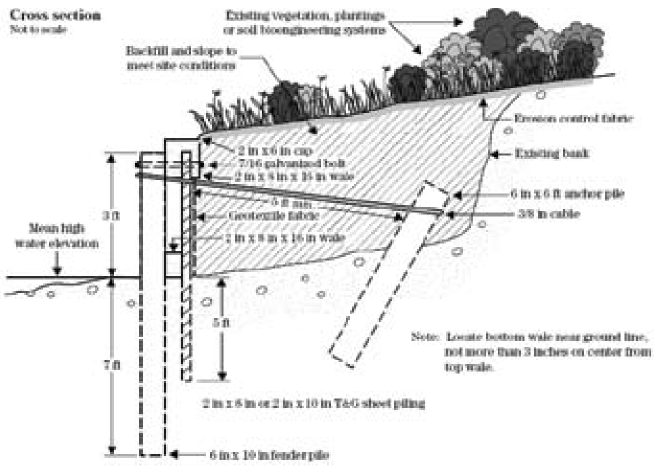
USDA (1996) provides some general guidelines for structure specifications based on wave height design parameters. If the calculated crest elevation exceeds 1.2m above the bed following scour, an alternative shore stabilisation technique should be used. Piles should be embedded to a depth that is the larger of either two times the height of the structure above the bed or two times the wave height. The horizontal logs should be embedded at least one wave height below the anticipated scour depth. The region behind the structure (with a slope of 3H:1V or flatter) should be a minimum distance of two times the wave height. However, in many areas of the river this should be wider to minimise impacts from high water level inundation.

The scour depth could be in the order of the maximum unbroken wave height that could occur in the depth of water at the log wall face. This is based on the theory of breaking waves in the *Coastal Engineering Manual* (USACE 2006). However, greater scour could occur in areas of high current velocities or boat wake or with relatively fine unconsolidated sediments.

If the crest level is greater than one metre above the possible scour depth, or the earth loads and surcharges are likely to result in over rotation of the structure, tiebacks should be placed (USDA 1996; CBBEL 1999). Tiebacks should be corrosion resistant metal rods placed through the vertical piles at approximate mean low water, sloped downwards slightly towards an anchor at least 1.5m landward of the walling (USDA 1996; NAVFAC 1988; Figure 6.5). Longer tierods may need vertical intermediate supports (NAVFAC 1988).

Placing rocks as toe protection can help reduce scour directly adjacent to the log walling. However, navigation and recreation safety in the vicinity of rock toes need to be considered.

Two further factors to be considered in determining if log walling is an appropriate technique are: the feasibility of a maintenance program; and if timber has sufficient durability for the required design life.



Source: USDA (1996)

Figure 6.5 Concept of tiebacks for log walling exceeding 1m

6.3.1 Loading

The design for log walling should consider loading due to:

- wave pressures and suctions — the calculations should include boat wake as the design condition for many riverine reaches
- currents — fluvial and tidal
- earth pressures — weight of fill and self weight, accounting for the moisture content of the wood
- surcharge loads — generally trees
- groundwater — including consideration of drainage requirements and effect of tree roots
- relative buoyancy of the timber piles — to ensure minimal to no structural uplift
- loading acting on the fill due to overtopping and surface flow.

Methods for calculating some of these loading forces are contained in Australian Standards AS4997 (2005) and AS4678 (2002) and NAVFAC (1988), though not specific to this type of log walling.

If the sum of the forces acting on the wall from the landward side are likely to result in rotation of the pile, the log walling will require a tieback system with anchors. The logs or timber panels themselves have negligible structural capacity to resist wave action, relying on the depth the vertical piles and tiebacks are embedded (Damara 2007). The maximum wave loading that log walling can sustain is approximately a 0.3m wave height, which may increase to 0.5m for walling with tiebacks that abut a low elevation foreshore (with low earth pressure and surcharge loading).

6.3.2 Considerations for detailed design

Designs should also include requirements for:

- landward foreshore treatment
- mitigating erosion adjacent to the structure
- drainage (geotextile filter, drain pipes, gravel filters)
- working with timber as a material.

Overtopping of the structure is likely to occur in high water level events and there will also be surface runoff across the backfill. Rigid structures such as concrete coping or paths should be avoided directly landward of the structure due to differential settlement and runoff (NAVFAC 1998). Kerbing and drainage management may be required, if the grade of the backshore will result in surface water flowing into the backfill. The backfill may require stabilisation with geotextile matting until (preferably low elevation) vegetation is established. If trees are planted behind the structure, the additional surcharge loading should be accounted for in the initial designs.

Fischenich (2001) provides comment regarding the influence of vertical structures on adjacent foreshores. The local scour and reduced sediment yield from the bank can result in exacerbated erosion of adjacent banks. In meandering rivers the structure may influence banks up to half a meander wavelength up or downstream. The log walling should be tied into adjacent banks and the downdrift banks may require renourishment.

The following elements should also be considered when using timber. Further information is contained in *Australian Standards 1604.1 (2000) Specification for preservative treatment*, *1720.1 (1997) Timber Structures* and *4997 (2005) Design of maritime structures*.

- **Treatment** — timber requires treatment with water-borne CCA (Copper Chrome Arsenic) preservative in accordance with hazard level H6 in the Australian Standards 1604.1-2000. This hazard level is applicable for wood subject to prolonged immersion in seawater that is subject to marine borers and decay. Concerns have been raised regarding health risks of this treatment (Green Skills 2005) and any changes to this regulation should be monitored by land managers. The CCA treated timber should not be applied where members of the public are likely to come into frequent contact (e.g. handrails).
- **Drying** — wood should be pre-dried before placement to minimise warping and gaps in the logs. Wet timber will usually dry once constructed and as water is lost below the 25–30 per cent fibre saturation point it will shrink laterally and distortion may occur (Perdok 2002). The shrinkage and expansion of the logs due to periodic wetting and drying would require bolts to be tightened during the first year following construction.
- **Log selection and gaps** — ensure pre-dried logs are selected that, when placed, will have minimal gaps. The logs often used in the Swan Canning river system are pine (*Pinus radiata*) plantation logs. Gaps will expand as the wood degrades and any openings should be blocked to ensure the filter cloth is not damaged. Timber planks are often selected in preference to logs as it is easier to minimise gaps.
- **Climate change** — should be incorporated into designs according to the most recent Department of Planning and Trust policies, based on Intergovernmental Panel on Climate Change (IPCC) predictions. Climate change is generally incorporated solely in terms of elevating design water levels. However, there is potential for increased storminess, flooding and increased wave energy transmission to the banks.

6.3.3 Design life/expected lifetime

Log walling has a shorter design life than other walling materials due to the durability of timber and the accelerated rate of damage once gaps are formed in the structure. Notably, the functional life of the structure depends on the level of maintenance conducted.

The life of the timber will vary depending on how it was applied, the quality of the timber, species durability and the preservative treatment (AS 4997-2005). Deterioration of the timber is by mechanical degradation, rot or attack by living organisms. For timber piles exposed to marine organisms, the service life is likely to be in the order of five to 10 years. The design life is reduced if significant throughflow occurs due to buoyancy of the piles or the formation of gaps between the weathered logs resulting in damaged filter cloth. Maintenance (filter cloth replacement, replacement of units, infill of sediment and puttying of gaps) can extend the functional life of the structure to 10 to 15 years. Removing logs and filter cloth is relatively straightforward, with minor excavation equipment required to extract the piles. Alternatively, piles may be sawn off at the bed level.

6.3.4 Materials and equipment

The following materials and equipment are required to construct log walling.

Materials

- Timber logs and piles — generally *Pinus radiata* pine logs that have been treated and pre-dried.
- Geotextile filter — should have the strength to resist movement due to waves and not tear due to tacking to logs.
- Tacks to attach filter cloth to logs.
- Fill sediment for behind the structure (crushed stone or granular fill).
- Perforated pipes and gravel for drainage management.
- Corrosion resistant tieback rods and anchors if required.
- Bolts, nuts and washers for fastening – galvanised to protect against corrosion. Any surfaces in contact with timber should be coated with a sealant. Washers should be placed under all bolts and nuts to distribute force evenly on timber (USACE 1981; Perdok 2002). For most situations 20mm and 25mm diameter bolts tend to be suitable (Perdok 2002). Washers should have a diameter at least three times the diameter of the bolt and a thickness of 0.3 times the diameter (Perdok 2002).
- Vegetation and stabilisation matting for the upper slope landward of the structure.

Equipment

- Pile-driving equipment — the type used will depend on the bed sediment characteristics, or holes should be excavated before pile placement and infill.
- Mini backhoe — may be required to excavate the bank, place the fill and regrade the bank.
- Hammer — to attach filter cloth to logs.
- Drill and wrench — to drill holes in the piles and logs and secure nuts and bolts.

Additional materials and equipment may be needed to tie the structure into adjacent banks. Sediment of adequate size and environmental quality should be sourced if renourishment of adjacent banks is required.

