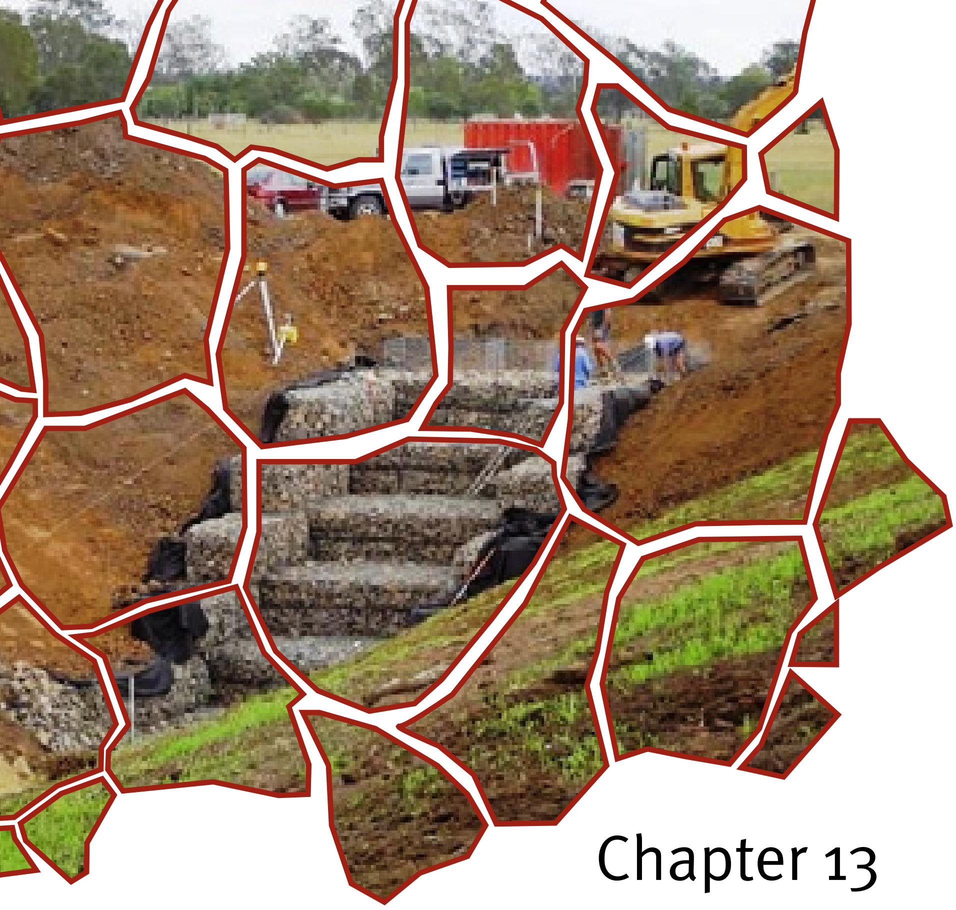


Chapter 13

Gully erosion and its control

Key points

- Gullying occurs in many parts of Queensland. Under natural conditions gullying is an important process of landscape evolution. However, human-induced gullying is a serious form of land degradation reducing soil fertility, inhibiting access, damaging infrastructure, reducing water quality and degrading habitat.
- Maintaining ground cover throughout the catchment, protecting drainage lines, dispersing runoff, and avoiding exposure of dispersive subsoils are all potentially important strategies to prevent gullies from forming.
- Remediating gullies and preventing them from forming requires an understanding of the processes of gully formation and of the characteristics that make particular parts of a landscape prone to gullying. These processes are often not well understood; the relative contribution of different downstream and upstream factors is, for instance, still a source of conjecture.
- Controlling a gully once it has started generally requires a combination of engineering structures, earthworks and revegetation. Gully control works are expensive, have a high risk of failure, and are only justifiable where the gully threatens valuable assets (such as infrastructure or highly fertile land).

Contents

Glossary

average recurrence interval (ARI): the average period in years between the occurrence of an event (usually a storm or a flood) of specified magnitude and an event of equal or greater magnitude.

back-push bank: a bank constructed by pushing soil uphill rather than the conventional method of constructing from the topside where the spoil-borrow area becomes the flow channel; preferably used where excavation of subsoil on the topside channel area may be vulnerable to erosion such as in dispersive soils.

badlands erosion: a severely eroded gullied landscape where surface soil has been stripped away; mostly devoid of vegetation.

basal sapping: an alluvial gully process that occurs where seepage exits at the base of a scarp within an alluvium, and which leads to undercutting of the scarp.

bentonite: a clay that has great capacity to absorb water and swell accordingly; used to seal dams and other earthen structures

breakaways: a system of advancing gullies on a floodplain, and which can coalesce to form a continuous eroding front.

broad-crested weir: a weir for which the face is long enough to allow parallel flow of water across the weir such that a nappe does not develop —compare with a sharp-crested weir.

builders' plastic: durable poly construction plastic film used on building sites or general areas where strong cover or under-lay is required.

bund: an earthen structure used to restrain or divert runoff flows; used in agriculture to collect surface run-off, increase water infiltration and prevent soil erosion.

colluvial soil: unconsolidated soil and rock material moved largely by gravity and deposited on lower slopes, and/or at the base of a slope.

compost blanket: a 3–5cm thick layer of loose compost made from biodegradable organic material and applied directly to the soil surface to reduce runoff, control erosion, and establish vegetation; seed commonly included either prior to or during application.

cut-off wall: a watertight barrier for preventing seepage or movement of water under or past a structure; made as a masonary structure or a core of impervious material that will reduce percolation of water.

dispersive soil: a structurally unstable soil with a high percentage of clay and which readily breaks down into constituent particles of clay, silt and sand. These soils are highly erodible and cause turbidity in water—dispersion occurs when linkages holding the clay platelets are broken.

drop structure: a vertical structure used to convey runoff from a higher level to a lower level, and commonly used for cross-drainage works on roads, and for control of gully erosion.

energy dissipater: an engineered hydraulic structure used to absorb the kinetic energy developed in flowing water; the kinetic energy is developed when flow velocities are high as over a weir, or flowing down a chute.

erosion control mat: a mat woven from synthetic material (polypropylene), or natural fibers such as straw, jute, or coconut; used to increase soil stabilization, effectively decreasing erosion and allowing vegetation to effectively take root.

frontage: in the context of rural land: the land abutting a stream or watercourse, that is, that part of a property that is riparian to a stream.

gabion: a rectangular wire mesh cage filled with rock, brick, or similar material, used for construction retaining wall and anti-erosion structures—see also **Reno mattress**.

geofabric, geotextiles: permeable fabrics used on earthen construction projects to reinforce and protect the soil surface; or to separate different layers of soil; typically made from polypropylene or polyester in three basic forms: woven (resembling mail bag sacking), needle punched (resembling felt), or heat bonded (resembling ironed felt).

gully: commonly used to describe any drainage line flowing towards a stream; in a soil conservation context: a section of a drainage line that is unstable, with evidence of soil removed by flowing water; highly visible form of soil erosion, with steep-sided, incised, drainage lines greater than 30 cm deep—also known as 'dongas', ' wadis', or 'arroyas'.

gypsum: a natural crystalline hydrated form of calcium sulphate, ($CaSO_4 2H_2O$); used as a soil ameliorant to improve soil structure; improves water infiltration, seed germination and root growth.

hydraulic head: the energy of a unit weight of a liquid, expressed as the vertical height through which it would fall to release the contained energy; the sum of three components: the elevation head, the pressure head and the velocity head.

hydraulic jump, (or 'standing wave'): an abrupt rise occurring in a liquid when a high velocity flow discharges into a zone of lower velocity; accompanied by violent turbulence; may be defined in terms of the sudden change from super-critical flow to sub-critical flow

hydromulching, hydroseeding: a procedure where a mixture of seed fertiliser and a mulch material is sprayed as a water slurry onto an exposed soil surface for revegetation purposes; mulch material can be paper, wood, sugar cane, flax. With hydromulching, the mulch is applied at heavier rates to protect the soil surface.

hydrostatic pressure: the pressure exerted on a portion of a column of water as a result of the weight of the fluid above it.

infiltration: the downward movement of water into a soil, governed largely by the structural condition of the soil, the antecedent moisture content of the soil, and the nature of the soil surface including presence of vegetation.

mitre drain, (or spur drain): a drain to conduct runoff from a road shoulder or table drain to a disposal area away from the road alignment.

nappe: a sheet (or curtain) of free-falling water flowing from a structure such as a weir; also used to describe the path of the falling water—see **broad-crested weir** or **sharp-crested weir**.

notch: an indented section of a runoff control structure designed to pass a flow over or through the structure at a predetermined depth.

pervious weir, (or leaky weir): a weir constructed from a permeable material designed to let the runoff pass through, but trap sediment to provide a seedbed for establishing a stabilising cover on a gully floor/bed; consist of brush, logs, wire netting with straw, or similar material.

Reno mattress: a thin flexible cage (less than 500 mm thick), made of woven wire mesh to contain loose rock or stone, and divided into cells to prevent the rock from moving under a runoff flow; filled with rock at a project site to form flexible, permeable, structures to promote growth of natural vegetation—see also **gabion**.

riparian frontage land: defined for some landscapes to be the width of land equivalent to the height of the streambank, plus five metres.

sharp-crested weir: a weir that the crest is such that water flowing over the weir falls cleanly away from the wall; a weir that causes the nappe to spring clear of the crest, leaving the flow to be free of viscous effects—compare with a broad-crested weir.

sheep-foot roller: an earth compactor consisting of steel drums on which projecting lugs are fixed for compacting fine grained soils such as heavy clays and silty clays; used for compacting soils in dams, embankments, earth-fill projects, subgrade layers in pavements.

slaking: the process where soil disintegrates and crumbles when exposed to moisture; the partial breakdown of soil aggregates when wet rapidly and due to the swelling of clay and the expulsion of air from pore spaces.

spalling: a gully advancement process where runoff water flowing over the sides of a gully can trickle back against the gully wall, causing flakes or layers of wetted-up soil to break off from the drier material underneath.

stilling basin (or stilling pond): a structure located at the outlet of a pipe, spillway or chute to reduce the energy (and turbulence) of the outflowing water and subsequently reducing the flow to non erosive velocities.

stoloniferous plant: a species with a horizontal-growing stem that runs along the ground surface and takes root at intervals, examples include couch, kikuyu, sand spinifex; useful as a protective cover against erosion.

table drain: part of a road formation, being a trapezoidal or parabolic-shaped drain adjacent to the edge of a road and designed to carry runoff water away from the road surface.

verandah chute: technically a drop structure made from corrugated iron, or similar roofing material, which is cantilevered over the head of a gully; runof water is discharged away from the face of the gully head and a natural stilling basin is formed in the gully bed by the falling water.

whoa-boy: a low trafficable bank across a road, designed to intercept runoff flowing down the road; normally an earth/gravel bank, but may be sealed.

wing bank: a bank located at the head of a structure to ensure runoff is directed to the structure and not able to bypass it.

13.1 Introduction

Gullies are a highly visible form of soil erosion, with steep-sided, incised, drainage lines greater than 30 cm deep. In lay terms, the word 'gully' is often used to describe any drainage line flowing towards a stream; in soil conservation it is a section of a drainage line that is unstable, with visible evidence of soil removal. In some countries, gullies are referred to as dongas, wadis, or arroyas.

Gully erosion is both a natural and a human-induced process. Natural gully erosion plays a major role in landscape evolution. Gullies, and the streams that they feed into, help carve out valleys and supply alluvial sediment to fill floodplains.

Gullies can occur anywhere in a natural drainage line as runoff flows from the most remote part of a catchment to its outlet. However, a natural drainage line is not a prerequisite for a gully to occur. Any management practice that leads to runoff concentration has the potential to cause a gully at any location in the landscape. This includes cultivation furrows, roads, tracks, stock pads and fence lines.

Gullying occurs on all soil types but those with dispersive subsoils are most vulnerable. Around 45% of Queensland has soils with at least some dispersive properties. In these areas, gullies can sometimes affect most of the landscape, creating what is referred to as 'badlands' erosion. Gully erosion is extensive in vulnerable landscapes, with approximately 80,000 km of gully network in Great Barrier Reef catchments (Thorburn and Wilkinson 2013).

Since the phasing out of the soil conservation extension service of government agencies in the 1990s, there has been very little documentation on the performance of gully control measures in rural areas. It is important that what has been learnt from the gully erosion control work is shared. This needs to be shared with people working on gully control both in Australia and overseas. It is hoped that this chapter can provide a useful basis for future discussions.

Wherever possible, it is best to prevent gullies starting rather than attempting to control them once a gully has formed.

Stabilising gullies with built structures can be difficult and costly and they are prone to failure. They have only ever been used to a minimal extent by landholders in Queensland. Gully control structures are often built in urban areas and incorporated into designs to provide road cross-drainage.

While gully control structures may be justified on better quality soils, or where a road or building is threatened by an advancing gully, the use of such structures to control numerous gullies over large areas of vulnerable soils is impracticable. This is especially so in the more remote grazing lands of the state, where graziers are often struggling economically due to the long distance to markets, the extreme wet/ dry climate, low soil productivity, land degradation from erosion and weed invasion and increasing costs of production in relation to the amounts received from sale of product. The result is little to no extra income or time to reinvest in long-term property management or soil conservation actions such as gully erosion control (Shellberg and Brooks 2013).

This chapter considers the impacts of gully erosion, the factors that contribute to gully development, strategies to prevent gully erosion and options for controlling it. Specialist advice should be sought before commencing a gully control project. Keep in mind that opinions on the best plan of attack can vary considerably depending on the past experiences of the specialist and on the resources available—including time, materials, expertise and finances. For these reasons, it is worth seeking several opinions.

Parts of this chapter have incorporated information prepared by Grant Witheridge in a series of erosion and sediment control fact sheets detailing a range of works used for gully control (see Catchments and Creeks 2010 a–e).

13.2 Impacts

Gully erosion is important because it affects soil productivity, restricts land use, degrades cultural sites and potable water supplies, and can threaten infrastructure such as roads, fences, access and buildings. As gullies have a direct connection to streams they have a major impact on water quality. Eroded soil ends up in waterways, road culverts, dams, reservoirs, creeks, rivers and marine environments. Depositions in streams can result in a decreased hydraulic capacity, leading to more frequent overbank flooding.

The dominant sediment supply from many rivers in the Great Barrier Reef catchment is from a combination of gully and streambank erosion, and subsoil erosion from hill-slope rilling, rather than broadscale hill-slope sheet erosion (Kroon et al. 2013). Wilkinson et al. (2015) reported that gully erosion contributes approximately 40% of all fine sediment to the Great Barrier Reef lagoon. Bartley et al. (2015) reported that approximately 30–40% of additional catchment sediment yields are derived from streambank erosion.

Sediment from eroding gullies does not necessarily go straight to creeks and rivers. Larger soil particles such as sand and silt are readily deposited and move downstream as a series of pulses during larger floods. However, gully erosion from soils with a high percentage of clays—dispersive soils—can produce very small clay particles that remain in suspension and can result in turbid water.

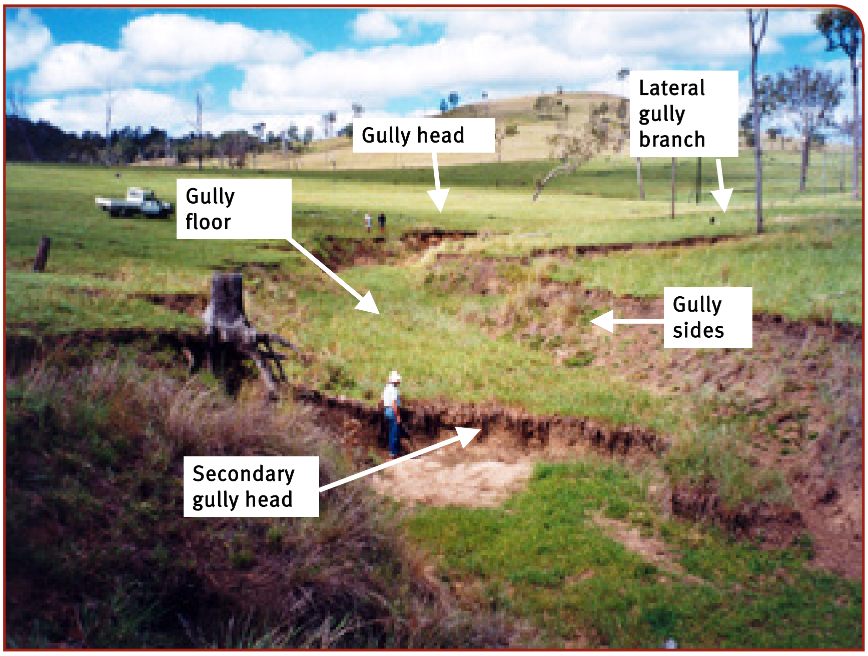
Any nutrients from applied fertilisers and pesticides that are attached to eroded particles will pollute watercourses and affect aquatic life. Cropping areas are more likely to deliver fertilisers and pesticides, but their usage is being better managed now as farmers adopt best management practices and strive for increased efficiency. However, there is virtually no use of fertilisers in the extensive grazing lands of Queensland. Pesticide use in these areas is normally limited to that required for the control of exotic weeds, with little risk of downstream impacts, unlike those risks from transported sediment.

Gullies associated with drainage lines or tracks can cause a considerable increase in the time to travel about a property; and are also a significant safety hazard, especially for smaller vehicles like quad bikes. When a property road becomes impassable due to gullying, often new access is made on adjacent land. Unless preventative measures are taken against erosion, the new road will suffer the same fate as the old road.

13.3 Gully components

The various components of a gully are illustrated in Figure 13.1. They include the head, sides and the bed or floor of a gully. As a gully lengthens, it develops lateral branches. There may be several gully heads advancing up a gully at any one time in what can be called a 'steps and stairs' pattern.

Figure 13.1: The components of a gully

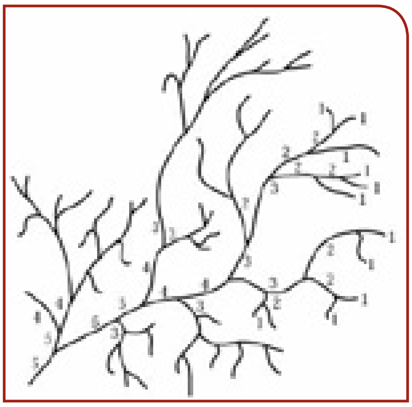


The difference between a creek and a gully

Just as there is no well-defined difference between a river and a creek, there is no well-defined difference between a creek and a gully. Figure 13.2 shows the numbering system used for different stream orders. Higher stream orders are rivers, while the lower stream orders can be gullies that flow into a creek. Some differences between creeks and gullies include:

- Gullies can retreat to the very top of their catchments.
- Gullies generally have far more capacity than they need to carry the flow they receive.
- Gullies may be short and isolated on hillslopes.
- Tree roots help to stabilise saturated streambanks, but trees have a limited role in stabilising gully heads.
- Gullies would not normally be a habitat for fish and any structures built in them should not need to cater for fish passage.

Figure 13.2: Numbering system of stream orders



13.4 Triggers for gully development

Any change in a land use or practice that reduces rainfall infiltration results in shorter times of concentration of runoff, increased volumes and velocities of runoff, and therefore higher risks of erosion.

Gullies can be created by local, upstream or downstream influences, and often there is more than one factor involved. In some circumstances, the local or downstream influences may be just as important as those upstream.

