43 RIPARIAN VEGETATION AND WATERCOURSE MANAGEMENT

43.1 RIPARIAN MANAGEMENT

Riparian vegetation plays an important role in the maintenance of stable watercourse morphology as well as in the preservation of ecology value. For these reasons the riparian zones of watercourses need to be included in stormwater management planning. This section discusses the management approach and objectives for riparian vegetation and provides some general background on the role of riparian zones.

Parts of this section have been adapted from "Managing Urban Stormwater: Strategic Framework" produced in Australia by NSW Environment Protection Authority in draft form in April 1997, while the discussion on riparian zones has been adapted from "The Importance of the Riparian Zone in Water Resource Management", a literature review prepared by Water Resources, New South Wales Government, 1992. The incorporation of this material is gratefully acknowledged. It is hoped that more Malaysian material will be available for inclusion in a future update.

43.1.1 Approach

The principal approaches to managing riparian and floodplain vegetation are retention and replanting with appropriate non-invasive species. Where possible the species should be natural to the area.

In practical terms a riparian zone at either side of the waterway should be reserved for such retention or replanting. The width of this zone is influenced by a number of factors including:

- waterway width,
- the nature of existing development,
- the importance of local flora and fauna bio-diversity,
- and the need to maintain wildlife corridors.

The causes of any existing channel degradation should be identified and addressed prior to undertaking replanting. This particularly applies to flow and water quality management and the possible need for structural bank protection works for eroding channels. Alternatively, the replanting could be designed to stabilise or modify these changed conditions.

The nature and size of riparian reserves should be determined early during the planning process. Larger watercourses, such as rivers, could be assessed during the Strategic Planning phase, with smaller channels being assessed at the Master Planning phase.

43.1.2 Objectives

(a) Vegetation Retention

The most important principle is to maintain existing indigenous riparian vegetation where practical.

(b) Vegetation Replacement

Restoration of riparian zones can generally be undertaken by planting indigenous vegetation. If only limited riparian vegetation remains, an indication of appropriate species can be obtained from catchments with similar climatic and soil conditions. In some circumstances, changed conditions such as increased wind exposure, temperature fluctuations (due to removal of adjacent vegetation) and loss of topsoil may preclude the use of indigenous vegetation. In these cases the use of species from other Malaysian catchments, or even no-invasive or well-managed exotic species may be necessary at least in the initial stages. A diversity of species is recommended to replicate as close as possible the pre-development condition of the riparian zone and to encourage terrestrial and aquatic bio-diversity.

A list of some riparian vegetation species suitable for application in Malaysia is provided in Chapter 42.

43.2 RIPARIAN ZONES

The riparian zone is the area of land (including floodplains) adjacent to a watercourse.

Riparian vegetation can be considered to include:

- emergent aquatic and semi-aquatic plants,
- terrestrial over storey (canopy),
- terrestrial under storey (cover).

The riparian zones contribute to the ecological value and geomorphological stability of a watercourse through a number of processes. These values and processes are discussed in the following sections.

43.2.1 Bank Stability and Channel Integrity

Vegetation plays a role in controlling erosion through its attributes of water interception, energy dissipation, and soil stabilisation and infiltration enhancement. Soil erosion is also influenced by ground cover vegetation, which filters storm runoff to remove sediment, while deep-rooted species affect soil moisture and groundwater levels.

Vegetation can exert a significant control over fluvial processes through two main mechanisms: resistance to flow (through the vegetation increasing roughness) and bank strength (through the binding of soil by root systems).

Bank vegetation disturbances can include:

- unrestricted access by people and animals,
- removal of vegetation/logging to the stream edge,
- agricultural development/cultivation to the stream edge,
- urban development to the stream edge.

These activities can lead to bank destabilisation, soil compaction and higher overbank flow velocities. Natural flooding events are then more likely to cause the erosion of valuable land that may require expensive rehabilitation.

43.2.2 Habitat Value

Riparian vegetation plays a major role in determining the structure and function of stream ecosystems. Ecological interactions between riparian zones and instream aquatic environments are continuous and interlinked. The riparian zone is an important source of habitat for both aquatic and terrestrial animals. Broadly, riparian reserves can be described as having a number of habitat functions:

- *habitat island*. This is a zone that has an adequate width of retention of natural vegetation to be able to permanently sustain communities of natural terrestrial fauna.
- *wildlife corridor*. This is a zone that has an adequate width of retention of natural vegetation to facilitate the movement of natural fauna from one "habitat island" to the next.
- *food source*. Riparian vegetation contributes to the ecology of freshwater communities by providing food in the form of fallen organic material and fallen insects and invertebrates (Figure 43.1).
- *aquatic habitat.* Trees and branches that fall into the stream and exposed tree roots provide shelter from high velocity flow, predators and sunlight.

43.2.3 Importance of Diverse Natural Vegetation

Natural vegetation is important to support the kinds of functions that are outlined above. The maintenance of diverse natural species of flora and fauna relies on the maintenance of the natural food sources. The basis for maintaining a natural food chain is natural vegetation.

Maintaining natural vegetation is also important in maintaining appropriate levels of shading for the watercourse. This directly affects water temperature, the rate of photosynthesis and shelter from predators such as birds.

43.2.4 Buffer Filters

The riparian zone provides a buffer strip between land use and watercourses. This buffer can provide a filter zone for sediments, nutrients and to some degree pollutants. Buffer zone width, the pollutant load and type will determine the long-term effectiveness of the buffer.

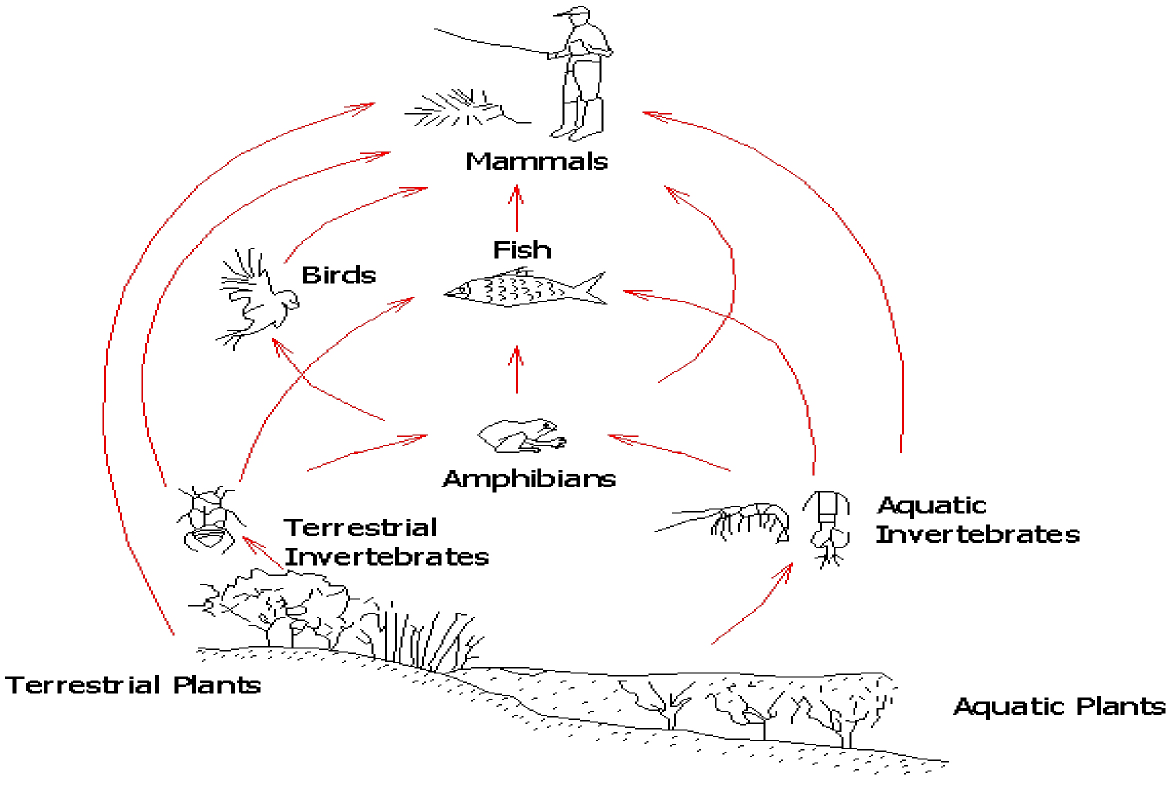


Figure 43.1 Riparian Food Chain (DCEV, 1990)

The filter buffer works by a process of slowing surface runoff and the interception and trapping of sediment particles around stems and roots. This process traps pollutants with the sediments. Nutrients in sediments can be taken up into the riparian vegetation, whilst non-organic pollutants may be bound into the soil system. These mechanisms obviously have a finite capacity for the uptake of pollutants.

The effectiveness of riparian filter buffers can also depend on site-specific factors such as soil type, permeability, vegetation type and density, and terrain slope.

Buffer zones should be used as a component of the Strategy Plan or Master Plan in reducing the amount of sediments and pollutants reaching watercourses. They are not a substitute for Best Management Practices for source control, soil and water management, fertiliser and pesticide usage etc, which should also be used as part of the overall strategy.

Without such alternate strategies the sediment and pollutant loads can have long term degrading effects on the viability of buffer zones.

43.2.5 Buffer Width

The required width of riparian vegetation buffers zones is dependent on all of the factors outlined above and is a major determinant in the effectiveness of the buffer.

The NSW Water Resources Department reviewed a range of Australian guidelines, legislation and regulations, as well as a number of American studies relating to Riparian Buffer Zone widths. The primary function of the buffer depends on its width. Minimum widths suggested for different functions are:

- Riparian Habitat Island 50-100 m wide,
- Wildlife Corridor 20-40 m wide,
- Filter Buffer 20-90 m wide.

The studies cited in this article indicated that buffers of less than 20 metres would not sustain invertebrate communities.

The slope of the site and the erodibility of the soils were the factors having the largest influence in determining buffer widths for the purpose of sediment control.

Site specific investigations will need to be undertaken to determine the width of riparian buffer zones. Such investigations will need to take into account factors such as channel and floodplain geometry, vegetation, flora and fauna requirements, adjacent land uses and soil erodibility.

Indigenous species will inhibit weed growth, although weed management may be required until the indigenous vegetation is established. Windbreak plantings may also be necessary to assist with riparian vegetation establishment in exposed areas.

43.2.6 Flow Management

Traditionally the management of the hydrological impacts of urbanisation has focused on reducing the danger to life and damage to property. This has led to flow management techniques that attempt to mitigate the effects of less frequent large magnitude storm events.

From an environmental perspective the damage caused by increases in the flow volume and velocities of more frequent smaller magnitude events in urban streams can be more damaging than those of the less frequent larger magnitude events. This is because the impact of urbanisation on the hydrological regime is greater for the smaller more frequent events.

Management of flow velocities and flow depths, in addition to the frequency and extent of inundation will enhance the viability of riparian vegetation.

Generally the type and extent of natural vegetation has adapted to the natural cycles of runoff and the frequency of inundation. Plants suited to frequent inundation have grown closer to the “normal” water level, while plants that are suited to less frequent inundation have grown further away.

The alterations to the hydrological regime discussed above can lead to the displacement of riparian vegetation from its natural level on the stream bank and may lead to erosion and reduced bank stability.

The primary tools for controlling increases in runoff are discussed in more detail in Part E of this Manual.

43.3 WATERCOURSE MANAGEMENT

43.3.1 Stream Processes

(a) Introduction

Stream management problems may arise from either underlying processes of change in the river system or localised perturbations. Frequently stream instability is the result of processes although often the process can be masked to the casual observer by localised factors. It is therefore important to identify the dominant stream processes present if stream management strategies are to be implemented, which are appropriate and unlikely to cause adverse responses elsewhere in the system.

The majority of streams on the coastal plains of Malaysia can be classified as alluvial streams. Alluvial streams are characterised by their ability to alter their own boundaries and, in the absence of external influences, will ultimately reflect a balance between the sediment supply, stream power and the hydrological regime within the catchment. Changes in any of these factors will precipitate a change, which may be manifested, by changes to the river slope, depth, width, planform, bedform or flow resistance. Natural processes may manifest as gradual imperceptible changes or they may occur suddenly as the result of a major flood or changes in catchment vegetation following a bushfire or similar episodic event, or urbanisation.

Stream instability may be initiated by natural or human induced causes such as:

- long term alteration to the hydrologic and/or sediment regime,
- a catastrophic flood or sequence of major floods,
- crossing of a geomorphic threshold,
- direct or indirect human interference.

(b) Bank Erosion Processes

Bank erosion can be the effect of morphological processes such as:

- meander processes,
- channel avulsion,
- bed degradation, or
- combination of the above, or
- the product of localised processes unrelated to the more general morphological changes in the river system.