6.3.5 Construction/installation

Before log walling is constructed, the site and timber must be prepared. Bank excavation will be required to allow for sufficient fill and, if relevant, tiebacks and deadman. The bank should be excavated to ensure the log walling does not encroach on the river channel. Timber should be treated and pre-dried before installation as discussed in *Considerations for detailed design* above.

Construction of log walling should be timed to coincide with a period of low water levels.

Following site preparation, the piles should be planted in the bed to the required depth. The technique used will depend on the site conditions. One option is to extract the sediment, place the pile and fill and compact the sediment around the pile. However, this will result in reduced hydraulic stability rather than if the piles were driven.

The base log should be placed at a depth of at least one wave height below the anticipated scour depth. Subsequent logs are placed horizontally and should be bolted to the bank side of the posts (with washers).

Filter cloth is placed and tacked so that it follows the log contours, to reduce the risk of tear as a result of stress placed by bridging the gaps.

If required, tiebacks and deadman/anchors are placed as described in the design guidelines above.

Backfill with crushed stone or granular fill and compact. When placing the backfill there should be sufficient drainage pipes (partially perforated PVC with gravel fill surrounding) exiting through the structure if needed. The backfill surface should be graded to a slope of 3H:1V or flatter, with matting to stabilise the soil. Local native sedges, rushes, groundcovers and shrubs are appropriate for planting behind the walling.

All bolts should be retightened twice in the first year following completion of the works because of wetting and drying of the wood.

6.3.6 Failure mechanisms

The main failure mechanisms are related to deterioration of the timber without appropriate maintenance. Timber will deteriorate in any units exposed to air while marine borers could contribute underwater. This can lead to gaps in the logs, which will cause tears in the filter cloth and loss of sediment through the structure. In addition, once the logs are loosened around the fixings mechanical wear due to relative movement accelerates deterioration (Yu and Kao 1989), leading to unit breakage. Regular maintenance to repair filter cloths, infill sediment and replace the upper one or two logs would reduce the amount of throughflow.

Failure can also result from inadequate drainage management, insufficient freeboard resulting in overtopping and loss of fill behind the structure, and not accounting for buoyancy of the posts resulting in loss of sediment under the structure.

Factors that could be considered to reduce the likelihood of these faults are discussed above in relation to design, construction and maintenance.

6.4 Monitoring and maintenance

Monitoring and maintenance are required to extend the life of log walling. General approaches to developing a monitoring and evaluation plan can be found in WRC (2002c).

Monitoring of log walling should include visual inspection and photographs of (NAVFAC 1993; Perdok *et al.* 2003):

- the state of timber units (cracking, broken, loose, missing, locations of deterioration, rotting, insect infestation, fungi damage, vertical and horizontal misalignment and size of gaps between units);
- the state of the bolts/fasteners (wear, breakage, loosening, missing, broken, rust and corrosion);
- the locations where there is any washout of backfill through the structure (gaps in units or through drainage outlets) or seepage behind the structure due to scour at the toe;
- the visibility and physical condition of any tiebacks and deadman anchors; and
- the area behind and at the ends of the wall including (locations and extent of erosion, settlement or slippage; lack of vegetation cover; surface drainage pathways and if there are any slopes steeper than 1V:3H).

Monitoring should be conducted twice a year, with focused monitoring after the first winter and immediately following any exceedances of the one-in-10-year water levels.

Maintenance may include repairing filter cloths, filling (with putty) gaps in the structure, or replacing the upper one or two units to reduce the amount of throughflow. Sediment infill should be conducted when any of these maintenance measures are conducted. More frequent sediment infill behind the structure may be required around drainage pipes.

Funding for maintenance and monitoring should be included in life-cycle planning for log walling.

6.5 Cost

Cost estimates are based on 2008 prices from various Western Australian suppliers (Table 6.2). These figures should be used as estimates only and quotes from suppliers should be obtained when producing final budgets.

In addition, maintenance and monitoring costs should be included. Monitoring should include (at a minimum) annual or biannual engineering inspection, including a site visit and report. The monetary requirements for maintenance and monitoring should be determined on a site-by-site basis. However, in the interest of approximating costs for budgets, estimates for log walling are approximately five per cent of total initial capital costs per year (accrued until maintenance is about 25 per cent of initial capital cost).

Table 6.2 Cost estimates for key elements to implement log walling protection

ITEM	APPROXIMATE COST (EX GST)
Timber logs and piles (pine)	$30/m
Perforated pipe (100 mm PVC)	$30/m
Geotextile filter cloth	$2 – $5/m^2
Crushed stone	$15 – $30/tonne
Gravel fill	$50 – $100/tonne
Trench mesh	$45 – 490/sheet
Concrete footings	
Concrete	$205/m^3
Pump for dewatering	$60/day (subject to size of pump)
Anchors	$100 – $150/m of walling
Labour for installation	$40 – $80/hour
Site supervisor	$110 – $150/hour
Drainage	$65 – $250 each
Soil compactor	$95/day
Excavator	$90 – $140/hour

Note: Costs sourced from Rawlinsons (2008) and various WA suppliers (2008)

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7 Cut limestone block walling

7.1 Description

Cut block walls are constructed of rock that has been cut into regular block shapes, fitted together with a cement mortar to form a nearly vertical wall. Cut block walling can provide foreshore protection while minimising the structure footprint and ensuring a high level of visual amenity. These types of walls are typically relatively low, bonded gravity structures. They are rigid structures usually (although not always) founded on reinforced concrete footings.

In the Swan Canning river system, local sandstones are commonly used, typically from the Tamala Limestone formation, which are readily cut. However, it has become increasingly common to use 'reconstituted' (synthetic) limestone, which is a blend of lime, cement and sand. Limestone blocks are widely available in the Perth region.

Advantages of these types of structures include their visual amenity, modest footprint, durability and ability to be constructed manually by a small team. However, as they are typically a vertical structure, wave reflection may exacerbate erosion of the adjacent foreshore and, as a rigid structure, they have limited capacity to accommodate differential settlement.

These structures are colloquially known as sea walls, limestone walls or retaining walls.

7.1.1 Case studies and examples

Limestone block walls have been constructed at various locations around the Swan Canning river system foreshore including:

- Riverside Road, East Fremantle
- Nedlands foreshore upstream of Qantas Boat Ramp, Nedlands (Figure 7.1; Figure 7.2)
- various locations along the Kwinana Freeway, Como
- near Matilda Bay Café, Crawley
- East Perth Power Station, East Perth
- next to the Causeway, Victoria Park
- Garvey Park Kayak Club, Ascot (Figure 7.3)
- Shelley Sailing Club on the Canning River, Shelley (Figure 7.4)
- Western Mounts Bay Road, Perth
- Claisebrook Cove, East Perth

The main issues associated with limestone walling observed in the Swan Canning river system include:

- not accounting for the lowering of the bed elevation in front of the structure during the design phase (Qantas Boat ramp; Garvey Park kayak club)
- overtopping and lack of drainage management (Qantas Boat Ramp)
- lack of regrouting or an absence of any filter cloth (Qantas Boat Ramp)

- flanking erosion (Shelley Sailing Club as walling is located riverward of adjacent foreshores)
- inadequate toe protection.

Source: Damara & Swan River Trust (February 2004)

Figure 7.1 Bed elevation lowering in front of a vertical cut block wall — Qantas Boat Ramp

Source: Damara & Swan River Trust (February 2004)

Figure 7.2 Overtopping, lack of drainage management, absence of filter cloth and re-grouting — Qantas Boat Ramp

Source: Oceanica & Swan River Trust (February 2007)

Figure 7.3 Bed elevation lowering in front of a terraced cut block wall — Garvey Park

Source: Oceanica & Swan River Trust (February 2007)

Figure 7.4 Flanking erosion (A — downstream; B — upstream) of cut block walling at Shelley Sailing Club

7.2 Purpose and application

Limestone block walls are generally used to protect valuable foreshore assets such as car parks, bike paths or foreshore parklands from erosion, while maintaining a high level of amenity. They are particularly appropriate in areas where there is limited space to construct a revetment structure with a larger footprint. This is equally significant for the area under water as well as above, as it can restrict the navigable area. Consequently, vertical walling, including use of cut blocks, is favoured for waterways heavily used by recreational craft.

Cut limestone block walling may stabilise banks for the bank profile locations, channel planform locations and type of erosion processes presented in Table 7.1.