13.4.1 Local triggers

Local triggers of gully formation usually occur on land that is not within a natural watercourse, but may divert and/or concentrate overland runoff flows to land that is vulnerable to erosion. They include:

- roads and tracks
- stock pads
- fences
- firebreaks
- dam by-washes
- furrows in cultivation that can develop into rills that become gullies
- failed contour banks and waterways
- sink-holes on alluvial plains from cracking soil, or old stump holes
- levee banks or diversion banks that direct runoff to an incised stream
- saline areas.

Saline areas have depleted vegetation and become very susceptible to erosion. On the positive side, the eroding gully may help to provide drainage to the area that could assist in alleviating the salinity problem by lowering the watertable. Control options in this situation should aim to stabilise the drain but allow it to maintain its subsoil drainage function.

Figure 13.3: Gully initiation as a result of concentrated flow down (a) a vehicle access track, and (b) a walking track/stock pad on a stream bank

13.4.2 Upstream triggers

Runoff first commences as overland flow when the rate of rainfall exceeds the rate of infiltration. This situation may occur as a result of raindrops impacting on bare soil and reducing its infiltration rate. This occurs more quickly on a bare soil compared to a covered soil, but can occur when rainfall rate exceeds infiltration rate, regardless of soil cover conditions.

An effective ground cover allows rain to soak into the soil, until it becomes so saturated that the rainfall becomes overland runoff. On sloping land, overland runoff can concentrate after a very short distance, perhaps only a few metres.

Upstream triggers include increased runoff from changed land use such as tree clearing, overgrazing, cultivation, burning or urban developments. Overgrazing results in degraded surface vegetation—a reduction in biomass, ground cover and vegetal basal area—leading to reduced rainfall infiltration, increased runoff and initiation of the erosion processes (Prosser and Dietrich 1995).

Increased runoff from hillslopes will concentrate in a natural drainage line and create a risk for gully erosion to occur. A change in the equilibrium of the stream may occur when a channel needs to modify its shape to allow for an increase in flood levels. The increase in runoff is said to destabilise the equilibrium of the drainage line.

The gully erosion process begins when scouring occurs at one location along an overland flow path (Figure 13.3). This may be due to a combination of factors including a lack of ground cover, a more erodible soil, and an increase in the flow velocity caused by the narrowing of the flow path or a sudden change in land slope. It may also occur after infiltrated runoff through the surface soil is impeded by impervious subsoil, resulting in the soil quickly becoming saturated.

13.4.3 Downstream triggers

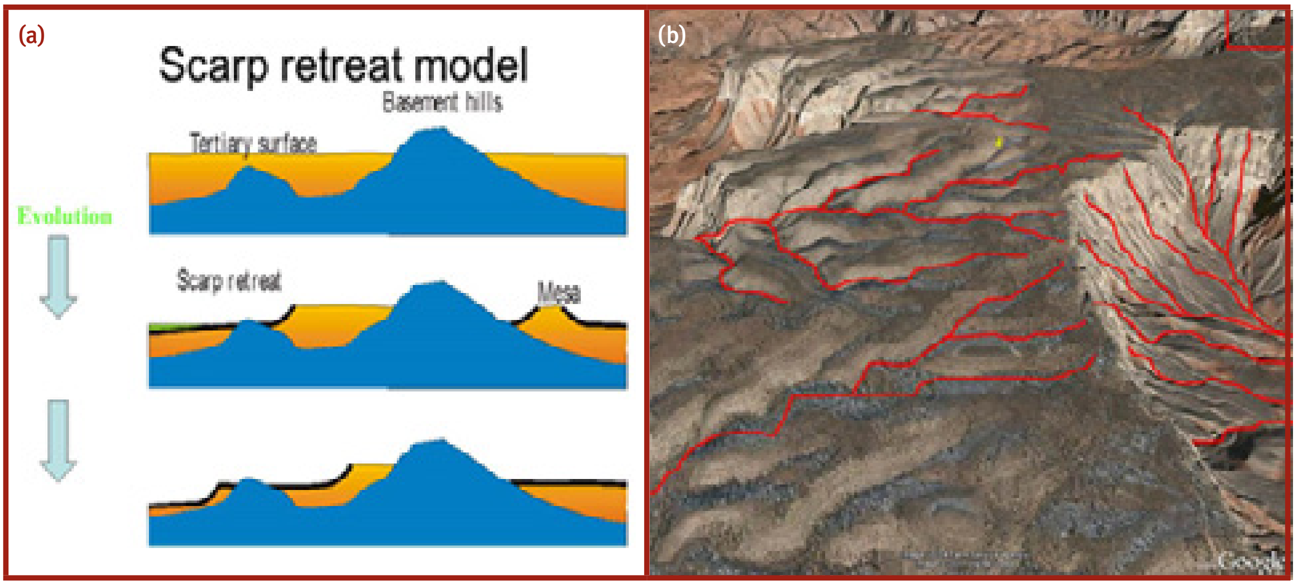
This form of gully initiation is quite common and yet it is rarely mentioned in most texts.

An example of a downstream influence is when the outlet of a stream is lowered, resulting in the overall length of its bed becoming steeper. In past geological eras, an increase in stream gradients may have occurred as result of a fall in ocean levels or a rise in the catchment landscape. Erosion of the streambed may steadily advance upwards into the catchment. When the stream bed erodes, the stream can become more incised. Drainage lines flowing into the stream then become eroding gullies over-falling into the stream. This sets off a system of advancing gullies throughout a catchment. Such gullies may eat their way back to the very top of their catchments even though their contributing areas can be very small. Where a gully has virtually no catchment, raindrop impact in the gully itself can become the main source of runoff, soil loss and subsequent downstream sediment.

There is evidence that gully development in the Fitzroy and Burdekin River catchment could be associated with downstream triggers. Jones (2006) pointed out that these two catchments were once small coastal catchments with their headwaters in the coastal mountain range that is still present today. These coastal streams were short and steep by comparison with those in the interior, and also a lot wetter, allowing a more active erosion environment along the coast. As the coastal streams expanded, the drainage divide moved rapidly westwards through gaps in the coastal range.

Stream capture began a phase of regional erosion, where rills and gullies transported large quantities of sediments to the coast (similar to that shown in Figure 13.4). Large volumes of sediment were transported beyond the present coast during periods of low sea level and contributed to a major eastward bulge on the central Queensland continental shelf. Much of the sediment from the Burdekin was deposited in what is now the vast agricultural area of the Burdekin Delta (Jones 2006).

Figure 13.4: Gully forming processes: a) the scarp retreat model; b) an example from a tributary of the Grand Canyon in the United States. The more active stream on the right is capturing the lower sloping stream network on the left. A similar process is occurring in the Fitzroy, Burdekin and other coastal catchments in Queensland. (Source: Google Earth)



13.4.4 Some examples of gully development in Queensland

Gully erosion in grazing lands

About 80% of Queensland is available for grazing, from the humid coast to the arid western rangelands. All of these lands are subject to soil erosion, most commonly by water but also by wind in more arid areas. Erosion can seriously affect the productivity of grazing lands. The movement of sediment, nutrients and organic matter, by wind or by water, also adversely affects water quality in streams.

The following quote from a study of the Upper Nogoa catchment reported by Skinner et al. (1972) described the situation where gully heads have retreated to the top of their catchments.

> *... most of the sharply defined gully heads have long ago advanced nearly to the tops of their catchments. The most striking change visible is the development of networks of rills and scour gullies on bare areas. Many new scours five chains long or more appeared between 1956 and 1965, and rills existing in 1956 were noticeably deeper and wider in 1965. So it appears that gullying is now essentially a sheet erosion/rill erosion process rather than one of upslope advance of sharply defined heads.*

Sheet erosion involves the loss of surface soil over large areas, caused by the action of water or wind. This form of erosion is not always obvious but it results in significant loss of productive soil. In some arid areas, all of the topsoil may be removed, leaving a scalded surface. Where runoff begins to concentrate, both rill and gully erosion may occur.

Gullies in grazing lands may be relatively isolated or they may occur frequently throughout a landscape, being influenced by any of the three triggers discussed above.

Soils with dispersible subsoils can develop tunnel erosion. Landscapes with such soils may develop closely spaced gullies similar to a 'badlands' situation. This occurs in some parts of the Burdekin and Fitzroy catchments as well as in other zones with extensive areas of dispersive soils.

Gully erosion in cropping lands

Gully erosion is not widespread on Queensland's cropping lands, which represent only 2.5% of the total area of the state. However, it is still significant, particularly where valuable on-farm assets are threatened.

Cultivated soil is vulnerable to gully erosion, especially under bare fallows or fast-flowing floodwaters. Bare soils readily produce runoff that is soon concentrated by the furrows in the paddock. Rill erosion occurs and as the rills deepen they soon become gullies that cannot be cultivated and cropped. This makes the paddock very difficult to manage, and rates of soil loss will be very high. By the middle of the last century, soil erosion had become a very serious problem in Queensland cropping lands, resulting in large areas of land withdrawn from cropping uses.

Soil conservation measures for cropping lands are now widely accepted by landholders and include the maintenance of surface cover and the construction of soil conservation works, like contour banks and grassed waterways. As a result, gullying is less common than previously, although there is a need for continued vigilance.

Contour banks direct runoff into grassed waterways. If these are not well maintained, they are likely to fail, resulting in the development of gullies within the waterways.

Significant areas of cropping land are still in need of conservation measures to control erosion and to prevent the development of gullies.

Gullies associated with streams

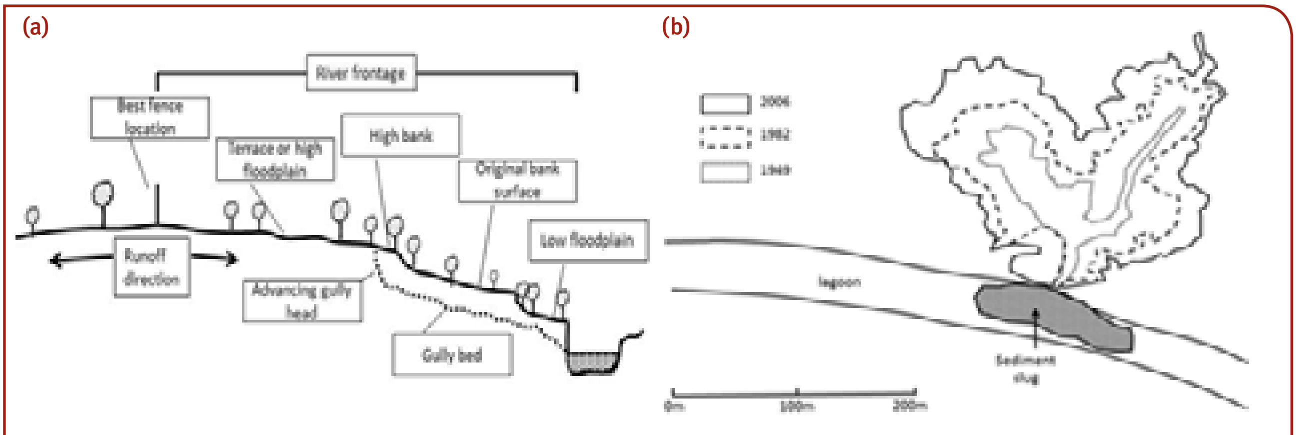
Many streams have steep banks that have the potential to initiate a serious gully erosion problem. Under natural conditions, runoff from adjacent land usually enters a stream via a drainage line that is stable with a relatively low gradient. However, if the natural flow is diverted by a road, diversion bank, cattle pads or other feature, then a highly erosive, cascading waterfall can form as runoff flows over the bank. This will result in a gully that can rapidly progress upslope; the greater the height of the streambank, the greater the potential for serious erosion.

Streambed erosion can be caused by a number of human-induced factors and has been discussed earlier (see Chapter 11 Stream stability). Streambed erosion is also a natural process that has been caused in the past by changes in climate which have led to falls in sea levels. A sea-level fall can initiate an increase in the rate of erosion along the length of the stream. If streambed erosion occurs where a drainage line enters a stream, the stability at this point will be upset, resulting in gullying in the associated, adjacent drainage line.

Alluvial gullies

Alluvial gullies are initiated in river- and creek-banks along river frontage lands. While gullies are normally associated with a relatively narrow flow path, a system of advancing gullies on a floodplain—also called ‘breakaways’—can coalesce to form a continuous eroding front (Shellberg and Brooks 2012). Where highly erodible soils occur, the wide gully head can retreat rapidly onto river terraces and elevated floodplains as shown in the cross-sectional view in Figure 13.5a, and in the aerial view in Figure 13.5b. Examples are found in some of the rivers flowing into the Gulf of Carpentaria.

Figure 13.5: Gullies on a floodplain coalescing to form a continuous front: (a) cross-sectional view; (b) plan view (source: Shellberg and Brooks 2013)



Alluvial gully erosion can result from both natural and human-induced processes. River incision over geologic time, dispersive soils, intense high-rainfall events and flooding are natural factors priming the landscape for gully erosion. Overgrazing and poorly located stock pads and roads on streambanks can accelerate the erosion process.

Growth of an alluvial gully system can occur as floods recede and floodwaters on the floodplain drain into the stream channel. However, raindrop impact on the gullied area and local runoff can also make significant contributions.

Most alluvial gullies drain directly into nearby rivers that deliver sediment and nutrients long distances and eventually settle in inland basins, estuaries and coastal waters. However, some alluvial gullies may drain away from the main rivers and deposit sediment into local creeks and lagoons.

Gully erosion associated with infrastructure

Runoff concentrated by property infrastructure such as roads, tracks, dam by-washes, fences and laneways all have the potential to cause gully erosion. Stock pads leading to poorly located yards and watering points can also develop into gullies.

This form of erosion may occur anywhere in Queensland but outback areas can be especially vulnerable. South-west Queensland has an average annual rainfall of around 125 mm but the road systems in this area are constantly being damaged by gully erosion. Dispersive subsoils are common and the low rainfall means that it is very difficult to maintain an effective vegetation cover to protect the soil surface.

Properly installed road structures—such as culverts, inverts or floodways—can safely convey overland flows and flood flows across the road corridor. These can act like a drop structure and safely convey runoff from a higher level above a road to a lower level below the road. The greater the spread of the flow below a road, the less likely it is that gully erosion will be initiated.

More information on this topic can be found in *Chapter 14 Property infrastructure*.

Gully erosion associated with mining activities

Seismic exploration activities require extensive road and track construction in a crisscross pattern. These roads were often constructed with a subsurface profile, resulting in the exposure of dispersive soils where concentrated runoff has then led to serious gully erosion.

Mining activities can create steep spoil heaps with exposed dispersive subsoils. Such sites are also prone to serious gully erosion.

13.5 Gully development and expansion

Runoff gains energy as it flows over a gully head into a plunge pool, causing various gully expansion processes to occur. A gully, like a stream out of balance, attempts to reach a new balance as it goes through processes that may change its length, depth and width.

Figure 13.6: Runoff in a gully after heavy rainfall

Gully depth is often limited by the depth to the underlying rock, which means that for many Queensland landscapes, gullies are normally less than 2 m deep. However, on deep alluvial and colluvial soils, gullies may reach depths of 10–15 m.

A gully floor can be subject to further down-cutting as secondary gullies advance up the channel in a 'stepwise' pattern (Figure 13.6). Gullies generally create far more capacity than they need to accommodate the runoff they are likely to carry, so it is rare for a flow to overtop the banks of a gully.

The following are processes that can cause gullies to expand:

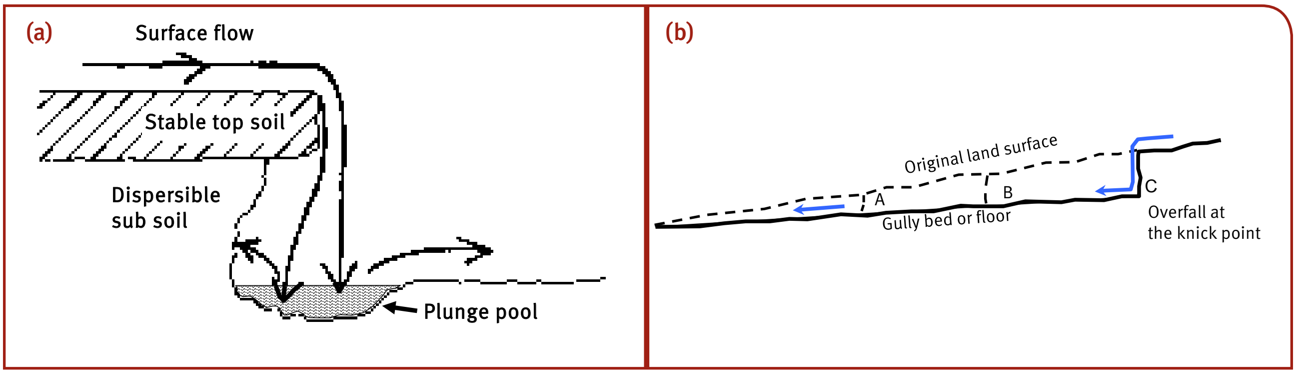
- gully head advancement
- development of lateral branches
- slumping initiated from subsurface flows (seepage)
- slumping initiated by erosion of the toe slope
- basal sapping
- spalling
- tunnelling in dispersive soils
- raindrop impact
- slaking
- trickle flows
- cracking.

13.5.1 Gully head advancement

Splashback at the base of the gully head erodes the subsoil, resulting in the surface soil falling into the plunge-pool and the gully advancing upslope (Figure 13.7a).

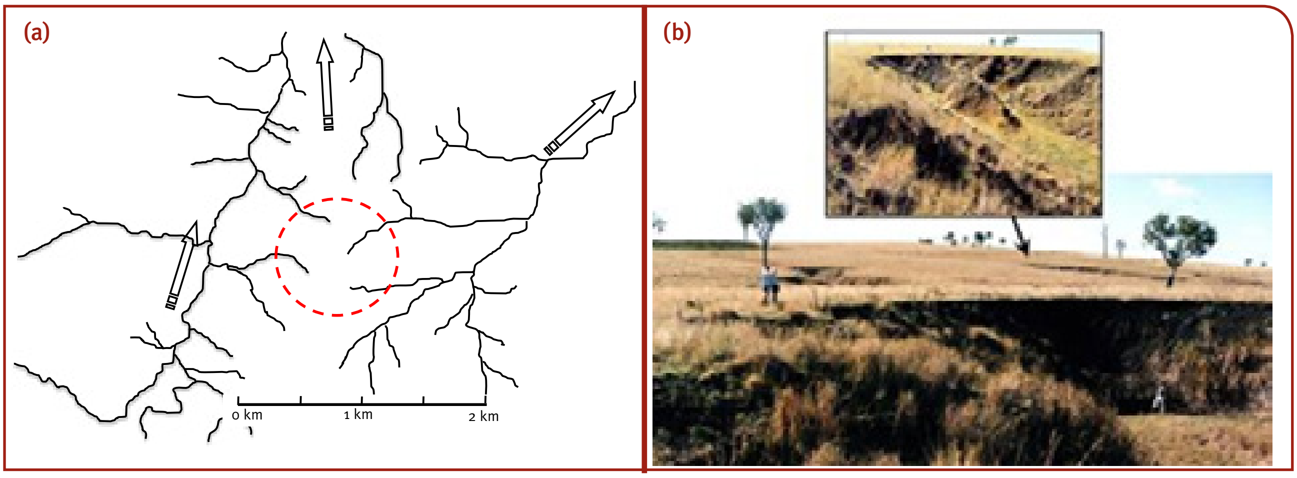
As a gully 'eats' its way upslope, the slope in the bed or floor of a gully will be less than the original land slope. For example, a gully advancing up a 3% land slope may have a floor with a bed slope of only 1%. This means that the height of the overfall at the gully head (points A, B and C in Figure 13.7b) and the height of the gully sides would increase as the gully advances.