The mechanism of bank failure will generally involve more than one failure mode. The most common failure modes involve mass failure such as:

1. Collapse following undermining,
2. Slumping (sloughing),
3. Rotational or slip circle failure,

or initial detachment of individual particles involving:

4. Attrition, or
5. Fretting

Other modes of failure include;

6. Erosion by overland flow entering or leaving the main channel creating a headward erosion gully,
7. Tunnel erosion (piping failure).

Some typical failure modes are illustrated in Figures 43.2 to 43.4.

(c) Causes of Bank Erosion

Typical factors, which may contribute to bank erosion, include:

- altered water-sediment ratio in the watercourse,
- altered flow patterns including tidal currents and heights,
- changes in stream flow velocities,
- loss of bank vegetation,
- wave action,
- soil pore water pressure.

43.3.2 Watercourse Erosion Types

Erosion mechanisms include bed scour, bank attrition, and bank collapse caused by undermining, piping, slumping, or rotational failure. Many of these failure modes can also occur in urban engineered waterways.

43.3.3 Bed Scour (Degradation)

(Refer Figure 43.2)

(a) Description

- A deepening of the stream bed that propagates in an upstream direction.
- The deepening moves upstream by an advancing erosion head that may take the form of a small waterfall or locally steeper section of stream bed (head cut or nick point). In some cases the location of the erosion head is not easy to identify.

(b) Indicators/Symptoms

- a visible waterfall,
- steep section of stream bed at head of scour hole,
- bell shaped scour hole immediately downstream of erosion head,
- exposure of foundations on structures such as bridge piers and culverts,
- steep raw banks caused by lowering of the bed and the consequential collapse of the adjacent banks,
- relatively sudden decrease in bank height in upstream direction,
- choking of downstream reaches by sediment deposits,
- steep banks,
- downstream flooding through loss of flood storage resulting from concentration of streamflow within the incised stream channel.

(c) Possible Causes

- Clearing and/or urbanisation of the catchment resulting in an increase in flow entering the stream at the original head cut location, or
- Direct human modification to the stream such as:

- channelisation works causing a sudden increase in mean flow velocity which has a knock on upstream effect,
- in-stream gravel and sand mining operations,
- de-snagging, and
- unstable drop inlets upstream of culverts.

The reverse case is bed aggradation (sediment deposition) which is also a form of stream instability. When excessive sediment loads are deposited in one area the required downstream sediment load to maintain dynamic equilibrium maybe depleted thus causing a new period of downstream erosion as the stream attempts to erode its bed and/or banks in an attempt to restore the sediment load balance with the unchanged flow regime.

43.3.4 Bank Attrition

(Refer Figure 43.3)

(a) Description

Bank attrition is the direct removal of material from the face and toe of the bank by entrainment into the streamflow. It maybe caused by either or both channel flow or runoff from the surrounding area flowing down the face of the bank.

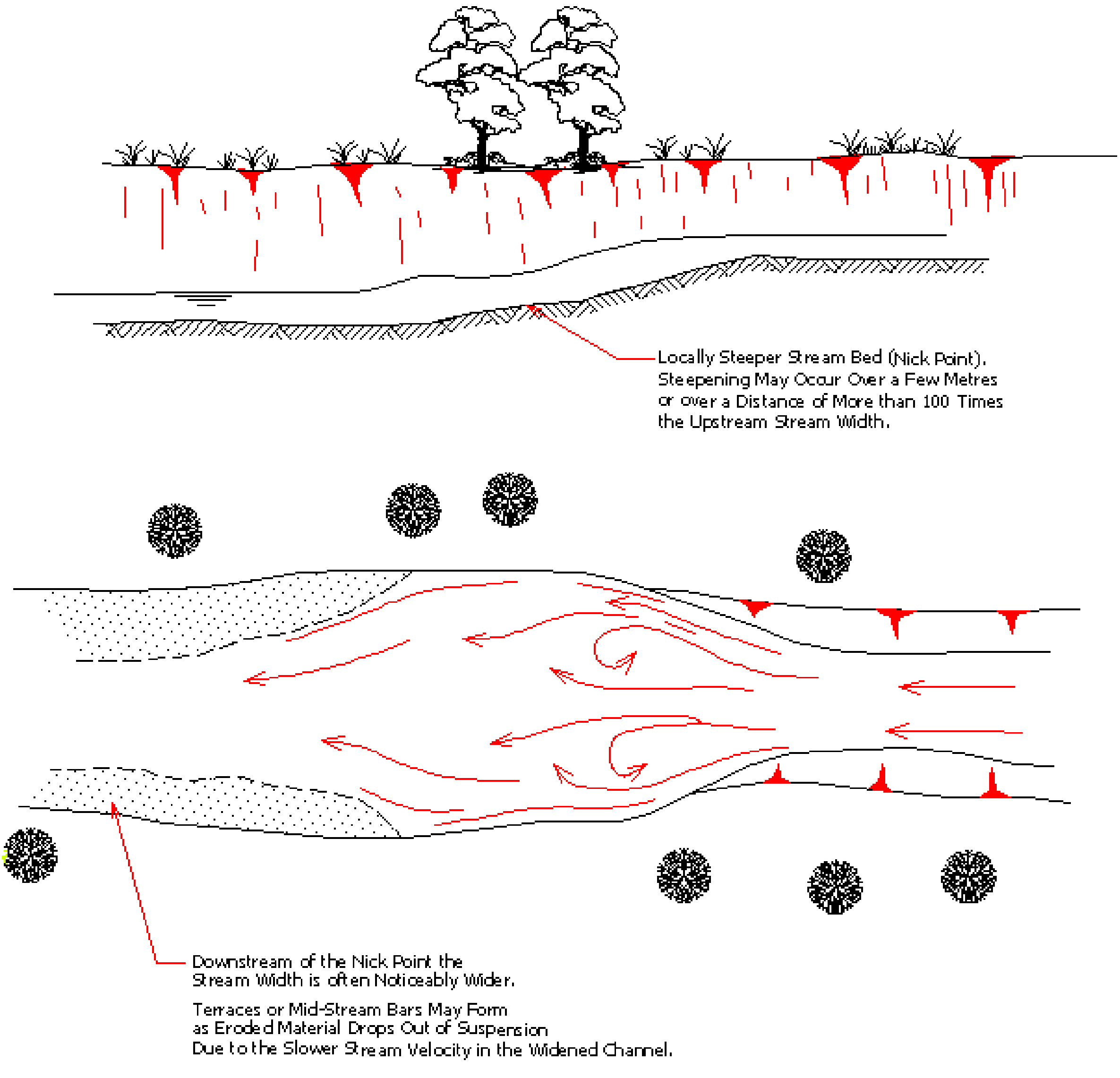


Figure 43.2 Typical Characteristics of Bed Scour

(b) Indicators/Symptoms

- steepening of the stream banks,
- absence of bank vegetation,
- lateral gullies and/or columnisation (this is a special case, refer to Section 43.3.9),
- widening of the stream,
- meander migration,
- downstream sedimentation.

(c) Possible causes

- high velocity flow in contact with the bank which maybe the result of 1 or more of the following:
- increase in the rate and volume of flow entering the stream attributable to clearing and/or urbanisation of the catchment,
- obstructions in the stream channel such as fallen trees, dumped material or bridge piers,
- a lack of vegetation on the bank due to shading, trampling from animals or humans, wave action, or direct removal by human activities.

43.3.5 Bank Undermining (Fretting)

(Refer Figure 43.3)

(a) Description

Fretting is the direct removal of material from an exposed underlying vulnerable soil layer by the continual movement of water (flow or waves) against the layer. An erosion scarf is formed which can lead to mass failure of the overhanging bank material.

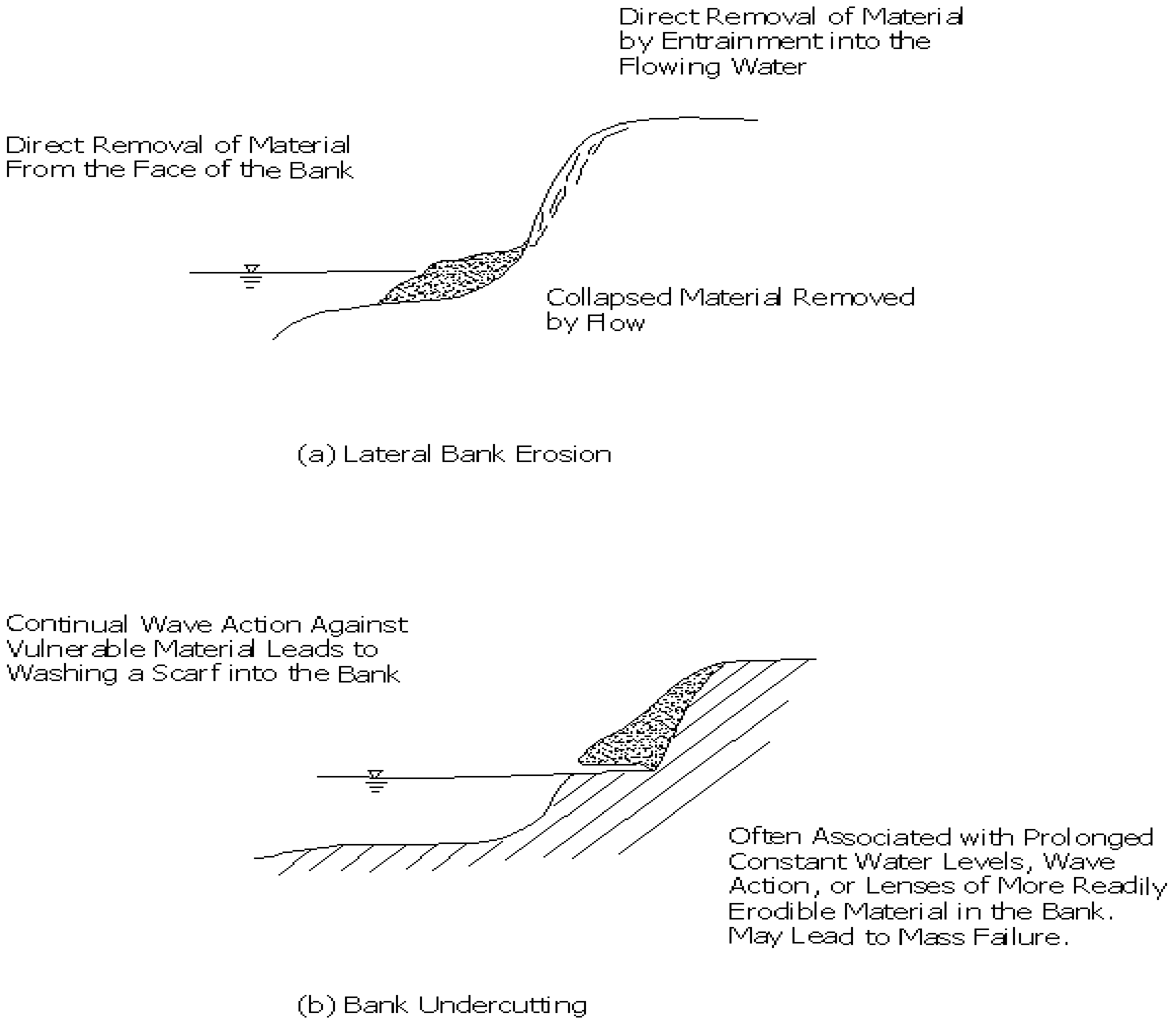


Figure 43.3 Bank Failure by Attrition and Fretting

(b) Indicators/Symptoms

- overhanging bank,
- a sharp steeping of the bank with a near vertical face close to the waterline.

(c) Possible Causes

- increase in water level making continual or frequent contact with an exposed more readily erodible soil layer,
- increased wave action due to boating, or change in the prevailing wind direction due to the removal or addition of nearby obstructions including trees or buildings.

43.3.6 Piping

(a) Description

Erosion tunnels or pipes are formed where surface flows seep into the ground behind the bank and daylight at the bank face. The seepage flows dissolve and/or dislodge soil particles from the soil matrix and transport them to the face of the bank where they are removed by stream flow. The phenomenon usually occurs where dispersive clays are present and where poorly drained low lying areas occur behind the stream bank. On occasions piping can be initialised by animal burrows or by decaying roots of dead trees which leave subsurface cavities.

(b) Indicators/Symptoms

- sink holes on the floodplain and especially when close to the stream bank,
- trenches or narrow line(s) of collapsed material extending laterally across the floodplain,
- concentrated seepage flows appearing on the bank,
- burrows or tunnels on the bank.

(c) Possible Causes

- poorly drained floodplain areas,
- animal burrows,
- decaying roots of dead trees close to the top of bank,
- adversely orientated dispersive soil layer.

