Indirect shore stabilisation approaches

A number of stabilisation techniques redirect flow or modify sediment transport to reduce erosive forces on a bank or bed. Three of the most common techniques are discussed in this section.

- Renourishment replacing eroded bank material to act as sediment source for adjacent foreshores after subsequent erosion.
- Groynes and headlands narrow structures constructed perpendicular to the shore (with renourishment) that reduce alongshore sediment transport, capturing sediment on the updrift side of the structure.
- Flow modification (large woody debris) felled trees placed against or on river banks to deflect/dissipate erosive currents and encourage sediment deposition at the base of eroding banks.

The three techniques are compared 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 indirect shore stabilisation techniques

Technique	PURPOSE	ADVANTAGE	LIMITATIONS	DESIGN LIFE & MAINTENANCE LEVELS	COMBINATION OPPORTUNITIES	Costs[1]
Renourishment	Replace eroded material Maintain a reasonable level of protection to the adjacent foreshore reserve from erosion	Foreshore protection provided without hard structures Restore a foreshore to its original appearance Rapidly and easily constructed Immediately effective	Availability and cost of suitable material Longevity of renourishment	Ranges from one year (i.e. an annual operation) to a number of years	Longevity of renourishment will improve if combined with secondary structures (e.g. groynes) Sills Revegetation Renourishment of beaches in front of any hard structure	Medium
Groynes and headlands	Protect foreshore assets whilst maintaining the public amenity of an existing sandy beach	Stabilise severely eroding shorelines without sacrificing the sandy beach/ foreshore Increases the effectiveness of medium to large sand nourishment projects	Risk of downdrift erosion Reduced effectiveness on beaches/ foreshores with significant reversals in sand movement	A robustly designed and constructed rock and/or Geotextile Sand Container (GSC) groyne should have a design life in excess of 20 years with a modest degree of maintenance	Groynes and headlands should always incorporate renourishment Often used in conjunction with toe protection/ low elevation structures in between groynes and headlands	High
Large woody debris	Deflect or dissipate erosive flows from an eroding bank and promote the deposition of sediment at the bank base	Armoured banks directly and can modify channel planform Promotes sediment deposition and revegetation Creates aquatic habitat and is aesthetically appealing	Armoured banks directly and can modify channel planform Promotes sediment deposition and revegetation Creates aquatic habitat and is aesthetically appealing	5–15 years if anchoring does not fail	Revegetation Any other forms of toe stabilisation Bioengineering Channel excavation Renourishment	Medium

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

2 Renourishment

2.1 Description

Renourishment involves replacing eroded bank material with a suitable, imported fill material. This is one of the most common shore stabilisation techniques used internationally. It is also known as nourishment, sand nourishment and replenishment. The technique's main advantages are:

- provides a reasonable level of foreshore protection without the introduction of hard structures;
- restores a foreshore to its original appearance;
- can often be rapidly and easily constructed;
- can be effective immediately; and
- can be undertaken with minimal disturbance to the surrounding foreshore, particularly where there is existing vehicle access to the foreshore or beach.

Renourishment can improve the amenity of a foreshore area by enhancing a sandy beach for river users. Provided proper site investigations are undertaken and the site is suitable, renourishment can provide foreshore protection for a reasonable design life and modest cost, while also improving public amenity of the foreshore.

Limitations include availability and cost of suitable material, and the longevity of the renourishment.

This technique differs from river reclamation, as renourishment replaces material lost from erosion, whereas reclamation aims to move the shoreline riverward of its historic location. Large-scale reclamation works in the Swan Canning river system between the 1920s and 1970s through the Public Works Department (Riggert 1978) include the reclamation of the Como foreshore to construct the Kwinana Freeway. Como foreshore has experienced progressive loss and thinning of the reclaimed beach, as have a number of other reclamation projects (Eliot et al. 2006, MRA 2010). This erosion is often episodic and is dependent on prevalent wind and wave conditions and high water level events. Additionally, instability at many sites, along with the desire to improve foreshore amenity, resulted in the construction of walling along the majority of Perth, South Perth and Nedlands reclaimed shores.

Significant channel excavation projects were also completed on the Swan Canning river system between the 1920s and 1970s. This was typically undertaken to improve navigation, to reclaim foreshores, for pool excavation to improve aquatic habitats or for sand extraction to use as a source for renourishment or construction. Channel excavation is not discussed further in this chapter, however references on this technique can be found in Appendix A.

2.1.1 Case studies and examples

Renourishment around the Swan River has typically been at much smaller scales than reclamation. Renourishment works are often implemented in response to foreshore damage caused by extreme events. The effective lifetime of renourishment is determined mainly by exposure at the site.

Intermittent renourishment has occured in front of Zephyr Cafe in East Fremantle. Sediment was sourced from various locations around the Swan River and placed at the site following storm events with high water levels and wind waves.

In 2009, a larger renourishment project at the Sir James Mitchell Park foreshore in South Perth was completed using approximately 4000 m of imported sand, forming five beaches. This nourishment was placed between a number of low, rock groynes. Figure 2.1 shows the nourished beaches constructed at Sir James Mitchell Park.

Source: MRA (November 2010) Sir James Mitchell Park

Figure 2.1 Sir James Mitchell Park Beach Nourishment

Beach monitoring between 2009 and February 2011 suggest the majority of the beaches are stable with the Mends Street beach losing some sediment (MRA 2011). Ongoing monitoring allows changes in the nourishment to be quantified and provides useful information to assist with beach management and future nourishment. Further details of the Sir James Mitchell Park groyne design are included in Chapter 3 - Groynes.

2.2 Purpose and application

The primary purpose of renourishment is to replace eroded material and maintain a reasonable level of protection to the adjacent foreshore reserve from subsequent erosion. The renourishment effectively becomes a sacrificial barrier to erosion for the adjacent foreshore reserve. This technique is more applicable to sandy estuarine beaches subject to gradual or storm erosion than a site where an established river bank has eroded or collapsed.

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

Table 2.1 Renourishment applicability

USEFUL FOR EROSION PROCESSES	
Description	**Feasibility**
Toe erosion with upper bank failure	
Scour of middle and upper banks by currents	1
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	
Enhanced erosion due to sedimentation of the channel	
Erosion due to interruption of sediment transport	

PROFILE SPATIAL APPLICATION	
Description	**Feasibility**
Deep channel	
In-channel adjacent to eroding bank	
Upstream/downstream 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

Renourishment is particularly appropriate in wave-dominated, low energy sites with a relatively shallow nearshore area and high public use. It can effectively replenish an existing beach that has been progressively losing material through erosion or storm damage.

This technique can re-establish estuarine beaches for public uses, such as kayaking, wind surfing, boating and swimming.

Renourishment is not suitable for sites where riverbed sedimentation is a management concern, or at sites with steep banks, as this would likely result in a rapid loss of material.

2.2.2 Complexity and sensitivities

Renourishment is a soft engineering foreshore management technique. This means the renourished foreshore may be subject to considerable change under extreme conditions or predominant coastal processes. Subsequently, managing a renourished foreshore requires understanding of the potential impact of a severe erosive sequence, with a minimum width buffer defined for this purpose, as well as a general understanding of the dominant coastal processes in the area.

Some complexities and sensitivities to consider in design of renourishment projects include:

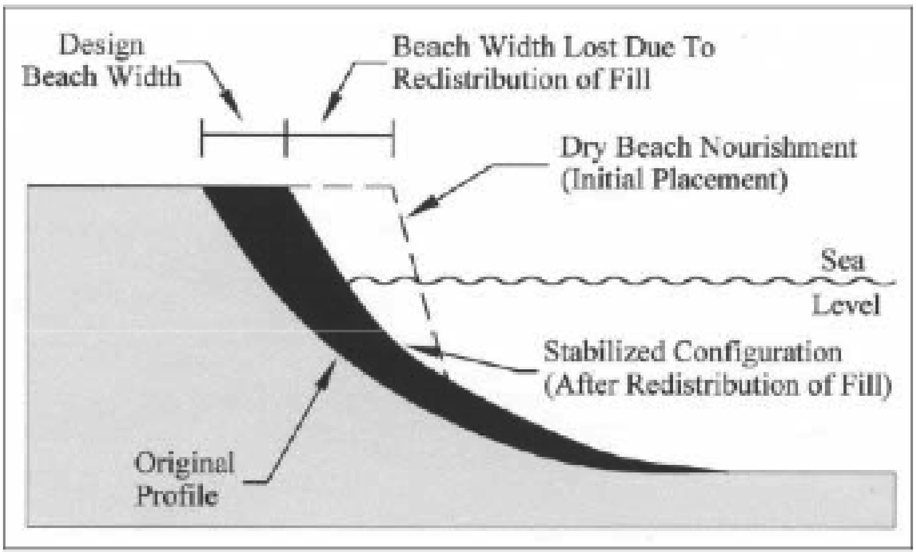
- The design profile that the sand is placed at or graded to (including an allowance for natural reworking of profile by waves).
- The type of material. High rates of erosion can occur if the imported (borrow) material has a greater proportion of finer particle sizes than the existing (native) material.
- Turbidity. Excessive fines in the nourishment material can cause excessive turbidity. However, a strict specification with minimal fines may make material difficult to source and expensive. Silt curtains may be required during the placement of the beach nourishment to manage turbid plumes.
- Contaminants. Nourishment material should not have concentrations of bioavailable metals or persistent organic contaminants that exceed ANZECC/ARMCANZ (2000) sediment quality guidelines. These should be tested by a certified NATA-accredited lab unless the supplier can provide documented assurance.
- Aesthetics. Appropriate nourishment material should have similar colour to the existing material and be free from debris.
- The location of appropriate material. Commercial sandpits may be a considerable haul distance from some sites. Relocating material from nearby areas of accretion (sand buildup) can be effective but should not be completed without an understanding of sediment movement along the shoreline adjacent to where you are removing sand, as taking sand from one area may cause erosion problems in other locations.
- Potential for wind blown sand issues for areas of wide nourishment beach fills. Stabilisation techniques such as brushing and fencing (to keep public off the beach fill) may be required to reduce these issues.
- Traffic management, access and site management. These items should be planned well ahead of contruction, especially for sites that are difficult to access (near busy roads etc) or popular recreational locations (beaches near cafes etc).

2.3 Design guidelines

The design and implementation of a renourishment exercise is relatively straightforward. Small nourishment projects (ca. <250 m^3) can typically be undertaken by foreshore land manager works crews, earthworks contractors or sand suppliers. The main consideration is ensuring the technique is appropriate for the site and a basic design process has been undertaken to determine the volume and type of material required.

For larger projects (ca. > 250 m^3) it is recommended that an experienced coastal engineer undertake a coastal processes study to determine if nourishment is an appropriate option for the site. This ensures sand is not placed in an area likely to lose sediment quickly through wave or current action.

The design beach width needs to account for extreme erosion events and ongoing erosion trends over the design life of the nourishment. Figure 2.2 presents a typical beach fill placement as well as the reworked profile following redistribution of sediment under the action of waves, currents and water levels.



Source: Bendell (2006)

Figure 2.2 Schematic foreshore profile-renourishment

The particle size distribution (PSD) of the native material, renourishment ratio of the proposed nourishment material and design profile are then used to calculate the volume of material required for the initial beach fill, as well as any ongoing/annual beach nourishment volumes.

A sample of the existing beach material is required to determine the PSD. Figure 2.3 shows an example of a PSD grading curve.

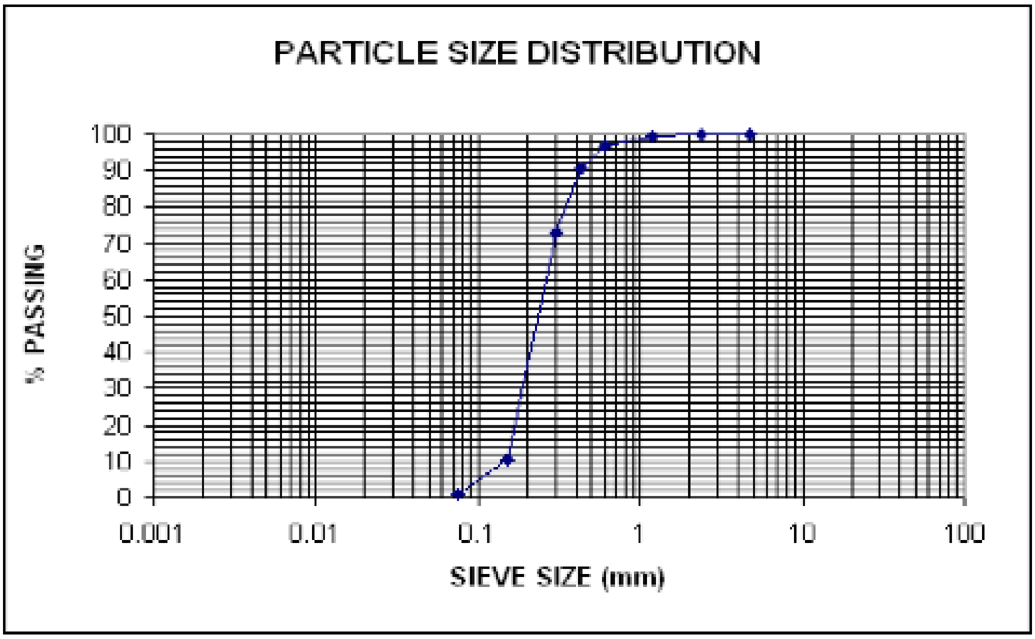


Figure 2.3 PSD Grading curve

Generally, a number of samples (to depth of active sediment movement) for the swash or tidal zone on the beach are required. An additional sample should be collected from the landward extent of active processes (such as the toe of a dune, beach ridge or landward extent of sand). A sufficient quantity of sand must be sampled to allow the laboratory to undertake a PSD analysis. Approximately 100 g of sediment per sample is sufficient to complete a PSD. The laboratory will supply a PSD curve (as shown in Figure 2.3) identifying the median grain size (d_{50}) and percentage of coarse and fine material.

The renourishment ratio is a measure of the size of the nourishment material in relation to the native material. A higher renourishment ratio means the nourishment material is finer than the native material and a larger volume of sand will be required to achieve the desired foreshore protection. Renourishment ratios are safety factors applied to estimated volumes of nourishment sediment to ensure that the desired volume is achieved.

2.3.1 Loading

The use of similar material will ensure the new beach is able to accommodate similar loadings to the previous beach. If sediment is placed too steeply on the beach it will be rapidly reworked by wave and tide action, which may result in erosion scarps. Coarser materials will typically lead to a steeper beach profile.

2.3.2 Considerations for detailed design

Detailed design considerations are minimal for a small renourishment exercise. For larger projects (ca. > 250 m^3) consideration should be given to detailed survey, modelling a design profile and investigating the full range of options for sourcing material.

For larger projects secondary structures, such as a groyne, to hold renourishment material should also be considered. The additional capital cost for small structures may be offset by reduced losses of renourishment material. The potential for downdrift erosion would need to be considered in detail if a groyne was to be implemented. The placement of a sill (a raised rock toe placed at depth) creates a perched beach and could reduce the quantity of sand required for renourishment. The sill could potentially extend the life of the nourishment project.

An experienced coastal engineer should be consulted before designing any secondary structures for renourishment projects.

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.

2.3.3 Design life/expected lifetime

The design life for many renourishment exercises on the Swan River would range from one year (i.e. an annual operation) to a number of years. Sites that have been actively managed for a number of years by renourishment provide the greatest certainty in predicting design life (i.e. placing 500 m3 every two years for the last ten years gives a reasonable expectation of a two year design life for subsequent projects). However, care should be taken in assuming a direct relationship between renourishment volume and design life. For example, doubling the renourishment volume may not necessarily double the design life as greater losses could be expected for a more unstable beach profile. Likewise, a design life cannot be guaranteed as large erosion events such as storms or higher than normal tides could rapidly remove sediment.

2.3.4 Materials and equipment

Materials are generally limited to the required sand. Equipment required ranges from small trucks and a bobcat for smaller projects to semi trailers and loaders.

2.3.5 Construction/installation

As mentioned in the complexity and sensitivity section of this chapter, traffic management, access and site management are important project aspects, and should be well thought out and planned before works start. Care should also be taken to prevent damaging adjacent foreshore vegetation or parkland during construction.

Construction typically involves back tipping sand in the required location and spreading the material to a design profile. This profile will be naturally graded to a finished profile by wind and wave action. Silt curtains may be required during the placement of beach nourishment to manage turbid plumes, particularly in sensitive environmental areas or if fine sediments are contained in the nourishment material.

Dune stabilisation, such as placing brush or planting native vegetation, may be needed to reduce the effects of wind blown sand. Brush should be kept above the high water mark to prevent debris entering the river. Temporary fencing should be installed to prevent public access to areas undergoing dune stabilisation.

2.3.6 Failure mechanisms

The main failure mechanism is erosion of renourishment material over time. This cannot be avoided but it should be recognised that in many places (typically within the estuary) sand moves offshore during a storm (i.e. the visible beach is eroded) but returns to the shore during normal wind, wave and tidal action within a number of weeks. However, there are areas with offshore sinks (deep channels) where material will not return naturally.