Figure 13.7: Gully advances: (a) gully head development; (b) changes in height and bedslope as gully advances upslope



Gully heads can advance almost to the very top of their catchment (Figure 13.8). The gully in the inset of Figure 13.8b has developed because it is flowing into a deep drainage line. Such gullies have very little catchment and often have far more capacity than is required to accommodate the runoff that might occur even in an extreme rainfall event. The Grand Canyon in the United States provides an example of this situation. The canyon is up to 1800 m deep, but the Colorado River that created the canyon by erosion is generally less than 10 m deep.

Figure 13.8: Examples of gullies that have advanced to the top of their catchment: (a) in plan view; (b) in the field



Development of lateral branches

Runoff may enter a gully from the sides, causing secondary gullies or branches, resulting in a 'badlands' landscape, (Figure 13.8b). The gully floor may be subject to further down-cutting as secondary gullies advance up the channel. Sediment deposition below gully heads results in a 'steps and stairs' pattern.

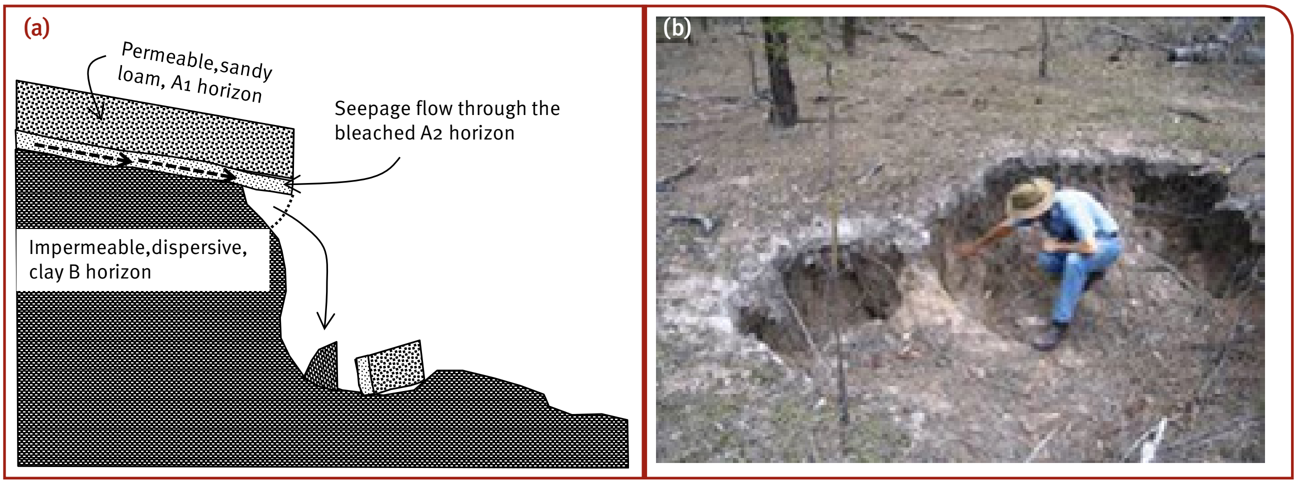
Erosion and sedimentation may occur simultaneously in different sections of a gully. In a sediment laden flow, sediment is deposited when vegetation is encountered, or when the grade becomes so low that the flow is too slow to carry the total load. This is most likely to occur in the downstream segments of a gully, and the deposition then gradually extends upstream.

13.5.2 Slumping initiated from subsurface flows (seepage)

In a prolonged rainfall event, the soil becomes saturated and runoff occurs, either above the surface (overland flow), or if local conditions allow, below the surface (subsurface flow).

Subsurface flow—seepage, through-flow or interflow—can cause the saturation of the walls of a gully, leading to slumping of both gully heads and gully sides. Figure 13.9a shows how seepage can occur in the A2 horizon of dispersive clay soils; Figure 13.9b is a field example of this process.

Figure 13.9: Sidewall gully expansion resulting from subsurface flows: (a) diagrammatic representation; (b) field example



New South Wales Soil Conservation Service (1992) and Milton (1971) point out the importance of seepage in gully development in New South Wales and Victoria, respectively.

The amount of saturation, and the subsequent impact on gully development, depends on the soil type. For example, some soils have permeable topsoil and impermeable subsoils. Where bleached topsoils occur on the side of a gully, water can seep out resulting in a collapse of the gully wall.

'Basal sapping' is a term used to describe an alluvial gullying process that occurs where seepage exits at the base of an eroding scarp within the alluvium and causing a similar process as shown in Figure 13.9b.

Groundwater flows, or seepage, can contribute to the failure of gully control structures, especially where flows are saline. These small but continuous flows can weaken vegetation and threaten the stability of a chute lined with vegetation. Where soils are dispersive, groundwater flows causing tunnelling can lead to the failure of structures. Groundwater flows may also cause a build-up in hydrostatic head behind a concrete structure, leading to uplift of the structure.

Where a gully control structure is being considered, it is essential to monitor seepage flow at a gully head and side walls, and ensure any structural works will not be affected by groundwater impacts.

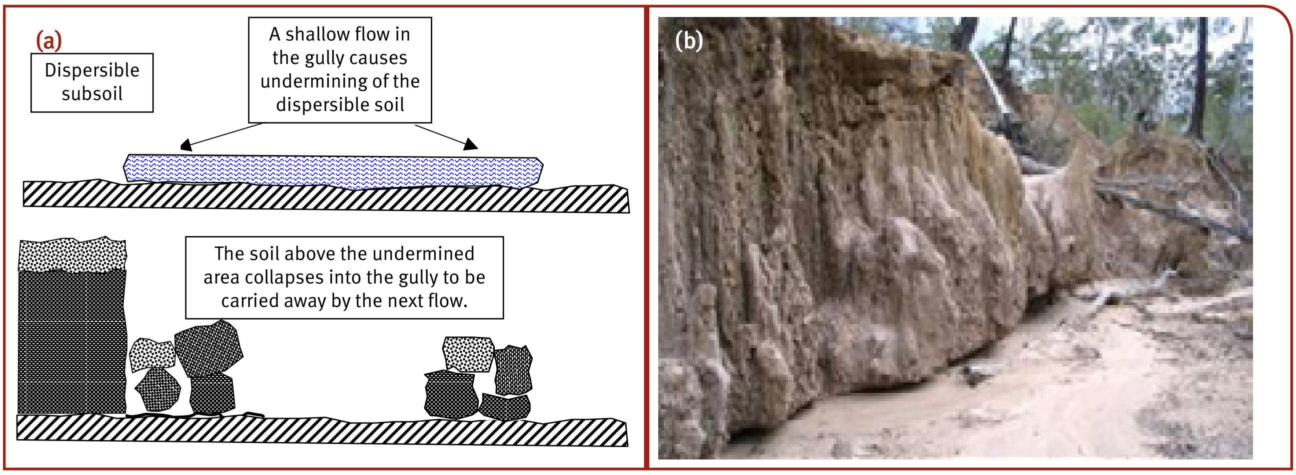
13.5.3 Slumping initiated by erosion of the toe slope

Figure 13.10 shows how a gully with dispersive soil can be undermined and widened by a shallow flow in the gully. Under these circumstances, gullies can expand with little or no surface flow.

Gully scouring of the toe slope can lead to mass failure of the side of the gully under gravity. This soil is then washed away by subsequent flows.

Unstructured soils and soils that slake are also vulnerable to sidewall slumping.

Figure 13.10: Gully widening by undercutting and slumping: (a) diagrammatic representation; (b) real-life example



13.5.4 Spalling

Water running over the sides of a gully can trickle back against the gully wall, causing a layer of wetted-up soil to break off from the drier material underneath. The process is known as 'spalling' and may cause gully advancement similar to that illustrated as a lateral gully branch in Figure 13.1. Collapse of the topsoil will occur if sufficient undermining occurs.

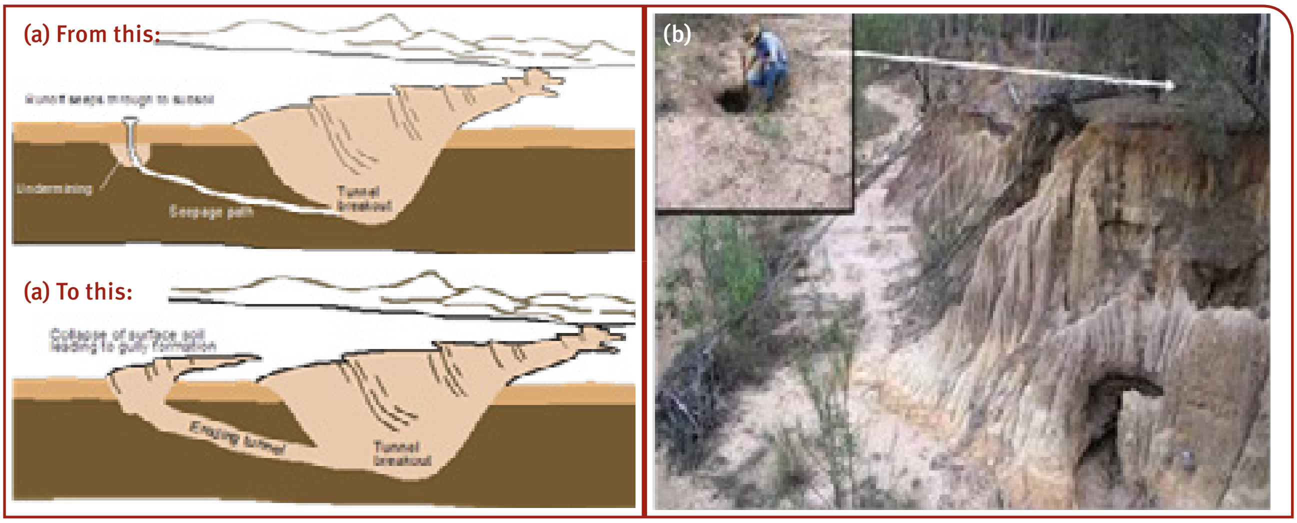
13.5.5 Tunnelling in dispersive soils

Dispersive soils are prone to tunnel erosion, an insidious process where subsurface water movement creates tunnels below the ground surface. The tunnels can remain unnoticed until they collapse to form potholes or sink-holes that can expand into gullies. Dispersed particles escaping from a tunnel system will cause turbidity of the runoff in the gully showing a muddy or milky appearance.

Tunnelling, or piping, can occur in susceptible soils in their natural situation, or following disturbance. It can occur in paddocks used for grazing or cropping, or in construction projects such as dams, gully control structures, trenches, roads, embankments and building sites.

Runoff can enter impermeable and dispersive subsoil via a crack or channel in the subsoil; post-holes, rotting tree stumps, old root lines or animal burrows may all provide an entry point. The whole process is speeded up significantly if water is able to find an exit point such as an adjacent gully. As the saturated clay acts as a fluid, it will exert hydrostatic pressure, forcing its way to an outlet lower down the slope or at the side of a gully (Figure 13.11), or at a road cutting—that is, where an hydraulic gradient exists from the entry point to a potential exit point.

Figure 13.11: Gully expansion by tunnel erosion: (a) diagrammatic representation; (b) field example (source: New South Wales Soil Conservation Service 1991a)



13.5.6 Raindrop impact

Where gullies have very small or no catchments, there will be very little runoff produced, and raindrop impact can be the main process leading to gully growth. Raindrops impacting on bare gully floors and sides can be responsible for the loss of significant quantities of soil. On gully sides with dispersive soils, this can result in the fluting or carving of subsoils into intricate patterns. In Figure 13.12, a flat pebble in the floor of a gully has protected a 5 cm high column of soil from raindrop impact. That pebble would have been removed, however, if a significant runoff flow had occurred in the gully.

Figure 13.12: Loss of soil from a gully due to raindrop impact

Slaking

Slaking, which can be linked to gully expansion, is the breakdown of soil aggregates into small sub-aggregates when wet rapidly. Slaking is similar to dispersion, and refers to the process where the soil disintegrates and crumbles when exposed to moisture; the smaller soil particles are then more vulnerable to dispersal.

Some soils are vulnerable to both slaking and dispersion while others slake but do not disperse. Slaking occurs in a range of soil textures and is linked to the desirable process of self-mulching that occurs in many cracking clay soils (vertosols). Self-mulching produces a loose surface layer of granular aggregates.

Non-dispersive clay soils can also lead to tunnel erosion, and this has caused the failure of some gully control structures constructed in these soils.

13.5.7 Trickle flows

Peak flows from intense rainfall can obviously cause considerable gully erosion; however, prolonged low flows can also exacerbate the growth of a gully. Constant trickle flows in a drainage line may occur as the aftermath of a large rainfall event, or when there is seepage of groundwater into an incised channel. Saturation of the trickle pathway can make the soil structurally weak and very susceptible to erosion. The constant wet conditions result in less cohesive strength of the soil and can weaken the ability of vegetation to resist the erosion process.

13.5.8 Cracking

In very dry weather, cracks of up to 2 m deep and 100 mm wide can develop in cracking clay soils, such as those found on the Darling Downs and in the Central Highlands. Large slabs of soil may fall into the gully, leaving vertical sides. The cracks are interconnected laterally and when runoff occurs, water penetrates the cracks and moves downslope through the soil. The soil swells and closes up eventually, but not quickly enough to prevent large volumes of water from filling cracks in the subsoil. If a lower outlet exists, the hydraulic head may cause a subsurface flow and tunnelling will develop.

In soils with dispersive clay subsoils, cracks can occur in the subsoil adjacent to a gully and will extend upwards to the surface. Runoff will then enter the cracks and cause rapid expansion of the gully (see Figure 13.13 showing examples from the Bowen Catchment)

Figure 13.13: Field examples from the Bowen catchment: a cracking vertosol overlying a dispersive sodosol has resulted in the expansion of the gully (P. Zund personal communication

13.6 Minimising gully erosion

It is essential that lands susceptible to gullying be monitored regularly to detect early stages of gully formation.

Economically, it is far better to prevent gullies from occurring than to attempt to control them once the erosion has started. Once they have started, some control measures are relatively simple; others are more complex and need care with their design and construction. Significant expense may be required and attempts to control gullies can end in failure.

A range of measures to avoid development of gullies is described below.

13.6.1 Grazing land management

Surface cover is the key to mitigating erosion in grazing lands. It prevents erosion by maintaining the soil in a condition that absorbs rainfall. Any runoff that does occur may have its kinetic energy dissipated by the cover and is less likely to concentrate into an erosive force. However, surface cover is only likely to be effective in reducing gully development where the gullies are initiated by upstream triggers. Where downstream triggers are influencing gully development, the gully head may continue to advance upslope into a well-managed pasture.

Wilkinson et al. (2015) suggest three land-use principles for the adoption of suitable grazing practices in the Great Barrier Reef catchments to reduce gully sediment yields:

- Promote revegetation of gully channels to reduce sediment transport capacity and so trap sediment, by reducing the slope gradient or by increasing hydraulic roughness.
- Maintain vegetation ground cover on gully features to reduce surface erosion. This was based on previous studies that showed gully erosion rates were slower where ground cover was higher; also that incision of new gullies was also sensitive to vegetation cover.
- Reduce surface runoff into gully systems and so reduce gully sediment yield.

Information on maintaining adequate surface cover in grazing lands [e.g. >70% at end of dry season; see Wilkinson et al. (2015)] can be obtained from the publication M*anaging grazing lands in Queensland* (Department of Environment and Resource Management 2011). This provides information under the following categories:

- managing total grazing pressure
- using appropriate pasture utilisation rates
- implementing appropriately timed spelling and herd management strategies
- monitoring pasture composition
- strategic use of hay, supplements, fodder trees and shrubs
- managing the tree/grass balance to avoid woodland thickening
- implementing forage budgeting strategies
- using climate and seasonal forecasting resources
- maintaining native grassland free of encroachment from woody vegetation
- using appropriate fire management practices
- fencing according to land types
- managing the distance stock has to travel to water.

Contour banks are not necessary on well-managed pasture land. Poorly maintained banks on former cropping land returned to pasture may lead to rilling and gullying. Banks located on such land may be levelled, or gaps created in them, to safely disperse overland runoff, particularly where it is not intended that the land will be returned to cropping uses.

Certain types of regrowth vegetation may be protected under vegetation management legislation and regulations. More detailed information on the legislative requirements related to vegetation management may be found at the Queensland Government website: ‹qld.gov.au/environment/land/vegetation/management/›.

13.6.2 Management of riparian lands

Riparian 'frontage' lands are defined in some landscapes to be the width of land equivalent to the height of the streambank, plus five metres. These areas need careful management as they are often fertile and generally retain high levels of soil moisture. As pastures in these areas are often 'sweeter' they are preferentially grazed by stock, potentially making the riparian land subject to severe erosion. Erosion of streambanks and gullies, as well as scalding, may be evident.

Fencing riparian zones and providing off-stream water points can have a number of benefits associated with restricting stock access to the area, including:

- preventing the disturbance and bogging of the streambed
- preventing the formation of cattle pads that can cause gullies
- assisting the rehabilitation of gullies
- improving water quality
- reducing the spread of weeds
- making stock mustering easier.

Fencing riparian areas allows grazing pressure to be more closely controlled. Restricting the grazing of riparian land until early in the dry season can have the following benefits:

- Grazing is directed onto the green leaf of pasture grasses (reducing the amount of browsing on trees and shrubs).
- High levels of ground cover are maintained—pastures have had a chance to be spelled over the wet season.
- Advantage can be taken of the high feed quality compared to surrounding areas.

Strategies for fencing riparian areas include:

- establishing a frontage paddock by fencing out the upland areas adjacent to the floodplain
- fencing out high-priority water bodies such as natural springs
- protecting areas that are especially vulnerable to gully and streambank erosion
- separating out the immediate riparian area.

Fencing is not necessarily intended to completely exclude stock from riparian areas and should create paddocks large enough to be workable management units. In most cases, it would be impractical to fence both sides of all riparian areas in extensive grazing lands.

Off-stream watering points (or troughs) supplied from permanent natural waterholes or from bores may be used as an alternative to fencing, as they reduce the time cattle spend in creeks and waterholes. In many cases, stock prefer to drink from well-placed troughs, particularly if access to the watercourse is difficult, water quality is low, or there is danger (e.g. crocodile habitats).

13.6.3 Management of cropping lands

Gully erosion can best be avoided in cropping lands by:

- adopting stubble retention and zero tillage practices
- constructing contour banks and vegetated waterways on sloping land, and maintaining them to appropriate specifications
- ensuring that contour banks discharge into waterways at stable locations; and the waterways discharge into naturally stabilised areas
- adopting strip cropping practices on cultivated floodplains to spread flood flows, and avoiding practices that concentrate flood flows.

Chapters 7–10 and Chapter 12 in these Guidelines contain more detailed information relative to managing cropping land to mitigate gully erosion.

13.6.4 Roads, tracks, fences and firebreaks

Property infrastructure is a common initiator and driver of gully erosion. The susceptibility of roads and tracks—and their table drains—to erosion may depend on soil types, the cross-sectional profiles and their location in the landscape. Similarly, fences and firebreaks oriented across the land slope may result in the diversion/concentration of overland runoff leading to the development of gullies.