43.3.7 Bank Slumping

(Refer Figure 43.4)

(a) Description

Bank slumping is the mass failure of the bank material due to either:

- deepening of the stream bed at the toe of the bank resulting in the bank becoming unstable and slumping into the stream under its own weight (or under some surcharge weight on the top of the bank),
- high pore water pressure in the bank material not being balanced by adjacent hydrostatic pressures in the stream. The high pore water pressure weakens the structure of the bank material causing it to slump into the stream.

(b) Indicators/Symptoms

- lateral movement or widening of the stream banks,
- tension cracks in overbank material running parallel to top of the bank,
- large dumps of vegetated bank slumped below the obvious original location of the vegetation,
- significant groundwater seepage from the face of the stream bank,
- near vertical, unvegetated banks,
- the presence of mature vegetation types not normally associated with regular and prolonged inundation at the toe of the bank.

(c) Possible Causes

- high velocity streamflow (often on the outside of stream bends) resulting in bed scour at the toe of the bank. This can be made worse by the clearing and/or urbanisation of the catchment,
- rapid drawdown of stream water level following a prolonged period of high flows, which have saturated the bank material. This is not common in urban streams and is more prevalent in regulated rural streams and irrigation channels,
- surcharge loading on the top of the bank,
- lack of binding bank vegetation.

43.3.8 Bank Rotational Failure

(Refer Figure 43.4)

(a) Description

Bank rotational failure (also known as slip circle failure) is the failure of an embankment along a curved surface, which approximates to the plane of least resistance within the soil mass.

(b) Indicators/Symptoms

- Block slippage of the bank exposing a curved failure surface on the bank. The slumped material may or may not be present depending on whether stream flows have removed the material from the base of the bank,

- Lateral movement or widening of the stream banks,
- Absence of bank vegetation,
- The presence of mature vegetation types not normally associated with regular and prolonged inundation at the toe of the bank.

(c) Possible Causes

- Deepening of the stream bed at the toe of the bank resulting in the bank becoming unstable,
- Surcharge weight on the top of the bank (vehicles, buildings),
- High pore water pressure in the bank material not being balanced by adjacent hydrostatic pressures in the stream,
- Removal of binding vegetation.

43.3.9 Lateral Bank Erosion

(Refer Figure 43.3)

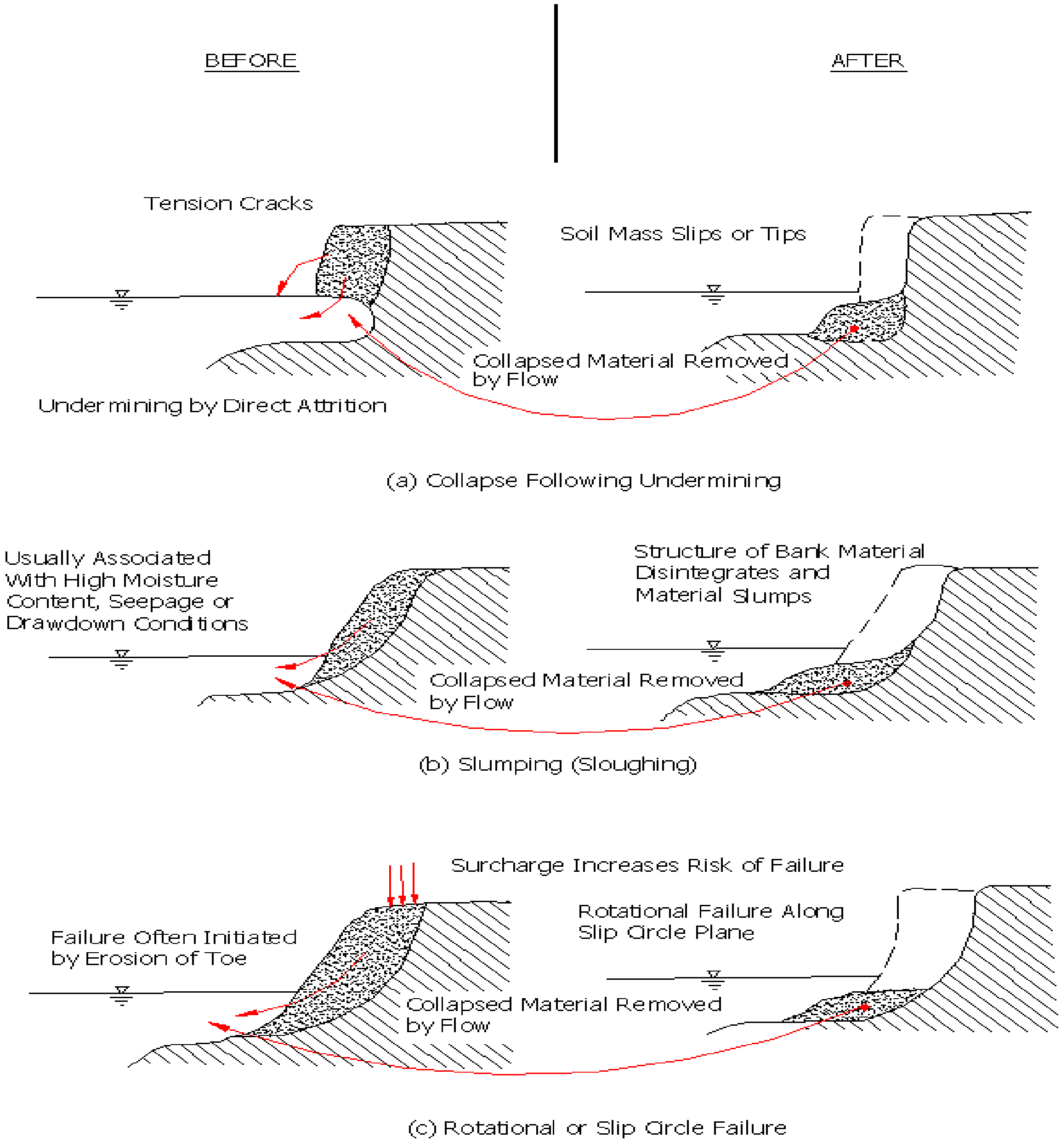


Figure 43.4 Mass Bank Failure Modes

(a) Description

Erosion of the stream banks resulting from both the entry and exit of flows from the stream channel. Lateral bank erosion is most prevalent at locations where runoff from adjacent land is concentrated within culverts, roadways and drainage lines and depressions prior to entering the main stream. It also commonly occurs on cultivated lands where furrows between plant rows direct excess runoff from rainfall or irrigation systems to the edge of the stream bank in an uncontrolled manner.

The erosion takes the form of an upstream progressing erosion head that propagates laterally from the main stream channel. Where the runoff reaches the top of bank as sheet flow the bank may display a columnar or vertical fold formation.

(b) Indicators/Symptoms

- Ephemeral gullies or rills entering the river bank above the normal water level,
- Columns or vertical erosion folds in the bank,
- Tension cracks in the bank and crumbling of the upper soil horizons.

(c) Possible Causes

- Culverts, roadways, drainage swales etc. discharging concentrated stormwater runoff to the stream channel,
- Redirection of the stream channel due to urbanisation of the catchment and/or clearing of fringing bank vegetation (particularly where this occurs on the inside of a meander),
- Erosion prone material at the top of the bank such as dispersive clays, soft silts, and unconsolidated sands and gravels,
- Lack of vegetation (especially ground cover) on the bank.

43.4 STREAM RESTORATION

The aim of stream restoration is to change human-induced alterations to watercourses in such a manner that the ecological functioning of the new state resembles a more natural river (Muhar et al., 1995). The resulting stream needs to be sustainable from both an ecological and geomorphological perspective.

The River Continuum Concept, nutrient spiralling and geomorphic zoning discussed in Chapter 2 provide a number of guidelines for appropriate stream restoration including the following:

- Any break in the naturally occurring aquatic or riparian corridor may induce a negative effect on downstream ecosystems. Stream reaches with poor habitat value may hinder the migration of fish and macroinvertebrates. Therefore restoration of a particular reach undertaken in isolation is likely to be less ecologically viable than if the entire watercourse was in a 'natural' condition. This is not to say that restoration should not be undertaken unless the whole stream can be restored but rather that reaches subjected to restoration work should be sufficiently large to a reasonable chance of long term viability. Additionally each reach should form part of an overall plan whose ultimate objective is the total restoration of the stream. As a guide the ideal reach length taken in isolation should satisfy the viability criteria for habitat islands.
- Aquatic fauna and flora characteristics change along the length of a stream and this fact needs to be recognised when habitat requirements are being considered.
- Physical habitat reconstruction needs to account for the location of the works within this continuum (Muhar et al., 1995; Richards et al., 1993; Rabeni and Jacobson, 1993). The reconstructed channel or stream should therefore replicate as closely as possible the probable stream and riparian ecological and geomorphological characteristics prior to human induced disturbance. For example, the construction of a channel with meanders and a sandy substrate in a headwater stream is likely to be inappropriate and probably unsustainable from a geomorphic perspective. It would also be ecologically incongruous by providing a habitat foreign to the fish and macroinvertebrate species normally associated with a headwater stream.

A wide range of techniques has been developed to restore or enhance the habitat characteristics of degraded watercourses for aquatic fauna. These techniques fall into four categories:

- Bank stabilisation,
- Bank armouring/protection,
- Grade controls, and
- Land and water management.

Stream restoration techniques developed for areas in temperate climates and differing geological conditions such as in North America, Europe and the Australia should be used as guides only and may need to be modified to account for the characteristics of channel morphology and aquatic ecology developed in response to local Malaysian conditions.

This is not unusual and the efficiency of the restoration should be monitored to provide data on any required refinements and to provide base data for future projects (Michell, 1995; and Newbury & Caboury, 1993). Following completion of works designed to restore the physico-chemical conditions in a degraded watercourse, induced recolonisation by fish and invertebrates may be required, especially if there is no direct link to natural "intact" areas containing appropriate species (Bayley and Osbome, 1993).

43.4.1 Natural Channel Design

The design of 'natural channels' is an extension of stream restoration. It involves the creation of channels with the attributes of natural watercourses pertinent to the location within the watershed and should be based on a sound understanding of fluvial geomorphic principles.

In the main, stream restoration and design will occur with alluvial streams as opposed to confined streams where the channel geometry is constrained by the naturally occurring bed and bank material (usually rock). Alluvial streams are characterised by their ability to alter their own boundaries and, in the absence of external influences, will ultimately reflect a balance between the sediment supply, stream power and the hydrological regime within the catchment. Therefore the channel design should recognise the six degrees of freedom in an alluvial stream (planform, bedform, flow resistance, stream slope, width, and depth), and in so doing provide consistency or gradual variation with the characteristics of the upstream and downstream channels. That is the longitudinal variation of ecological and geomorphological processes is recognised and reflected in the design.

Guidelines on natural channel design methodology are provided by OMNR (1994a). The suggested design steps are:

<u>Define design objectives:</u> Identify the objectives to be met for the design. Multiple objectives regarding conveying flood flows, aquatic habitat, recreation, aesthetics and maintenance may exist and frequently will appear to be in conflict.

<u>Define existing conditions:</u> The existing flow regime, sediment load, channel, valley and catchment conditions can be obtained or estimated.

<u>Define the expected conditions:</u> The expected flow, sediment loading and channel slope conditions can be estimated or calculated.

<u>Identify inconsistencies:</u> Any inconsistencies between the existing and expected conditions are identified and resolved.

<u>Design parameters:</u> The design parameters for the channel for unconstrained design conditions are developed to satisfy the objectives.

<u>Identify constraints:</u> Constraints to the channel design are to identified. Some of the more common constraints include funding, property boundaries, roads, services, flooding, and different agencies having responsibility for different reaches of the same watercourse.

<u>Identify compromises</u>: Compromises maybe required between the optimum design conditions and the site constraints.

<u>Develop design:</u> The design of the channel system is undertaken, based on creating a channel in dynamic equilibrium with appropriate habitat features.

<u>Evaluate design:</u> The resulting design is compared to the optimum design and the extent of any discrepancies (there are usually some) are identified and assessed as to their importance in achieving the overall design objectives.

43.4.2 Developing a Channel Design

Every watercourse is uniquely defined by the catchment hydrology, geology and soils, climate, vegetation, landuse, stream use, and its geological age (stream maturity). There is therefore no prescriptive recipe, which can be applied to all streams based on historical, existing, or expected conditions. There are many areas where fluvial geomorphology is still in its infancy and channel design is often more an art based on an understanding of observed behaviour of streams under similar conditions than it is a science.

In designing an alluvial channel consideration should be given to the following criteria. The brief comments provided are intended to flag the generally more important issues to be addressed rather than providing a complete set of design guidelines.

<u>Planform:</u> This refers to the shape or stream configuration when viewed on a plan. It covers characteristics such as:

- stream sinuosity (a measure of meander shape, size and frequency),
- meander length and amplitude,
- channel pattern (straight, multi-channel, braided),
- presence of ox-bow lakes, meander cutoffs, etc.