2.4 Monitoring and maintenance

Maintenance and monitoring can be as simple as an experienced foreshore manager visually monitoring the site and undertaking additional renourishment exercises as required.

For larger exercises, fixed survey profiles should be taken before and a successive period after renourishment (annually, biannually or seasonally) to monitor performance. Additional renourishment can be completed as required.

2.5 Cost

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

Cost considerations include the volume of material required, mobilisation costs and the unit cost of the material. Specific considerations include:

- Payment for renourishment material in either tonnes or cubic metres. While cubic metres are typically used for design purposes, commercial sandpits typically work in tonnes as this is directly related to the haulage costs.
- Significant cost savings can be made by sourcing material locally in areas of nearby accretion. However, this should only be completed if sediment movement where nourishment material is sourced is well understood.
- Wet sand (winter) can be more expensive to cart than dry sand (summer), although stockpiling sand prior to loading and carting can reduce costs.
- Consideration needs to be given to the bulking of sand during excavation and trucking. This is the process of air moving into the spaces formed between disturbed sand particles, which can increase the volume of trucked material between 10 to 20%.

In addition, costing should be included for maintenance and monitoring. Maintenance and monitoring costs for indirect stabilisation techniques require detailed site-specific estimates and do not lend themselves to simple approximations.

Table 2.2 Costs estimates for key elements to implement renourishment protection

ITEM	APPROXIMATE COST
Sediment fill (raw feed from sandpit)[1]	\$5-\$15/tonne
Crushed stones	\$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)

[1] Washed sand is likely to be much more expensive than raw feed

2.6 References

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Riggert T 1978, *The Swan River Estuary: Development, Management and Preservation*, Perth, Western Australia.

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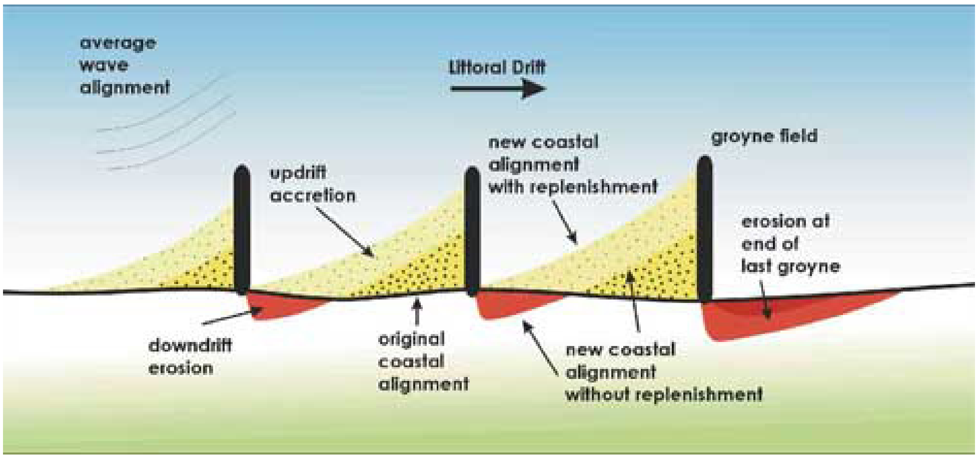
3 Groynes and headlands

3.1 Description

Groynes (spelt 'groins' in the USA) are generally narrow structures constructed perpendicular to the shoreline. Groynes capture sand on the updrift side and can cause erosion on the downdrift side. A series of groynes along the shoreline, called a groyne field, results in a saw-tooth-shaped beach with a different beach level on either side of the structures, as shown in Figure 3.1.

Groynes are sometimes referred to as headlands, which are typically built around existing features such as drainage outlets. Headlands can also describe an offshore structure not connected to the foreshore and often constructed on the open ocean coastline.

The design of headlands requires consideration of crenulated bay theory and is generally only appropriate in low wave energy environments (Silvester & Hsu 1997). For the purposes of this report, headlands are shore connected structures like groynes.



Source: Reed (2010)

Figure 3.1 Typical groyne field layout

Groynes are generally constructed using rock, timber and more recently Geofabric Sand Containers (GSCs).

The advantage of groynes is they can stabilise severely eroding shorelines without sacrificing the sandy beach or foreshore. Groynes can increase the effectiveness of medium to large sand nourishment projects. Effectively the sandy beach becomes both the shoreline protection system and a high amenity public recreational area. While there will always be some uncertainty in predicting the response of a shoreline to groyne structures, particularly in estuaries where there can be a wide range of forcings, there is an established body of knowledge on their design and construction (USACE 2006).

Limitations include the risk of downdrift erosion (if groynes are not saturated with sand during construction), potentially reduced effectiveness on beaches or foreshores with significant reversals in sand movement, and the potential reduction of amenity associated with segmenting long sections of foreshore. Groynes may have limited success in reducing flow velocities on the outside of river bends in most areas upstream of the Causeway on the Swan River and upstream of the Nicholson Road Bridge on the Canning River, due to relatively low river flow. The equivalent shore-perpendicular structures for current-dominated reaches are baffles, spurs and the use of large woody debris.

Groyne construction in the Swan Canning Riverpark is generally discouraged unless the reason and objectives are clear, impacts on downdrift foreshore or navigation channels are minimised, and other methods are deemed unsuitable (Swan River Trust 2002b).

3.1.1 Case studies and examples

There are a number of groynes on the lower Swan River:

- the Coombe in Mosman Park
- Nedlands (Nedlands Yacht Club)
- the Narrows Boat Ramp
- East Fremantle (Swan Yacht Club and Aquarama)
- Como Foreshore (Comer Street Footbridge)

The 2009 Sir James Mitchell Park project on the South Perth foreshore is an excellent example of a groyne and beach nourishment project on the Swan River. Groynes or low headlands trap sediment and maintain the desired beach width with ongoing monitoring and minor renourishment. Some of these groyne structures are presented in Figure 3.2.

Source: MRA (September 2009)

Figure 3.2 Groynes in the lower Swan Canning river system at Sir James Mitchell Park, South Perth

The groynes at Sir James Mitchell Park protect existing trees and incorporate existing storm water drainage outlets. They have been planted with native vegetation as shown in Figure 3.2.

Groyne structures along the Perth open ocean coastline in higher energy wave environments with much larger volumes of sediment transport include the training walls at the Port of Fremantle for the Swan River entrance, South Beach groynes and Cottesloe Groyne.

3.2 Purpose and application

Groynes protect foreshore assets while maintaining the public amenity of an existing sandy beach. Generally, this requires combining groyne construction with ongoing sand nourishment.

Groynes may stabilise banks for the bank profile locations, channel planform locations and type of erosion processes presented in Table 3.1.

Table 3.1 Groyne 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	
Enhanced erosion due to sedimentation of the channel	
Erosion due to interruption of sediment transport	

PROFILE SPATIAL APPLICATION	
Description	**Feasibility**
Deep channel	
In-channel adjacent to eroding bank	
Upstream/downstream 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, see table notes

'Black' = not feasible

3.2.1 Condition where practice applies

Groynes are generally constructed in environments with wave-driven alongshore sediment transport and persistent and ongoing erosion. These sites are generally wave-dominated beaches on the lower estuary rather than the current-dominated upper reaches of the Swan and Canning rivers.

Groynes are more effective along beaches with largely unidirectional sediment transport. While there may be some negative public perception of groynes, they are generally only considered on higher use public beaches or foreshores where the construction of a revetment would lead to an unacceptable loss of the public beach and amenity.

Groynes contructed from GSCs may be more appropriate in high use public areas, as they are 'softer' under foot and are often perceived as less intrusive than rock structures.

3.2.2 Complexity and sensitivities

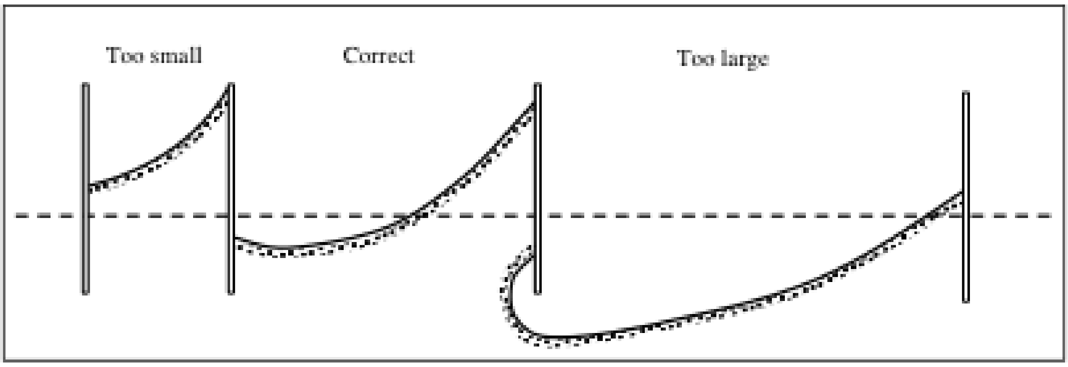
Significant investigations are generally required before constructing a groyne or series of groynes. These include consideration of erosion rates, direction and reversals of longshore transport, and, if offshore transport is dominant, nearshore bathymetry and geotechnical considerations.