Roads, fences and firebreaks should be situated in locations that do not readily divert overland runoff and concentrate it to areas that lead to gully erosion. The best place for a road is to follow a ridge line. An examination of satellite imagery in seriously eroded paddocks in the Burdekin catchment shows that graziers being aware of this consistently use ridge lines for access. Roads that run directly up and down the slope will divert or concentrate less runoff than those diagonal to the slope.

Roads should have a profile that does not concentrate overland runoff. Roads that are below normal ground level through constant use or inappropriate maintenance should be re-profiled to a form that does not concentrate overland runoff; alternatively, they should have drainage works incorporated to ensure runoff is dispersed onto stable areas. Associated table drains and mitre drains should have a trapezoidal shape with a flat bottom, and not a triangular shape that is more conducive to eroding.

Access on vulnerable, steep riparian frontage land can be located so as to restrict the amount of runoff that can be diverted or concentrated. Whoa-boys can be located within the access to ensure concentrated runoff is directed to stable areas. Similarly, fences can be located in riparian areas such that stock tracks do not develop into gullies through the banks of watercourses.

More information about the effects of property infrastructure on erosion is provided in Chapter 14 Property infrastructure.

13.7 Managing gully erosion

13.7.1 Options for the control of gullies

Prior to undertaking any repairs or rejuvenation of gullied areas, it is important to carry out a full assessment: causes, options and resources available, including a plan for ongoing monitoring and maintenance.

SEQ catchments (2015a) list the following as a gully erosion planning checklist:

- define the problem
- design a solution
- implement the design
- check effectiveness.

In general, options that should be initially considered include managing the contributing catchment in a way that increases rainfall infiltration, and reducing overland runoff. Installing engineering measures can be very expensive, and not always with a great measure of success.

Management options for controlling gully erosion include a combination of:

- improving the vegetation cover in the contributing catchment by:
  - reducing grazing pressure at critical periods
  - maintaining tree cover
  - revegetating
- fencing off a gully system to encourage revegetation and natural recovery
- filling or reshaping the gully and stabilising the drainage pathway
- stabilising the bed of the gully
- stabilising the head of the gully by:
  - diversion of runoff
  - installing a dam
  - installing a chute or a drop structure
  - reducing the effects of seepage.

In southern areas of Queensland, where engineering options are to be undertaken, autumn is a good time for gully reclamation work. There is less chance of heavy rainfall and high volumes of runoff, yet there is sufficient soil moisture and warmth to promote the growth of vegetation where required.

In northern areas the best time to carry out construction works is when there is a low chance of heavy rain occurring soon after any works are completed, yet soil moisture is adequate to aid germination. This is likely to occur at the end of the wet season through even to the beginning of the next wet season.

Gully control structures may be designed vegetated waterways, or they may be made of earth, concrete, rocks, sandbags, masonry, wood or other building material. Specialised skills are required for their design and construction, and they may be expensive to implement. These structures have an inherent risk of failure and may be undermined (or bypassed) by uncontrolled flows, or by flows that exceed the design runoff event.

13.7.2 Preliminary assessment

The following factors should be considered before any gully control attempts:

- **The cause:** As discussed in Section 13.4, gullies may be initiated by local, upstream or downstream triggers. Local triggers are often more obvious, but the downstream or upstream triggers may indicate additional options that should be addressed.
- **The effect:** Is the gully threatening the productivity of the surrounding land, or threatening farming operations? What is the value of the potentially affected land? Is the gully threatening property infrastructure such as a road or dam? What are the downstream impacts on water quality?
- **The catchment and its hydrology:** The amount of runoff depends on catchment area. However, large gullies may develop independently of catchment area, and may be more influenced by soil type, vegetation and land slope or landscape position. The occurrence of seepage flows also needs to be considered and, where present, a check should be made on salinity levels.
- **Soil type:** Compared to gullies in poor soils that are highly erodible, those in fertile soils are easier to control with stabilising vegetation. Soils with dispersive subsoils, particularly, are very prone to gullying and are more difficult to rehabilitate.
- **Gully components:** Where is the most actively eroding part of the gully—the gully head, the gully bed (floor) or the sides? Is the gully branching out? What is the height of the gully head?
- **Sediment movement:** If there is considerable sediment moving through a system, it may be captured to assist in filling a gully or stabilising the floor. However, sediment loads may be minimal where the upstream catchment is well managed, or where the gully is very large in relation to its contributing catchment.

A useful exercise when assessing a gully is to consider how an agency such as a road authority would control a gully if there was the road structure was being threatened by an advancing gully head. In many cases, there may be no simple solution and a project costing many thousands of dollars may be necessary to protect the road.

13.7.3 The role of vegetation

Engineering structures may be needed to stabilise a gully head or to promote siltation and vegetative growth in the gully floor. They are, however, subject to decay and will become less effective over time.

Vegetation is the primary, long-term defence in preventing or reducing gully erosion; and, in a favourable climate, it can multiply and thrive and improve over the years. However, gullies are a harsh environment in which to establish vegetation as they dry out rapidly and often have exposed infertile subsoils. Establishing suitable vegetation in the dry climatic zones of western Queensland can be especially challenging.

The chances of gully initiation and expansion can be reduced if there are high levels of native pasture to minimise the amount of runoff from a catchment. This reduces the effects of raindrop impact and improves rainfall infiltration.

Native pastures are mostly tussocky species and, in general, are better adapted to Queensland climatic conditions in the grazing lands compared to many of the introduced stoloniferous species. The tussock native species generally have deeper root systems, provide increased roughness—and therefore increased infiltration—and produce more biomass and shed more litter (Scott Wilkinson, personal communication).

On the other hand, in the wet tropics, stoloniferous grasses provide better surface protection than clumping grasses such as guinea grass (Panicum maximum). In these high rainfall areas, species such as signal grass (Bracharia decumbens), creeping signal grass (B. humidicola) and carpet grasses (Axonopus spp.) can quickly provide cover with no exposed soil (Darryl Evans, personal communication).

Most grasses with runners and stolons are exotic species. Many of these are well established in the agricultural cropping lands and have been used successfully for controlling erosion, particularly in the higher-rainfall areas. A list of possible species is provided in Appendix 4, although local advice should also be obtained to see if a proposed plant could be a potential weed.

Grass seed sown directly on gully scarps, sidewalls and excavated subsoils will usually have poor success with germination. Establishment rates can be greatly improved by ensuring soil moisture content is adequate, battering sidewalls, adding organic and chemical soil amendments and excluding grazing stock.

For very small gully heads some success has been obtained by simply planting a suitable grass above the eroding head of the gully. The grass could be a stoloniferous species, or maybe one or two rows of a species with an extensive root system, such as vetiver grass (see Figure 13.14). Once grass is established, wing banks will be required to direct flow through it. As the gully advances into the grassed area, some degree of stability may be achieved so long as undercutting does not occur at the gully head.

Vegetation alone may not be able to fully stabilise an actively eroding gully head, but the rate of advancement may be reduced by planting erosion-resistant grass immediately above the head of the gully (Figure 13.14). Vetiver grass, with a very deep root system, is suitable for this purpose in some coastal areas in Queensland as well as in higher-rainfall, inland areas.

Figure 13.14: Vetiver grass planted above a gully head to reduce its rate of advancement

Trees are desirable in the areas surrounding gullies but are not likely to be successful in stabilising an actively eroding gully head. Trees growing in gullies should not be too dense and should have an open canopy to allow protective vegetation to grow on the soil surface.

Retaining or re-establishing trees in grazing lands will lessen the risks of gully heads advancing by regulating soil moisture; and, by reducing rainfall splash, the risks of sediment transport will be lessened.

Where subsurface flows are contributing to gully erosion, trees and other deep-rooted vegetation above and beside the gully may assist by helping to lower the watertable and drying out the soil profile. They may also provide structural support to subsoils in gully walls prone to slumping.

As discussed in Chapter 11, tree roots help to stabilise streambanks in a similar manner to reinforcing rods in concrete. However, most gullies have far more capacity than they require and over-bank flooding is unlikely to occur. Unlike streambanks that become saturated and heavy during a flood, the banks of gullies are generally not prone to slumping.

Shrubs in the gully floor can provide erosion control if they are so closely spaced that their interlocking branches prevent high-velocity water from coming into direct contact with the soil. This can occur on the outside banks of channel bends. Shrubs on and above the bank may increase its strength while shrubs at the bank base can reduce toe erosion and undercutting.

The branches of low-growing trees and shrubs in the beds of gullies can reduce flow velocities and their roots may help stabilise the bed. However, if trees suppress the growth of surface vegetation cover, they can create a higher risk of erosion. Trees are not likely to be successful in stabilising an actively eroding gully head.

As soils in gullies are often infertile and/or shallow, the strategic use of fertiliser can meet the nutritional needs of stabilising plants when there is a depth of adequate soil and soil moisture. Stock can apply heavy grazing pressure to fertilised gullies where fresh, green growth occurs, so fertiliser use should be carried out in fenced-off areas that can control grazing pressure. Hand application of fertiliser would normally be required as gullies are usually inaccessible to machinery and, if used, machinery could create an erosion risk from the resulting wheel tracks. An area to be treated with fertiliser would usually be small; for example, a gully 1000 m long and 10 m wide will occupy one hectare.

13.7.4 Fencing off gullies

In many situations, fencing is the most practical option for stabilising a gully. Grazing animals are attracted to gullies, where there may be shade and shelter provided by trees and where there may be fresh growth of palatable plants after rain. Such areas can be subject to heavy grazing, and the development of stock pads can create further gullying. Stock walking around the head of a gully will create a pad that can hasten the advance of the gully head.

Fencing off a gully in a triangle with the apex above the gully head can result in stock pads that divert water away from the head (Scott Wilkinson, personal communication). This is a suitable option only if the diverted runoff is distributed over a stable area. It would not be suitable if it is likely to create another gully head where it enters the gully lower downslope.

When fencing off individual gullies, a buffer zone should be included to cater for tree growth outside of the gullied area, and also for occasional vehicle access—the wider the buffer, the better. Where it is likely that the growth of the gully can be controlled, a minimum width of 20–30 m is recommended. Where future expansion of the gully is likely, this area needs to be included within the fenced-out area. For riparian areas, any gullies feeding into the stream should be included in the fenced-off area.

For gullies occurring throughout a large management unit, it may not be practical to fence off individual gullies. Such areas need careful management. Rather than allow stock continuous access, a useful strategy can be to graze these for a short period only, following the summer growing season. This ensures minimal creation of stock pads and stimulates future pasture growth.

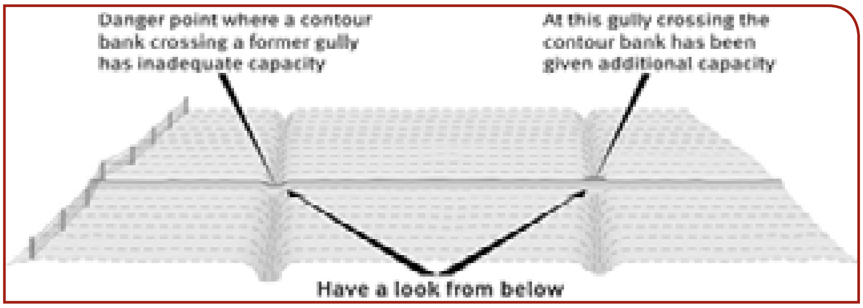
Contour ripping and seeding may help to rehabilitate degraded areas between gullies, except where dispersive subsoils may be at risk of tunnelling due to the subsoil becoming saturated following runoff events.

Fencing and good pasture management can slow down the rate of advancement of a gully head, but its growth up the catchment may still continue. Methods of dealing with gully heads are considered in following sections.

13.7.5 Stabilising gullies in cultivation and farm waterways

Gullies in cropping lands can be filled when constructing contour banks. It is important that banks have sufficient capacity where they cross old gully lines as this is where contour banks often fail. Land levelling between contour banks should be should be carried out to remove, as much as possible, any wash lines and rills so that runoff along rows does not concentrate towards old gully lines (Figure 13.15). Where contour banks discharge into eroding waterways, they can be stabilised by reshaping or filling followed by establishment of suitable vegetation.

Figure 13.15: Check for low sections in contour banks by looking uphill across the line of banks



Gully filling of an eroded farm waterway has a good chance of success where there is a good establishment of a stoloniferous plant species adjacent to the gullied area. Construction work, and establishing the vegetation, is best done following the wet season, when the risk of heavy rainfall is less and temperatures are still warm enough for grass to grow. Soil from an adjacent area, with plant runners, may be used for filling. Depending on the size and shape of the waterway channel, it may be possible to take soil from waterway banks that are higher than necessary, and from areas of silt deposition.

13.7.6 Reshaping or filling a gully

This option will rarely be cost-effective in grazing lands, unless the gully is threatening a valuable asset. In cropping lands filling a gully may be cost-effective only if the land can be reclaimed for cropping purposes, or for other more intensive land uses. Similarly, reshaping a gully may only be practical if the outcome provides other benefits, such as an alternative land use or provision of a stable drainage structure.

Past practices of dumping car bodies or other similar waste in gullies is not recommended. Use of such waste materials can exacerbate erosion as the voids created can encourage tunnel erosion, or lead to subsidence, or can concentrate flows against unprotected gully banks.

All earthmoving activities should be undertaken with great care, especially with steep-sided gullies and where undercutting has occurred. The use of earthmoving equipment should adhere to all workplace safety procedures.

Whether a gully can be shaped or refilled depends on its size and the amount of fill needed to restore it to a desired shape. Where there is insufficient soil to fill a gully, the sides can be battered to a more gentle grade of 1:2 or 1:3 (V:H) to allow for vegetation to be established.

When filling or reshaping a gully, it is always easier to move soil following ripping. Bulldozers are the most suitable to fill a gully, but a grader or scraper may also be used, depending on the distance the material has to be moved from source to gully. For reshaping a gully, an excavator may be more practical, depending on the size and depth of the gully.

Further information on this topic can be found in the publication Gully filling and shaping (New South Wales Soil Conservation Service 1991d).

Filling a gully

The planting of stoloniferous plant species adjacent to and above the gully, the year before filling and levelling is to be carried out, will reduce costs and ensure the success of the project. Alternatively, the area may be sown to a cover crop/grass seed mixture after the gullied areas have been filled.

When filling a gully, each layer of soil progressively pushed in should be well compacted. Loosely deposited soil will offer little resistance to runoff erosion. Soils that are either too dry or too wet cannot be effectively compacted and may require watering (if too dry) before construction works, or alternatively (if too wet), should be left to dry out to an appropriate moisture content. Sheep-foot rollers are recommended for compaction of the layers—the tracks on bulldozers are designed to distribute weight and are not as suitable. Excavators with a roller/compactor attachment are also suitable.

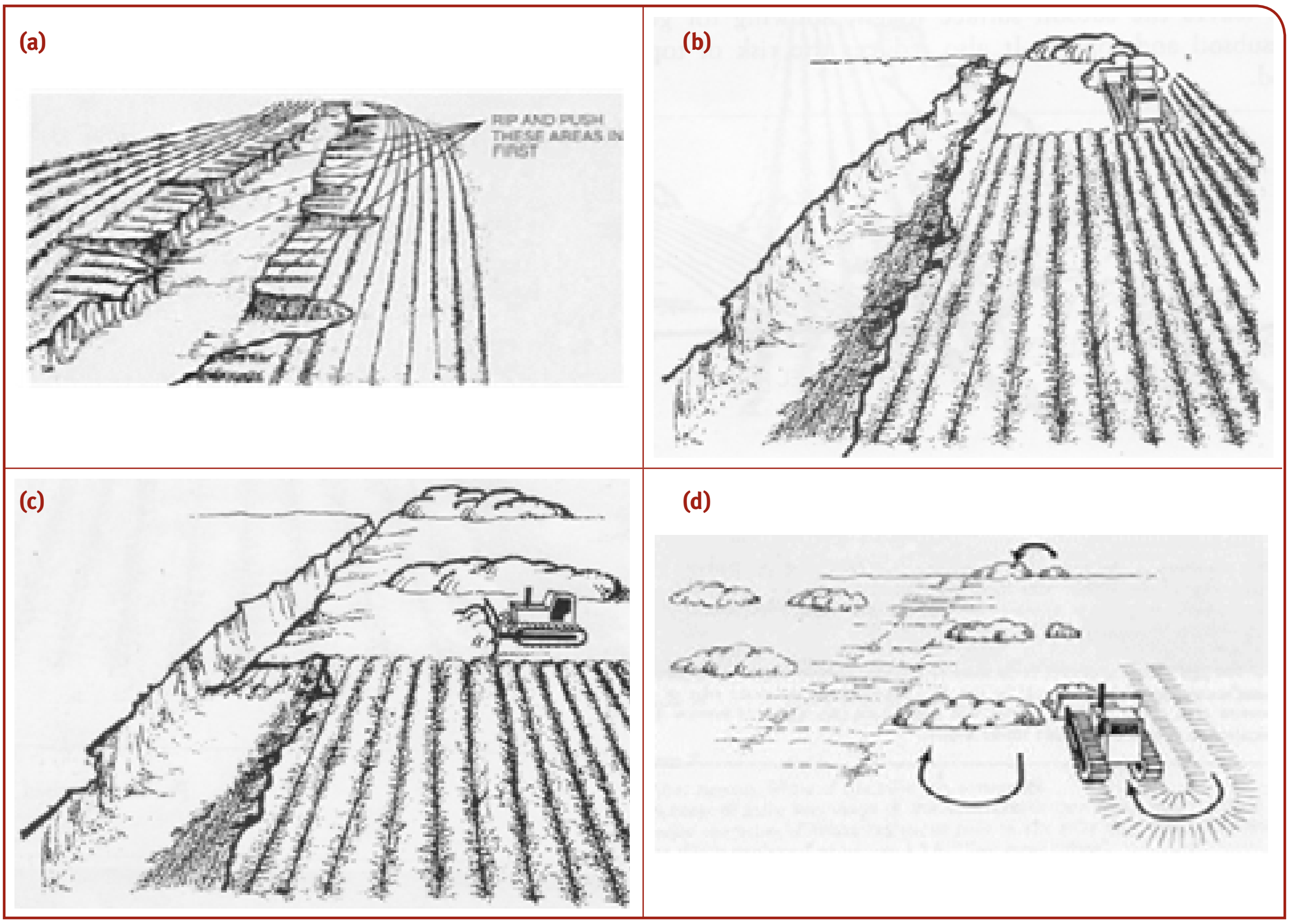
Gullies that are filled with dispersive subsoils will be susceptible to tunnel erosion that can easily develop if the soil is left uncompacted. The risk of tunnel erosion can be reduced by mixing gypsum into dispersive subsoils at a rate determined by soil analysis. An approximate guide is to apply 2.5–3.5 t/ha to each 10 cm layer of soil.

Gully filling is not recommended in saline areas. An eroding gully may help to provide drainage to the area, thereby assisting in alleviating the salinity problem by lowering the water table. Control options in this situation may be not to fill it in, but to aim to stabilise the gully as a drain; and/or to address the root cause of the salinity problem.

A practical method of filling a gully is described in the New South Wales *Soil Conservation Service* (1991d) publication. The technique involves the following steps as illustrated in Figure 13.16:

- Rip and fill the lateral branches first.
- Rip along the sides of the gully; this levels the surface and mixes the topsoil with any exposed infertile subsoils.
- Stockpile the topsoil.
- Push fill into the gully; progressively, each layer should be well compacted, preferably with a sheep-foot roller or alternatively with rubber-tyred machinery.
- Re-spread the topsoil to completely fill the gully.
- Fertilise and seed with appropriate vegetation; if available, an overlay of a hay mulch is beneficial.
- Fence off the area.