An examination of a stream's planform can give an indication of whether the meanders are migrating, increasing or decreasing, or whether different reaches of the stream are aggrading (areas of deposition) or degrading (eroding). An examination of sequential aerial photographs taken over several decades can be particular useful in identifying historical and possible future changes in planform.

A natural stream does not necessarily contain meanders and therefore during the design process care is needed to establish the likely meander pattern and size for the new channel to remain stable.

Bedform: This overlaps to some extent with channel patterns but also includes a consideration of the shape of the stream bed and its variation over one or more reaches together with the nature of the material forming the bed. Bedforms can provide important clues to the stream processes present. For example, the presence of a trench on the outside of a bend may indicate migration of the river bend either laterally and/or longitudinally. The presence of recently formed or growing mid-stream bar(s) will generally indicate an area of deposition, which may have ramifications for stability of the banks opposite the bars.

The presence of pools and riffles will usually conform to a natural frequency of occurrence along a reach. In some European streams this is often in the order of 5 to 7 times the stream width but there is little data available for streams in more tropical climates. Additionally pools and riffles are not always naturally present. In sand bed streams they are frequently barely noticeable often only being defined by regular alternating deposits of coarser and finer bed deposits.

Flow resistance: This design characteristic influences the velocity profile both vertically and horizontally across a section. It is affected by bedform, bed and bank material, vegetation, and natural or artificial obstructions in the channel or on the floodplain. Thus the removal bank vegetation will usually lower the surface resistance to flow thus increasing the near bank stream velocity. If the velocity increases to above the scour threshold value for the bank material erosion will occur. Sudden changes in bank flow resistance will often result in eddy flow, which in the case of bank hard armouring may destabilise the protection works, and it is therefore good practice to provide a transition zone.

Stream slope: This is a measure of the longitudinal slope of the stream thalweg (line traced by the low point on successive cross sections). An examination of the stream slope can assist in identifying any sudden changes in slope, which may indicate the presence of stream instability due to bridge, dam or other in-stream structure. The causes of slope change can be natural or artificial (i.e. bridges, dams, or other in-stream structure or activity such as gravel or sand extraction). Changes in slope maybe sudden (i.e. a waterfall) or they maybe gradual and only noticeable over a considerable distance. Where a structure or activity has caused a change in stream slope the long term effects may be experienced a long way from the original site and for this reason extreme care is required when designing any in-stream structures or approving of in-stream mining or diversions which result in a change in the reach length.

Stream width: When stream width is usually considered together with depth and the ratio of the two dimensions can provide further clues as to the dominant stream processes in the reach. In an alluvial stream a high width:depth ratio will often indicate that the stream is in a deposition stage where the load carrying capacity of the stream is greater than the sediment input at the top of the reach. Alternatively the presence of an exposed resistant stratum across the stream bed may induce a widening of the stream without appreciable deepening and in which case the stream sediment load capacity may still be lower than the available sediment supply. Urban watercourses are frequently relatively deep and narrow which is a reflection on the increased water supply following urbanisation of the catchment. In these cases the stream is still actively eroding its bed and banks in an attempt to balance its sediment load capacity with the available flow.

Stream depth: Refer to discussion on stream width.

Vegetation: The presence of appropriate vegetation along the stream bank and the floodplain is a vital component of a stream and must be given careful consideration when designing a "natural" stream. Additionally in some cases in-stream vegetation may also be appropriate. While vegetation maybe absent from sections of a natural stream it is a temporary phenomenon and should not be regarded as a permanent feature to be incorporated into a design. When specifying the vegetation for a channel design an assessment of the height and extent of flooding for a range of flood frequencies and durations should be made and the plants selected according to the expected flooding regime, light conditions and soil types present. Unless the stream bank is particularly stable care should be exercised when planting large trees close to the top of the bank where they maybe subject to undermining from stream flow, or are subjected to high winds which may cause them to fall into the stream and expose the bank.

Often natural vegetation is unable to cope with the expected hydraulic loading and consideration can be given to reinforcing the vegetation with either temporary or permanent matting or other proprietary products. There are a wide range of reinforcing mats available which allow root penetration and greatly increase the capacity of the vegetation to withstand high velocity flows. Alternatives to matting include soil confinement systems, which contain pockets of soil in which the root system is shielded from direct attack by stream flows.

43.4.3 Road Crossings

In selecting the site for a road crossing acknowledge that even stable streams are in a state of dynamic equilibrium and may alter their dimensions or course in response to natural causes and that crossings will restrict this natural process or be undermined/outflanked by it.

Recommended techniques to minimise the impact on a natural stream include:

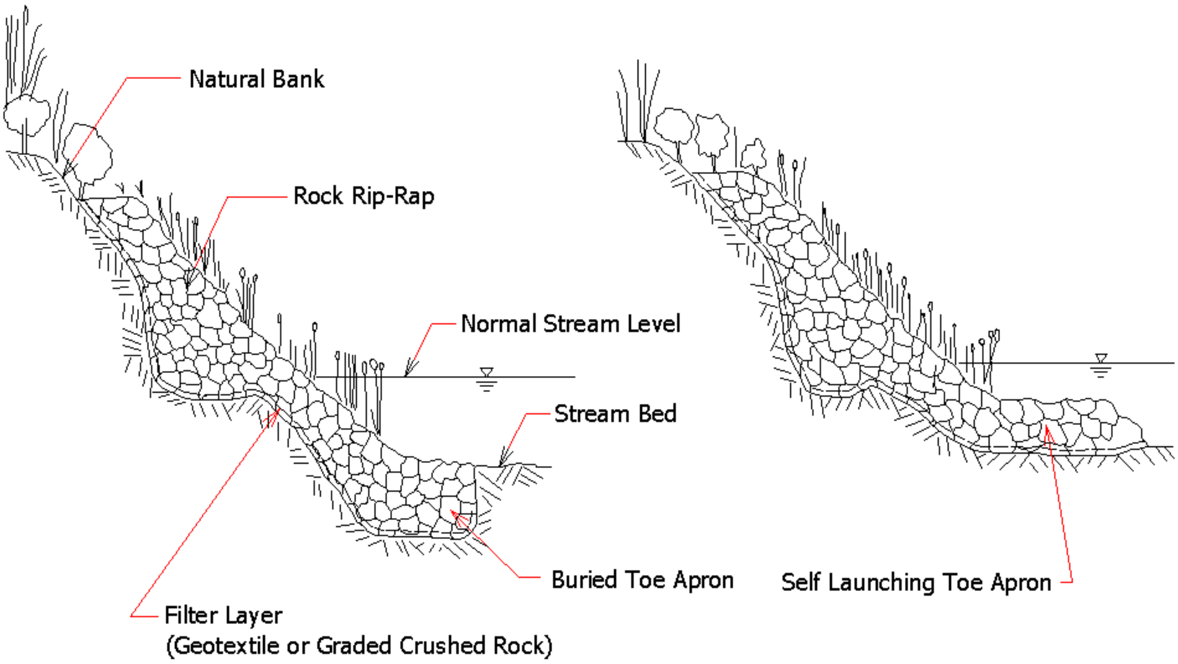
- aligning the road crossing to match the stream rather than altering the stream alignment, and

- enabling the migration of fish and aquatic invertebrates past the crossing by;
  -) maintaining a culvert invert at or below the natural stream bed,
  -) providing a culvert or bridge waterway area which avoids marked increases in stream velocity upstream and downstream of the crossing for 1 Year ARI flows or bank full conditions whichever is the lesser,
  -) minimising scour potential which will increase sediment loads and may create a sharp drop which acts as a barrier to fish migration, and
  -) providing fish ladders where sharp differences in bed levels are unavoidable. Generally fish ladders are designed for low flow conditions and should be graded no steeper than 5% and include rest areas of quiet water created by shielding rocks or other low profile obstructions.
- For estuary crossings, changes in tidal flushing can be minimised by using flat bottomed crossings (i.e. box culverts) rather than pipes, and consideration should be given to the changed flow characteristics (rate and volume) on any seagrass beds or similar.

43.5 WATERCOURSE MANAGEMENT TECHNIQUES

The following techniques are not an exhaustive list but represent the most commonly applied techniques suitable for urban streams and rivers. However not all techniques described below would always be suitable in an urban environment. Public safety, aesthetics, and cost will often preclude the adoption of a technique. In each case the local constraints must be carefully evaluated and compared with the advantages and disadvantages of a particular technique to ensure that the optimum solution is selected.

43.5.1 Bank Armouring – Rock Rip-rap



Description

Graded rock is placed (not dumped) and spread over the face of the river bank to provide a protective layer against erosive river flows. A filter bed of well graded finer rock or a geotextile is used to limit material being leached from the parent bank. Rocks should be angular so as to promote interlocking between individual rocks in the mass.

Variations

Large boulders maybe individually placed in random but interlocking arrangement to reduce the volume of rock required for stability.

Application

Direct protection against erosion.

Increased stability of bank against mass slip circle failure, sloughing, and fretting, as a result of seepage, drawdown or direct scour.

Limitations

Requires a nearby supply of hard sound rock.

Advantages

Flexible and easily maintained.
Allows vegetation to establish.
Provides a long term solution although rock may
Require topping up following a large flood.

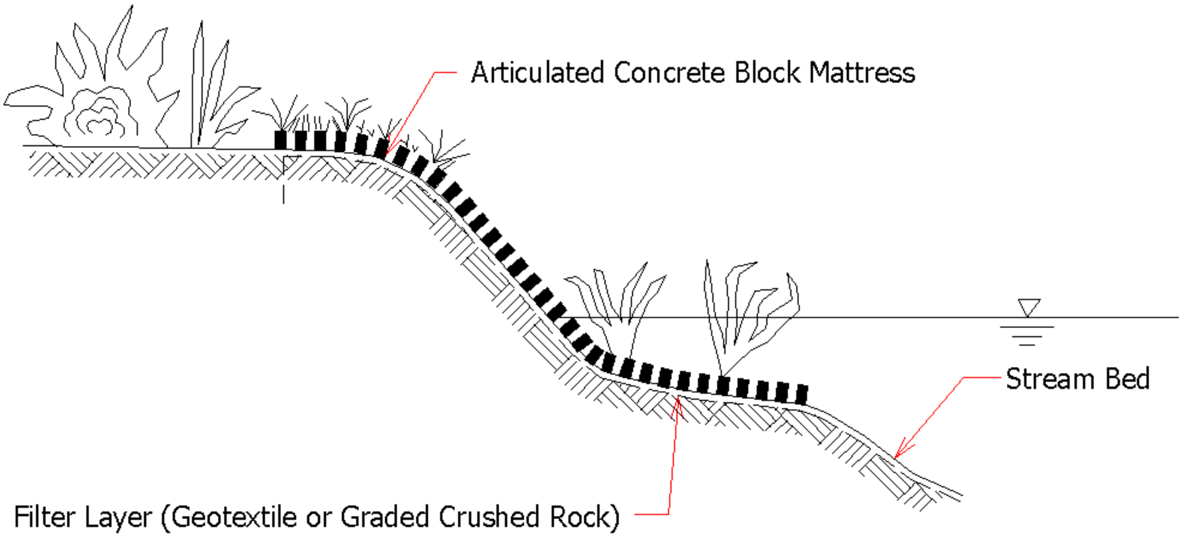
Disadvantages

Can be expensive if long haul distances are required for rock.
Is not suitable where the river bed is unstable.

Indicative Cost

Variable depending on availability of suitable rock.

43.5.2 Bank Armouring – Articulated Concrete Block Mattress



Description

An articulated concrete block mattress is laid on a prepared stream bank to provide a physical barrier between the bank and the flowing water.

Variations

1. Rock filled wire mattress may be used ("Reno" mattress).
2. Bank may be battered before placing mattress.
3. Mattress can be placed on the lower bank only if desired.
4. May be constructed with either a buried or self launching toe.

Application

Provides protection and stability to eroding banks. Suitable for a range of bank conditions including fretting and direct attrition.

Providing it is suitably anchored it can withstand high velocities for prolonged periods.