Table 7.1 Cut limestone block walling applicability

USEFUL FOR EROSION PROCESSES	
Description	**Feasibility**
Toe erosion with upper bank failure	
Scour of middle and upper banks by currents	■
Local scour	■
Erosion of local lenses/layers of non-cohesive sediment	■
Erosion by overbank runoff	■
General bed degradation	■
Headcutting	■
Piping	
Erosion by navigation waves	
Erosion by wind waves	
Erosion by debris gouging	
Bank instability/susceptibility to mass slope failure	
Erosion due to uncontrolled access (either boat launching, human or animal trampling)	■
Erosion due to inappropriate focusing of drainage	■
Enhance erosion due to sedimentation of the channel	
Erosion due to interruption of sediment transport	■

PROFILE SPATIAL APPLICATION	
Description	**Feasibility**
Toe	
Midbank	■
Top of bank	

HYDROLOGICAL GEOMORPHIC SETTING	
Description	**Feasibility**
Resistive	
Redirective	■
Continuous	
Discontinuous	■
Outer bends	
Inner bends	
Incision	
Lateral migration	
Aggradation	

Feasibility method

'White' = feasible

'Grey' = possibly feasible

'Black' = not feasible

7.2.1 Condition where practice applies

Cut block walls can be used in a variety of situations but are particularly applicable in areas where amenity value is high and space is limited. For example, the limestone block wall along East Fremantle foreshore protects high value assets (bike path and road) in a busy public area adjacent to boat moorings. The structure footprint is minimal and the generally non-exposed sandy beach is potentially affected by enhanced erosion from the reflection of boat wake and wind waves.

7.2.2 Complexity and sensitivities

Some complexities and sensitivities associated with the design and construction of cut block walling include:

- potential for bed movement in front of the wall, this is a combination of local response to wave reflection and current focusing at the wall, along with regional sediment movement patterns
- ground conditions, including changes in density of soil strength due to soil saturation or vibration
- structure toe level — consideration of enhanced wave scour due to reflection from vertical walls
- structure crest level — consideration of wave overtopping, inundation during elevated water level events and earth loads
- foundation design — engineers should be consulted regarding the need for and specifications of any strip footings
- consideration of both wave loads on the wall and earth loads and surcharge behind the wall
- strength of grout between units is strongly reduced in tension, sometimes requiring additional support for the upper blocks (USACE 1984a)
- durability and design life
- drainage.

Wave reflection may also adversely affect navigational safety, particularly for recreational vessels such as kayaks, small yachts and dinghies, and may need to be considered in some areas of the Swan River.

Cut block walls are conventionally designed to act as gravity walls, where the mass of the blocks acts to resist the destabilising effects of earth loads, surcharges and hydrodynamic loads. For a shallow wall, this may involve two or three courses of blocks laid on top of one another. However, the required thickness of walling is proportional to its depth, such that the block wall becomes increasingly massive for deeper walling (Figure 7.5). The practice of using multiple retaining walls to reduce earth loads is generally not practical, as soil loss from an intermediate terrace significantly reduces the upper wall stability.

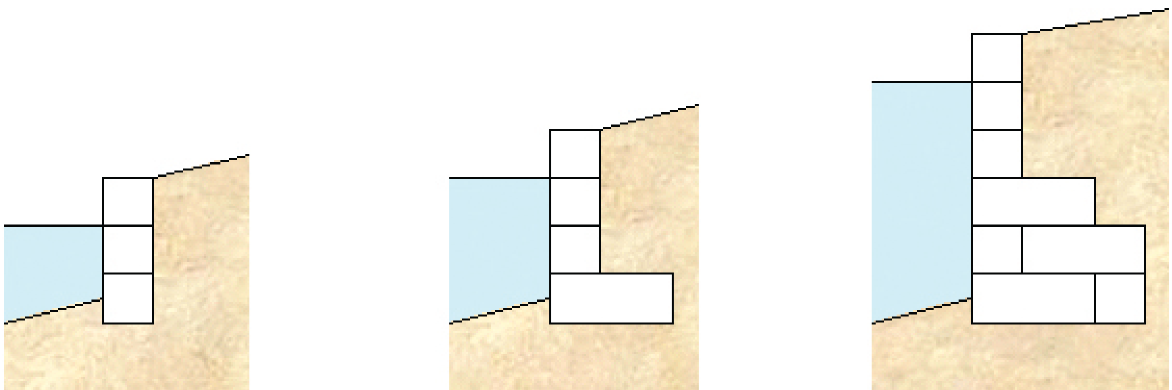


Figure 7.5 Increasing block wall mass with depth - schematic only

Techniques to reduce the sheer mass of block walling include using tiebacks, deadmen, buttressing, and column foundations. Modern cut block walls commonly incorporate geosynthetics, such as geofabric filter cloth backing the wall, or Tensar(R) geogrid providing soil reinforcement. The stability of individual blocks may be enhanced through high strength grout, pinning or interlocking blocks. Blocks at the crest of the wall may be given greater stability by contructing an extended beam or coping.

Although many of the principles of design for cut block walls in a fluvial or estuarine environment are similar to those for conventional land-based retaining walls, there are several significant differences.

- The effect of buoyancy reduces the effective mass of the block wall below the water surface, making the walls more prone to rotation.
- Very high local pore pressures may be associated with wave action, reducing the life-time of grout between blocks, and amplifying potential throughflow of fill material.
- There are enhanced requirements for drainage from behind the wall due to tides, surges and overtopping.

7.3 Design guidelines

Cut block walls in the river typically require more complex design than land-based retaining walls of a similar scale. It is typical that a marine structures engineer and a geotechnical engineer are needed to develop a detailed design. In particular, there is a need to consider regional sediment movements and the requirement for toe protection to accommodate any bed level changes in front of the wall.

The general design approach should include the following aspects.

- Calculation of earth loads, surcharges and hydraulic loads.
- Calculation of overall geotechnical stability, including global stability analysis.
- Monolithic stability for sliding, overturning and bearing.
- Where monolithic stability is limited, the use of tie-backs, broader foundation or buttressing should be considered.
- Internal stability for shear stress and moments, including grout.
- Evaluation of fill stability due to throughflow and undercutting.
- Consideration of appropriate minimum geotextile grade with regards to fill materials and construction technique. Generally a random filament, non-woven fabric with >2.5mm thickness is required.
- Determination of drainage requirements to enable adequate drawdown and cater for overtopping.
- Use 7 MPa reconstituted limestone in preference to lesser grade natural material as it is more consistent quality, although this may have lower density.
- Use good quality (M4 as an absolute minimum) mortar in walling as repointing is expensive and time consuming therefore the longer it lasts the better.

Australian Standards *Guidelines for the Design of Maritime Structures* (AS4997-2005) and *Earth Retaining Structures* (AS4678-2002) provide design guidelines for cut block walls. The guidelines include recommendations on:

- site investigations and planning
- dimensional criteria
- design requirements — including the effect of scour, siltation and sea level rise

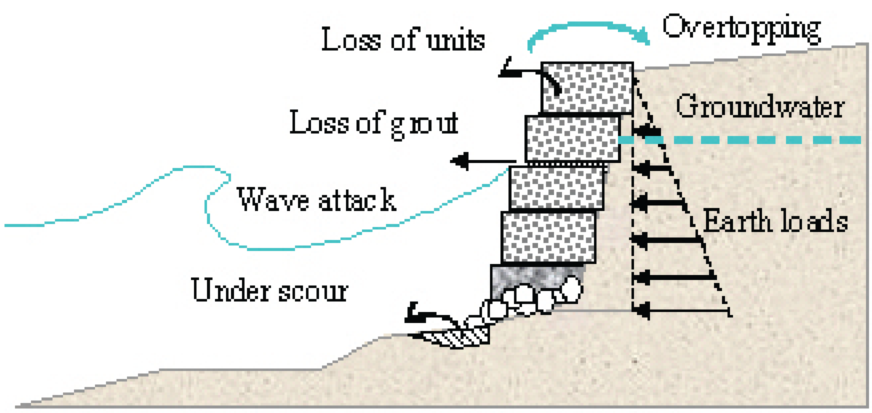
- design action — including wind, current and wave loads, earth actions and construction and maintenance actions
- durability.

With regards to concrete footings for limestone block walls, it is noted in AS4997 that 'concrete deterioration is usually a result of corrosion of reinforcing steel due to chloride ingress' and that 'recent history has shown some maritime concrete structures experiencing significant premature deterioration as a result of inappropriate selection of materials for the required design life'. The guidelines provide recommendations for specifying structural concrete including requirements for reinforcement, prestressing steel, exposure classifications and cover to reinforcement (AS 2005).

The reduced effective mass of submerged units due to buoyancy makes the density of the cut rock a critical parameter for wall stability. Although natural rock density of Tamala limestone in the Swan River region is quite variable, it is often greater than reconstituted limestone blocks.

7.3.1 Loading

Walling stresses typical of a limestone block seawall are illustrated in Figure 7.6. Australian Standards AS4997-2005 and AS4678-2002 provide guidelines for determining earth and hydrostatic loads, while USACE (2006) provides more detail on the calculation of wave loads.



Source: Damara (2007)

Figure 7.6 Walling stresses

7.3.2 Considerations for detailed design

Considerations for detailed design include design life, durability and maintenance. It is also important to consider the means by which the walling structure is tied in to the adjacent banks upstream and downstream. The potential for high construction loads should be considered. However, the appeal of these structures is that a small team without significant construction plant can generally build them.