Figure 13.16: Filling a gully to eliminate erosion: (a) dealing with lateral branches; (b) ripping and stockpiling topsoil; (c) filling the gully with subsoils; (d) re-spreading topsoil (source: New South *Wales Soil Conservation Service*, 1991d)



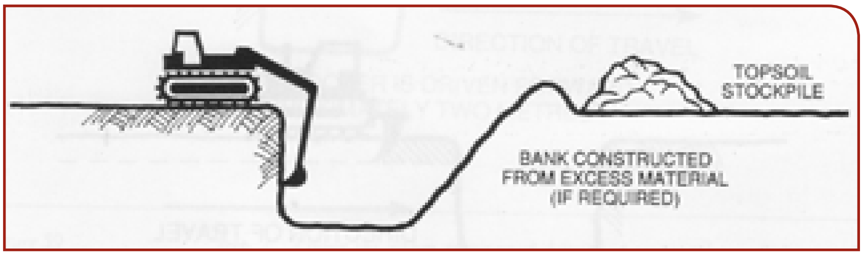
Reshaping a gully

Before beginning to reshape a gully, overland flow should be temporarily diverted away from the gully until vegetation has become established, but only if a suitable runoff disposal area exists.

Shaping of the gully walls should be carried out only after the head of a gully has been stabilised with a structure such as a chute or flume. Preferably, the walls should be shaped back from the gully floor so as to not restrict water flow in the gully—that is, fill is not placed into the flow channel, except maybe later, for topdressing to encourage revegetation.

Figure 13.17 shows the use of an excavator to reshape the sides of a deep gully with steep sides. The area to be reshaped should be pegged out before construction. In a 2 m deep gully, for a batter slope of 1:3 (V:H), topsoil would be removed from a 6 m width on the gully edges. After marking the topsoil line to give the desired batter length, all the topsoil is removed using a bulldozer, and stockpiled beyond that line, leaving room for the excavator to operate. On completion of the shaping, all exposed surfaces are re-covered with topsoil from the stockpiles.

Figure 13.17: Shaping a gully side using an excavator



Stabilising batters with erosion control mats

Erosion control mats assist with seed germination and provide protection from raindrop impact erosion. They are not intended for use in high-flow velocity areas, but can be useful in stabilising batters. Although these products are commonly used in urban projects, they are economically questionable over large areas of a rural property.

The mats are made from a range of fibres including man-made materials and natural fibres such as jute, wool and coconut fibre in various thicknesses; and as they are usually biodegradable they are used only for temporary protection against erosion. They provide an ideal environment for seed germination by retaining moisture and heat in the surface soil; they protect the soil and encourage plant growth. By the time vegetation is established, the mats will break down and eventually provide mulch for new vegetation.

Some erosion control blankets have a nylon mesh incorporated into the blanket to provide strength. The Local Government Association of Queensland (2006) recommends the mesh side be placed on the ground so that the nylon mesh does not otherwise trap wildlife such as snakes, lizards and birds.

Some of these products may be sprayed on to the surface of the batter with hydromulch machinery. Hydroseeding can be applied in conjunction with biodegradable erosion blankets to improve the establishment of vegetation. Compost blankets provide excellent protection as well as a very suitable medium for establishing vegetation (Bhattarai et al. 2011). Hydromulching may also be useful for stabilising the areas surrounding chutes (Landloch 2002, 2004) (see also Section 13.11 of this chapter).

Due to the vast range of proprietary products available, independent advice should be sought on the appropriate blanket for a particular situation. Manufacturers supply product specifications and installation guidelines, and design and installation information on the more common types of erosion blankets is provided in Institution of Engineers, Australia (1996).

13.7.7 Gully floor/bed stabilisation

The floor of a gully—or gully bed—may be well grassed and stable, or may be bare and eroding. Some gully beds reach stability by eroding down to the rocky parent material. The soil in a gully bed can be an inhospitable medium for plant growth. It may be either exposed subsoil material or redeposited sediments that are often infertile with limited moisture storage capacity.

Weirs, check dams, grade stabilisation or grade-control structures are all bed stabilisation measures that aim to improve the environment for the growth of vegetation by trapping coarser sediments and some of the suspended sediment of minor flows. They may also reduce the rate of sidewall expansion of a gully by stabilising the toe of the gully sides. However they are not likely to prevent a gully head from advancing up its catchment; additional measures are required to control the headward advancement.

Other gully control measures, such as improved management of the catchment, and stabilising a gully head, should be considered in conjunction with installing any bed stabilisation measures. An advancing secondary gully head may threaten a structure built to control the main gully head, so a gully floor needs to be stable before a head control structure is built. Failure to do this may result in the undermining of the head structure.

The long-term success of bed stabilisation work depends on establishing a good vegetative cover on the gully floor. This prevents further gullying and allows the floor to gradually silt up, and so reduce the fall over an upstream head. Stabilising the bed of a gully will promote the colonisation of vegetation and reduce the risk of further down-cutting and gully development. It may be the best option for stabilising a gully in situations where control of the head otherwise is difficult.

In grazing lands, branches of dead shrubs or trees can play a useful role in stabilising a gully bed by providing hydraulic roughness to slow water flow, trap sediment and restrict animal access (Figure 13.18). Branches should face towards the head of the gully to reduce the velocity of the runoff after it flows over the gully head. The interwoven branches act as semi-permeable barriers to flow, detaining runoff and resulting in increased soil moisture in the gully floor.

Figure 13.18: Tree branches stabilising a gully bed

The amount of sediment moving down a gully depends on the condition and size of its catchment as well as the stability of the gully itself. While the upstream section of a gully may be stable, it is possible there will be insufficient sediment moving to any structure that may be constructed lower downstream. Failure of this structure can result in the subsequent removal by erosion of any stored sediment, unless it has been adequately stabilised by vegetation.

Although it is unlikely that a gully can be completely filled, growth of vegetation can assist in stabilising the gully floor. Most gullies carve out far more capacity than they require, even for a major runoff event, and many gullies in upland areas have advanced almost to the head of their catchment, meaning they will deliver very little runoff or sediment.

Pervious weirs

Weirs that are constructed from a permeable material—such as brush, logs, wire netting with straw—are termed 'pervious weirs' or 'leaky weirs', as they let the runoff pass through, but trap sediment. A series of small weirs made from wire netting, logs or concrete, or bundles of small tree branches, can trap sediment that encourages vegetative growth.

Stiff grass barriers planted across a gully floor can assist in building up deposited sediment—vegetation grows through the sediment after it has been deposited. The success of this measure depends on finding a species that is suited to the local climate and can grow in the often infertile soils in a gully floor. Lomandra is a native species that has provided successful stabilisation of bed and banks in reshaped watercourses in south-eastern Queensland.

The Monto strain of vetiver grass, Vetiveria zizanioides L. (Figure 13.19), has been one species found to be suitable for a range of soil types in southern Queensland. It has been used in establishing rows across gully floors, where it acts as a barrier to flood flows, resulting in sediment being deposited in front of the rows.

Unlike earth structures that often fail due to cracking or undermining, vetiver grass weirs do not easily wash away because of the species' dense, deep root system. As water flows over and through the grass 'weirs', turbulence and scouring of the bed or bank is minimised. The vetiver rows should extend out onto the shoulders of the gully to prevent water from cutting around the ends into the walls of the gully.

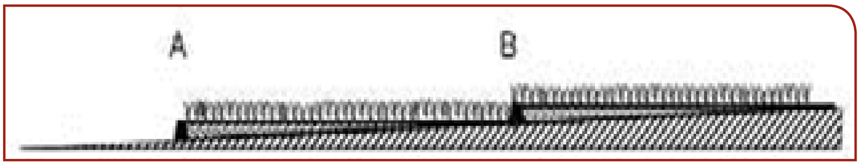
Figure 13.19: Vetiver grass used as a bed stabilisation measure

Sediment deposition

Bed stabilisation structures have not been used widely in Queensland. However, limited experience has shown that they can be successful in trapping sediment and encouraging plant growth. Care needs to be taken in their construction, especially where there are dispersive soils.

If sediment is being carried in a gully, a series of small, grade-control structures, or weirs of around 20–50 cm in height can trap sediment to encourage vegetative growth along the length of the channel. Such structures aim to reduce the effective slope in a gully floor by creating a series of 'stairs' as shown in Figure 13.20.

Figure 13.20: A series of continuous bed stabilisation structures on a gully floor



A common method is to construct a series of structures in the bed of a gully where each structure deposits sediment as far back as the structure above (Figure 13.20). However, as shown below, this approach is likely to be impractical in many situations.

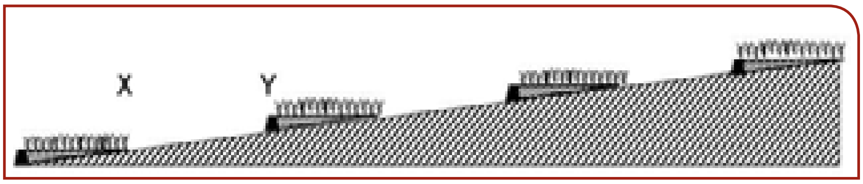
Table 13.1 shows that for a 1 km long gully on a 2% slope, there would be a need for 20 weirs with a height of 1 m, or 80 weirs with a height of 0.25 m; either option would be a major undertaking involving significant cost.

Table 13.1: Number of weirs needed to stabilise a 1 km gully on a 2% bed slope

Height of weir (m)	Length of deposited sediment on a 2% slope (m)	Number of structures required on a 1 km length of gully
0.25	12.5	80
0.5	25	40
0.75	37.5	27
1	50	20

However, sediment is rarely deposited in a level plane. As with natural levees, heavy particles will be deposited first into water ponded behind the weir, leading to a grade in the deposited sediment. Sediment deposition will naturally grade out to a bed slope up to about 1%; depending on particle size, sand will grade out to about 0.5%. Therefore, a more practical option is to build a limited number of weirs at strategic locations, or at wider spacings, as shown in Figure 13.21. The success of such an option will depend on revegetation occurring in the gaps between the structures, for example, X to Y.

Figure 13.21: A series of spaced bed stabilisation structures on the gully floor



Care needs to be taken when selecting the location of a weir. It is tempting to reduce costs by choosing a location where the gully is relatively narrow. However, it may be much safer to choose a location where the width is greater and flow velocities will be lower.

13.8 Weirs for stabilising a gully bed

13.8.1 Types of weirs

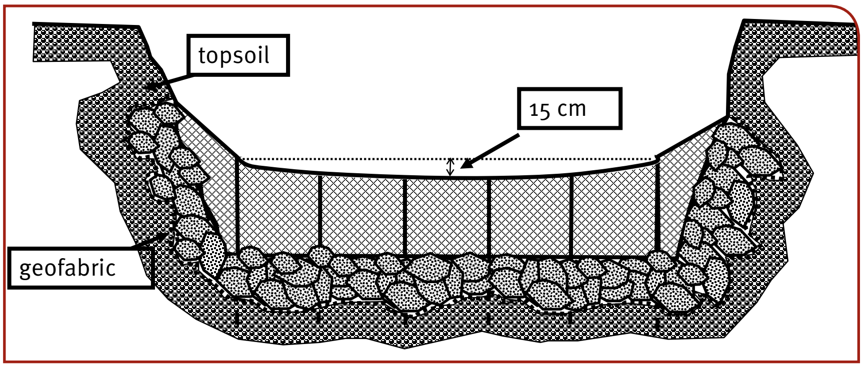
The durability of a weir depends on the construction materials used. Weirs can be made from wire netting, rock, gabions, logs, tyres, concrete, steel sheet piles or hay bales. Strips of suitable vegetation can also be used to act like a pervious weir. Where the vegetation has a relatively short life, the intention is that the weirs will retain some sediment and promote vegetative growth before the weir decays.

Wire netting weirs

Wire netting weirs, Figures 13.22 and 13.23, should have a maximum height of 30–50 cm; the higher the weir, the greater the risk of failure in a large runoff event. As the wire netting is likely to rust, these weirs should not be considered as permanent control measures.

At the weir site, a trench is dug across the gully floor to a depth of 30 cm and keyed into the sides of the gully for a distance of 0.5 m–1.0 m.

Figure 13.22: Diagrammatic view of a wire netting weir with a rock apron



Steel pickets are hammered into the trench at a distance of 0.5 m to 1.5 metres apart; the higher weirs, the closer the pegs. Plain wire should be threaded through the top holes of the pickets and twitched tight. The steel pickets near the centre can be further hammered in to provide a dish shape for the crest of the weir.

Wire netting with a maximum mesh diameter of 10 cm can be folded in half over the crest wire to form a double thickness and is then secured to the pickets. The wire netting placed in the trench will prevent runoff flowing underneath the mesh. The trenches should be filled in with layers of soil, each layer being well compacted.

An alternative to digging a trench for some netting weirs is to have the netting extended upstream and secured to the ground surface by the use of wire pegs. If necessary, a second strip of netting can be secured on the upstream side of the weir so that it overlaps the first strip by 20 cm.

To ensure protection of the side walls, the wire netting should be extended up the sides for a distance greater than the expected height of flows over the crest. Angular rock could be placed below the weir to dissipate the energy of runoff flowing through or over the weir. The rock should be covered tightly with netting and secured with steel pegs.

Figure 13.23: Field examples of wire netting weirs: (a) sediment trap used to encourage vegetation in the gully floor; (b) a variation—sticks and small branches or rocks, wrapped in wire netting, secured to the gully floor with stakes (Source: Wilkinson et al. 2013)

Hay bale weirs

The use of weirs made of hay bales should be restricted to low-flow, minor gully situations. They are virtually impervious but some water can flow between the bales. The intention is that the bales will cause some sediment deposition and vegetation growth before they decay and fall apart. Where bales are used they should be checked to ensure undesirable weed seeds are not introduced.

Hay bale weirs are relatively easy to install but they should be staked to the ground to prevent them from floating away. This can be achieved by hammering two steel pegs through each bale around 20 cm from the ends. Wire is threaded through the tops of the pegs, then secured at each end of the weir. The pegs are then hammered in until the wire presses firmly on top of the bales.

Provided the bales are used only in low-flow situations, there would be a limited need for energy dissipation measures below the weir. Because of the temporary nature of hay bales, an elaborate runoff dissipation measure below the weir is not justified.

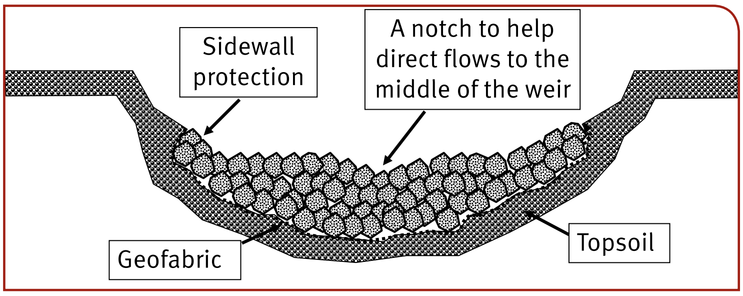
Rock and gabion weirs

Rocks can be used to construct weirs, as shown in Figure 13.24—gabions (wire baskets filled with rocks) can also be used. These are suited to all soil types, including cracking clays, however, care is required when used on dispersive soils where it may be necessary to treat the soil with a gypsum amendment.

For a rock or gabion weir, a trench should be dug across the gully floor to a depth of up to 30 cm and keyed into the gully sides to a distance of 1 m. The trench should be lined with a suitable geofabric (filter cloth) that is then covered by a layer of topsoil before rocks are placed to form the weir.

A rock apron is required for energy dissipation, with the downstream end of the apron level with or below the gully floor so there is no risk of a new gully head being established. Netting should be laid over the rock and pegged securely on a 1 m by 0.5 m grid. A stoloniferous grass planted into any sediment deposited among the rocks provides greater strength to the structure.

Figure 13.24: Rock weir with a notch in the middle to direct flows to the centre of a channel



Tyre-rock weirs

Recycled tyres filled with rock can be used to construct a weir as, shown in Figure 13.25. However, there may be environmental concerns with use of recycled tyres in certain locations. Before using this technique a landholder should check with the local government authority for any relevant environmental regulations

Recycled tyres can be obtained with one sidewall removed. This makes it easier to fill the tyres with rocks and eliminates the chance for pockets of air to cause flotation and subsequent damage to the structure. Steel pickets secure the tyres in place and rust-resistant wire netting is placed over the top of the tyres to assist in containing the rocks.

Figure 13.25: Weir made of rock-filled old truck tyres (source: Ecoflex)

Concrete and log weirs

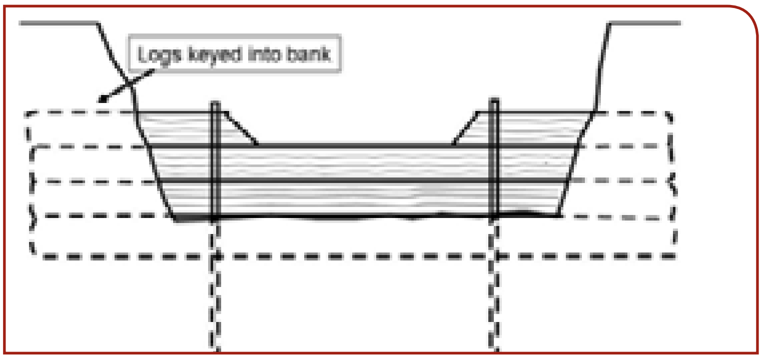
Concrete weirs are generally a high-cost option and are not suited to cracking clay soils. As an alternative, a weir can be constructed using logs that may provide more flexibility (Figure 13.26).

For their installation, a 15 cm wide trench should be dug to a depth of 45 cm across the gully floor and 1 m into the sides of the gully wall. This is to ensure that deep flows do not come into contact with the gully walls. For the concrete weirs, formwork should be fabricated with a notched shape, similar to that shown in Figure 13.26 for a log weir.

A dissipater is required to absorb the energy of runoff flowing over the weir. Side protection should also be provided to accommodate the expected height of flow plus freeboard. More detail is provided for the design and construction of energy dissipaters and sidewall protection, in sections 13.11 Chutes and 13.12 Drop structures.

For concrete weirs, reinforcing mesh should be used in the weir and in the dissipater, and weep holes through the wall are necessary for drainage to relieve hydrostatic pressure behind the structure. This can be achieved with short lengths of pipe installed at 1 m intervals and exiting just above the dissipater. The inlet ends should be covered with a filter cloth.

Figure 13.26: Weir constructed from logs



Sandbag weirs

An alternative form of a concrete weir can be made with sandbags filled with a 5:1 sand/cement mix. The bags should be no more than three-quarters full and should be filled on site, as vibration during transportation will cause sorting of the particles. The bags are laid lengthwise, on geofabric, overlapping by one-third. Steel rods driven through the bags anchor them to the gully floor. As with a concrete weir, drainage weep holes will be necessary.

The bags should be thoroughly wetted to set the concrete. An alternative is to place prepared wet concrete into the bags. These will be heavier to handle but can be made to fit more tightly into place than bags with a dry mix. This method also avoids the risk of the cement and sand mixture not being sufficiently wetted to set completely.

Rocks covered with netting may be used to form the energy dissipation apron below the weir.

13.8.2 Design of bed stabilisation structures

The following should be considered when designing bed stabilisation structures:

- soil type
- weir spacing and height
- expected depth of flows in the gully
- weir shape
- risk of undermining by scouring or tunnelling
- a need for sidewall protection to control scouring, soil dispersion, tunnelling and bypassing of a structure.
- energy dissipation below a weir.