Limitations

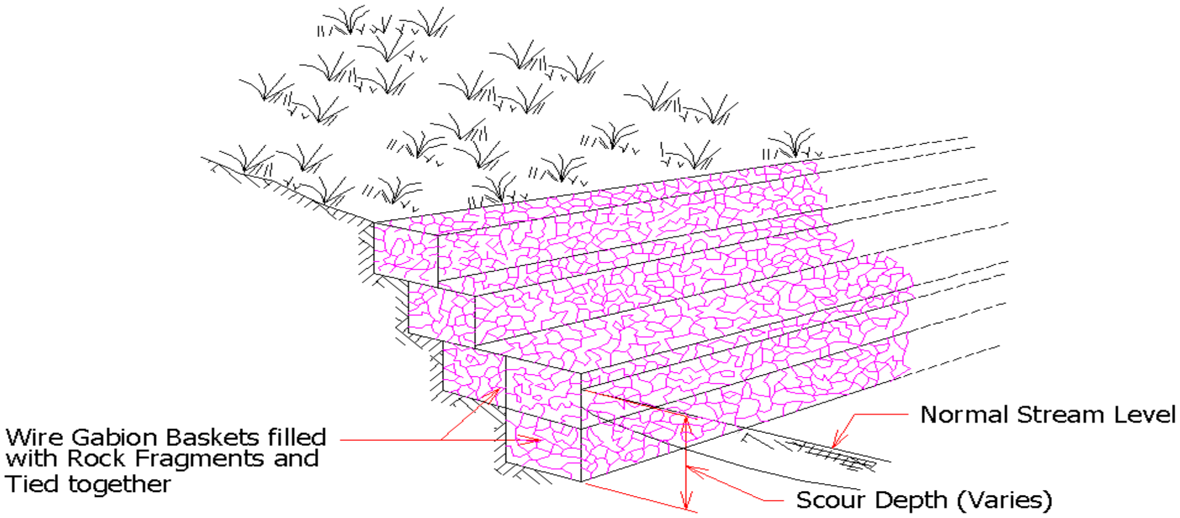
- Toe apron requires anchoring,
- Where the stream is prone to bed scour an extensive toe apron is required which will requiring anchoring.

Advantages	*Disadvantages*
Near permanent solution	Aesthetically harsh in the short term
Flexibility	More difficult to use with vegetation compared with rock rip-rap or placed rock
Low maintenance	

Indicative Cost

Low to medium.

43.5.3 Bank Armouring – Rock filled Wire Baskets and Mattresses



Description

Gabion wire baskets or mattresses are filled with rock fragments or river cobbles and laid adjacent or on the stream bank.

Variations

Bank may be battered before placing rock.

May be constructed with either a buried or self launching toe using mattresses ("Reno" mattresses).

May be coated with a protective skin (e.g. concrete) or a sacrificial coating of timber or bitumen.

Application

Provides protection and stability to eroding banks.

Suitable for a wide range of bank conditions including;

- fretting,
- direct attrition, and
- undermining leading to mass failure.

Limitations

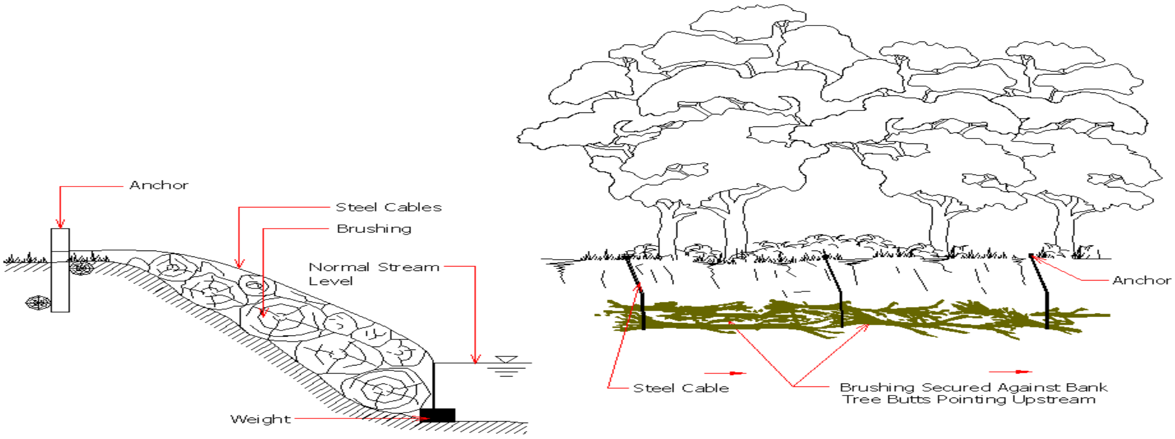
Usually fail by wire breakage due to high sediment loads carried by stream or by vandalism or by undermining.

Advantages	*Disadvantages*
Suitable where suitable large rock is unavailable.	Requires sacrificial facing when stream sediment load is high.
Can use broken concrete pieces instead of rock.	Subject to corrosion in hostile environments following damage to protective wire coating.
Requires infilling of rock interstices to enable vegetation to establish.	

Indicative Cost

Low to medium.

43.5.4 Bank Armouring – Brushing



Description

Cut or fallen trees and woody scrub are layered on the eroding bank, tied to anchors and weighted if necessary. Anchors may be buried logs or driven posts. Weights may be concrete blocks or wire mesh bags filled with river gravel or similar. In an urban environment this technique is only used adjacent to large parks and golf courses, and where potential blockage of downstream crossings caused by dislodged brushing is minimal.

Variations

1. Bank may be battered before brushing is placed.
2. Piles driven out from the bank may be used to secure brush or logs in position. Offset piles may be used to create a mini groyne effect.
3. Willow spars or other local fast growing tree cuttings may be laid on the bank before placing the brushing.
4. Mattress brushing can utilise lighter material.

Application

Provides bank protection for a limited time to enable “permanent” vegetation to become established on the bank. The technique is effective against fretting and attrition erosion mechanisms. It may also contribute to lowering the risk of mass failure by reducing the risk of material being removed from the toe of the bank.

Limitations

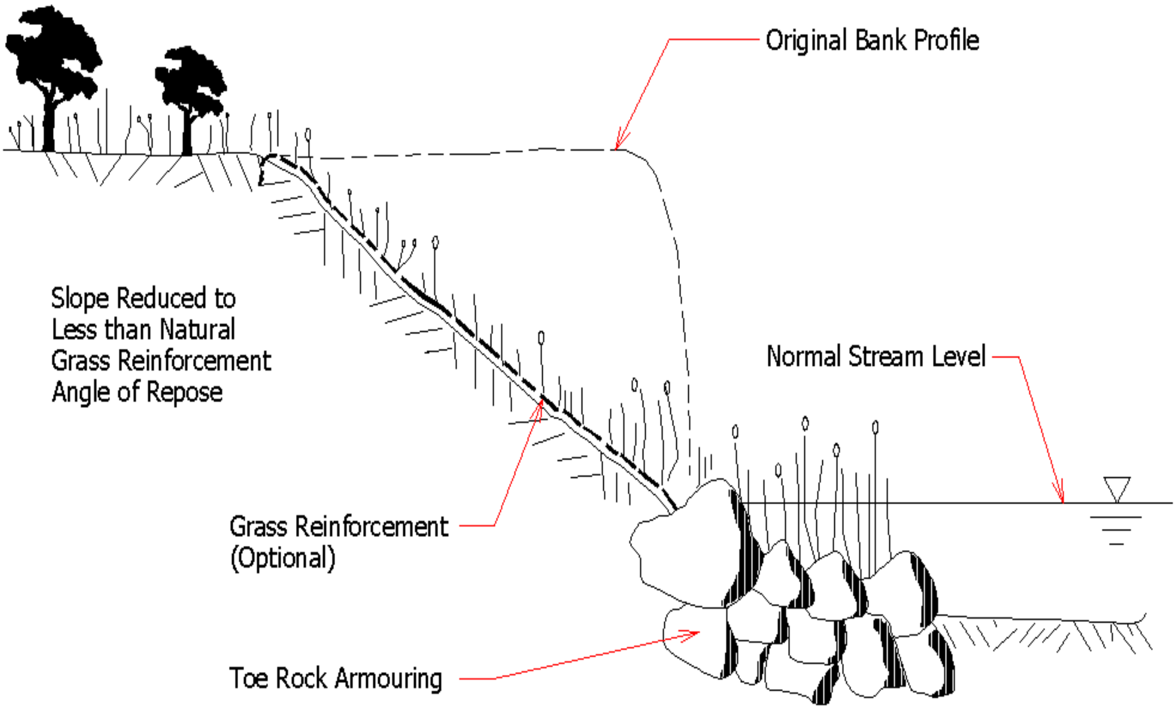
Only provides short term protection.

Advantages	*Disadvantages*
Low material cost when suitable material is nearby.	Limited to when suitable material is available.
Allows vegetation to establish.	Effect of cutting/removing nearby trees can be significant.
Has a positive effect on the river environment.	Labour intensive.
	Security of end result is variable.
	Generally best suited to banks under 3 metres high unless only the bank close to the water line requires protection.

Indicative Cost

Low.

43.5.5 Bank Stabilisation – Battering



Description

The slope of an unstable bank is excavated to reduce the slope to a value less than the repose angle of the in-situ bank material. The amount the bank slope is reduced will depend on the required factor of safety, which may range from 1.1 where the consequences of bank failure are minimal to 1.5 or more where buildings would be threatened.

Variations

Treatment maybe applied to the upper bank only with alternative treatment used on the lower bank.

Application

Used to; reduce public safety hazard caused by steep banks, to reduce erosion hazard caused by fast flowing overland flow, to increase bank stability against rotational failure or mass failure, and to provide an environment conducive to establishing vegetation.

Limitations

Land take behind the bank line maybe considerable if flat slopes are required.

Advantages

Simple procedure which utilises commonly available earthmoving machinery.

Disadvantages

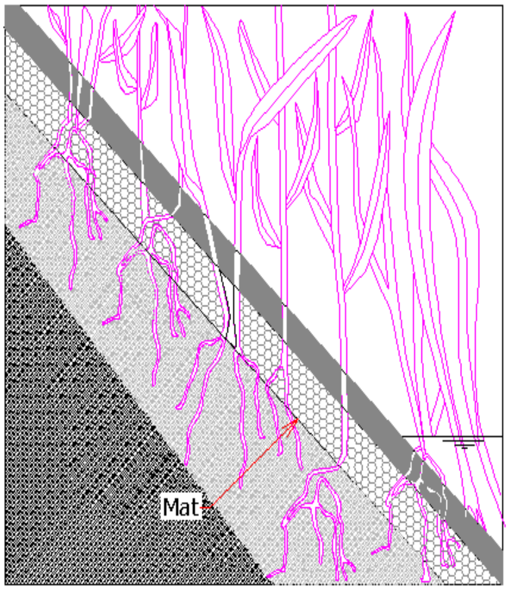
Limited application for perennial streams, best suited where flow is intermittent.

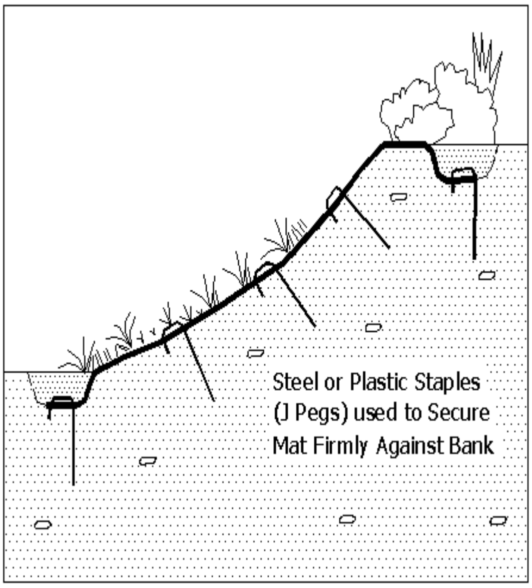
Susceptible to rilling unless supplementary protection is provided until vegetation is established.

Indicative Cost

Low.

43.5.6 Bank Stabilisation – Reinforced Vegetation





Description

A thin open non-biodegradable mat is secured to the prepared river bank, covered with topsoil and seeded. The mat works by allowing the plant roots to penetrate the mat, which then binds individual plants into a single mass, which has a substantially greater resistance to dislodgement by erosive river flow.

Variations

Bio-degradable mats made from natural fibres (often coconut fibre) is used as a temporary stabilising system.

Mats maybe impregnated with a sand – bitumen mastic and or with pre-grown grasses.

Application

Use a separating layer between river flows and an eroding bank. Often combined with bank battering.

Limitations

Limited effectiveness below normal river level.

Advantages

Suitable where high flow velocity occurs for short periods (less than 9 to 12 hours).

Low cost and easily installed with non skilled labour.

Readily combined with techniques using flexible scour.

Suitable over a wide range of flows.