For example, groynes will not be effective if the zone of major sediment transport is largely offshore due to a shallow nearshore bathymetry and offshore bars. The downdrift implications of a groyne system should always be considered carefully. In areas of strong alongshore currents, maximum downdrift erosion may not be located directly in the lee of the groyne.

A related consideration is that many structures such as boat ramps and stormwater drains act as groynes without this being their primary or intended function. In particular, the risk of downdrift erosion from structures that unintentionally act as groynes should always be considered carefully. Ongoing renourishment may be required in some areas to mitigate erosion.

3.3 Design guidelines

The design of groyne/s should be completed by an experienced coastal engineer familiar with coastal structure design. Once it is decided that a groyne is required, preliminary design considerations should include the length, location, spacing (Figure 3.3) and number of groynes.



Source: Perdock (2002)

Figure 3.3 Spacing of groynes

Depending on availability of information on local sediment characteristics, sediment transport rates and the complexity of coastal processes at the site, various models can be used to assist with design. However, investigating the performance of existing groyne fields in similar environments should be an important component of the design process. This would include investigating historical aerial photographs, survey data, site photographs and understanding the local coastal forcings (waves, water level fluctuations and currents).

3.3.1 Loading

The main hydraulic loadings to be considered in the preliminary design phase are the wave- and tide-generated currents responsible for sediment transport. The potential for storms to quickly move large sediment volumes should be considered.

The loads associated with construction equipment should also be considered. For example a groyne constructed by end tipping rock must be able to support a fully laden rock truck and an excavator during construction. The estimation of design rock sizes using Hudson's equation is discussed in more detail in Part B, Chapter 8 Rock Revetments, Section 8.3 Design Guidelines.

3.3.2 Considerations for detailed design

Local wave heights and water levels can be used to determine the material used to construct the groyne. There are established stability criteria for relating wave heights and armour size for rock groynes. See Part B, Chapter 8 Rock Revetments, Section 8.3 Design Guidelines, for further detail. For additional information on GSCs also refer to Part B, Chapter 9 Geotextile Revetments.

Other considerations at the detailed design stage include:

- variability in rock density (particularly limestone);
- specifying rock quality ;
- armour class sizes and its influence on quarry yield and cost;
- geotechnical investigations (particularly in silty areas);
- core (consideration of average weight and grading is required);
- geotextile filter layer (for tie-in areas where soil is retained by the groyne); and
- site access for construction.

Generally, an experienced coastal engineer will determine detailed design considerations for a particular site and project. The scale and nature of the project and the peculiarities of the site will influence the level of detail required in the design.

A minimum rock diameter of approximately 0.4 m or 300 kg should be specified for the outer rock layer on groynes. This has a number of benefits, such as:

- reducing the potential for movement of rocks when people walk on the structure; and
- reducing the potential for vandals to displace the rocks by picking them up or rolling them down the structure.

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

3.3.3 Design life/expected lifetime

The design life of groynes depends on initial design conditions and the maintenance regime. A robustly designed and constructed rock groyne should have a design life in excess of 20 years with a modest degree of maintenance.

Timber groynes are more dependent on materials used and the maintenance regime. They are also vulnerable to marine attack. Generally they will have a lower design life than rock groynes. GSC groynes may also have a reasonable design life, provided the potential for ultraviolet degradation and vandalism are acknowledged in the design and a suitable maintenance regime implemented.

Groynes can be removed if no longer required, although total recovery of the materials may not always be possible. GSCs are generally more easily removed and can be used in particular cases as temporary structures. The implications of removing structures should be considered very carefully.

3.3.4 Materials and equipment

Materials generally used are rock, timber and, more recently, GSCs.

The equipment required for construction depends upon the materials used. Generally a combination of earthmoving plant (excavator, loader, backhoe) and trucks are required for a rock groyne. GSCs require specialised filling, lifting and closing apparatus that can be hired from the manufacturer. The availability of this specialised equipment should be considered carefully for its impact on construction timelines.

3.3.5 Construction/installation

The basic construction process is as follows:

- 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);
- groyne construction;
- as constructed survey;
- final site inspection; and
- cleanup, restoration and demobilisation.

Care should be taken to ensure the core design has sufficient elevation to allow construction using this method. Lower levels requiring barge access will result in a more expensive structure. Care should also be taken to ensure large sections of core are not exposed during severe weather events.

Rock groyne construction generally requires the same material and equipment as an interlocked revetment wall. Groynes are usually end-tipped, where a truck will back up and place core material, which is pushed out along the groyne layout by a loader. Armour stone will then be dumped and pushed into place before being reworked and interlocked by an experienced excavator operator. Care should be taken to prevent damaging adjacent foreshore vegetation or parkland during construction. Haul roads can be temporarily installed and removed after construction.

The construction of GSC groynes requires specialist filling, sewing and handling equipment, which can typically be hired from the supplier for use on projects. The availability of this specialist equipment needs to be considered when planning construction works. The contractor should also be experienced in the handling and placing of GSCs, which can be damaged if not handled properly. The supplier will often provide advice on filling, sewing and handling procedures, and site demonstrations can often be arranged if the contractor is not experienced with GSCs. The construction sequence for a GSC groyne is similar to that of a rock groyne, with the groyne extended from the shoreline to deeper water. Care needs to be taken to avoid damaging GSCs when driving tracked vehicles on the groyne.

3.3.6 Failure mechanisms

Failure mechanisms are similar to revetments. Generally, damage occurs after a severe storm with the head of the groyne usually the most vulnerable. Damage can occur by wave overtopping and removal of the core, downdrift scour, and slumping and movement of loose armour units, resulting in less effective interlocking. Failure may also be exacerbated by inappropriate design or construction.

Standard GSCs can be easily vandalised with a knife cut across the material leading to a rapid loss of sand fill during wave action. This can cause the groyne structure to fail if the damaged GSCs are not identified and repaired. Vandal detterent GSCs can be placed in areas of high vandalism potential.

Vandal detterent GSCs are made of a stronger material that can not be readily cut, reducing the potential for complete loss of the sand fill material. However, vandal detterent GSCs can still be punctured by a sharp object and require ongoing monitoring and maintenance.

3.4 Monitoring and maintenance

Structures should be regularly inspected and maintained after severe storms. Historically, groyne maintenance is rarely undertaken until complete failure is imminent. The implications of delaying maintenance include:

- costs may be significantly higher and could approach replacement costs;
- timeframes for undertaking the work will be large due to the required consultation, approvals, redesign, tendering and construction;
- there is a risk of further damage to foreshore assets during a long maintenance lead time;
- additional works may be required on damage to infrastructure (i.e. additional cost); and
- additional sand may be required to minimise downdrift erosion (i.e. additional cost).

Incorporating these types of structures in an Asset Management Plan and ensuring maintenance works are of a scale that can be readily undertaken by the foreshore land manager's works crew is generally the most efficient and straightforward way of monitoring and maintaining these types of structures.

Maintenance of GSCs is outlined in Section Part B, Chapter 9 Geotextile Revetments. Guidelines on the maintenance of timber structures are also available in Part B, Chapter 6 Log Walling, Perdock (2002) and Crossman & Simm (2004).

3.5 Cost

Costs for rock groynes generally follow the costing basis for revetments Part B, Chapter 8 Rock Revetments. Additional considerations may include the influence of weather and the supply and placement of smaller core material inside the groyne.

Costs for GSC groynes generally follow the costing basis for geotextiles outlined in Part B, Chapter 9 Geotextile Revetments. Costs related to construction time will depend on the size of the structures, difficulty of the site and design complexity.

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.

In addition, budgets should include maintenance and monitoring. Monitoring should include (at a minimum) annual or biannual engineering inspection, including a site visit and report. Maintenance and monitoring costs for indirect stabilisation techniques require detailed site-specific estimates and do not lend themselves to simple approximations used for direct techniques.