Any control measures in dispersive soils are prone to failure if appropriate measures are not taken to prevent the works or measures are not bypassed or undermined by runoff flows in the gully.

When a weir overtops, water falling from the crest can cause undermining of the structure by creating a downstream 'plunge pool'—again, the greater the height of the weir, the greater the potential risk. Some form of energy dissipation is required to reduce the risk. Water flowing over the crest of a weir can also erode the sides of the gully and this can be prevented by using wire netting, or a suitable geofabric for sidewall protection.

Weir spacing and height

In some situations, a few bed stabilisation structures near the head of a gully may be all that is necessary. In other situations it may be desirable to stabilise a kilometre or more of a gully using a series of weirs. In the latter case, the height to which they will be built should be determined, and an assessment made of the number of structures required.

Using Figure 13.27 as an example, depending on the bed slope, doubling the height of a weir from A to B creates a considerable increase in the amount of sediment that may be captured and stored, assuming that sediment is being transported within the system.

Figure 13.27: Doubling the height of a weir greatly increases the potential to store sediment

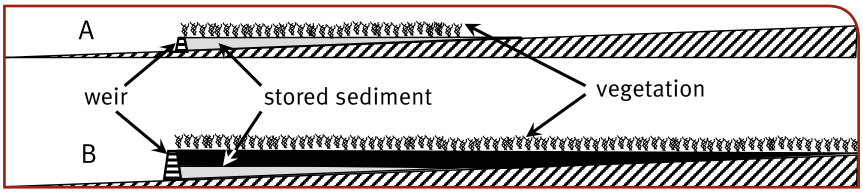


Table 13.2 shows how the length of sediment deposited behind a weir varies with the weir height and the bed slope. For example, on a two percent bed slope, a 0.5 m high structure would be capable of depositing sediment upstream for a distance of 25 metres, assuming arbitrarily, it will be deposited on a horizontal plane.

Table 13.2: Length of sediment behind a weir as a function of weir height and bed slope

Weir height (m)	Length of sediment deposited (m)				
	Bed slope (percentage)				
	1	2	3	4	5
0.25	25	13	8	6	5
0.50	50	25	17	13	10
0.75	75	38	25	19	15
1.00	100	50	33	25	20

As shown in Figure 13.27 and Table 13.2, the higher the weir, the more sediment it will trap and the greater the distance the weirs can be apart.

However, high weirs are more prone to failure because:

- the greater the depth of water behind a weir, the more strength is required of the weir.
- erosion of the sidewalls, or undermining of the structure by both scouring and tunnelling, is more likely. Dispersive soils are especially prone to failure by tunnelling, and the greater the head of water, the greater the risk of tunnelling.
- water flowing over a high structure will release more kinetic energy, requiring greater attention to dissipation below the structure.

As a consequence, it is recommended that maximum weir heights should be 30–50 cm. Structures can be built to a greater height but more attention to their engineering design is required.

Flow depth over the weir

The expected height of flow over a weir during a major runoff event should be estimated to determine the likely risks involved with a structure. This will also provide design parameters such as the size of rock to use, or the height to which netting or fabric protection is required on the gully walls.

Equation 13.1

$Q = CLH^{1.5}$

Where:

Q = design discharge, m^3/s

C = weir coefficient, 1.5–1.6 for a broad-crested weir; 1.9 for a sharp-crested weir

H = height of flow over the crest, metres

L = length of the weir crest, metres.

The first step in estimating flow height is to determine the rate of runoff discharge (in cubic metres per second, m3/s) likely to flow over the weir during a runoff event for the selected design period. Factors affecting the discharge rate include the catchment area, soil type, catchment condition and the intensity of rainfall expected for a nominated design frequency (refer to Chapter 3, 4).

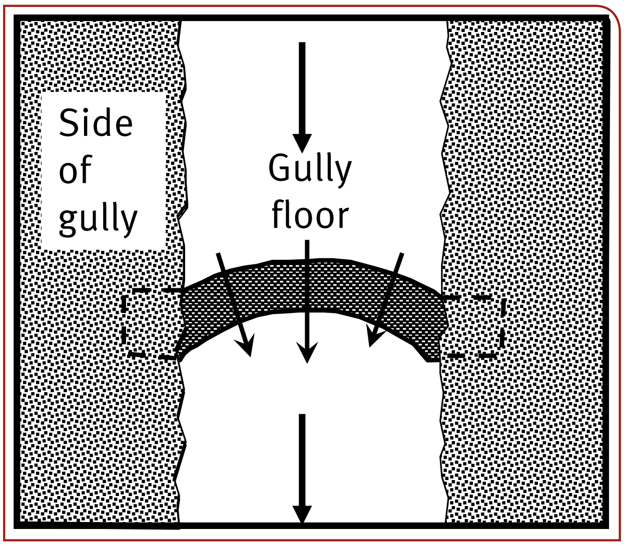
Degraded catchments contributing to gullies will produce more runoff than well-managed catchments of the same area. However, some gully heads, even in well-managed catchments, have almost advanced to the top of their catchment. In such cases, they have very small catchments in relation to their size and even in a major runoff event they may only experience relatively shallow flows.

Once the expected discharge rate is determined, the depth of flow over a weir can be estimated using the weir formula—Equation 13.1. This formula applies to an impervious weir; some allowance should be made for when a pervious weir is proposed.

Weir shape

In plan view, weirs may be arched-shaped or V-shaped, with the arch or V directed upstream, as shown in Figure 13.28. This encourages overtopping flows to concentrate towards the centre of the channel, thus reducing the risk of bank erosion adjacent to the weir. An arched- or V-shaped design will also provide more strength to the structure.

Figure 13.28: Plan view of an arch-shaped weir, with the arch facing upstream



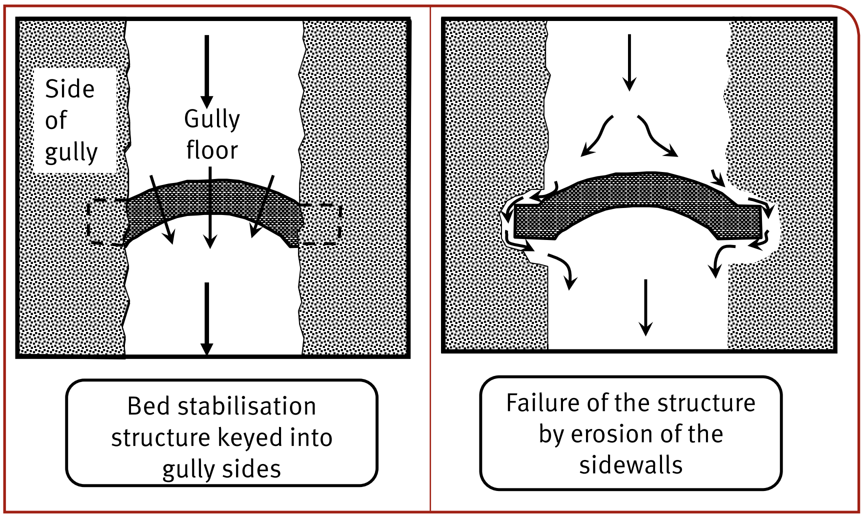
As a general guide, the sides of the gully should be protected against erosion for at least one-and-a-half times the estimated flow height above the weir crest. This can be achieved by extending the weir up the sides of the gully, as shown in Figures 13.22 and 13.24.

It is recommended that the centre of a weir crest is about 15 cm lower than the outside edges so that the strongest flow is directed down the middle of the downstream channel (Figures 13.22 and 13.24). This low point in a weir will also take the residual flows after a big event; although small, these flows can cause significant erosion on saturated sides of a gully.

Bypassing flows

A common cause of failure of bed stabilisation measures is the bypassing of the structure when runoff finds a way around it. The risk is much greater in dispersive soils, as shown in Figure 13.29. The greater the depth of water retained by the weir, the more likely it is that tunnelling will develop in a dispersive soil leading to failure of the structure.

Figure 13.29: Failure of a bed stabilisation structure by erosion of dispersible soils in the gully sides

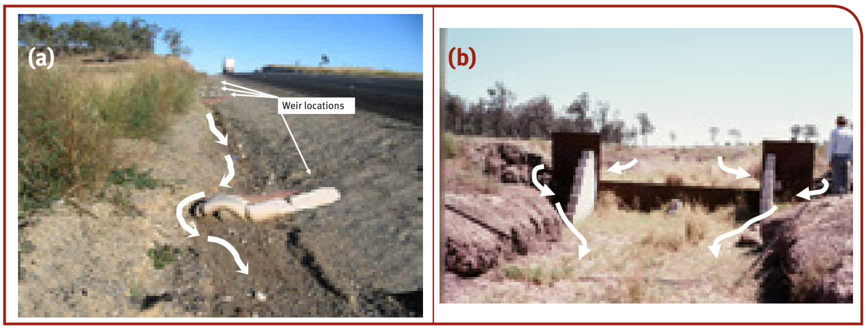


To prevent undermining and/or bypassing, the weir structure must be keyed well into the floor and the sides of the gully—the higher the weir, the more important this requirement becomes. The joint between the keyed-in soil and the material used to construct the weir can expand as soil shrinks in dry weather. Water may find its way through this space in the next runoff event and, if the soil is dispersive, a tunnel can form.

Compaction of the backfilled key trench will reduce the risk of failure. It is suggested that bentonite or gypsum be added to backfill material to reduce the risk of tunnelling under or around the weir structure. Compaction of the backfill material in shallow layers as it is added to the keyed-out trench is essential.

Figure 13.30 illustrates field examples of where bed-stabilisation structures have failed because: (a) inadequate capacity has directed flow to a side wall; and (b) the structure was located in a dispersive soil, despite being keyed into the gully walls.

Figure 13.30: Field examples of runoff bypassing a bed stabilisation structure: (a) sandbag weir in a road table drain; (b) a sheet steel weir in a dispersive soil

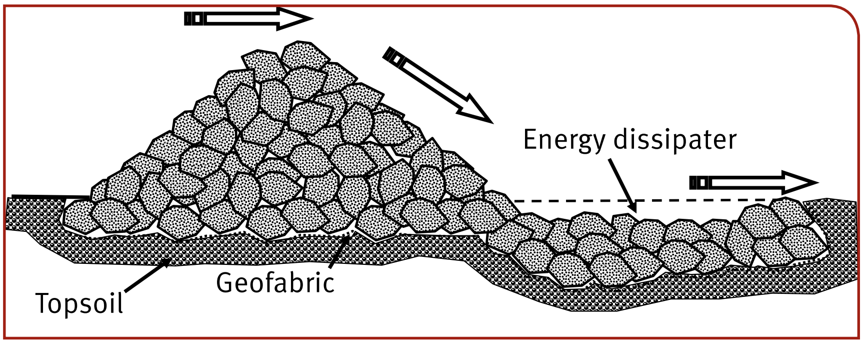


Energy dissipation

The energy of the flow exiting a broad-crested weir structure is dissipated through a process known as the hydraulic jump, where gouging and removal of the soil immediately below the weir is likely to occur, unless protective cover is provided. The hydraulic energy can be dissipated by the use of a stilling pond or an erosion-resistant surface such as rocks, sand/cement bags or erosion-resistant geofabric (Figure 13.31), sometimes referred to as an 'apron'.

The need for energy dissipation depends on the expected flow, the weir height, the size of rock, the land slope and the downstream condition of the channel. Greater detail is provided in Section 13.11.

Figure 13.31: Rock weir with an energy dissipater



13.8.3 Bed stabilisation structures and revegetation

The rehabilitation of a gully can be assisted by planting vegetation into sediment deposited behind and between weirs. Planting into moist sediment will improve the chances of success. Revegetation of areas disturbed by the installation of a structure should be encouraged as soon as practical.

Plant species with extensive ground cover and those with stolons or runners provide the best erosion control and encourage the deposition of sediment that improves vegetative growth. However, annual plants such as cereal crops like wheat, oats, millet and forage sorghum can provide a rapid temporary cover. Stock should be excluded until the vegetation is well established; after establishment any grazing should be only for short periods and carefully managed.

Appendix 4 provides a list of suitable species for different parts of Queensland.

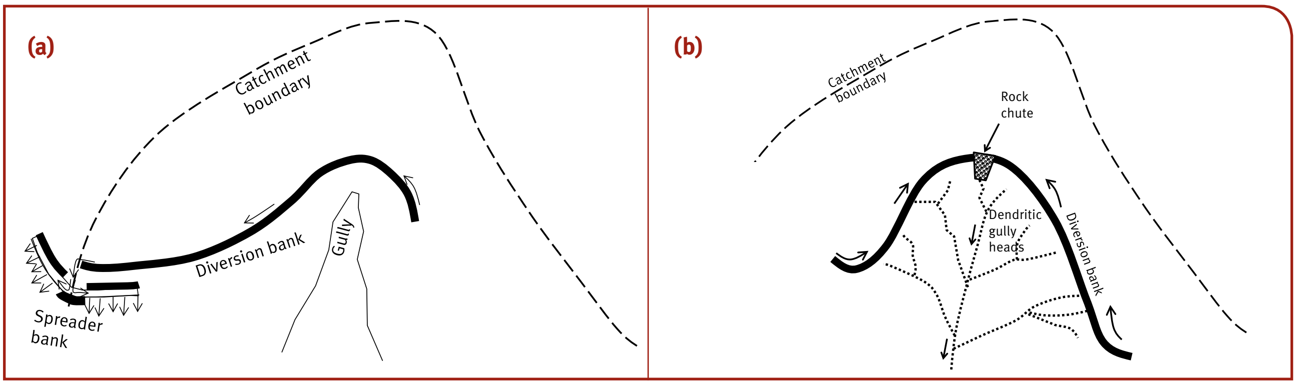
13.9 Diversion of runoff

Diversion banks, or bunds, divert runoff from above the gully head to a stable outlet as shown in Figure 13.32a. Stable outlets can often be difficult to find, and the instability may be transferred from one area to another if the diversion bank discharges too close to the eroding gully. Further, if runoff is diverted out of its natural catchment into another drainage line, the additional runoff may increase the risk of gullying to that area.

Where a gully has occurred away from a natural drainage line, such as along a road or track, the diversion of runoff may be a practical option.

As shown in Figure 13.32b, another option for managing runoff from a diversion bank is to construct a rock chute to the drainage line below one of the gully heads (see Section 13.11). This may be a practical option in more arid areas where a supply of rock is available but there is a limited choice of suitable vegetative species to stabilise a sod chute. Vegetation growth between the rocks should still be encouraged, to improve the stability of a rock chute.

Figure 13.32: Diversion bank diverting runoff to: a) a stable outlet; b) a rock chute in the drainage line



Where soils are dispersive, the diversion bank can be constructed by pushing the soil uphill rather than downhill—a 'back-push' bank. This ensures that the diverted water flows on land that is undisturbed and the channel is vegetated. Alternatively, the division bank could be built from more stable, imported soil.

A temporary diversion may be used until a structure has stabilised. Where several structures are being installed on a multi-branched gully, runoff may be diverted temporarily to a completed chute to provide time for subsequent chutes to be stabilised.

Detailed information on diversion banks is provided in Chapter 8.

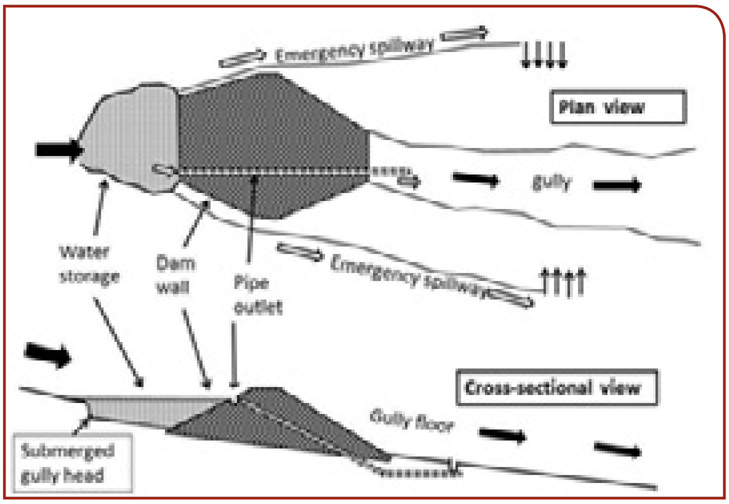
13.10 Gully control dams

One option for controlling an advancing gully is to 'drown' the gully head by building a dam just downstream (see Figure 13.33). The dam submerges the gully head and the subsequent reservoir of water removes the erosive force of water flowing over the head and prevents it from further erosion.

Due to the cost of building a dam, this option should only be considered if it is an asset other than for gully head control purposes. If the a dam spillway requires a chute to return runoff safely to the gully floor then the more practical and lower-cost option maybe to simply build the chute to control the gully head.

A potential risk of this type of structure is that the gully head could cut back when the dam is empty and runoff then flows over the edge of the gully head. This is referred to by Hudson (1995) as 'the gully climbing back out of the dam'. This situation can best be avoided by allowing the full supply level to be well above the level of the gully head.

Figure 13.33: Gully control by 'drowning' the gully head within the dam storage area



The construction of dams for gully control can be a challenge in the highly erodible soils where gullies are often found and, as a consequence, there has been minimal use of this practice in Queensland. However, there have been some successes and the technique does provide another option. One example of favourable outcomes with this technique has been in the Brigalow/Belah soils on low-sloping lands (<1%) in the Goondiwindi district, where the technique is popular with landholders (Doug Muller, personal communication, 03/05/2015).

Building a dam for gully erosion control is not simply a matter of pushing up an embankment. A contractor experienced in farm dam construction should be engaged. The success of gully control dams depends on the following factors:

- The soil type must be suitable for dam construction.
- The water level should continually inundate the gully head. There is limited opportunity to use the stored water, unless it will be supplemented by inflowing springs to maintain inundation over the gully head.
- The construction method should ensure a stable structure, properly keyed into bed and banks.
- An appropriately sized and stable by-wash is required to ensure the water level is not lower than the gully head.

The Queensland Water Resources Commission publication, Farm water supplies design manual (Horton and Jobling 1984), provides detailed information about the design and implementation of farm dams. More general information for landholders about farm dams is provided in *Saving Soil* (Alt et al. 2009).

13.10.1 Licensing requirements

Before constructing a farm dam, checks should be made with relevant agencies to determine if there are any licensing requirements.

In Queensland, overland flow water is defined as water—including floodwater—that flows over land after having fallen as rain or after rising to the surface naturally from underground. Overland flow structures that may require assessment include gully dams, ring tanks and flow-concentrating channels and levee banks.

A gully control dam that takes and stores overland flow water may be required to comply with the provisions of a water resource plan (WRP) approved under the *Water Act 2000*. A self-assessable development notice is required where a gully control dam is located within a WRP area, and which stores water used for stock or domestic purposes. Under the WRP provisions such notice is to be given to the agency administering the Water Act 2000.

Local councils may also regulate activities such as levee bank construction on floodplains. Development approval may be required from the local government under the Sustainable Planning Act 2009. Depending on the potential impact of such works on other resources, the proposed development may be self-assessable, impact-assessable or code-assessable. Advice should be obtained from the local Council before proceeding with such earthworks.

13.10.2 Soil type

To prevent seepage, dam embankments require soils with a high percentage of clay. To avoid seepage under the embankment, it should be keyed into impervious clay strata or into fresh rock.

On large dams, zoned embankments have a central core of impervious clay with a pervious layer on either side. Zoned embankments are difficult to construct and are not normally used in small farm dams.