Disadvantages

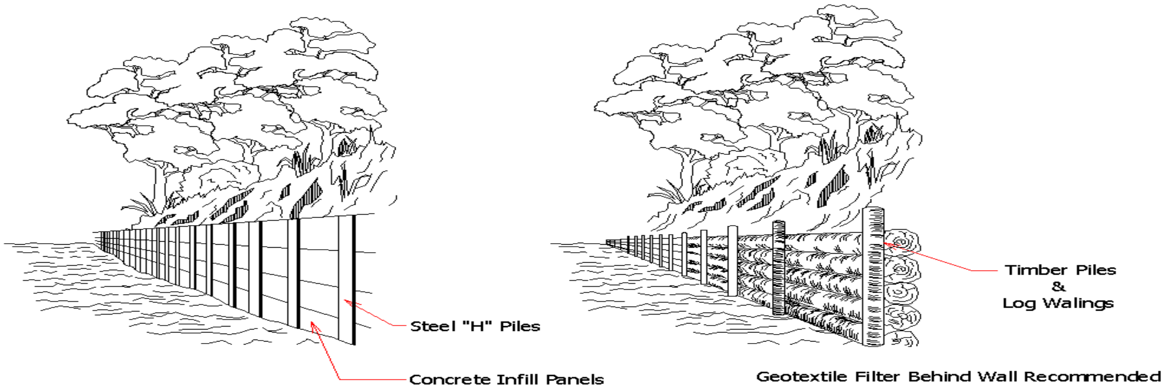
Deep anchoring system required in soft and non-cohesive material.

Mat can be damaged by slashing and/or mowing.

Indicative Cost

Medium.

43.5.7 Bank Stabilisation – Retaining and Training Walls



Description

A wall is constructed at the toe of or in front of the eroding bank using driven steel piles and concrete panels to physically separate the stream bank from the flowing water.

Variations

Wall may be constructed from:

1. timber piles and log wallings (a permeable wall), or
2. steel sheet piling, or
3. reinforced concrete or masonry blocks.

The wall is sometimes constructed only to protect the lower bank, to a level such as the 2 year ARI flood level.

Application

Normally used as an alignment training technique but also provides protection and stability to eroding banks. Suitable for bank conditions involving,

- fretting, and
- direct attrition.

Limitations

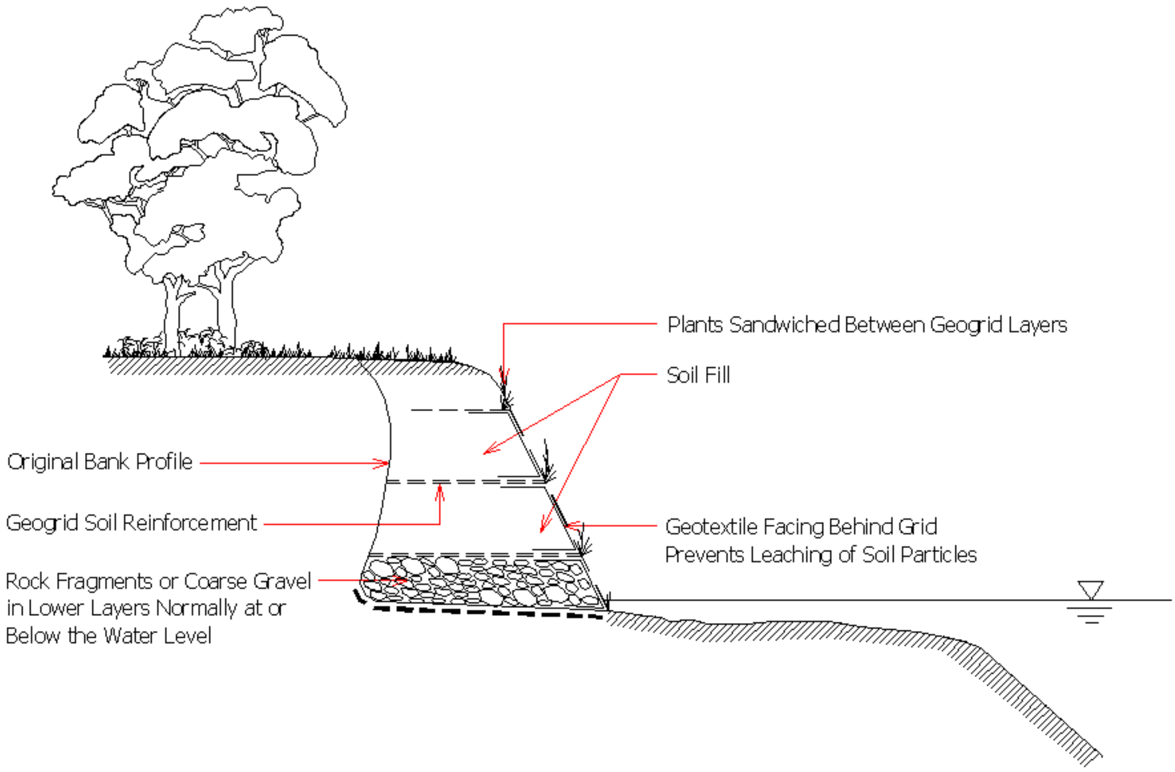
- Where the stream is prone to bed scour the wall may be de-stabilised by undermining,
- Pile driving equipment may be required.

Advantages	*Disadvantages*
Useful where limited space is available, re-vegetation can be used behind the wall.	Cost is usually high compared with other techniques for bank protection. Potential scour problem along entire length of wall. High velocity flows can develop behind the wall unless lateral fences are used. Aesthetically harsh.

Indicative Cost

High to very high.

43.5.8 Bank Stabilisation – Bio-reinforced Embankments



Description

A geogrid is used to construct a reinforced earth bank in front of, or to replace the eroding bank. Suitable vegetation is sandwiched between successive geogrid layers as the bank is constructed. A light weight geotextile is used to face the bank and prevent loss of material while the vegetation becomes established. Where a suitable bench exists in front of the re-constructed bank semi emergent and emergent vegetation can be established to blend with the bank planting.

Variations

Reinforced earth bank may be near vertical or sloped.

A timber crib wall can be used in lieu of the geogrid. The bottom lifts are usually filled with cobbles if subjected to wave action.

A soil confinement matting system maybe used in lieu of the geogrids.

Application

Provides bank protection against undermining, piping, rotational, and slumping failure modes.

Limitations

Requires a supply of suitable vegetative material. Toe scour may occur especially where the reinforced bank is terminated above the low water line.

Advantages	*Disadvantages*
Suitable for a wide range of bank conditions.	Labour intensive (placement of vegetation).

Provides immediate protection while vegetation becomes established.

Geotextile is prone to degradation if exposed to UV light for prolonged periods.

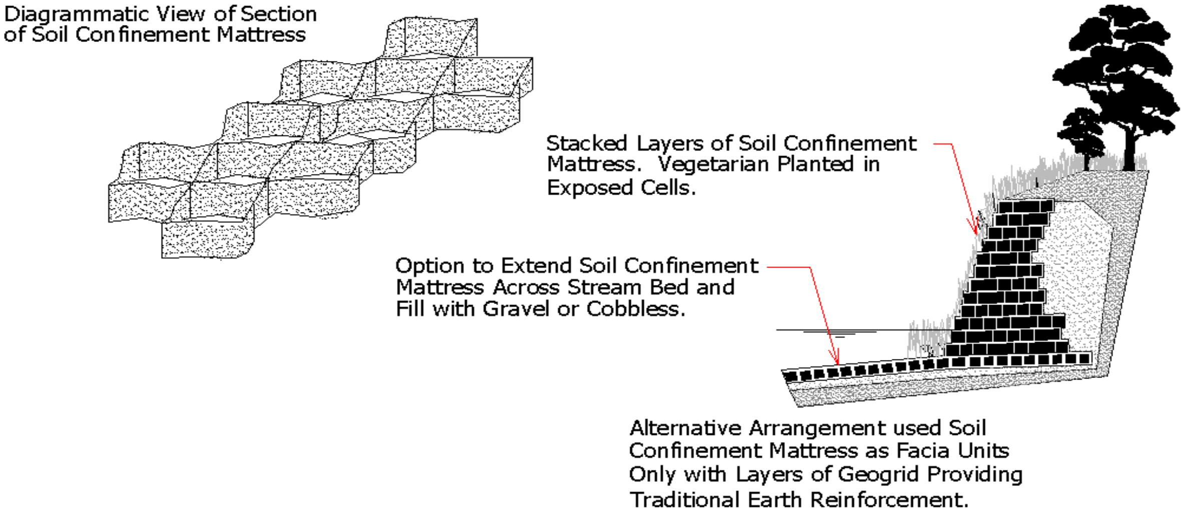
Flexible system which can yield and rebound under stress.

Does not require specialised construction equipment.

Indicative Cost

Medium.

43.5.9 Bank Stabilisation – Reinforced Earth Proprietary Products



Description

Layers of soil confinement mattresses are used to construct a reinforced earth bank in front of, or to replace an eroding bank. A wide variety of soils types ranging from silt to non-cohesive sand and gravel or small cobbles maybe used. Where silt or sand is used to fill the cells, vegetation can be established on the face of the bank.

Variations

Flat geogrids can be used in soils with high friction angles and vegetation, usually cuttings, planted between the geogrid layers to form a vegetated embankment. The face of the embankment maybe treated with a vegetation reinforcing mat (Refer to Reinforced Vegetation technique).

Application

Used to re-establish an eroded river bank or to reinforce an existing bank.

Limitations

Requires a facing to limit the risk of continued scour.

Advantages

Suitable over a wide range of bank heights.

Ideal for streams with generally low flow depths.

Readily combined with riparian vegetation.

Disadvantages

Requires bank facing to prevent continued scour.

Stream channel must be wide enough to accommodate method.

Adaptable to awkward or remote areas where the in-situ bank material is suitable.

Low cost compared to other techniques.

Indicative Cost

Low to medium. Vegetation costs are additional.

43.5.10 Grade Control Structures – Check Weirs

Description

Check weirs are low ungrouted rock barriers normally between 0.75 m and 1.5 m high constructed across the bed of a stream and incorporating an impervious membrane (usually high density polyethylene sheet, but sometimes steel sheet piling or concrete), to create an upstream pond. The downstream face of the weir resembles a rock chute.

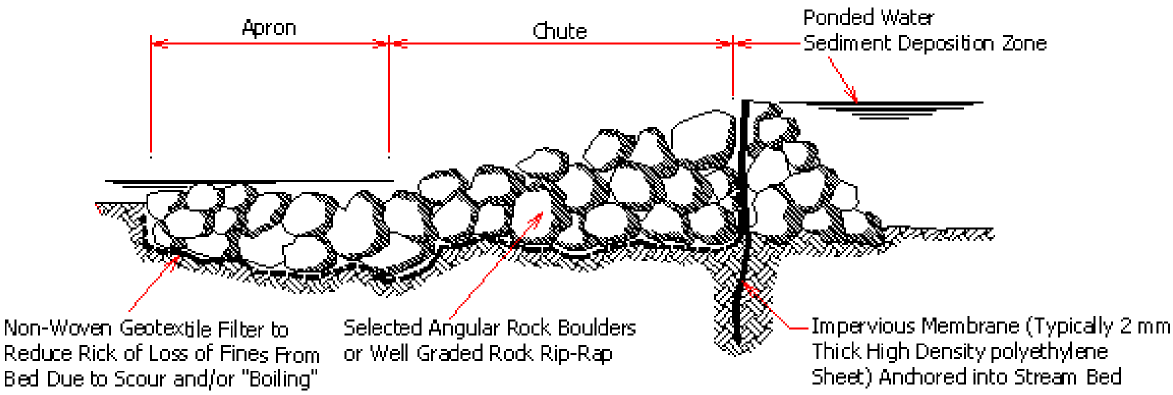
Variations

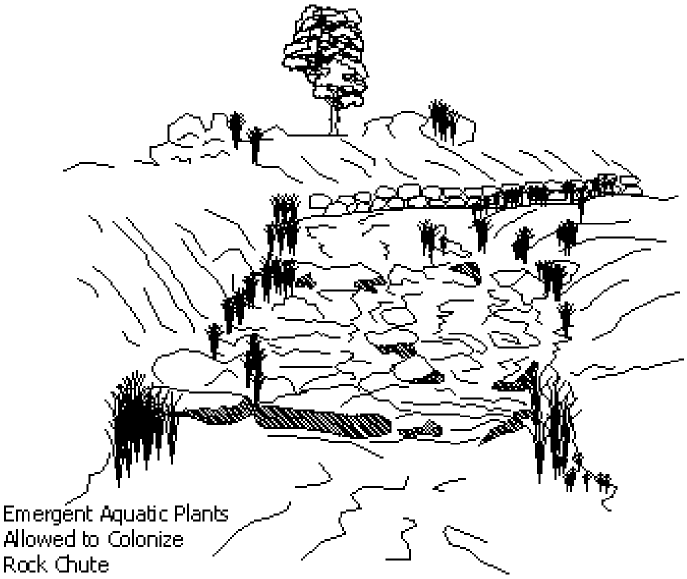
The impervious membrane may be omitted to allow the upstream area to fully discharge under low or nil flow conditions. This form of the weir is often used for sediment control on construction sites.

Timber maybe used instead of rock but at the expense of some structural flexibility.

Application

Used to reduce the effective hydraulic grade and control stream bed degradation (deepening) by promoting controlled sedimentation upstream of the weir. When the upstream ponding area is full of sediment the check weir behaves in the same manner as a Rock Chute.