Table 3.2 Costs estimates for key elements to implement groynes obtained from rock revetments and geotextile sand containers

ITEM	APPROXIMATE COST
Geotextile sand container bags (dependent on size)	\$30-\$300 each
Limestone rock	\$30-\$60/tonne
Granite rock	\$45-\$85/tonne
Filter size rocks (limestone, density of 1.8 tonne/m^3) 1) 0.1–0.3 m diameter (2-15 kg) 2) 0.3-0.6 m diameter (50-225 kg)	 \$30-\$50/tonne \$40-\$70/tonne
Geotextile filter cloth	\$2-\$5/m^2
Sediment fill	\$5-\$15/tonne
Crushed stone	\$15-\$30/tonne
Labour for installation	\$40-\$80/hour
Site supervisor	\$110-\$150/hour
Excavator	\$90-\$140/hour
Bobcat	\$85-\$110/hour
Truck and transport costs	\$80-\$90/hour

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

3.6 References

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4 Large woody debris

4.1 Description

Whole trees, limbs or branches that have fallen or been purposefully placed into the river are called large woody debris (LWD) or snags. They can be found exposed, submerged or semi-submerged along the watercourse. Large woody debris provides a number of important roles in the river system by providing habitat for birds, fish and other aquatic life, providing energy sources for the food web, protecting river banks from erosion (Water and Rivers Commission 2000b).

Using LWD as a stabilisation technique involves either:

1 Reorientating existing debris

Tree branches, trunks, roots or whole trees naturally fall into rivers and contribute to river stability and ecological health. Bank erosion can be exacerbated when flow is directed towards the bank by large woody debris (LWD) angled across the river flow and when currents are accelerated in a constricted channel. In this situation, the LWD can be reorientated to reduce erosion and prevent navigational hazards.

2 Creation of a new LWD structure

Installing trees or logs by anchoring them to the bed or bank.

New structures are generally designed to mimic natural LWD, deflecting or dissipating erosive flows and promoting sediment deposition at the base of the bank (Shields et al. 2004; McCullah & Gray 2005).

LWD structures may be constructed for ecological restoration and/or foreshore protection. This can be a relatively low-cost foreshore protection technique, if suitable materials are available locally, and can have significant ecological benefits.

The technique is largely suited to streams in sandy substrate and needs to be combined with foreshore revegetation. However, the ecological and aesthetic benefits of LWD structures are often associated with a relatively low design life and occasionally unreliable foreshore protection outcomes.

Four broad types of LWD structures are distinguished based on the portion of the tree used, the source of the debris and the placement within the channel (Table 4.1): (1) reoriented LWD; (2) anchored LWD; (3) rootwads; and (4) engineered log jams.

Table 4.1 Types of large woody debris

NAME (S)	DESCRIPTION	ALTERNATE NAMES	REFERENCES
Reoriented large woody debris (RLWD)	Debris naturally occurring in the river is reoriented to improve bank stability	Naturally occurring large woody debris	Cederholm et al. (1997) WRC (2000e; 2001a)
Anchored large woody debris	Single or multiple logs anchored to the banks to deflect flow from the bank using single or multiple units. Logs can be parallel to the bank, oriented with the flow or form a type of pyramid structure	Snags Debris groynes Log toes Log vanes	Brooks et al. (2001) Cederholm et al. (1997) D'Aoust & Millar (2000) DPIW (2003) Frissel & Nawa (1992) Hilderbrand et al. (1998) MDoEWMA (2000) McCullah & Gray (2005) Shields et al. (2004) WRC(2001a)
Rootwads	The root mass of the tree (with a portion of the trunk (bole)) is embedded in the bank to deflect flows and provide structural support to the bank	Rootwad composites Rootwad deflectors Rootwad revetment Roughness trees	GCSWCD (SR-04) Harman & Smith (2000) MDoEWMA (2000) McCullah & Gray (2005) Muhlberg & Moore (2005a)
Engineered log jams (ELJs)	Logs/trees are placed across the width of the river to act as a weir, decreasing velocities upstream and causing pools to scour downstream	Log riffles Full crossing logs Log jams Bar apex jams	Brooks et al. (2001) Cederholm et al. (1997) McCullah & Gray (2005) Shields et al. (2004) WRC(2001a)

Source: Water and Rivers Commission (2000b)

Figure 4.1 Naturally occurring large woody debris

Naturally occurring LWD (Figure 4.1) should not be removed unless it represents a significant flooding risk, navigational hazard or is contributing to erosion. The preference is to reorientate/prune to reduce channel restriction or relocate the debris elsewhere on the river.

The advantages of LWD include:

- Ecological benefits: improved aquatic habitat for fish and other aquatic animals, as well as a direct and indirect food source for aquatic invertebrates and colonisation substrates for invertebrates (Harman and Smith 2000; MDoEWMA 2000; Fisch 2000). Providing that a significant proportion of the woody debris is above the maximum water level reached, it can offer roosting sites for birds. Additionally, LWD is often the most important pool-forming structure in smaller systems due to generating turbulence (Cederholm et al 1997).
- Aesthetics: natural looking foreshore stabilisation. Flows are deflecting or dissipating from the bank, reducing energy along the streambank/water interface, allowing riparian vegetation to enhance bank protection and habitat values (Sytle and Fisch 2000).
- Cost effective: can be cost effective as materials are often free (compared to rock and stone for habitat construction).

The limitations of LWD include:

- Design uncertainty: design guidelines are reasonably general and dimensions and nature of LWD can vary considerably. There is a degree of uncertainty in the effectiveness of foreshore stabilisation and adverse downstream or cross-stream erosive impacts. LWD is particularly susceptible to erosion behind the structure.
- Navigation hazards: structures with roots facing upstream (rootwads) can be a significant navigation hazard, particularly to paddle craft in high flow reaches and at bends.
- Constructability: anchoring of LWD may be difficult and dislodgement of LWD during high flow events can cause downstream damage to foreshores and structures.
- Flooding: LWD may exacerbate flooding if a large portion of the flow is constrained. LWD is unlikely to affect upstream water levels unless it is blocking more than 10% of the cross-sectional area of a river (WRC 2000b).
- Availability of materials: generally limited to areas where materials are available locally.

4.1.1 Case studies and examples

To date there have been limited examples of LWD projects in the Swan Canning river system. Recent examples include the Tranby Foreshore Restoration Project in Maylands and the Swan River Regional Park works in Viveash.

Works at Pioneer Park on the Canning River in Gosnells were completed in 2004 by the City of Gosnells with technical support from the Department of Water and University of WA. The project involved the installation of large woody debris in the river channel, riverbank armouring using large woody debris and rock (Figure 4.3), creation of engineered log jams and extensive revegetation of the riverbanks and riparian area. To date, all structures have performed well and remain intact.

The works have led to a number of positive environmental outcomes including reduced riverbank erosion and increased in-stream habitat diversity through the creation of pools, riffles and still reaches. This new habitat diversity has led to more observations of mussels and western minnow in the area.

Source: Department of Water (2004)

Figure 4.3 Large woody debris at Pioneer Park, Gosnells

The Water and Rivers Commission (2000b) also describe a large LWD project on the Dandalup River. This demonstration site was established on a 500 m stretch of the Dandalup River in the Shire of Murray. The project involved the installation of approximately 40 large tree trunks to create riffles and toe protection structures along the banks of the river (Figure 4.4). Further detail, including site maps, can be found in the original reference.

Source: Water and Rivers Commission (2000d)

Figure 4.4 LWD trial at Dandalup River

4.2 Purpose and application

The purpose of LWD foreshore stabilisation is to utilise local materials to divert flow (and therefore erosive forces) from the bank, allowing sediment to deposit and vegetation to establish, slowing the rate of erosion. It is a short to medium term technique while revegetation establishes.

Large woody debris may stabilise banks for the bank profile locations, channel planform locations and type of erosion processes presented in Table 4.2.

Table 4.2 Large woody debrisapplicability

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	
Enhanced erosion due to sedimentation of the channel	
Erosion due to interruption of sediment transport	

PROFILE SPATIAL APPLICATION	
Description	**Feasibility**
Deep channel	
In-channel adjacent to eroding bank	
Upstream/downstream 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

4.2.1 Condition where practice applies

Ideally, LWD should be placed in an area and in a configuration it could naturally occur (McCullah and Gray 2005). Replacement of LWD, in combination with revegetation, has been shown to be very effective, even in high-energy streams (EMRC 2007). In these instances, LWD can be designed, engineered, and anchored in a manner that will accommodate flood flows and stabilise banks by redirecting, deflecting, or resisting erosive flows while providing beneficial habitat.