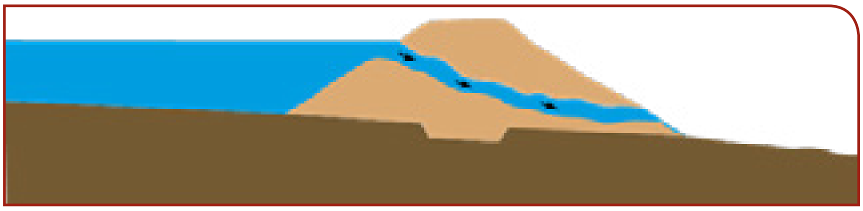
If there is limited suitable clay, a layer can be placed on the upstream batter to provide an impervious section. A layer of pervious soil over the impervious soil will reduce the chance of cracking in the impermeable layer.

Unit 10 of the Earth Movers Training Course on the construction of farm dams (New South Wales Soil Conservation Service 1991c) describes the use of builders' plastic as a membrane in preventing tunnel failure and sealing small farm dams. All pipes, drains and spillway devices that penetrate the membrane must be suitably flashed and sealed to prevent leakage. The membrane needs to be totally covered with at least a 30 cm layer of soil

Dispersive soils

The impact of tunnel erosion that occurs in dispersive soils is described in Section 13.5 of this chapter. Similarly, dam embankments that are constructed from dispersive soils are subject to failure by tunnel erosion, as shown in Figure 13.34. Small pipes may form when fresh water seeps into the embankment, and these develop into tunnels, resulting in a breached embankment. The pipes usually develop in a very short time following the first filling of the dam, and failure can occur in a matter of hours. Small farm dams and amenity dams are particularly prone to tunnel failure as they are often built without regulation, soil testing, or engineering advice.

Figure 13.34: Dam walls constructed with dispersive subsoils, subject to failure by tunnelling



The likelihood of failure of dams built with dispersive soils depends on the following factors, as detailed by Vacher et al. (2004):

- the rate of first filling
- degree of compaction during construction
- dispersibility of materials used to construct the dam
- electrolyte balance of the soil solution
- the electrolyte concentration of the stored water.

Provided the soil is well compacted at the right moisture content, a dispersive soil can provide a better water seal than a non-dispersive soil that may be prone to leaking. New South Wales Soil Conservation Service (1991a) points out that the quality of the stored water can affect the dispersion process. While too much dispersion can result in tunnels or pipes, some dispersion is necessary to form a seal in earth dams as the fine particles move to block voids in the face of the dam.

Although dam failure with dispersive soils is common, it is possible to construct a successful dam with such soils. Hardie (2009) advises that the risk of tunnel or piping failure in small earth dams can be minimised by a combination of control measures including:

- adequate compaction
- chemical ameliorants
- sand filters
- construction with non-dispersive clay
- topsoiling.

Chemical ameliorants such as hydrated lime (calcium hydroxide), gypsum (calcium sulphate), alum (aluminium sulphate) and long-chain polyacrylamides have been used to prevent dispersion and piping in earth dams (Hardie 2009). Hydrated lime is the most commonly applied product, with the rate varying between 0.5% and 4.0 % by weight, depending on soil chemistry and dispersivity.

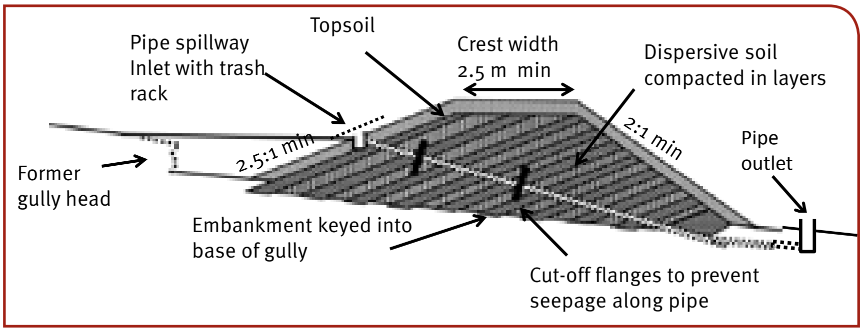
As a new dam is first filled, the water should be dosed with gypsum or alum to raise the electrolyte (salt) concentration, to reduce the risk of dispersion in the dam wall and subsequent failure. Treatment of a sample of the water is recommended before adding electrolyte to the dam. McDonald et al. (1981) suggest raising the electrolyte level from around 70 mg/L to 300–600 mg/L. Information about interpreting soil test results to determine whether there is risk of soil dispersion is provided in Hazelton and Murphy (2007).

When a dam is built for gully erosion control in a dispersive soil, an added challenge is the need to provide a stable by-wash. This can best be achieved by the construction of trickle flow pipes as discussed in the following section.

13.10.3 Dam construction

The fill material excavated from the borrow pit and by-wash areas should be built up to form the embankment in layers not greater than 20 cm in depth. With each layer, attention must be given to the moisture content and compaction of the material. The cut-off trench must be excavated at least 30 cm into impermeable material, or into fresh rock (Department of Natural Resources and Water 2006).

Figure 13.35: Features of drowning a gully head with a farm dam



The top of the dam embankment should have sufficient width and strength to prevent the structure from failing when it is filled to the surcharge level. Generally, for most erosion control dams, the top of the embankment is 3–4 m wide. The grade of the batters depends primarily on the depth of water stored and soil type, but batters are generally 1:3 (V:H) for most dams or 1:4 for those built with sodic/dispersive soils and/or in drier climates. Flatter batters may be necessary where the vegetation cover is to be maintained mechanically.

When excavated, dispersive soils form strong, tough, impermeable clods. Considerable force is needed to break down these clods and compact the material, otherwise air voids can form in an embankment. Compaction eliminates void spaces and reduces permeability. Appropriate levels of compaction can be difficult to achieve when soils are dry, as would be common during a drought. The best time to build a dam is when the soil is moist, but not too moist to cause difficulties with earthmoving equipment. If a clay sample can be rolled to pencil thickness by hand without it breaking, it will be at the correct moisture condition. If available, water can be applied to the construction site to increase moisture to adequate levels.

Where soils are dispersive, construction should start with a soil wedge at the downstream edge of the embankment and is done by applying 20 cm layers in a sloping fashion through additions of soil upstream, as shown in Figure 13.35. This ensures that any voids that may develop will not run horizontally through the dam.

Adequate compaction cannot result from normal earthmoving equipment. Scrapers, when loaded, only have the ability to compact thin surface layers of wet clays. The use of sheep-foot rollers is recommended for compacting the layers. The tracks on bulldozers are designed to distribute weight and provide minimal compaction. For example, a D6 dozer will apply a pressure of 0.6 kg/cm2, a loaded scraper 2.8 kg/cm2, but a sheep-foot roller 9.3 kg/cm2 (New South Wales Soil Conservation Service 1991c).

The weight of a sheep-foot roller should be such that it applies sufficient pressure to destroy the clod structure of the soil and produce a uniform density throughout the embankment.

Dam by-washes and pipe outlets

Dams require a by-wash that allows runoff to flow past the structure once the dam has filled to its design capacity. Failure of a dam because of an eroding by-wash is common, and often such failure is caused by an inadequate design that results in erosive velocities over the by-wash and/or lack of sufficient grass cover.

Another problem with by-washes arises when a spillway runs parallel to the stream and then turns a sharp angle to return to the stream. This creates a high erosion risk due to the extra fall at the end of the spillway producing supercritical flows (see Section 13.11.3). The risk is not so great when the stream is in flood.

When considering options for gully control, the use of a vegetated chute can be compared with the construction of a gully control dam with a by-wash. However, the construction of a by-wash in this situation may be a greater challenge. For a given situation, a dam's by-wash will need to be longer and/or steeper than a vegetated chute at a gully head.

Erosion of by-washes is often associated with trickle flows that can occur for several days after a rainfall event. An alternative for an earthen by-wash of a gully control dam is to provide an outlet with a flexible pipe that delivers low flows from the storage, through the dam wall, to the bed of the gully below the dam (see Figure 13.35).

Design charts to determine the required size of a pipe spillway are available from product manufacturers. Where a pipe bypass is installed, an emergency by-wash should still be provided to handle large runoff events.

Where a pipe passes through an embankment, two or more flanges (baffles or cut-off collars) installed around it prevent seepage flow along the pipe barrel, which can otherwise lead to tunnelling and failure of the pipe structure.

Three different types of cut-off collars are commonly used:

- Rigid collars of concrete or steel plate (welded to steel pipes), sometimes called baffles
- Bentonite or expansive clay collars. These swell when wet and will reduce seepage along any type of pipe when well mixed with the backfill material and compacted evenly around the circumference of the pipe. The bentonite should be mixed with the soil, water added if necessary, and the soil is then packed around the pipe by hand and well tamped down
- Flexible collars of PVC, or polythene sheeting, glued to the PVC pipe.

More information on this topic can be found in New South Wales Soil Conservation Service (1991e), and a list of plant species that could be used for protecting a by-wash is provided in Appendix 4.

Topsoiling

Non-dispersive topsoil should be stockpiled during construction, so that it can be used to top-dress the finished dam. This is done to encourage vegetation that will reduce the erosion risk on the batters of the embankment. Topsoiling will also inhibit the formation of cracks and assist in the blockage of any continuous voids in the embankment.

When top-dressed, the crest and batters of an embankment should have an even finish and be free of irregularities such as tyre marks. Runoff concentrating in irregularities can result in rilling that exposes the underlying clays, leading to more serious erosion.

13.10.4 Management

The embankment should be kept free of deep rooted vegetation that can accelerate drying out and cracking of the embankment.

The embankment, by-washes and by-wash return slopes should be fenced off from stock to prevent grass cover being eaten, and to prevent the formation of deep cattle pads that promote scouring.

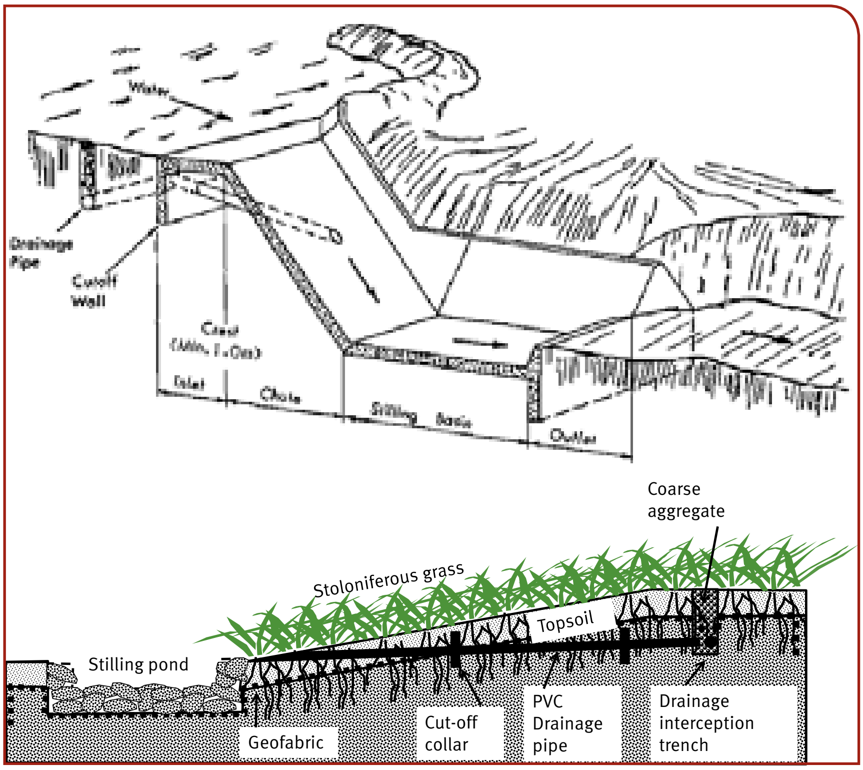
13.11 Chutes

Gully control chutes are formed by battering gully heads to an acceptable slope depending on the method used to stabilise them. As well as for controlling gullies, chutes are used as by-washes in farm dams. They are also used to convey water over steep road batters, to control bed erosion in streams, and for urban developments such as sports fields.

Although they have been commonly used in New South Wales and Victoria, there has been limited use of chutes for the control of gully erosion on rural properties in Queensland. They generally involve significant costs and a high level of expertise to ensure they are constructed correctly. These limitations are especially significant in more remote areas.

Components of a typical gully control chute are shown in Figure 13.36. The chute surface may be protected with erosion-resistant materials such as stoloniferous grasses, reinforced turf, rock, rock mattresses, erosion control mat and rubber or PVC sheeting.

Figure 13.36: Cross-section views showing the components of a typical chute



Chutes require some form of energy dissipation at the outlet to help dissipate the energy gained when runoff flows down the chute.

Chute failure often occurs when runoff fails to enter the chute properly. It is critical to control potential leaks and flow bypassing, especially at the chute entrance, and also to ensure suitable side walls contain the flows within the chute.

Because gullies are dry for most of the year they are not a habitat for fish, and the provision of a gully chute to cater for fish movement is not necessary.

Limitations

The cost of materials and equipment required to build a chute can be very high. In rangeland areas in particular, such construction costs may be prohibitive, except where an active gully may threaten a valuable asset such as a building, roadway or water storage.

Where chutes with reasonably large catchments are considered, specialist advice should be sought for carrying out detailed design and supervision of the construction works to avoid failure by undermining, overtopping or bypassing. The risks associated with a large runoff event that exceeds the capacity of the structure should be assessed to determine whether an emergency spillway should be incorporated to handle large flows that exceed the capacity of the chute.

The soil type needs to be considered when constructing a chute. Chutes built on cracking clay soils require some flexibility and use of concrete structures should be avoided.

Trickle and seepage flows

In a prolonged rainfall event, the soil becomes saturated and runoff occurs. The amount of rainfall required to saturate a soil depends on the soil type and its infiltration rate. Some soils have permeable A horizons and impermeable subsoils. When these soils occur on the side of a gully, water can often be seen seeping out of the lowest layer of the A horizon, which forms a bleached A2 horizon.

Seepage is an important contributor to gully development in New South Wales and Victoria (New South Soil Conservation Service 1992; Milton 1971). When a gully control structure is being considered, it will be worthwhile monitoring the occurrence of seepage flows to enable suitable measures to be included in the construction, where necessary.

Groundwater flows or seepage can contribute to the failure of structures, especially where flows are saline. These small but continuous flows can weaken vegetation and threaten the stability of chutes lined with vegetation. Where soils are dispersive, groundwater flows can lead to failure of structures by tunnelling. Groundwater flows may also cause a build-up in pressure behind structures made of concrete and this leads to uplift of the structure.

Sites with seepage flows need special consideration. The continued flow of seepage down a grass chute may weaken vegetation and make it vulnerable to erosion. The seepage may need to be controlled by use of cut-off trenches and/or a subsurface drainage system.

Deep-rooted vegetation such as trees and shrubs in the drainage line above a chute may assist in minimising seepage flows. A deep-rooted species such as vetiver grass may also assist.

13.11.1 Types of chutes

A range of materials have been used to construct chutes:

- grass—sod chutes
- rock and gabion baskets and mattresses
- geofabrics—synthetics such as PVC sheeting, butyl rubber
- sandbags
- concrete, and concrete revetment mattresses.

Corrugated iron or similar roofing materials may also be used to construct ‘verandah chutes’ that are technically drop structures. These are described in Section 13.12.

Grass or sod chutes

The ability of these chutes to withstand erosion damage depends on an effective cover of a good mat of grass. The grade of such chutes should be kept as low as possible to minimise the flow velocities. Ideally, the grade should be 1:8 (V:H) or flatter, although steeper grades may be effective on stable soil types where a complete sod cover can be assured. If grass seed or runners are used, it may take two years or longer before an effective grass cover is established to stabilise the chute.

A factor limiting the use of chutes in drier environments is the unavailability of suitable grass species to provide the necessary erosion control. In urban areas, the grass used in a chute normally can be obtained from a turf supplier. In rural areas such external supplies may not be available and turf may need to be established from seed, or by planting sods dug up from a local source. An irrigation supply would greatly assist in establishing the grass.

Because of the risk associated with sod chutes, their use should be confined to small catchments and, in view of the limited ability to cope with prolonged flows, caution should be taken when siting them in seepage lines or other constantly wet locations. Where it is not possible to avoid this situation, it may be necessary to install trickle pipes and subsurface drainage pipes to minimise the risk of failure. Requirements for the installation of subsurface drainage are outlined in Section 13.11.4.

Sod chutes are generally not recommended for stabilising gully heads greater than 0.5 m in depth unless a good vegetation cover is assured. For the side walls, the side slopes can be constructed at grades of 1:2 (V:H), to minimise excavation. However, where mowing with a tractor is intended, the side slopes should be 1:4 (V:H) or flatter.

The aspect of a sod chute may be a factor to consider. A chute with a southerly aspect in the temperate zones of the southern hemisphere will get little sunshine during the winter months. Vegetation may be slow and weakened during winter months, resulting in an inadequate cover over a long period.

Reinforced grass chutes

A number of commercial products can greatly improve the durability and performance of sod chutes. Some of these products enable vegetation on a chute to withstand much higher velocities. Such chutes may have a steeper grade and require less width than a conventional grassed chute. The suppliers of these products can provide advice on design requirements.

Geotextile polyester filters

Grass chutes can be made more stable by incorporating a geotextile, polyester filter material under the topsoil. The geotextile provides strength and stability to the soil profile and plant roots will grow through it. If these products are not UV stabilised they can degrade in sunlight and must be covered by soil or rocks.

Turf reinforcement mats

Turf reinforcement mats provide permanent protection from the high-velocity flows that would be experienced in a chute. They consist of various products woven into a three-dimensional web. They provide good initial ground coverage while allowing the growth of vegetation through the mat. Sediment is trapped in the three-dimensional mat and provides additional stability to the system. The synthetic fibres used to construct these mats are UV-stabilised and therefore permanent. The synthetic fibre matrix reinforces the root zone of the subsequent vegetation, providing higher resistance to flow and shear forces than vegetation alone.

Rock chutes and gabions

Where the soil is likely to move and where suitable rocks are handy to the site, rock chutes are used in preference to concrete or other inflexible materials. For example, in self-mulching black clay soils that shrink and swell with moisture differences, the rocks are able to marginally relocate without affecting the stability of the structure.

Compared to sod chutes, rock chutes are more suitable for higher flow velocities, allowing for steeper grades and greater overfalls. The grade of rock-lined chutes should be less than the natural angle of repose of the rock—usually around 38º (1:3, V:H), for smooth round rock, up to 41º (1:2, V:H) for angular rock. For the side slopes of a chute, the recommended maximum grade for a large rock-lined chute is 1:2 (V:H); however, side slopes as steep as 1:1.5 can be stable if the rock is individually placed (Catchments and Creeks 2010e).

Rock materials should be hard, angular, durable, and weather-resistant, have a specific gravity of at least 2.5, and include a range of sizes so the small rocks will fill the voids between the larger rocks. If there are voids in the rock, there can be a high pressure build-up under flowing water, causing the rocks to move. The diameter of the largest rock size should be no larger than 1.5 times the nominal rock size (Catchments and Creeks 2010e).

Grouted rock is generally used when the rock size is too small to withstand flow velocities, and the grout must be placed such that it penetrates the rock voids. Ideally, concrete slurry is poured in place and the rock manually placed into the concrete. Concrete cut-off trenches should be installed to anchor the structure and to minimise erosion under the structure.