Limitations

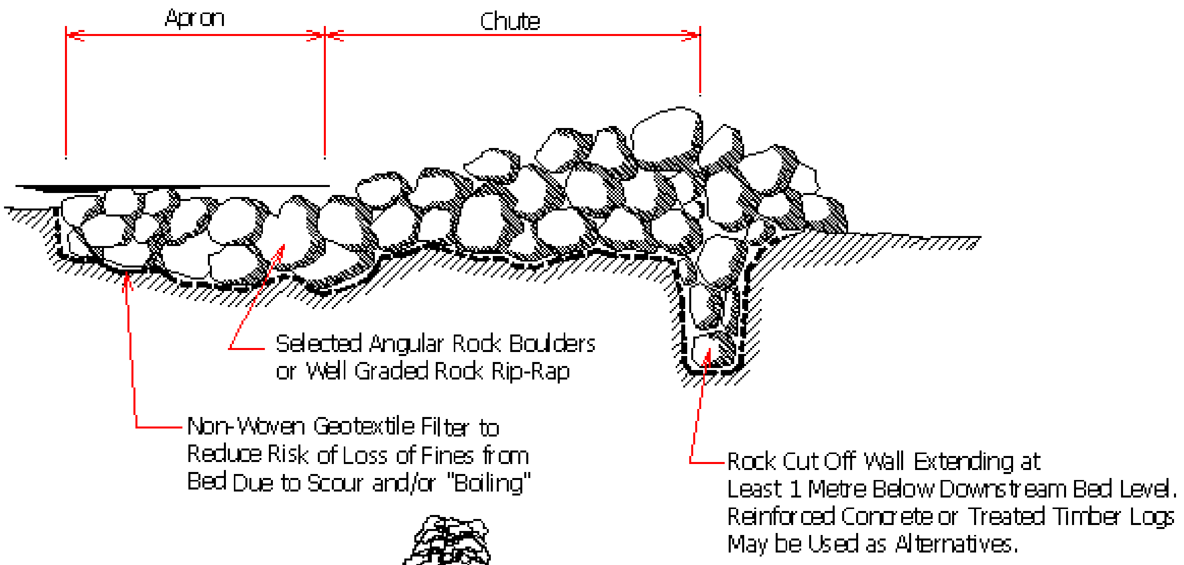
Maybe subject to damage under high depths of inundation. Disturbance of the bank is necessary to anchor the weir and prevent outflanking.

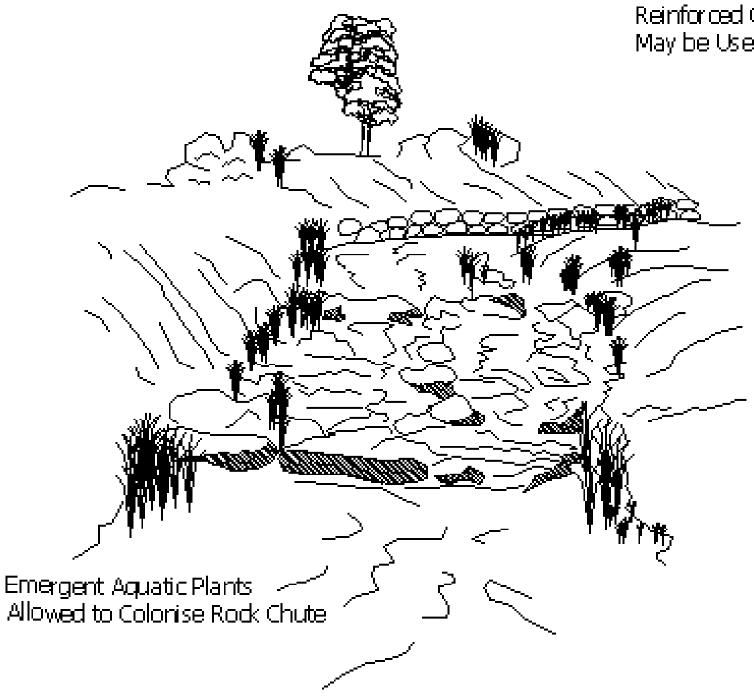
Advantages	*Disadvantages*
Flexibility avoids catastrophic failure associated with rigid structures.	Quality control maybe difficult with graded rip-rap but the use of large placed boulders and geotextile filter layers overcomes most of these drawbacks.
Environmentally sympathetic.	Close attention required to prevent outflanking at the abutments and "boiling" of the stream bed on the downstream face.
Shorter construction period compared to concrete weirs.	Strong currents on the downstream face may inhibit fish migration.
When used in series they create diverse aquatic conditions conducive to a wide range of faunal species.	Where permanent pools are required and sediment loads are high, periodic dredging will be required.

Indicative Cost

Low to medium.

43.5.11 Grade Control Structures – Rock Chutes and Fish Ladders





Description

A rock chute is a drop structure where a relatively short steep section of the stream bed is armoured with rock. Sized and graded rock is placed on a specially prepared section of the stream bed and on adjacent banks. Chutes are typically from 1 m to 5 m high and from 10 m to 50 m long but where provision is to be made for fish migration the slope should be no steeper than 5%. A filter layer (crushed rock or geotextile) is usually placed under the rock armouring.

Variations

Chutes may incorporate a fixed crest and upstream or downstream cutoff walls.

When used as a fish ladder large rocks protruding from the rock mass are used to create staggered shelter zones as resting places and gaps between the rocks in the base of the chute are filled with gravel to ensure water flows on the surface.

Application

Used to stabilise an erosion head and prevent it from moving upstream. Offers an alternative to other forms of drop structures such as steel sheet piling or reinforced concrete weirs.

Limitations

Availability of suitably sized rock.

Effect of chute maybe drowned out at flows, which mobilise bed material. Supplementary techniques such as vegetation are required.

Rock stability considerations limit flow per unit width, thus very wide structures maybe necessary if design flows are high.

Advantages	*Disadvantages*
Flexibility avoids catastrophic failure associated with rigid structures.	Quality control maybe difficult with graded rip-rap but the use of large placed boulders and geotextile filter layers overcomes most of these drawbacks.
Environmentally sympathetic.	Can impede fish passage if slope is too steep.
Has an indefinite design life.	Fixed crest may add significantly to construction costs.
Does not require concrete construction skills.	
Easily maintained.	

Indicative Cost

Low to medium.

43.5.12 Grade Control Structures – Drop Structures

Description

A structure build on the stream bed and used to transfer water from a higher to a lower elevation without erosion. Usually incorporates a downstream stilling basin (vertical drops) or an inclined chute with an energy dissipator.

Variations

Structure may be of concrete, steel sheet pile, timber, rock filled wire baskets (gabions), stacked layers of soil confinement mattresses, or for low vertical drops, rock boulders.

Drops for small flows can be formed using either rigid pipe sections or flexible piping. These are mostly used to convey local runoff into the stream in a controlled manner as part of water land management techniques. Energy dissipators are placed at the pipe outlet unless it is normally submerged.

Application

Used to stabilise an erosion head and prevent it from moving upstream. Also used with a projecting crest to reduce the overall grade of a stream by providing a weir within the channel to cause controlled sediment deposition.

Limitations

Reinforced concrete and steel sheet piling require experienced constructors. Steel sheet piling requires specialised equipment.

Advantages	*Disadvantages*
Designs can be standardised.	Environmentally unsympathetic and impede fish passage.
Some elements can be pre-fabricated.	Many failures have occurred due to inadequate cutoff walls, abutment treatment, and structural failure.
Becomes economic for large design flows and/or high drops.	Inflexible, making partial failures, piping and cracking defects difficult to repair.

Indicative Cost

Medium.

43.5.13 Grade Control Structures – Rock Plunge Pools

Description

Large diameter rocks (boulders) are placed in the creek bed and on the banks to control an upstream progressing erosion head. The boulders are placed so as to line the scour hole immediately downstream of the erosion head thus providing a hard surface to dissipate energy and prevent further progression of the erosion head. The boulders are placed so as to concentrate low flows into the centre of the stream.

Variations

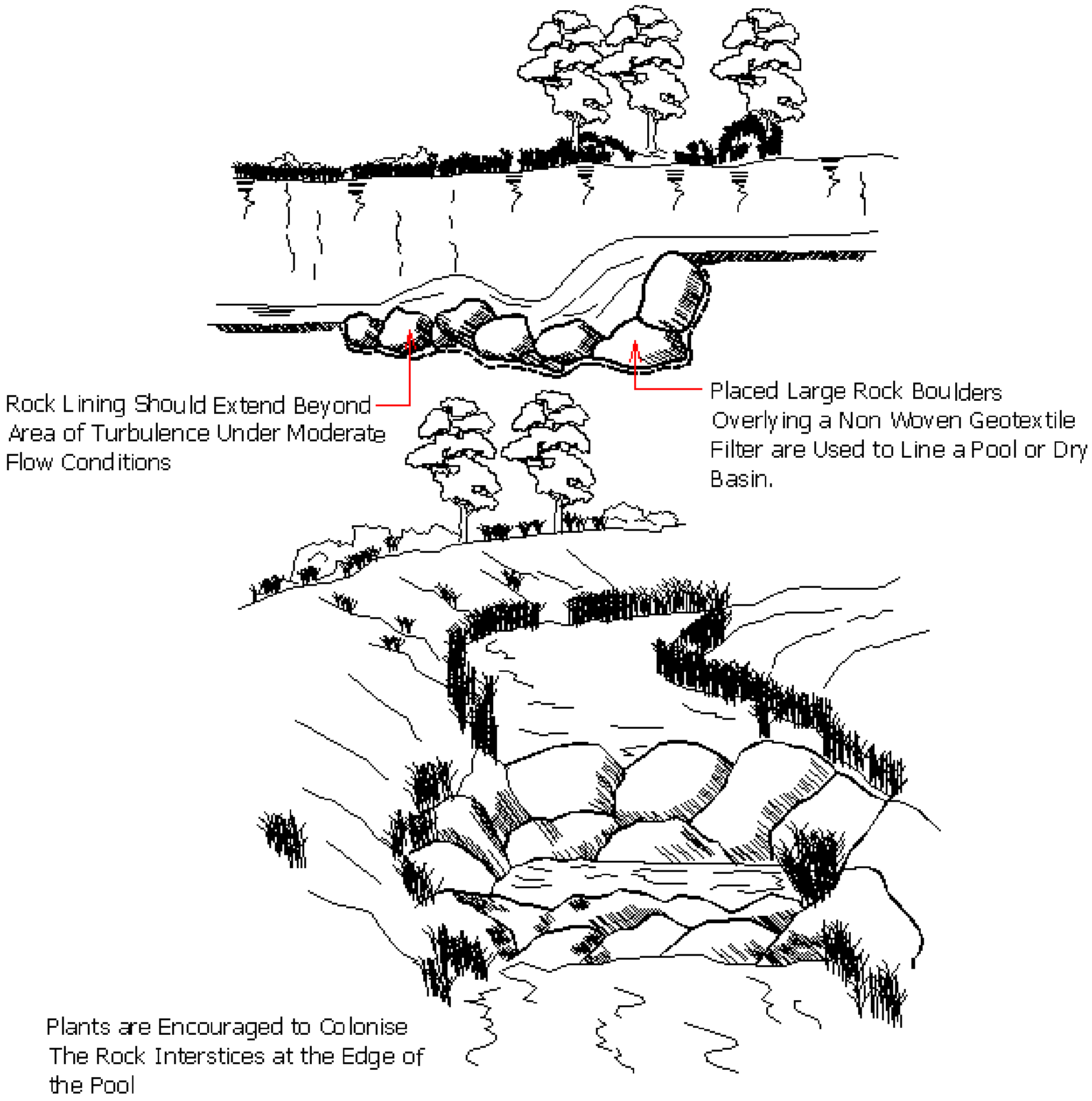
Grouted boulder drop structures, rock filled wire baskets, timber drops with rock apron to dissipate energy.

Application

Control of upstream progressing erosion head in small to medium sized streams.

Limitations

Availability of suitable large rock. Typical boulders have a minimum mass of approximately 1000 kg.



Advantages

Does not require specialist skilled labour.

Easily constructed and maintained.

Aesthetically compatible with the environment.

Disadvantages

Impede fish passage.