The structure's height may be limited by the level of the adjacent foreshore for amenity or aesthetics reasons (i.e. local communities may not want a structure higher than the existing foreshore parkland). Where wave overtopping is significant, concrete or limestone 'overhanging lips', extending towards the water at the crest of the wall, may be considered. However, the additional uplift forces on the wall need to be accounted for in the design. Drainage of overtopping water may be managed through paving on the crest of the wall, such as concrete coping at Nedlands foreshore, or the asphalt path along Como foreshore. However, these systems may conceal when sediment is being lost via throughflow or undercutting, enabling large holes to develop behind the wall before they are evident.

Climate change should be incorporated into designs according to the most recent Department of Planning and Trust policies, based on Intergovernmental Panel on Climate Change (IPCC) predictions. Climate change is generally incorporated solely in terms of elevating design water levels. However, there is potential for increased storminess, flooding and increased wave energy transmission to the banks.

7.3.3 Design life/expected lifetime

The design life is defined as the period for which a structure remains fit for use for its intended purpose with appropriate maintenance. It is noted that components of the structure with limited access (such as the wall footing) should have a design life (with no maintenance) equal to the design life of the structure.

The identification of an agency responsible for maintaining the structure and a realistic maintenance program should allow a comparable design life to be achieved with reduced capital costs.

7.3.4 Materials and equipment

The materials required are generally limited to the limestone blocks themselves, cement for bonding the blocks, concrete, reinforcement and formwork for the footing, geotextiles and tie-ins or anchors (if required). A pump may be required to remove seeping water from the formwork to lay the footings, particularly for deeply founded footings.

Limestone blocks are generally natural cut blocks or manufactured (reconstituted) limestone. A range of standard sizes are available, although the natural limestone blocks are generally a standard length and height (500mm x 350mm) but variable width (200mm, 240mm or 300mm). They are generally graded as 'firsts', higher quality and uniform blocks, and 'seconds', lower quality and partially damaged units. Manufactured limestone blocks are generally either 500mm x 350mm or the larger 1000mm x 350mm, with variable widths available. Generally the smaller blocks (500mm x 350mm x 200mm or 240mm) allow easy construction with a small team of builders.

Block size is a matter of choice, but larger blocks are preferable as there is less mortar and therefore less maintenance. Use only good quality blocks. Reconstituted blocks with 7 MPa can be considered. 'Seconds' should be avoided. It may be possible to use concrete blocks to construct the inside skin of walling with a limestone face.

Materials and equipment for footings are readily available but will depend on the footing design and specification.

Construction/installation

Construction generally requires a small team with the appropriate level of experience and supervision. Contractors should have skills and experience in constructing walls in a river environment.

Failure mechanisms

Failure mechanisms are noted in Figure 7.6. These include loss of units, loss of grout, scour, wave overtopping and excessive earth loads. While limited movement of blocks may be repaired easily, scour of the footings or widespread tilting of the wall and loss of bonds may require large sections of a wall and footing to be demolished and rebuilt.

7.4 Monitoring and maintenance

Monitoring is generally limited to visual observations at reasonable intervals by an experienced operator or engineer. Australian Standard AS4678-2002 sets out a minimum standard for monitoring and maintenance including a minimum annual monitoring frequency. Particular attention should be given to measuring bed level changes in front of the walling. Exposure of the footing suggests the need for some form of toe protection. Maintenance may be limited to replacing dislodged units and filling voids. Degradation of the footing from concrete cancer would be more severe.

Sediment may be lost from behind the cut block walling through overtopping or throughflow. It should be replaced using limestone or a coarse granular fill, such as blue metal or gravel. Using rigid fill, such as blinding concrete, typically does not prevent further loss, but enables caverns to form underneath the blinding.

Other modifications available to respond to perceived structural failures include:

- near surface blocks subject to movement due to lack of grout resistance can be pinned together
- locations subject to undercutting may be given enhanced performance through addition of a flexible scour blanket, typically of loose rock
- walls experiencing overturning may be strengthened using tieback systems, typically attached to a short secondary wall.

7.5 Cost

The cost for a limestone block wall would include design, footing construction, supply of stone, associated transport costs and labour (Table 7.2). Costs for site preparation would vary substantially depending on the difficulty of the particular site and wall design. The cost estimates in Table 7.2 are based on 2008 prices from various Western Australian suppliers and should be used as estimates only. Quotes should be obtained from suppliers when producing final budgets.

In addition, costing should be included for maintenance and monitoring. Monitoring should include (at a minimum) annual or biannual engineering inspection, including a site visit and report. The funds required for maintenance and monitoring should be determined on a site-by-site basis. However, in the interest of approximating costs for budgeting, estimates for limestone block walling are approximately 2–3 per cent of total initial capital costs per year (accrued until maintenance is about 25 per cent of initial capital cost).

Table 7.2 Cost estimates for key elements to implement cut block walling protection

ITEM	APPROXIMATE COST (EX GST)
Cut limestone blocks	\$8 – \$10 each
Geotextile filter cloth	\$2 – \$5/m^2
Crushed stone	\$15 – \$30/tonne
Gravel fill	\$50 – \$100/tonne
Trench mesh	\$45 – \$90/sheet
Concrete footings	\$200 – \$250/m^3
Coping	\$110/m^2
Anchors	\$100 – \$150/m of walling
Labour for installation	\$40 – \$80/hour
Site supervisor	\$110 – \$150/hour
Shotcrete	\$250 – \$450/hour
Soil compactor	\$95/day
Drainage	\$65 – \$250 each
Excavator	\$90 – \$140/hour

Note: Costs sourced from Rawlinsons (2008) and various WA suppliers (2008)

7.6 References

Damara 2007, 'Swan River Lower Estuary – Foreshore Condition Assessment', Unpublished report to the Swan River Trust, Perth, Western Australia.

Rawlinsons 2008, *Australian Construction Handbook*, Edition 26, Rawlhouse Publishing, Perth, Western Australia.

Standards Australia 2002, *Australian standard: earth retaining structures*, (AS4678-2002), Standards Australia, Sydney, NSW.

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US Army Corps of Engineers (USACE) 1984, *Engineering and Design – Grouting Technology*, Department of the Army, US Army Corps of Engineers, Report no. Engineering Manual No 1110-2-3506, Washington, DC, USA.

US Army Corps of Engineers (USACE) 2006, *Coastal Engineering Manual*, United States Army Corps of Engineers, <http://chl.erdc.usace.army.mil/cem>.

8 Rock Revetments

8.1 Description

Rock revetments are a system of graded, interlocked, quarried armour stone laid on an embankment designed to absorb erosive forces and protect the adjacent foreshore embankment. Revetments are one of the oldest and most widely applied shore stabilisation techniques and may be colloquially referred to as riprap, rubble-mound armour, seawalls, retaining walls or rock walls.

The main advantage of revetments is the ability to design and construct the structures with a relatively high degree of confidence due to the availability of detailed design guidelines and examples of the application of this technique (Biedenharn *et al.* 1997), including in the Swan and Canning rivers and throughout Western Australia. Additionally, well-designed structures have the capacity to sustain damage without failing catastrophically in comparison to rigid structures. These structures provide significant advantages due to absence of earth pressures, flexibility, ease of maintenance, porosity and low wave run-up. Material availability (limestone, granite) and local construction experience with revetments in Western Australia is typically good.

Limitations of revetments include the large amount of space required (as they are laid at a relatively flat angle), potential scour of adjacent foreshores and a relatively high dependence on the skill of the operator placing the armour stone. Many revetments may have been constructed under emergency situations using only partial construction of the revetment system. These emergency structures are valuable in the short-term but if left in place for a longer term may degrade and require excessive maintenance and upgrade.

8.1.1 Case studies and examples

Damara (2007) and Oceanica *et al.* (2007) identified 46 revetments on public land on the Swan Canning foreshore. The majority of these structures were assessed to be performing moderately to well in terms of their retaining function. The following are examples of revetments in the Swan Canning river system with mixed retaining function.

- Bicton Baths, Bicton — Good retention (Figure 8.1). This revetment has 0.2–0.5m limestone rocks constructed with a 1H:2V slope, geotextile filter and a loose stone toe. A dual use path is located above the structure. Several upper units have moved, exposing and tearing the filter cloth and there is some evidence of scour. However, this has not affected the function of the revetment and there has been no undermining of the path above.
- East St Jetty, Fremantle — Moderate retention (Figure 8.2). This revetment is made up of one to three tonne limestone rocks. It experiences significant overtopping as it is susceptible to tidal currents, significant storm surge and refracted ocean swell. Sediment is removed from behind the structure as the overtopped water drains through the gaps between the larger units. As the dual use path is located at least one to two metres landward of the revetment crest, the reduced retention is not a significant cost concern.
- South-west of the Narrows Bridge, Perth — Poor retention (Figure 8.3). This revetment is made up of 0.2–0.5m limestone rocks with a 1H:3V slope. The rocks have been cemented in place. High pore pressures behind the cement have caused the sediment to become unstable and caused a loss of backfill material resulting in the collapse of the revetment.
- Preston Point walling, East Fremantle — Good retention. This revetment was recently constructed using 0.3 – 0.6m limestone rocks with a 1H:2V slope. The rocks were mortared in place.