Caution should be applied in large or unstable streams or where revegetation is likely to have limited success. LWD should be avoided if it could impede navigation or damage other structures if anchoring failed. LWD is generally less effective where waves and non-unidirectional flow occur, as the forcing on the logs will increase mobility (i.e. in the lower and middle Swan).

In environments where wood decays rapidly, the ultimate success of a project depends on creating conditions that lead to successful revegetation or colonisation on and around the structures by permanent terrestrial vegetation. Without this, the effects of LWD may be short-lived.

4.2.2 Complexity and sensitivities

Complexities and sensitivities in designing LWD foreshore protection include:

- Sourcing material: Projects should be planned well in advance so logs can be sourced opportunistically (eg. general parks maintenance, local developments, local tree lopping companies) and stockpiled. Alternatively, they may be purchased from timber suppliers, but this could significantly increase project costs. It is important not to remove too much natural debris from around the restoration site, as logs with natural holes also provide habitat for terrestrial native fauna. Further information is included in the design guidelines section.
- Quality of LWD: The quality of LWD will vary in terms of size, age, extent of decay, resistance to further rot, type of timber, extent of branches (main log, bole) and buoyancy.
- Anchoring: Larger, dense LWD may not need to be anchored in low-flow reaches. However, mobilisation of LWD during floods can cause damage downstream and the need to anchor LWD needs to be considered during project design and implementation.
- Bank reshaping: Consider the requirement for bank reshaping in regards to access and improved stability.
- Site access: The type of LWD design adopted should recognise site access constraints. In areas with limited access, manual installation may be required (Figure 4.8).
- Revegetation: The revegetation plan should follow the design requirements in Part B, Chapter 2 Revegetation, including a landscape plan (with densities), species selection and what to plant in the various hydrology and planting zones. The consequences of poor seedling survival to the LWD structure need to be considered.

4.3 Design guidelines

The use of LWD as an erosion stabilisation technique is widespread; however, like many techniques, scientifically-based design guidelines are scarce (Shields et al. 2004). Many projects have been undertaken primarily for ecological purposes with a secondary consideration given to foreshore stabilisation.

Key design variables and considerations include:

- stream geomorphology and cross section
- stream flow and water levels
- extent of protection required
- availability of materials
- access during construction (only possible via a barge in some locations)
- layout of LWD structures
- stability and anchoring requirements
- scour, retention and downdrift impacts

Stream flow and water levels

A LWD structure providing toe protection to an eroding bank should be designed and constructed to account for variable water levels at the reach, particularly those with return intervals less than 10 years. By nature, the structures have a limited design life; however, they should be able to survive modest high water level events within the first few years of construction. This should allow vegetation time to establish. The consequences of failure during more extreme events should be considered.

Extent of protection

The extent of protection provided by LWD may be governed by the geomorphology of the reach, availability of materials and budgetary constraints. Like all techniques, downdrift effects need to be considered.

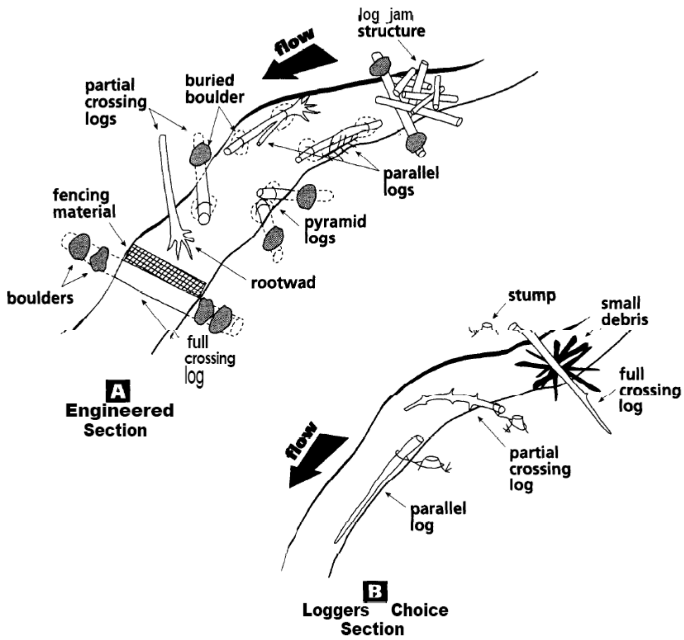
Availability of materials

Materials should always be sourced in an environmentally sensitive manner and in opportunistic circumstances (e.g. when trees have been removed for other reasons or if a tree has fallen over and is blocking the channel). Ideally, local timber should be used and trees should never be felled for the sole purpose of in-stream LWD projects. Trees used for LWD projects should have as many limbs left in place as possible to maximise the surface area and interstitial spaces that provide the best fish and invertebrate habitat. Trees with many small branches can also have beneficial effects on stream morphology by trapping sediments and reducing bed degradation. However, unless they provide anchoring, limbs often need removing from the side of the tree that is anchored to the bank. In some cases, limbs will need to be removed for transport and placement.

Care must be taken when introducing LWD and rootwad material from other areas due to the threat of dieback from any soil in the rootwad or on the tree. Stock should be sourced from known dieback-free zones and no soil should be transported into the restoration site on the LWD.

Layout of LWD structures

Conceptually, LWD structures can be built parallel to the flow (i.e. revetment-type structure), partially protruding into or across the flow channel (e.g. groyne type structures, spurs, rootwads), and across the extent of the channel (e.g. flow riffles, log jam type structures (Figure 4.5)).



Source: Cederholm et al. (1997)

Figure 4.5 Large woody debris placement options

Specific guidance on the layout and implementation of LWD reorientation, modifying or replacing LWD, and of rootwads are provided below.

Reorientating or replacing LWD

The Water and Rivers Commission (WRC 2000c, WRC 2000e) provides significant guidance on introducing or reorientating LWD to stabilise channel alignment by directing flows away from the toe of the bank.:

- Stream flow should be directed smoothly around the meander to the centre of the channel.
- Logs should typically be installed against the outer bank, pointing downstream at an angle of 20–40 degrees to the streambank (Figure 4.6a).
- The butt of the log should be buried approximately one metre into the bank and the logs pegged or anchored into position. The end of the log can be sharpened to reduce disturbance to the bank during installation.
- When installing or reorientating woody debris, they should not block more than 10% of the cross-sectional area of the channel to minimise impact on water levels during high flow events.
- Pieces of LWD that are closely located (2–4 m apart) will have a similar affect on flow to a single item, and will increase bank stability.
- Remove isolated branches that protrude above the water level and trap large amounts of debris moving downstream.
- Nearby undisturbed river reaches of similar size can be used as a reference to determine the amount and type of large woody debris that should naturally be present in the waterway.
- Wood from tree species native to the area should be used.
- Logs of different size and shape and with rough surfaces and hollows should be used to increase habitat diversity.

Riffles

Tree trunks and large branches can be used to construct riffles and pools, modifying river flow velocities to reduce erosive stresses on the foreshore. Two logs can be used to form a ‘V’ shaped riffle across the channel, with the butt of the logs buried into the bank and the tapered end pointing slightly upstream (Figure 4.6c). The lowest point of the riffle should be at the join of the two logs in the centre of the channel. Alternatively, a large log, at least two metres longer than the channel width, is required to form a whole channel structure (EMRC 2007).

The end of the log riffle needs to be buried at least one metre into the bank, and below a minimum of 0.3 m of bank material. The end of the log can be sharpened to reduce bank disturbance during installation. In the water, riffles should not be constructed more than about 0.3 m in height to allow fish passage. Logs can be anchored by wiring to posts or metal stakes driven into the bed, or chained to weights such as logs buried beneath the bed level.

When using log riffles to control bed erosion in unstable, sandy bed systems, filter cloth should be installed on the upstream side of the riffle, wrapped over the log and pinned. The edge of the cloth should be buried about 1.5 m into the bed to prevent undermining of the structure.

Rootwads

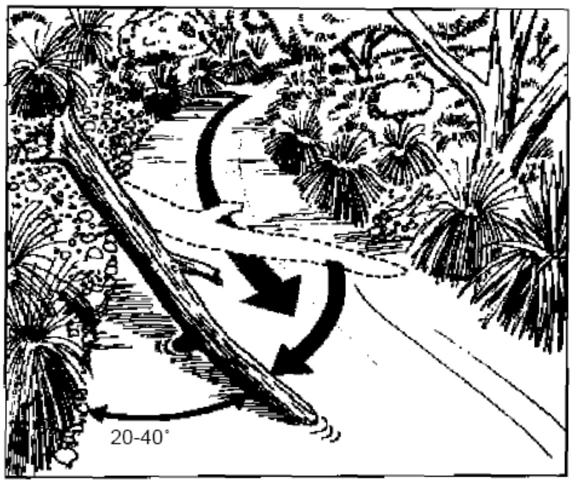
Rootwads are LWD structures that utilise the bole and lower trunk of a large tree, embedded into the bank with the root mass extending into the stream, to act as a groyne-type foreshore protection structure (Figure 4.6b). Rootwads have particular value in high flow areas where the embedded mass (trunk) provides additional stability for the LWD. However, safety issues associated with introducing this type of structure into a high flow recreational river need to be carefully considered.