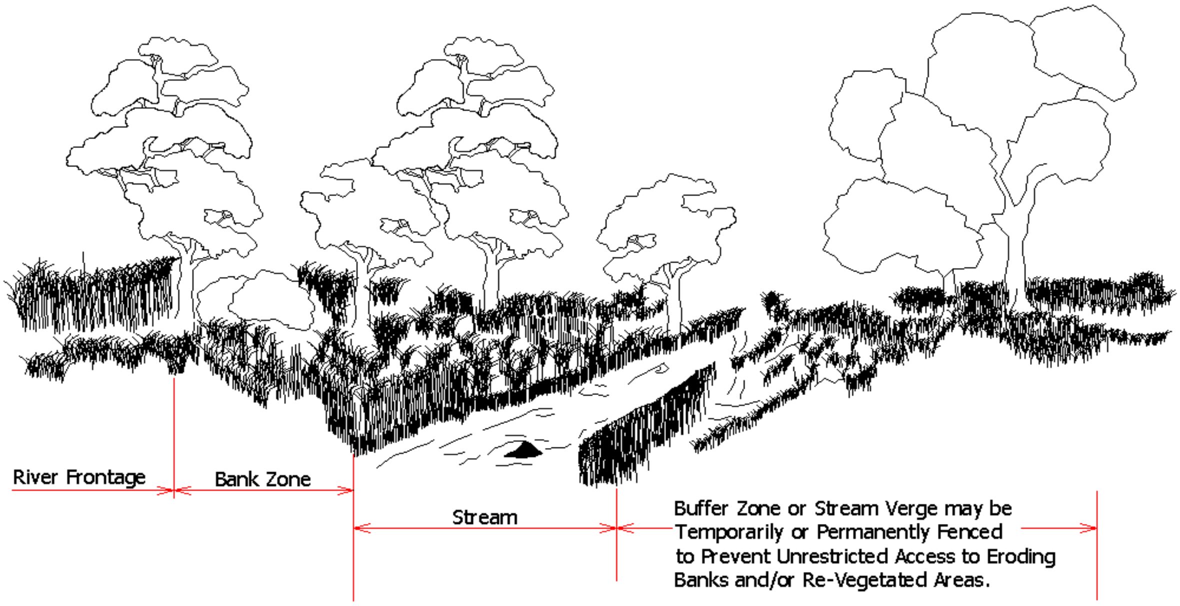
Can fail by outflanking unless cutoff walls are provided on the banks.

Boulders may not be readily available.

Indicative Cost

Medium.

43.5.14 Land and Water Management – Vegetation Management



Description

Vegetation is chosen and established / or protected according to a management plan for both in-stream and terrestrial zones. Typically the riparian vegetation is contained within a buffer zone based on the minimum habitat requirements for the local natural fauna. Vegetation maybe chosen / retained for its root system to assist in slope stability (e.g. vetiver grass – *Vetiveria zizanioides*) or for creating hedgerows capable of assisting the formation of deep sediment deposits in a stream or on the floodplain (e.g. elephant grass – *Pennisetum purpureum*).

On a smaller scale local grasses and other ground covers can filter sediments and other large particulate matter in runoff and thus improve the quality of stream water. Ground covers also help protect the edge of the stream bank from crumbling (attrition).

Fencing can have a valuable role in vegetation management. Bank and near bank vegetation is often protected (temporarily or permanently) by fencing to restrict humans and larger animals. The appropriate use of moveable fencing allows old access routes to re-generate.

Application

Generally to stabilise banks against surface erosion, to filter stormwater runoff, and to improve the appearance of a stream corridor, and to provide suitable faunal habitat. Specialist plants, which may not be natural to the area, can act as structural members in stabilising stream banks and bed scour.

Limitations

Species must be adaptable or suitable for the soil type, climate and flooding regime. Technique is labour intensive if weed species are to be kept under control. When plants are used as hedgerows or groynes or retards, the stream of floodplain must be sufficiently wide so as to not create adverse flooding impacts upstream.

Advantages	*Disadvantages*
Forms a natural part of the environment.	Requires specialist skilled horticultural labour.
Complements and improves structural techniques.	Labour intensive.
	Establishment is subject to the vagaries of the weather.

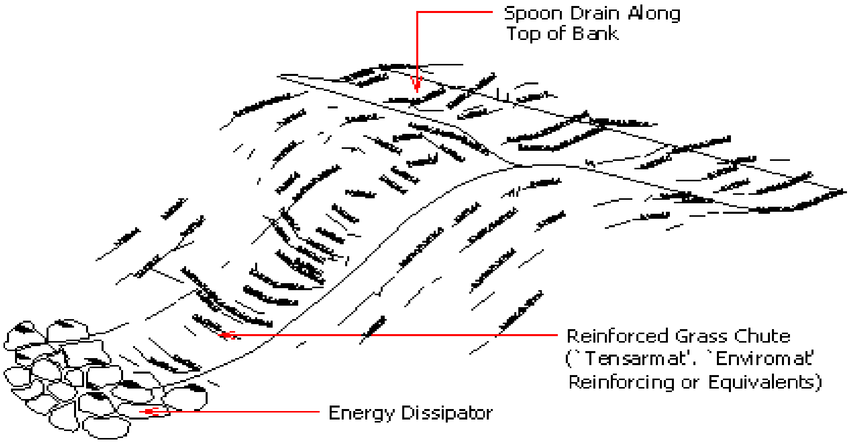
Species with good structural characteristics may not be compatible with the local environment.

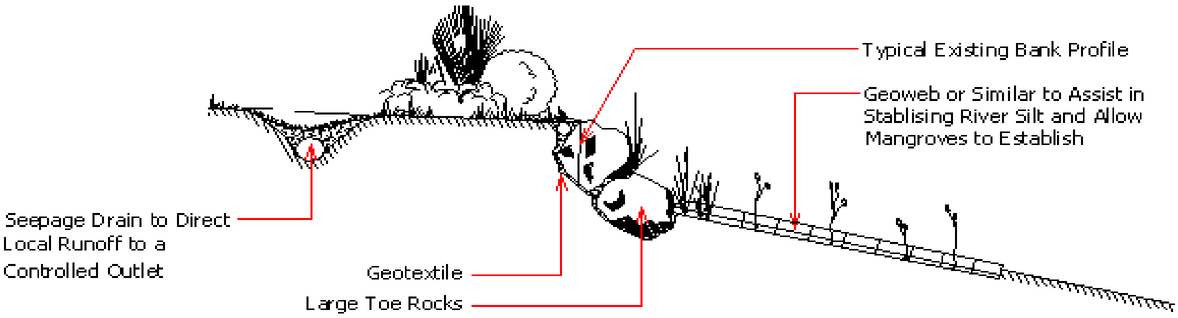
Fencing recommended during establishment period.

Indicative Cost

Highly variable depending on source and type of plants. Fencing costs will vary depending on the type.

43.5.15 Land and Water Management – Local Drainage and Runoff





Description

This includes a wide range of practices with many variations, some of which incorporate techniques described elsewhere in this manual but applied on a smaller scale.

One of the most common issues is the management of uncontrolled runoff entering a stream as either sheet flow or in concentrated rivulets. A typical arrangement for managing the runoff comprises the construction of a stabilised swale drain with or without a subsurface pipe to intercept runoff and direct it to a controlled discharge point(s) which maybe a pipe drop structure or grassed chute with an energy dissipator at the toe of the bank.

Application

The control of otherwise unrestricted runoff entering a stream.

Limitations

Most suited to broad flat floodplains. Where low bunds are used in lieu of a swale drain wide areas may be subjected to shallow flooding.

Advantages

Inexpensive to construct and requires no specialist equipment.

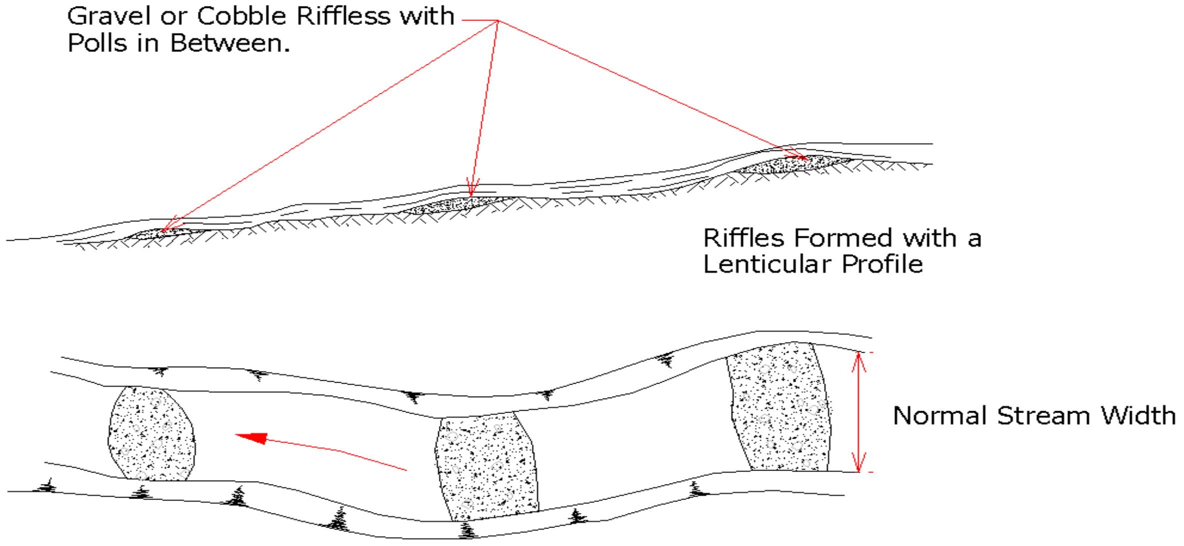
Disadvantages

Required maintenance may be high. During the wet season maintenance such as grass cutting may be difficult.

Indicative Cost

Low capital cost but may involve relatively high maintenance costs.

43.5.16 Land and Water Management – Pools and Riffles



Description

Pools and riffles are the terms used to describe variations in bedform commonly found in small to medium size streams. They are created by placing suitably graded gravel or cobbles across the full width of the stream at specified intervals. The spacing of the gravel bars varies for each stream but as a guide an interval of between 5 and 7 times the normal stream width is suggested. The gravel is roughly formed into a lenticular shape such that the maximum thickness of the gravel bar is about 75% of the normal stream depth up to a maximum thickness of about 0.75 metres.

Application

Used to create variation in habitat that caters for a diverse range of aquatic animals and organisms.

Limitations

Suitably graded cobbles and gravel are required. Unless the gravel is replenished periodically (either naturally or by human intervention) high flows can mobilise the material. Transported material may block downstream culverts.

Advantages

Inexpensive to construct and requires no specialist labour.

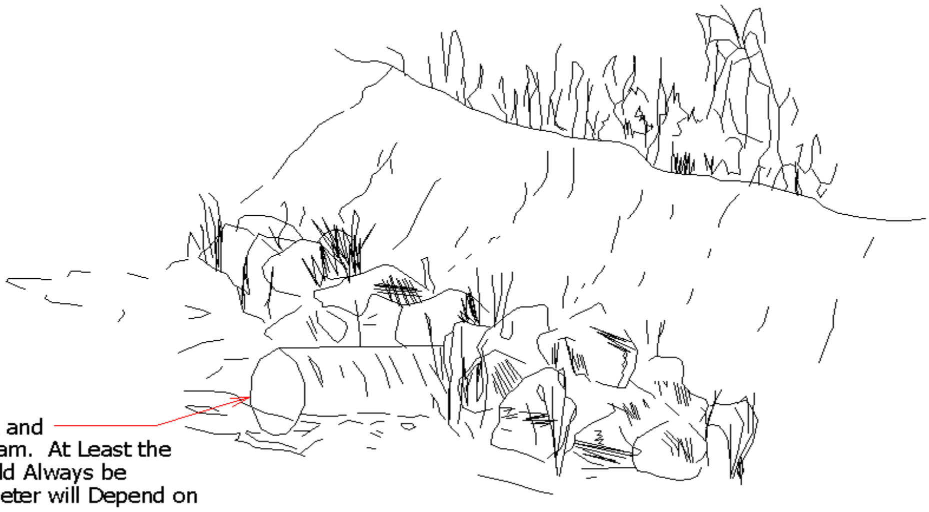
Disadvantages

In streams with a large flow range the gravel bars will be lost downstream unless there is a natural supply further upstream.

Indicative Cost

Depends on local costs of suitable quarry material.

43.5.17 Land and Water Management – Fish Refuges



Description

Sanctuaries are areas of refuge for fish from land based predators. Typically they are formed from rock overhangs incorporated into rock armouring of a stream bank or submerged pipe stubs built into the bank.

Variations

Woody plants established close to the water edge and featuring low branches overhanging the stream. Alternatively small timber jetties or boardwalks can be designed to provide a similar function.

Pipes maybe anchored away from the bank and lateral to the flow to reduce access opportunities by predators.

Application

Used to create variation in fish habitat that provides a variation in water temperature and velocity as well as protection from predators.

Limitations

Stream must be sufficiently wide if jetties or boardwalks are contemplated. A good fishing location may be inadvertently created if there is a high level of people access along the stream.

Advantages	*Disadvantages*
Inexpensive to construct and requires no maintenance.	Unless fish studies relevant to the stream are available it may be difficult to predict the optimum location for the refuges.

Indicative Cost

Low.