Source: Swan River Trust & Damara (December 2003)

Figure 8.1 Bicton Baths revetment

Source: Swan River Trust & Damara (December 2003)

Figure 8.2 East Street Jetty revetment

Source: Swan River Trust & Damara (January 2004)

Figure 8.3 South-west Narrows revetment

8.2 Purpose and application

The primary purpose of revetments is to increase the stability of eroding foreshores.

Rock revetments may stabilise banks for the bank profile locations, channel planform locations and type of erosion processes presented in Table 8.1.

Table 8.1 Rock revetment applicability

USEFUL FOR EROSION PROCESSES	
Description	**Feasibility**
Toe erosion with upper bank failure	
Scour of middle and upper banks by currents	
Local scour	
Erosion of local lenses/layers of non-cohesive sediment	
Erosion by overbank runoff	
General bed degradation	
Headcutting	
Piping	
Erosion by navigation waves	
Erosion by wind waves	
Erosion by debris gouging	
Bank instability/susceptibility to mass slope failure	
Erosion due to uncontrolled access (either boat launching, human or animal trampling)	
Erosion due to inappropriate focusing of drainage	
Enhance erosion due to sedimentation of the channel	
Erosion due to interruption of sediment transport	

PROFILE SPATIAL APPLICATION	
Description	**Feasibility**
Toe	
Midbank	
Top of bank	

HYDROLOGICAL GEOMORPHIC SETTING	
Description	**Feasibility**
Resistive	
Redirective	
Continuous	
Discontinuous	
Outer bends	
Inner bends	
Incision	
Lateral migration	
Aggradation	

Feasibility method

'White' = feasible

'Grey' = possibly feasible

'Black' = not feasible

8.2.1 Condition where practice applies

Revetments can be used in a wide range of conditions where bank stabilisation is required. In particular they are appropriate in high-energy wave environments where severe bank erosion has occurred. The potential for scour in high flow environments of the upper reaches needs to be considered carefully. Revetments have the advantage of being flexible and can therefore adjust to scour or bank subsidence (Biedenharn *et al.*1997).

Revetments may be perceived to have a lower amenity value than other structures such as limestone block walls. However, a well constructed and maintained revetment can accommodate public use. Aesthetics need to be considered on a case-by-case basis but, as a general principle, local rock is preferable for revetments (i.e. granite on the upper reaches, limestone on the lower coastal estuarine reaches).

Environmental considerations include the scale of back preparation required (and possible loss of vegetation and habitat), the footprint of the structure and potential for plumes to be generated during construction. In general, plumes can be minimised by tighter specifications for armour material (particularly in regard to the percentage of fine materials permissible) and careful supervision during construction.

8.2.2 Complexity and sensitivities

The design and construction of revetments is relatively straightforward for experienced practitioners. Additionally, contractors can achieve good outcomes, as can land manager works teams with general civil experience supervised by an experienced coastal engineer.

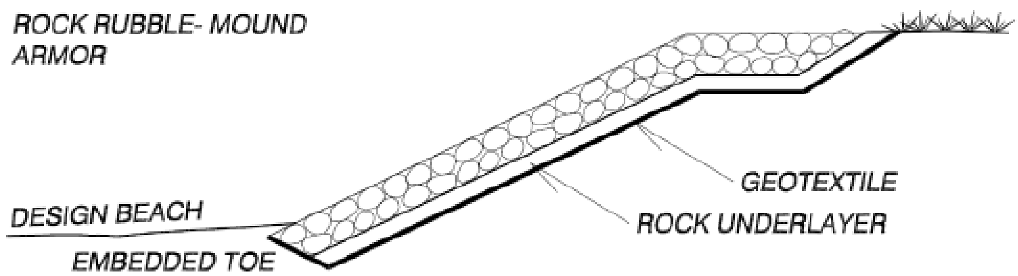
Some complexities and sensitivities in design include:

- estimating design conditions (wave or flow dominance)
- consideration of existing bank conditions and history of change
- selection and specification of filter layers and geotextiles
- ensuring the toe is well founded and risk of undermining is low
- appropriate crest height with consideration of overtopping scour, amenity and drainage
- specification of locally available materials
- site access
- maintaining public access.

Mortaring or cementing of revetments may be used to enhance stability of the armour units and prevent vandalism. However, this places additional backpressure on the revetment and increases run-up and wave reflection. The implications of mortaring or cementing need to be considered for specific sites.

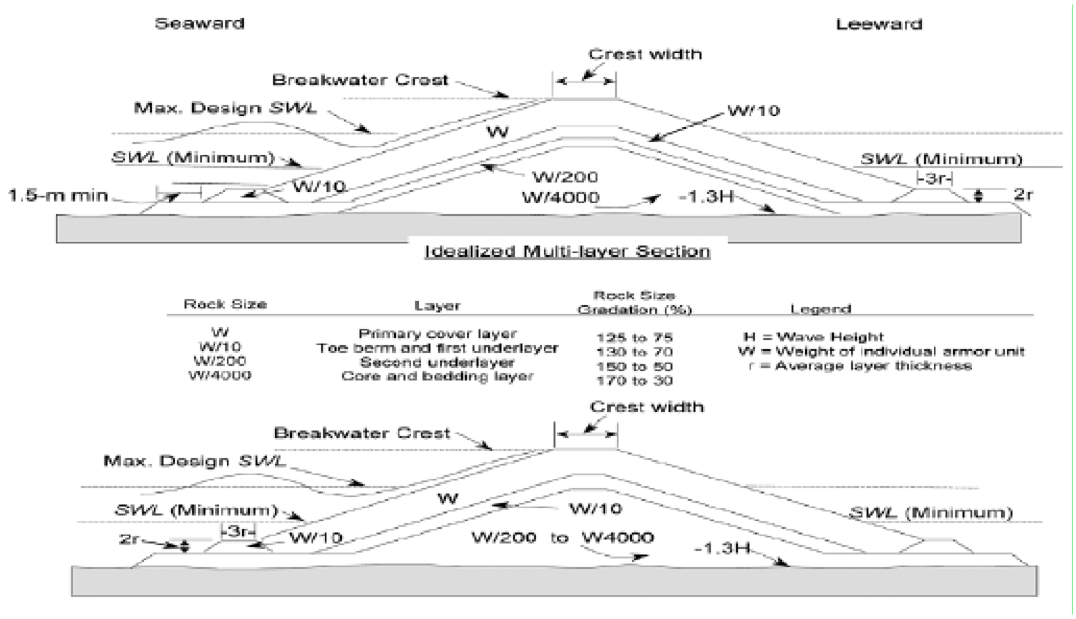
8.3 Design guidelines

During the design phase careful consideration should be given to crest and toe elevation, slope, material and underlayer design. Particular care should be taken regarding the function of the revetment. These notes largely relate to providing foreshore protection from erosion as opposed to flood protection or levee banks. The revetment structure includes a sloping profile, a larger external layer (primary armour) that overlays a finer rock layer (thus providing a filter system) and geotextile fabric throughout the under layer. A typical design section is included in Figure 8.4. A range of design references is included in Appendix A.



Source: USACE (2006)

Figure 8.4 Typical section — revetment



Source: USACE (2006)

Figure 8.5 Weight ratios for rock sizes in rubble mound structure

There are several approaches used by engineers to design revetments. Typically, first principle design approaches are available for determining armour size, wave overtopping and filter specifications, as summarised below.