In general, trees used as rootwads must be sound, and free from significant decay. Installing rootwad requires a length of tree trunk with the root mass attached as well as a second footer log. Rootwads should be of substantial size, and a minimum of 4.5 m of the trunk must be attached to allow adequate anchoring in the bank. Footer logs should be a minimum of 45 to 60 cm in diameter and free of limbs.

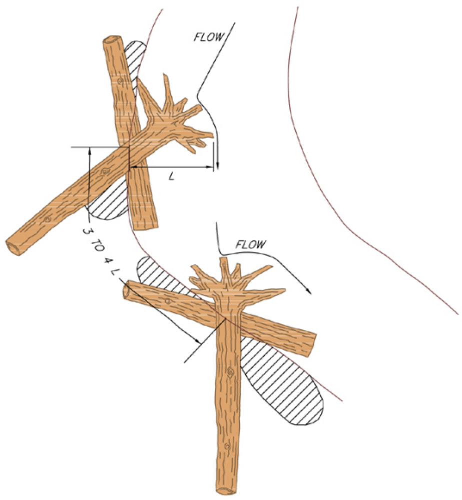
The following limitations should be considered before incorporating root wads into stream restoration plans:

- The adoption of this measure as a stream restoration technique is rather recent, therefore its performance is currently being assessed and documented.
- Root wads should not be used in stream sections where the bed is severely eroded or undercutting is likely to occur, such as in rocky terrain or where narrow channels are bound by high banks. They should also be avoided in braided streams and reaches with sandy or silty soils.
- Flows greater than bank full discharge may cause local scour around the top of the structure and may even cause total bank collapse. Therefore, root wad revetments require systematic monitoring, especially after high flows, for local erosion and decay of the structure.
- Rootwads are not appropriate near bridges or other structures where there is high potential for downstream damage if the LWD dislodges during flood events (USDA 1996).

Design guidelines for LWD structures are in an early stage of development compared to other bank stabilisation techniques. Design requires analysis of forces acting on the debris; destabilising forces include fluid drag and buoyancy, while forces resisting motion include gravity and the weight of anchors or forces exerted by anchoring systems. Example design computations are presented by Abbe et al. (1997), D'Aoust and Millar (2000), and Shields et al. (2004).

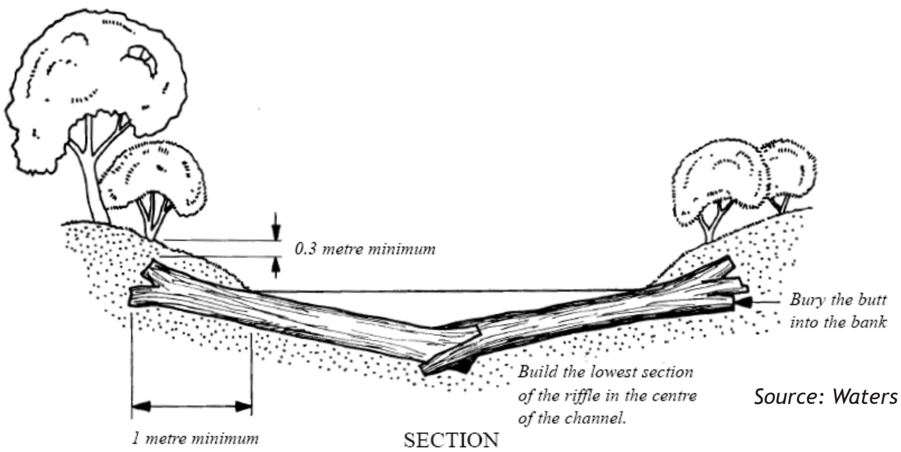


Source: Waters and Rivers Commission (2000e)



Rootwad revetment plan view

Source: McCullah & Gray (2005)



Source: Waters and Rivers Commission (2001a)

Figure 4.6 Concept sketches for LWD placement (a) along-bank placement angle (b) rootwads; and (c) riffles

Anchoring techniques

The most common anchoring technique is to use stakes or posts to secure the LWD. This is generally sufficient for lower flows; however, the consequences of failure during higher flows should be considered. Anchoring techniques for LWD (Table 4.3) and materials for attaching LWD to anchors (Table 4.4) are outlined below.

The use of a particular anchoring technique will be determined from an assessment of local conditions. Historically, partially buried and weighted anchors have been used successfully in the Swan Canning river system (where low flow velocities generally prevail).

Table 4.3 Anchoring techniques for LWD

ANCHORING TECHNIQUE	APPLICATION
Live tree stump	Live tree, which when cut falls with trunk remaining sufficiently attached to a secure stump Least labour-intensive method of adding LWD as it does not require any attaching of LWD to an anchor Can only be used when a suitable tree is appropriately located
Tree stump	Tree stump present close to stream can be used as anchor Cable (or other material) can loop around stump or bolt to it by drilling a hole and using a nut and washer on each side. If looping cable, ensure it will not come off if LWD floats above elevation of anchor Be aware of: (1) unknown capacity of the tree stump to withstand strain; and (2) site may be in active state of erosion as exposed tree stumps are often an indicator that a bank has recently been cleared and sediments may be more mobile
Live trees	Live trees close to the stream used as anchors. Be aware of potential to injure the tree (e.g. cable looped around trunk may cause ring-barking). Ensure tree trunk is protected (e.g. wooden blocks, a conveyor belt, or other durable but relatively soft material). The strongest tree(s) should be used as anchors to avoid possibility of uprooting
Reinforcing rod (rebar)	Three-quarter inch reinforcing rod is probably most useful for attaching logs directly to other logs, but it can also be used to anchor LWD to the substrate Reinforcing rod has very little holding power in soil and is best suited for small streams that are not prone to flooding Advantages of reinforcing rod are low cost and ease of driving into relatively coarse substrates such as large gravel and small cobble
Weighted anchor	Containers, ranging in size from a 20 L bucket for small structures, up to a 200 L drum for whole trees, can be filled with concrete and used as anchors Most effective when used in low-gradient streams with fine substrates where they can become partially buried Weighted anchors should be used in conjunction with another anchoring method due to inability to withstand high flows (note that they may also be aesthetically unappealing)
Dead man	Post (often a reinforced concrete post) that is partially buried with an attachment point on the protruding portion Expensive anchor as heavy equipment is usually required to install dead men, but where installation is feasible, they can be useful for anchoring LWD to stream banks
Commercially manufactured anchors	Usually the most desirable anchors because they are easy to install, estimates of approximate holding power are usually available from the manufacturer, and most are designed to have cables attached directly to them There are a variety of commercially manufactured anchors that can be easily installed in soft substrates (screw-type, duckbill or other) and solid rock substrates (requires drilling a hole in the rock and grouting)

ANCHORING TECHNIQUE	APPLICATION
Partial burial	When feasible, it is desirable to partially bury the LWD to increase stability Partial burial can sometimes be achieved by sharpening the butt of the tree (or the trunk portion of a rootwad) with a chainsaw and driving it into the bank with heavy equipment, or with hand tools for smaller debris. Alternatively, a backhoe or extractor can be used to excavate a trench in the bed or bank into which part of the trunk can be placed and then buried with backfill or rock The partially buried log can sometimes be used as an anchor for other LWD

Source: Fischenich & Morrow (2000) and WRC (2000d)

Some material will be necessary to secure the tree to an anchor. Cable is often used but chain and rope may also be appropriate. The main considerations are strength, corrosion resistance, ease of pulling tightly, and ease of clamping or tying. The material should be strong enough to hold the LWD for the highest flows expected during the life of the project and additional forces from accumulation of debris behind the structure. Loss of strength through corrosion or rot should be taken into consideration. A tight connection with limited pay between the anchor and the LWD is important.