Armour size — wave dominated reaches

Determination of an appropriate armour size for a revetment requires an understanding of the design wave characteristics, revetment slope, rock density and expected maintenance regime. The 'Hudson's equation' is a method widely used by engineers to determine armour size in wave-dominated environments. A range of stability coefficients (KD) are provided in USACE (2006) for different revetment configurations.

$$\frac{H}{\Delta D_{n50}} = (K_D \cot\alpha)^{1/3} \quad \text{or} \quad M_{50} = \frac{\rho_s H^3}{K_D\left(\frac{\rho_s}{\rho_w} - 1\right)^3 \cot\alpha}$$

where	H	Characteristic wave height (H_s or $H_{1/10}$)
	D_{n50}	Equivalent cube length of median rock
	M_{50}	Medium mass of rocks, $M_{50} = \rho_s D_{n50}^3$
	ρ_s	Mass density of rocks
	ρ_w	Mass density of water
	Δ	$\left(\rho_s / \rho_w\right) - 1$
	α	Slope angle
	K_D	Stability coefficient

Source: USACE (2006)

Figure 8.6 Hudson's equation

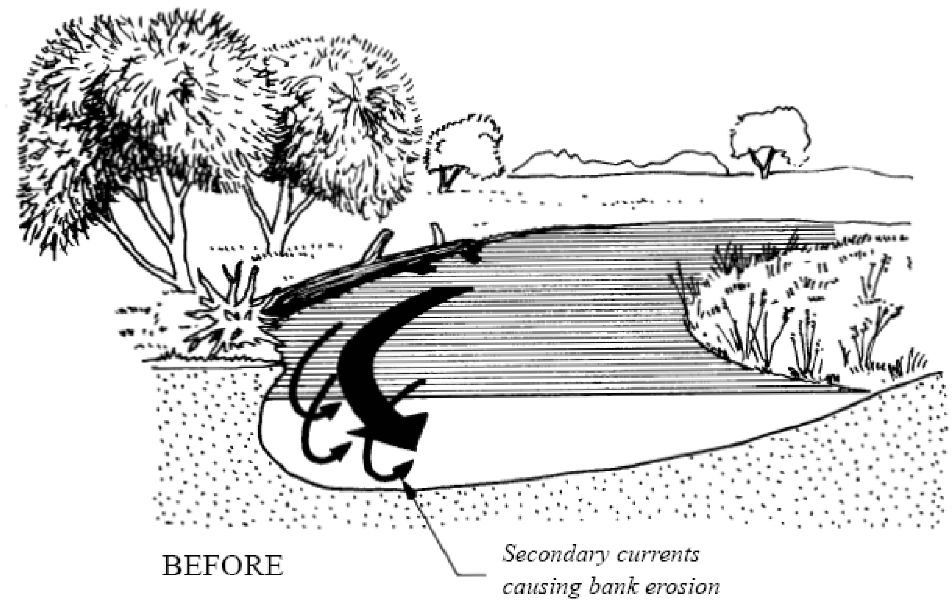
The required armour size depends on the rock density. Rock density in the Perth region varies from approximately 2.3–3.0 tonne/m^3 for granite and 1.2–2.4 tonne/m^3 for limestone. The density of limestone can be highly variable throughout a quarry and should be tested before use in a revetment. Dense armour units of the same mass will be more stable against wave attack.

Where a limited range of armour material is available, the revetment slope and layer thickness can be varied to accommodate the available armour type and available size range.

Armour size — current dominated reaches

Biedernharn *et al.* (1997) provides an excellent overview of the approach and design considerations for revetments in current-dominated reaches. More detailed references outlining empirical approaches to the hydraulic stability of armour include Pilarczyk and Breteler (1998), and BAW (2005).

Biedenharn *et al.* (1997) notes that design considerations include the design discharge, tractive force and permissible velocity, secondary currents (Figure 8.7), variation in river stage, elevation of protection, wave and vessel forces and protection against toe scour. In particular, it is noted that secondary currents are often complex but can be fundamental to the mechanisms of bank failure, and may influence the effectiveness of various types of bank and channel stabilisation. Typically in the Swan Canning river system, armour units range in size from 0.2 to 0.6m in diameter.



Source: WRC (2001a)

Figure 8.7 Secondary currents causing bank erosion

Crest elevation — wave-dominated reaches

The crest elevation in a wave-dominated reach is typically based on an acceptable level of wave overtopping, which would depend on the values and uses of the land immediately behind the revetment. Guides exist for determining an acceptable level of overtopping based on threshold overtopping discharges (USACE 2006, CIRIA 2007). Generic thresholds have been determined with regard to: safety of traffic (either vehicles or pedestrians); or structural safety (no damage, damage if promenade is not paved and damage if promenade is paved).

Crest elevation — current-dominated reaches

It is recommended that the crest elevation in current-dominated reaches be set as a level equal to the design flow level plus a margin for freeboard.

Layer thickness of rock filters

Factors such as permeability and interlocking need to be considered in designing rock filters. Where there is too great a difference in unit size between two adjacent layers, the smaller internal rock layer may be lost through the voids of the larger external armour layer. Geotextile fabrics placed between the rock and the earth reduce losses of bedding material. However, the type of material that can be placed directly on them without causing puncturing or rupture of the fabric is limited. While some tears can be repaired if they are accessible, larger tears can compromise the integrity of the filter layer. Granular filters can also be considered. USACE 1984a provides guidance on filter design.

Toe protection

Biederharn *et al.* (1997) notes two approaches to toe protection, 'dig it in' or let it 'self launch'. The first involves extending the toe to below the predicted scour depth or to a layer of hard, unerodible material. The self launch approach involves constructing the revetment behind the bank. As scour occurs, the protective material settles and prevents the scour moving further inshore. A common practice in Western Australia is to place large toe stones, embedded 0.3–0.5m below bed level with the revetment placed on top.

Care should be taken in ensuring a structure is deep enough to prevent scour. USACE (2006) notes that scour for a vertical wall is in the order of the maximum wave height expected at the wall. Scour at the toe of a sloping wall is generally less than for a vertical wall.

8.3.1 Loading

The hydraulic loads that should be considered in the design of a revetment include the design waves, water levels and current speeds.

The design wave in the exposed areas of the lower Swan River are often wind generated, particularly in those areas with a large south-west fetch (Damara 2006). However, in many areas of the river, boat wake is more significant than local wind waves.

Water levels to consider include tides, storm surges and river flood levels (Damara 2006). In the upper estuary, bank current speeds associated with winter rainfall and floods are significant and will be the principal design loading. Constrained areas close to the ocean entrance may also be subject to significant tidal currents (e.g. Pelican Point, East Fremantle).

Earth loads and surcharges behind the structure would also need to be considered by the designer if the angle of repose of the bank sediments is flatter than the revetment slope.

8.3.2 Considerations for detailed design

The detailed design for revetments is relatively straightforward, provided the design loadings have been properly considered and proper site investigation completed. Site investigations have been discussed previously in Section 3.1.

More generally, developing good quality, scaled and geographically referenced drawings, clear specifications, and an appropriate level of site supervision are critical to ensuring all facets of the detailed design are incorporated in the revetment construction.

With regard to drainage, consideration needs to be given to the restriction of the natural drainage paths by the structure, the drainage of overtopped water and relevant Trust policies for stormwater drainage.

Climate change should be incorporated in designs according to the most recent Department of Planning and Trust policies, based on Intergovernmental Panel on Climate Change (IPCC) predictions. Climate change is generally incorporated solely in terms of elevating design water levels. However, there is potential for increased storminess, flooding and increased wave energy transmission to the banks.

8.3.3 Design life/expected lifetime

The design life of revetments depends on the initial design conditions and maintenance regime. A robustly designed and constructed revetment should have a design life in excess of 20 years, with a modest degree of maintenance. Generally, a significant maintenance exercise would be required in the first few years of construction as the structure settles and is bedded down. Inspections undertaken biannually and following severe storms and floods would determine the ongoing maintenance requirements. Maintenance of well designed and constructed revetments should be limited to occasional repacking and replacement of armour. Other types of structures may be more dependent on the maintenance regime for their intended design life.

Responsive approaches to a severe erosion event (emergency works) often result in poorly sized and poorly interlocked dumped rock revetments. These structures may meet the immediate needs of the foreshore manager but require a high level of ongoing maintenance or significant upgrade to meet engineering standards, provide a reasonable design life and maintain the amenity of the foreshore.

8.3.4 Materials and equipment

The materials required to construct a revetment typically include limited range of rock classes, fill material and geofabric.

Rock can be obtained from commercial quarries. Typically, granite quarries are in the Darling Scarp and limestone quarries in the coastal regions. Contracts usually involve the supply, delivery and placement of material.

The equipment required depends on the scale of works, but typically involves excavators, trucks and a small work crew. Loaders or bobcats may be required for larger or smaller jobs respectively. The size of construction plant is often determined by the reach required during construction. However, in most situations, carefully staged construction can reduce the need for large construction plant.

8.3.5 Construction/installation

The construction sequence for a revetment is generally determined by the contractor undertaking the works in consultation with the client's supervisor. Stages involved in constructing a revetment include:

- site feature survey
- preliminary site meeting to discuss design and construction sequence
- site access and fencing (traffic management plans)
- demolition and excavation (preparation of site)
- construction of revetment (geotextile, rock & armour) including carting, dumping, placement and reworking
- as-constructed survey
- final site inspection
- cleanup, restoration and demobilisation.

Construction at these sites will be influenced by weather and site conditions and this should be considered in determining an appropriate construction window for the works.

8.3.6 Failure mechanisms

Failure mechanisms include armour displacement, toe scour, slumping, sliding, piping, and reduction in interlocking and overtopping damage. Failure mechanisms identified in the Swan River include subsidence and loss of sediment through the structure.

Generally, catastrophic failure of revetments is unusual as the structure's dynamic nature allows gradual settlement rather than complete failure. Routine inspection of the structure can identify damage and failure mechanisms and recommend an appropriate course of action.

8.4 Monitoring and maintenance

Monitoring of revetments is relatively straightforward and involves visual inspection (supported with photographs) of the structures using a standard assessment sheet. A biannual or post-event inspection by an experienced coastal engineer would generally be sufficient. This is to identify areas of damage or change since the previous inspection. Structures can be rated in terms of condition and performance (Damara 2006). More detailed inspection assessments are also available (USACE 1998).

Maintenance can be undertaken on individual structures by the land manager's workforce or as a wider, coordinated approach. Shared maintenance contracts between land managers for a wider stretch of the river could be considered.

8.5 Cost

Construction costs (particularly at the time of writing) are highly variable and can escalate rapidly. For example, unit rates to supply, deliver and place limestone armour can vary from less than $20/tonne to more than $40/tonne. Factors influencing price include proximity of quarry, availability of required size range, demand, site access and complexity of design. Unit rates for the construction plant and operators can vary from less that $50/hr for smaller bobcats to more than $200/hr for larger excavators and loaders.

Generally, lower unit prices are expected for rates schedules or construction plant hire contracts where the risk of quantity estimates is borne by the principal rather than the contractor. Lump sum contracts can provide the principal with greater certainty upfront but can be more expensive where the actual quantities of rock and construction time are subject to some uncertainty. This is particularly the case where the construction period is heavily influenced by weather and predicting the time for construction is difficult.

A price schedule for a larger revetment should typically include the following items.

- Preliminaries: insurances; mobilisation of plant and equipment; site establishment; survey; construction management plans.
- Materials (supply, deliver and place): armour (various size ranges or classes) core; geotextile.
- Plant hire: excavator; loader
- Reinstatement works: as-constructed survey; demobilisation; and site clean-up.

In general, the cost per metre of foreshore protected can be relatively high for revetments (compared with other techniques). However, this technique provides a high degree of erosion protection and security to high value assets.

Cost estimates are based on 2008 prices from various Western Australian suppliers (Table 8.2). These figures should be used as estimates only and quotes from suppliers should be obtained when producing final budgets.

In addition, costing should be included for maintenance and monitoring. Monitoring should include (at a minimum) annual or biannual engineering inspection, including a site visit and report. The budget requirements for maintenance and monitoring should be determined on a site-by-site basis. However, in the interest of approximating costs for budgeting, estimates for self-adjusting rock revetments are approximately one to two per cent of total initial capital costs per year (accrued until maintenance is about 25 per cent of initial capital cost).

Table 8.2 Cost estimates for key elements to implement rock revetment protection

ITEM	APPROXIMATE COST (EX GST)
Limestone rock	\$30 – \$60/tonne
Granite rock	\$45 – \$85/tonne
Filter size rocks (limestone ,density of 1.8 tonne/m3) 1) 0.1 – 0.3m diameter (2-15kg) 2) 0.3 – 0.6m diameter (50-225kg)	 \$50 tonne plus travel cost of \$0.20/tonne/km \$45 tonne plus travel cost of \$0.20/tonne/km
Sediment fill	\$5 – \$15/tonne
Crushed stone	\$15 – \$20/tonne
Gravel fill	\$50 – \$100/tonne
Labour for installation	\$40 – \$80/hour
Site supervisor	\$110 – \$150/hour
Drainage	\$65 – \$250 each
Shotcrete	\$250 – \$450/hour
Soil compactor	\$95/day
Excavator	\$90 – \$140/hour
Truck and transport costs	\$80 – \$90/hour

Note: Costs sourced from Rawlinsons (2008) and various WA suppliers (2008)

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9 Geotextile revetments

9.1 Description

Geotextiles can be used in a variety of ways to protect eroding foreshores, including as a soil retaining layer under a revetment structure, as geofabric sand containers forming the armour units of an interlocked revetment, and as concrete filled scour mattresses. The dimensions, strength, thickness and application of fabrics can vary considerably.

In this section, the main focus is placed on geotextile sand containers (GSC). GSC are typically available commercially as ready-made containers or mattresses. They may require specialised filling and placement apparatus. Commercial names include: Elcorock®, Elcomax®, Terrafix®, Softrock® and bidim®.

The advantages of the GSC include flexibility in application, a 'soft' finished product and moderate design life (>10 years) in appropriate applications. Limitations include: vulnerability to puncture during construction and placement; and vulnerability to vandalism, puncture by debris, vessel strike and ultra-violet degradation.

9.1.1 Case studies and examples

More than 40 revetments have been identified along the lower Swan River foreshore (Damara 2007; Oceanica *et al.* 2007). However, the presence of geofabric cloth beneath existing revetments is difficult to identify. At the time of writing, no purpose-built GSC have been constructed in the Swan Canning river system. Temporary sand bags or cement stabilised bags may have been used for emergency works.

GSCs have been used in coastal environments for foreshore protection, including as buried revetments along the Rockingham foreshore, seawalls in Geographe Bay (Figure 9.1) and to construct groynes adjacent to the Busselton Jetty.

Source: Shore Coastal

Figure 9.1 Geotextile sand container revetment – Geographe Bay foreshore

The success of this technique, like many foreshore stabilisation techniques, depends on the appropriateness of the design for the site and the quality of construction.

Recently a geosynthetic revetment (ecocell©) was installed in the Swan River in the Town of Bassendean. This uses a stack of semi-rigid plastic forms with a honeycomb structure to retain soil (Figure 9.2). The ecocell acts as an earth reinforcement thereby making the soil mass a gravity revetment which is suitable only for low walling. The system relies on vegetation to establish on the outer face to prevent turbulence and pore pressure effects that causes sediment scour from in the honeycomb cells.

Source: Oceanica (2008)

Figure 9.2 Ecocell revetment on private land in the Town of Bassendean

9.2 Purpose and application

Geotextiles are used for filtration, drainage, separation and reinforcement. They can be used in revetment applications requiring a structure to protect foreshore assets. They are widely used to prevent the migration of fine soil particles through a structure.

GSC may be used to stabilise banks for the bank profile locations, channel planform locations and type of erosion processes presented in Table 9.1.

Table 9.1 Geotextile sand containers applicability

USEFUL FOR EROSION PROCESSES	
Description	**Feasibility**
Toe erosion with upper bank failure	
Scour of middle and upper banks by currents	
Local scour	
Erosion of local lenses/layers of non-cohesive sediment	
Erosion by overbank runoff	
General bed degradation	
Headcutting	
Piping	
Erosion by navigation waves	
Erosion by wind waves	
Erosion by debris gouging	
Bank instability/susceptibility to mass slope failure	
Erosion due to uncontrolled access (either boat launching, human or animal trampling)	
Erosion due to inappropriate focusing of drainage	
Enhance erosion due to sedimentation of the channel	
Erosion due to interruption of sediment transport	

PROFILE SPATIAL APPLICATION	
Description	**Feasibility**
Toe	
Midbank	
Top of bank	

HYDROLOGICAL GEOMORPHIC SETTING	
Description	**Feasibility**
Resistive	
Redirective	
Continuous	
Discontinuous	
Outer bends	
Inner bends	
Incision	
Lateral migration	
Aggradation	

Feasibility method

‘White’ = feasible

‘Grey’ = possibly feasible

‘Black’ = not feasible

9.2.1 Condition where practice applies

Geotextiles can be used in a wide variety of applications. GSCs may be used in preference to rock structures in high use locations where the ‘soft’ finish will provide better amenity. Care should be taking in applying appropriate hydraulic stability for GSCs. They have been used at:

- Busselton foreshore (groynes)
- Siesta Park (seawall)
- Maroochydore, Queensland (groynes)
- Adelaide foreshore (groynes)
- Byron Bay, New South Wales (seawall).

9.2.2 Complexity and sensitivities

The design of GSC structures, like all revetment structures, is based on consideration of erosion rates, causes of erosion, assets at risk and the requirement or otherwise to protect these assets. Design considerations of location, toe depth, crest level and structure length are important regardless of the materials used to build the structure.

Design considerations specific to geofabric mattings include the purpose of the geofabric (filtration, drainage, separation, reinforcement) and thickness and type of geotextile required to prevent damage during construction or the expected design life.