Table 4.4 Materials for attaching LWD to anchors

MATERIAL	STRENGTH	CORROSION RESISTANCE	EASE OF TIGHTENING/ TYING	COMMENT
Cable	High	High Standard steel cables should be coated with a corrosion-resistant material	Secure with cable crimp links or wire rope clips Securing requires special tool (though hammer can suffice) If using wire rope clips, the saddle should always go on the load bearing side Two clamps recommended	Most often used. Should never be secured by knotting.
Chain	More flexible, heavier and more expensive than cable of comparable strength	Medium-high Most durable is the hot-dip galvanised chain from marine supply dealers	Easily secured by bolting links together. Bolts should be the maximum size that will fit through the link and washers and should be placed at the head and the nut end. Lock nuts or washers are recommended.	More expensive than cable, but more flexible and easier to secure.
Rope	Those designed specifically for marine use are usually strongest and most durable	High	Ropes can be secured with a variety of knots but most situations can probably be addressed using bowline, slipknots, and square knots.	Desirable where attachments are visible and aesthetics are important.

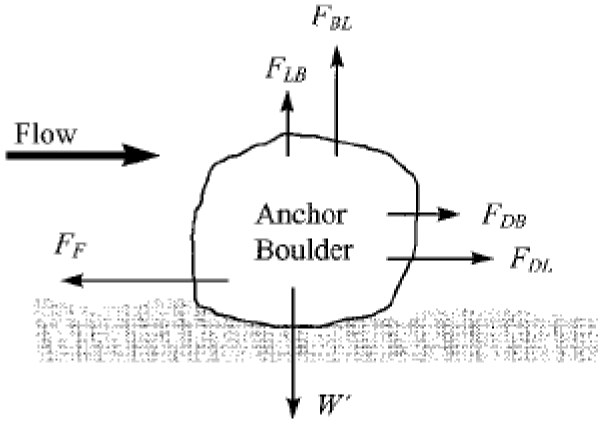
Source: Fischenich & Morrow (2000)

4.3.1 Loading

The loading on a LWD structure and consequences of failure should be considered for all projects. Detailed loading estimates should be calculated for more substantial LWD structures by seeking advice from an engineer with experience in river environments.

D'Aoust & Millar 2000 provide guidance on estimating the stability of anchored woody debris structures. The principal forces considered are as follows (Figure 4.7):

- F_{BL}—net buoyancy force acting on the LWD and transferred to the anchor
- F_{DL}—horizontal drag force acting on the LWD and transferred to the anchor
- F_{DB}—horizontal drag force acting directly on the anchor
- F_{LB}—vertical lift force acting directly on the anchor
- W'—immersed weight of the anchor
- F_F—frictional force at the base of the anchor that resists sliding



Source: D'Aoust & Millar (2000)

Figure 4.7 Principal forces acting on anchor on a single large woody debris structure

Log length and orientation influence stability; logs longer than the bankfull width oriented parallel to the flow appear to be most stable (Bilby 1984; Lienkaemper and Swanson 1987; Cherry and Beschta 1989; Robison and Beschta 1990; Abbe and Montgomery 1996; Braudrick and Grant 2000). Hilderbrand et al. (1998) reported that channel scouring was associated with LWD oriented across the flow, while sediment deposition occurred adjacent to LWD oriented more parallel to the current. Field studies indicate that smaller LWD have a limited influence on channel morphology and aquatic habitat, but larger pieces (>5 m in length) can be important (Berg et al. 1998; Urabe and Nakano 1998). Flume experiments indicate the stability of single logs is significantly enhanced for logs longer than the channel width (Braudrick and Grant 2000).

Due to their low specific weight and large surface area, lift forces on LWD can place a heavy strain on anchoring systems. This is exacerbated by the tendency of LWD structures to capture floating debris, increasing the drag force on the anchors during high flows. The force on the anchors should be calculated by estimating the surface area of the LWD structure exposed to current (perpendicular to the flow).

4.3.2 Considerations for detailed design

Considerations for detailed design are addressed in Design Guidelines, Loading, and Complexities/ sensitivities.

Climate change should be incorporated in designs using 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.

4.3.3 Design life/expected lifetime

The primary objective of LWD structures is to provide temporary (5-15 year) stabilisation to allow a streambank and riparian system to recover from instability (Style & Fischenich 2000). This would allow vegetation to establish before the anchoring system and wood within the structure degrades. Long-term stability relies on establishing vegetation. If the cause of erosion is not addressed, retreat may continue to occur, the design life may be reduced and more permanent engineered structures may need to be considered.

The type of wood used can also significantly alter the project's design life. Durability is influenced by climate, wood density, natural rate of decay and exposure to wetting and drying. Frequent wetting and drying reduces life while continuously submerged wood will be more durable. Soil contact influences durability; microbial digestion in soils limits life while burial in anaerobic soils significantly prolongs life (Fischenich and Morrow 2000).

4.3.4 Materials and equipment

The following materials and equipment may be required for a large woody debris project:

Materials

- logs
- topsoil (typical landscape topsoil mix that is certified weed and disease free)
- plants for revegetation (refer to Part B, Chapter 2 Revegetation)
- anchoring materials (refer Table 4.3 and Table 4.4)
- winch
- rock for anchoring and/or toe protection (particularly for up and downdrift ends)
- geofabric and/or biodegradable matting for soil retention

Equipment

- winch
- earthmoving plant to install LWD (excavator, tractor, loader)
- pile driver (mallet sledgehammer through to hammer attachment for excavator depending on scale of project)
- backhoe or shovel
- chainsaw or loppers
- temporary irrigation system if necessary

4.3.5 Construction/installation

Construction methods for LWD projects depend on the project's scale and site. Smaller projects can be undertaken using smaller LWD from the area and manual labour to move and build the structure. Larger projects require sourcing significant volumes of timber offsite, transport, and earthmoving equipment for installation.

It is critical to protect the existing riparian zone and bank integrity. Therefore, access and staging areas need to be carefully planned. Turbidity should be monitored and managed during construction to ensure ecological impacts are minimised.

4.3.6 Failure mechanisms

The main failure mechanisms for LWD are failure of either anchoring or revegetation. These, together with other faults are outlined below:

- Insufficient anchor design or maintenance to resist floatation of the structure;
- vegetation not established prior to the end of the design life of LWD;
- failed revegetation with no subsequent replanting;
- overtopping or undermining of toe structures;
- bank loss through gaps in the structure; and
- instability caused by inappropriate site selection.

4.4 Monitoring and maintenance

Monitoring and maintenance will extend the life of LWD structures 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 LWD should include visual inspection and photographs of:

- plant health;
- integrity of anchor system (presence and state);
- any mobilised or missing logs;
- presence of weeds; and
- state of adjacent banks.

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

Maintenance should be conducted as required to replace plants, remove weeds, re-anchor (replace cabling/ties, increase anchoring capacity), reorient mobilised debris and replace missing units. Additional maintenance may be required where sediment is lost from the ends of the structures. Maintenance works may include sediment replacement and additional anchoring.

4.5 Cost

Cost estimates are based on 2008 prices from various Western Australian suppliers (Table 4.5). These figures should be used as estimates only and quotes from suppliers be obtained when producing final budgets.

The project budget should include design and site survey costs, along with monitoring and maintenance. All revegetation projects require replanting due to some losses in the first three years. Additional costs may be incurred for reanchoring should any of the anchoring fail.

The large woody debris restoration project on the North Dandalup River involved installing about 50 logs along a 600 m reach of the river. The average bank-full width of the river reach is 12.5 metres. Three LWD riffles were installed along the reach. The riffles cross the low flow channel, forming small weirs. Between the riffles, woody debris was strategically placed as toe protection to direct flow around the channel meanders. The construction cost for the installation and enhancement of the log riffle structures and toe protection was approximately $10,500 (WRC 2001a).

Projects should be planned well in advance so logs can be sourced opportunistically and stockpiled. Alternatively, they may be purchased from timber suppliers, but this could significantly increase project costs.

Table 4.5 Costs estimates for key elements to implement large woody debris foreshore protection

ITEM	APPROXIMATE COST (EX GST)
Trees/logs	Free, plus transport costs if applicable (purchasing timber may significantly increase project costs)
Geotextile filter cloth	$5–$14/m2
Biodegradable matting (eg jute or coconut fibre)	$160-50m2 roll
Plants	
Tree tubes	$1-$2 each
Cells	$0.5-$1 each
Strips sedge	$10-$12 each
Block sedge (per m2)	$100-$120 each
Large stock	Varies depending on species and size Eg. $6 for a 13cm pot, $160 for a 100L pot
Labour for installation	$40 – $80/hour
Site supervisor	$110 – $150/hour
Chainsaw	$90 – $120/day
Soil compactor	$90 – $120/day
Bobcat	$85 – $110/hour
Excavator	$90 – $140/hour
Truck and transport costs	$80 – $90/hour

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

4.6 References

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