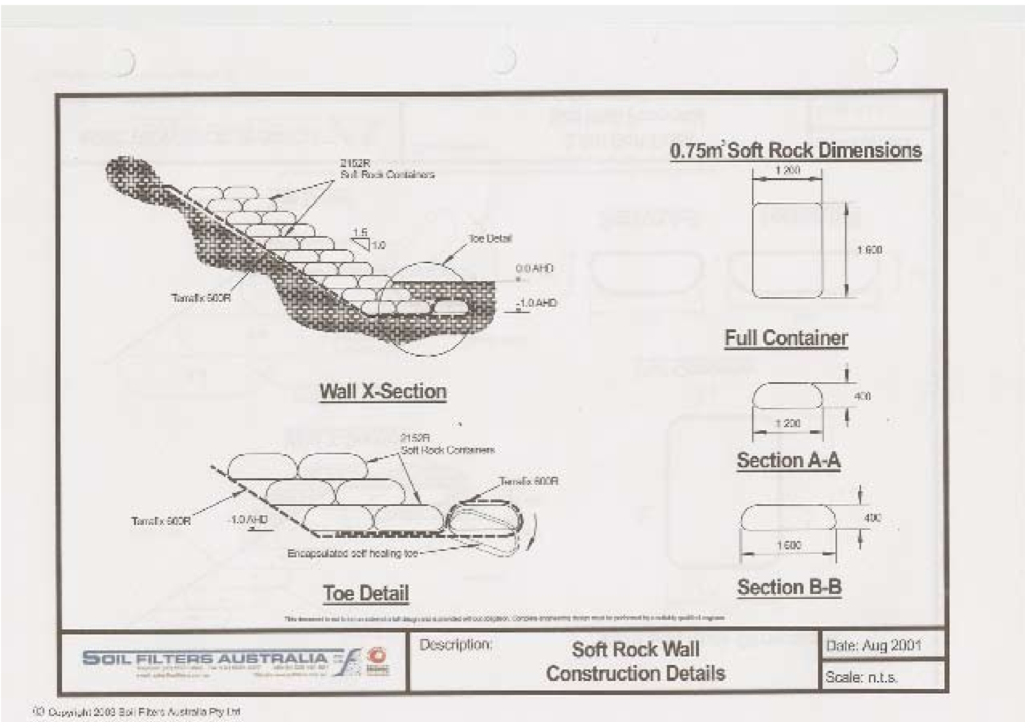
Considerations for GSCs include:

- stability criteria for determining the size of container required
- constructability of any design
- specialised equipment required for construction and its availability
- risk of vandalism, damage to fabric (debris and vessel strike) and ultraviolet degradation
- settlement or elongation of individual GSCs
- appropriate foundations
- ability to replace or repair damaged units.

9.3 Design guidelines

Geotextiles are generally specified by a brand name (or equivalent) or the required technical properties of the fabric. These properties include mechanical filter effectiveness, water permeability, durability, friction, impact resistance, adaptation to uneven surfaces, tensile strength and strain and creep. While international guidelines for specifying geotextiles are available (AASHTO M288-96) there does not appear to be a generic Australian Standard for geotextiles. Design references (Pilarczyk *et al* (1998) and Pilarczyk (1998)) provide sufficient information to undertake design. However, these references are empirical and should be applied with caution. Recent testing of GSC for applications in revetments has been completed by Manly Hydraulics Laboratory.

Design of revetment structures should be undertaken by experienced coastal engineers, however generic designs are provided by some manufacturers (Figure 9.3). In particular, the engineer should specify the crest and toe elevation of the wall and the required slope during detailed design.



Source: Geofabrics Australia

Figure 9.3 Geotextile sand container revetment - construction details

9.3.1 Loading

Basic stability criteria are available for GSCs (Pilarczyk *et al.* 1998). The criteria are expressed in a similar way as for rock revetments, namely in terms of the KD factor in Hudson's formula (Section 8) or in terms of a relationship between wave height, density and layer thickness.

GSCs available in Australia have recently undergone testing for stability under elevated water levels and wave attack. This involved more than 150 tests during an 18-month period. The NSW Water Research Laboratory conducted the tests for a local GSC supplier. The design curves from this testing will be available for future designs but are not publically available at present (Geofabrics Australia 2008).

There is a small range of containers commercially available in Australia (0.75m^3 and 2.5m^3). For inland waterway applications, such as the Swan River, the requirement to use larger 2.5m^3 containers would be rare.

9.3.2 Considerations for detailed design

Considerations for detailed design include: site investigations; design loadings; regional context; constructability; design life; and expected maintenance. Constructability issues include consideration of appropriate weather windows for works at a particular site.

Climate change should be incorporated into designs according to the most recent Department of Planning and Trust policies, based on Intergovernmental Panel on Climate Change (IPCC) predictions. Climate change is generally incorporated solely in terms of elevating design water levels. However, there is potential for increased storminess, flooding and increased wave energy transmission to the banks.

9.3.3 Design life/expected lifetime

The design life of the structure varies depending on its application. Care should be taken that warranties provided by the manufacturers indicating design life (e.g. 10–15 years) may only relate to the natural degradation of the geotextile fabric rather than integrity of the structure or the risk of damage by vandalism and debris. Like all foreshore protection structures, an appropriate maintenance regime is required. Removal of these types of structures is relatively straightforward, although complete recovery of all the geotextile material can be difficult.

9.3.4 Materials and equipment

Materials are generally proprietary geotextile products. The construction of GSC revetments would require the hire of specialised filling frames and lifting devices. These could be used by land manager works crews or earthworks contractors with the appropriate plant. Sand is required to fill the bags and water is pumped to the filling frame to create a slurry for filling the bags. In areas where the sand is not available locally it would need to be imported from further afield.

Sand for the GSCs should generally be sourced offsite. In some cases appropriate material may be available at the site (i.e. beach sand). Care should be taken to ensure the sand is appropriately specified and tested (coarse fragments can be abrasive, fines can leach). The manufacturer will generally supply the required equipment to fill and seal the bags. Smaller bags require sewing equipment to be supplied, while large bags are sealed by rope and a marine sealant.

The availability of the specialised equipment required to construct the GSCs (filling frame and J-bin) should be considered.

9.3.5 Construction/installation

The construction sequence for a revetment is generally determined by the contractor undertaking the works in consultation with the clients' supervisor. Stages involved in constructing a revetment include:

- site features survey
- preliminary site meeting to discuss design and construction sequence
- site access and fencing (traffic management plans)
- demolition and excavation (preparation of site)
- construction of revetment including filling, stockpiling, placement and reworking of GSC
- as-constructed survey
- final site inspection
- cleanup, restoration and demobilisation.

The contractor may consider filling the GSCs onsite and placing them directly on the structure. Filling and stockpiling bags during poor weather may improve productivity. There may also be instances where filling bags offsite may be considered, however this eliminates many of the techniques' advantages.

Figure 9.4 Placement of 2.5m^3 geotextile sand container

9.3.6 Failure mechanisms

Individual containers may break and leak due to puncturing, ultraviolet degradation of containers exposed to sunlight and movement of individual units by wave attack or inundation. These failure mechanisms should be considered during design. A common application is for the GSC revetment to be used as a back-up defence underlying renourishment sand. In this manner the sand provides protection against vandalism and ultraviolet degradation.

Catastrophic failure of the structure is unlikely in most designs where GSCs are used as individual units in a structure. Like rock revetments, movement or damage to individual units should not mean widespread damage to the structure.

9.4 Monitoring and maintenance

Recommended monitoring would include:

- construction supervision and documentation (site photographs during construction)
- as-constructed surveys
- visual inspections at appropriate intervals.

Maintenance required may include patching individual units, replacing units and installing additional units as required. Consideration should be given to stockpiling additional containers and access to filling apparatus. Patching kits can be supplied by the manufacturer and are relatively straight forward to apply.

Damaged GSCs can be repaired, provided the location and size of the fabric tear is reasonable. Repair involves patching with a similar geotextile material and an appropriate 'glue'. Screws may also be required to secure the patch.

Individual bags can be replaced on a coordinated or an opportunistic basis, if possible without affecting the structure's performance. Several bags can be replaced in one exercise, minimising the cost of mobilising and hiring the specialised filling and placement equipment.

9.5 Cost

Cost components for these types of structures include:

- mobilisation
- site establishment
- insurances (if required)
- materials (sand, fabric, containers)
- plant and equipment (filling frame, lifting and placing mechanism, closing apparatus (i.e. sewing machines, yarn and silicon), labour, site earthworks plant)
- labour.

Care should be taken in estimating the production level (i.e. bags filled and placed per hour), site access, influence of weather and sea state, and estimated design life and maintenance requirements.

The price of individual bags can vary from less than $200 to more than $500. However, the material costs will only be a percentage of the total construction costs, which also include approvals, design, transport, labour, machinery hire and sand.

Cost estimates are based on 2008 prices from various Western Australian suppliers (Table 9.2). These figures should be used as estimates only and quotes from suppliers should be obtained when producing final budgets.

In addition, maintenance and monitoring costs should be included. Monitoring should include (at a minimum) annual or biannual engineering inspection, including a site visit and report. The budget requirements for maintenance and monitoring should be determined on a site-by-site basis. However, in the interest of approximating costs for budgeting, estimates for GSC revetments are approximately two to three per cent of total initial capital costs per year (accrued until maintenance is about 25 per cent of initial capital cost).

Table 9.2 Cost estimates for key elements to implement geotextile sand container protection

ITEM	APPROXIMATE COST (EX GST)
Geotextile sand container bags	$20 – $180 each
Sediment fill	$5 – $15/tonne
Geotextile filter cloth	$2 – $5m2
Crushed stone	$15 – $30/tonne
Labour for installation	$40 – $80/hour
Site supervisor	$110 – $150/hour
Excavator	$90 – $140/hour
Truck and transport costs	$80 – $90/hour

Note: Costs sourced from Rawlinsons (2008) and various WA suppliers (2008)

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