Rock chutes work best when they have a vigorous vegetative cover, such as kikuyu, that helps to hold the rocks in place. High rates of runoff from rain falling on the rocks will seep into the soil and the rocks reduce evaporation, thus encouraging grass growth. The grass helps to reinforce the rocks, provides additional roughness and improves its visual appeal. Placing topsoil between the rocks at the completion of the project will encourage grass growth.

Gabion baskets and mattresses

Rock gabions are baskets made from flexible steel wire mesh, laced together with wire and filled with rock to form monolithic structures. The wire mesh is typically galvanised or plastic-coated (or both) to protect the mesh from corrosive forces (Local Government Association of Queensland 2006). Damage to the protective coatings can result in basket failure.

Gabions are designed to provide erosion protection in a wide range of environments where rock protection is not sufficient. In addition to erosion protection, rock-filled wire baskets are commonly used for geotechnical purposes such as retaining walls.

Typical erosion control applications include chutes and flumes, grade stabilisation structures, streambank protection, bridge abutment protection, culvert headwall, inlet and outlet protection, and open channel lining. Formal design is required, and manufacturers can provide design specifications, procedures and software packages.

Geofabrics, rubber sheeting, PVC-lined chutes

Two different types of product are used in the construction of chutes:

1. Erosion control mats are designed to resist concentrated flows and are made from durable materials. Two-dimensional erosion control mats protect the soil surface from the shear stress of flowing water. Three-dimensional erosion control mats combine with grass roots and stems to reinforce the soil surface. Non-biodegradable products can provide permanent protection.
2. Pervious structures allow water to seep through them and may require a geotextile (also referred to as geofabric or filter cloth) underlying the structure to prevent fine soil particles from being washed away from the face of the chute, causing tunnel erosion and undermining the protective surface. Where rock is used, the geotextile filter cloth must have sufficient strength and must be suitably overlapped to withstand the placement of the rock.

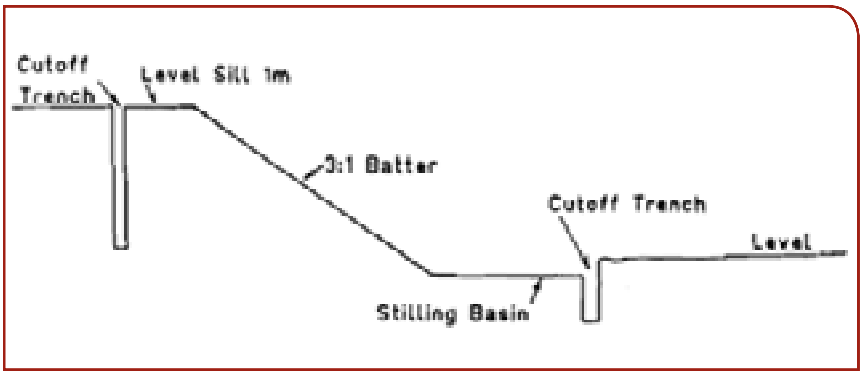
Armour rock will not require an underlying filter layer, if it is intended to be vegetated by appropriately filling all voids with soil and pocket planting generally, unless the long-term viability of the vegetation is questioned due to possible high-scour velocities or limited natural light or rainfall conditions.

If the soils adjacent to the rock surface are dispersive (e.g. sodic soils), then prior to placing the filter cloth or filter layer, the exposed bank must be first covered with a layer of non-dispersive soil.

PVC sheeting resistant to ultraviolet light is a relatively inexpensive product suitable for temporary use on non-cracking soils. Butyl rubber is the more expensive but it is very durable and its stretching properties improve its suitability for cracking clay soils. Discarded wide conveyor belts from the mining industry may be a cheaper source.

The synthetic products can be supplied in sheets suitable for covering the whole of the required area. The material is held in place in cut-off trenches (see Figure 13.37), and the sides secured in a trench or covered with soil. To prevent puncturing of a PVC liner, it should be laid on a heavy, non-woven geotextile; however, this may be difficult to justify in the short-term situations where PVC sheeting is typically used.

Figure 13.37: Site preparation for a rubber chute protected by sheeting



Rubber sheets have the advantage of being extremely flexible and are particularly suited to shrink–swell soil types, dispersive soils and other situations where concrete chutes, for example, are subject to failure because of their rigidity and likelihood of undermining.

As these forms do not reduce any of the flow energy, rock or rock mattresses may be required downstream.

Where butyl rubber is used as a more permanent option, a drainage system under the material is recommended to intercept the through-flow of water that can cause slumping on the face of the batter.

Sandbag chutes

Information in this section has been derived primarily from Unit 19 (Flumes and chutes) of the New South Wales Soil Conservation Services' Earth Movers Training Course (New South Wales Soil Conservation Services 1992).

These chutes (see Figure 13.38) are constructed of sandbags filled with a 5:1 mixture of sand and cement. A number of these have been constructed for gully reclamation in south-east Queensland. The floor and sides of a chute are lined with sandbags filled with a dry mix of sand and concrete on site. They should be placed on a suitably specified geotextile and laid lengthwise starting from the stilling pond. The bags should be overlapped by one-third of a bag. After the bags have been placed on the chute, a light sprinkling of water is applied to set the concrete.

Chute grades of 1:1.5 to1:2 (V:H) are required to give optimum overlap of the placed sandbags.

Figure 13.38: Example of a sandbag chute

The use of sandbag sheets for gully control should be considered a temporary measure only, as there are concerns that once the bags rot or wear away, the sand–cement mix, while hardened, would have very little strength and could readily fail. Given the significant amount of time and expense associated with any structural controls, any measures undertaken should, where possible, be appropriate for both the short- and long-term. Labour requirements for installing a sandbag chute are likely to be more than that for a rock chute.

Concrete chutes

Concrete chutes (see Figure 13.39) are useful in providing a stable, long-life means of conveying catchment runoff to the floor of what would previously have been highly active gullies.

Concrete, reinforced with F62 steel mesh, is usually applied to a depth of 0.2 m. Drainage under the chute and weep holes in the face of the chute are required to avoid a build-up of hydraulic pressure and the removal of soil from underneath the concrete.

These chutes eliminate the risk of failure commonly associated with sod chutes but are not suited to cracking clay soils where rock chutes would be a better option. Causes of failure of concrete chutes include cracking of the concrete due to soil settlement or vegetation growth and tunnel erosion under the structure.

Another version of this chute is to use rocks embedded in concrete.

Information on the materials used in the construction of a concrete chute, as well as techniques for pegging out the site and constructing the chute, is provided in New South Wales *Soil Conservation Service* (1992).

Figure 13.39: A field example of a concrete chute

Revetment mattresses

Concrete chutes can also be made using a concrete revetment mattress. This product consists of a nylon mattress of connecting tubes in a honeycomb shape (Figure 13.40). These tubes are pumped full of concrete under pressure. A suitable drainage layer is required under the chute as hydrostatic pressures are not readily released through the nylon fibres.

Figure 13.40: Example of a concrete revetment mattress

13.11.2 Design of chutes

This section provides generic information about the design of chutes. More detailed information is provided in the sections on grass chutes and rock chutes which follow.

Catchments and Creeks (2010b) is a recommended source of specific information on the design of synthetic-lined chutes.

Chutes with reasonably large catchments need to be designed and constructed to avoid failure by undermining, overtopping or bypassing. For small catchments, a chute can be constructed to fit the existing gully and an individual design may not be necessary. Where the design of chutes is required, advice should be sought from those with experience in hydraulic design.

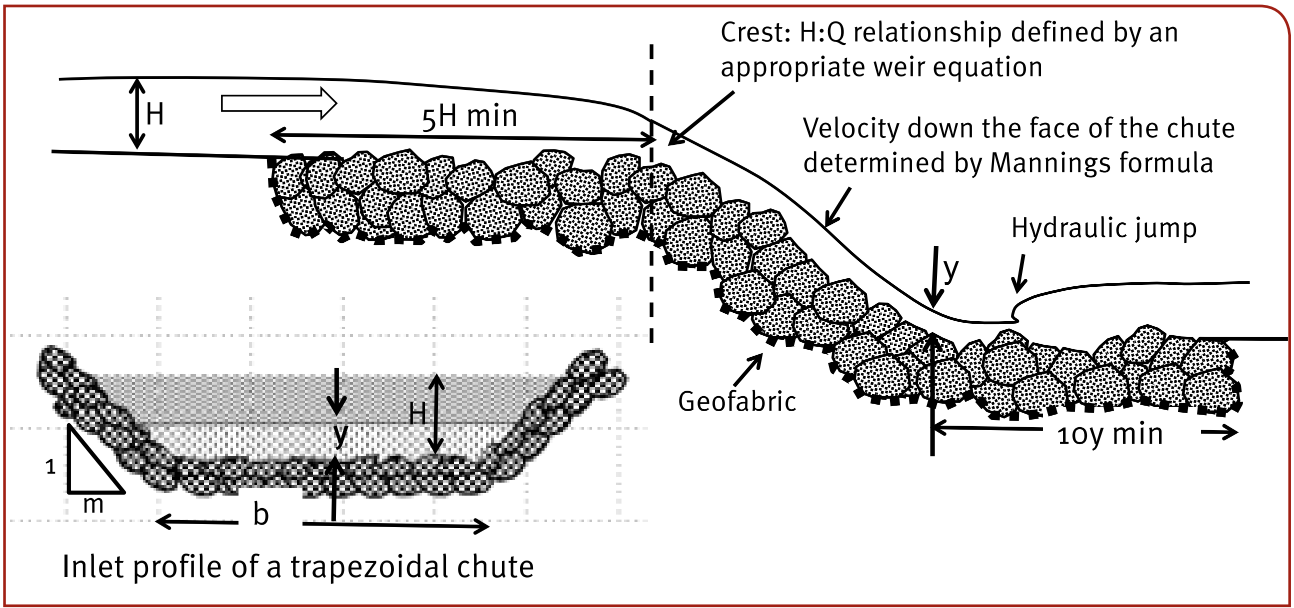
The computer program CHUTE produced by the CRC for Catchment Hydrology (Keller 2003) can be used to design a chute. However, it appears to have had minimal use in Queensland and may require further evaluation.

The design of chutes can be broken down into four components:

1. Rate of runoff delivered to the chute. The Rational Method as described in Chapter 4 can be used to estimate the value of Q (m3/s) for an adopted average recurrence interval (ARI). Since a chute can be a significant structure it should be designed for an ARI of 50–100 years.
2. Chute inlet design. Flow conditions upstream of the chute may be determined using an appropriate weir equation. It is important to ensure that the water level upstream of the chute does not cause undesirable flooding or flow-bypass conditions.
3. Chute face design. Selection of an appropriate chute lining is governed by the estimated flow velocity that can be determined on long chutes through use of Manning's equation.
4. Chute outlet design. Suitable energy dissipation conditions are required at the base of the chute.

Flow criteria through a chute are depicted in Figure 13.41, using longitudinal and cross-sectional views typical for a rock chute.

Figure 13.41: Longitudinal and cross-sectional view of a rock chute showing criteria used in its design (Source: Catchments and Creeks 2010c)



Inlet design

Equation 13.2

$$Q = CbH^{1.5} + 1.26\,mH^{2.5}$$

Where:

Q = calculated discharge (m^3/s) for the selected ARI,

C = A coefficient related to flow conditions to the chute:

- 1.6 is used where water tends to pond above the entry to a broad-crested weir, and
- 1.7 if the gradient and channel shape will deliver flowing water to the chute

b = length of the crest (width of the flow), (m)

H = the total energy head of the approach flow, (m)

m = side slopes, V:H—i.e. 1:m.

The inlet to a chute is considered to be a broad-crested weir and can be designed using the weir formula described in Chapter 6, Section 6.6. This formula has various forms depending on the cross-sectional shape of the weir. The weir formula, based on a trapezoidal cross-section that is typical for chutes, is shown in Equation 13.2

For any given value of Q, there will be a number of solutions to the weir formula. Table 13.3 shows various crest widths for a trapezoidal shaped, broad-crested weir based on varying depths of flow at the chute entrance. A suitable crest width and head can be selected to accommodate the calculated discharge. A minimum freeboard of 0.15 m should be allowed for on the crest and face of the chute.

Scour protection at the inlet can be achieved by extending the chosen chute lining (e.g. rock, concrete, geotextile fabric) upstream of the crest a distance of around five times the depth of the approach flow, or by ensuring flow velocities are below the scour velocity of the surrounding surface material.

Wing banks are often required to confine runoff and direct it down the chute. It is important that the chute entrance be positioned in line with the entry flow and central to it. For this reason, a chute should not be located on a bend in a drainage line.

Table 13.3: Inlet weir capacity for various trapezoidal chutes, [m3/s]

Head (H) upstream of chute inlet (m)	Crest width (b) of a trapezoidal chute (m) with 1:2 (V:H) side slopes									
	0.3	0.5	1	1.5	2	2.5	3	4	5	6
0.1	0.0	0.0	0.1	0.1	0.1	0.1	0.2	0.2	0.3	0.3
0.2	0.1	0.1	0.2	0.3	0.3	0.4	0.5	0.7	0.8	1.0
0.3	0.2	0.3	0.4	0.5	0.7	0.8	1.0	1.2	1.5	1.8
0.4	0.4	0.5	0.7	0.9	1.1	1.3	1.6	2.0	2.4	2.8
0.5	0.6	0.7	1.0	1.3	1.6	2.0	2.3	2.9	3.5	4.1
0.6	0.9	1.1	1.5	1.9	2.3	2.7	3.1	3.9	4.7	5.4
0.7	1.3	1.5	2.0	2.5	3.0	3.5	4.0	5.0	6.0	7.0
0.8	1.8	2.1	2.7	3.3	3.9	4.5	5.1	6.3	7.5	8.7
0.9	2.4	2.7	3.4	4.1	4.8	5.6	6.3	7.7	9.2	10.7
1.0	3.0	3.4	4.2	5.1	5.9	6.8	7.6	9.3	11.0	12.7

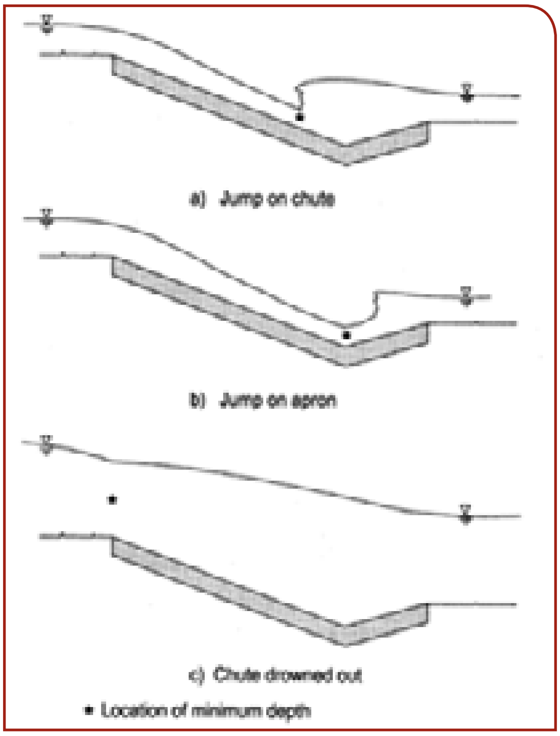
Design of the chute face

The flow depth at the crest—or weir component—of the chute is critical. As water starts to flow from the weir down the face of the chute it goes into supercritical flow (Figure 13.42). Depending on the roughness on the surface of the chute, the flow will accelerate and get thinner and thinner until the increased friction changes the kinetic energy into potential energy, and it reaches its terminal velocity. Consequently, material on the face of the chute should be able to withstand high flow velocities, or alternatively, as in sod chutes, velocities should be reduced to suit the requirements of the surface material.

Depending on the surface material, flow velocities may be reduced by using a flatter grade, and/or by increasing the width of the chute. If the chute is relatively short, with minimal slope and roughness, terminal velocity may not be reached.

Procedures for designing a chute face involve use of the Manning formula (see Chapter 6) and depend on the material on the chute face. In this chapter, following sections give design guidelines for both grassed and rock chutes.

Figure 13.42: Location of supercritical flow and hydraulic jump varies with depth of flow over the chute (source: Keller 2003)



Design of the chute outlet

In all situations where water passes from tranquil or subcritical flow through the critical flow barrier to become shooting or supercritical flow, special provision is necessary to dissipate the energy contained in the water, to bring it back to subcritical flow as it exits the structure. Figure 13.42a and b shows how a hydraulic jump occurs when a higher-velocity flow discharges into a zone of lower velocity. When this occurs, the water slows in an abrupt rise to form the jump. The situation in Figure 13.42c will occur when the chute is drowned out during a high flow in a stream. Such high flows are not likely to occur in gullies.

A stilling basin may be constructed using large rocks, concrete, or gabion mattresses but in small catchments, vegetation may provide sufficient stability. A degree of submergence of the toe of the chute will aid in energy dissipation.

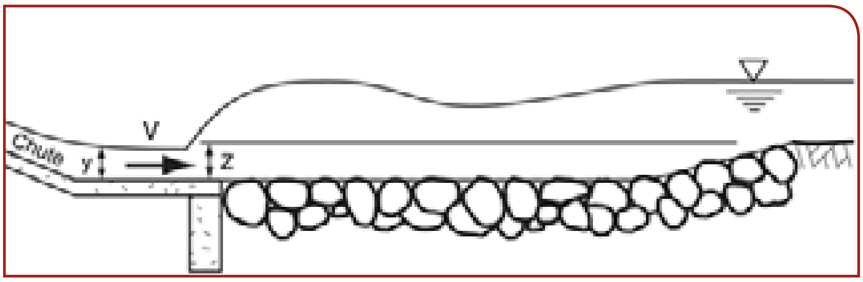
Energy dissipation—stilling basins

The function of an energy dissipater at the outlets of both chutes and drop structures is aimed at returning the high-velocity flows to non-erosive subcritical flows at the downstream end of the structure. An energy dissipater can take the form of a non-erosive apron or a stilling basin. Chute-type structures are preferred to drop structures if the overfall is greater than 1m (New South Wales Soil Conservation Service 1992).

Stilling basins may include rock material, gabions or Reno mattresses. The sides of a stilling basin must be high enough to contain flow turbulence, and the wing walls must be flared outwards to spread the flow and reduce its depth and velocity. A reasonable depth of flow below the structure may improve the effectiveness of dissipating flow energy (Stephens 1989).

As indicated in Figure 13.43, outlet structures for minor chutes should be recessed below the surrounding ground level to promote effective energy dissipation (Catchments and Creeks 2010a).

Figure 13.43: Typical profile of recessed outlet structure for chutes



The recommended recess depth (Z) can be determined from Table 13.4.

Table 13.4: Recommended recess depth, Z (m), for batter chute outlet protection

Depth of approach flow, y (mm)	Flow velocity, V, at base of chute (m/s)						
	2.0	3.0	4.0	5.0	6.0	7.0	8.0
50	0.13	0.20	0.28	0.36	0.43	0.50	0.60
100	0.14	0.23	0.32	0.42	0.50	0.60	0.70
200	0.12	0.21	0.31	0.42	0.50	0.60	0.70
300	0.07	0.16	0.25	0.35	0.44	0.55	0.65

In circumstances where the outlet structure is located downstream of a smooth surface chute, such as a concrete-lined chute, then the rocks should be grouted in place to avoid displacement.

Stephens (1989) noted the equation to determine the length of a stilling basin—see Equation 13.3.

Equation 13.3

$L = F\,(2.28\ h/F + 0.52)$

Where:

L = length of stilling basin (m)

F = depth from crest of spillway to top of end sill (m)

H = depth of notch (head of water over the crest) (m)

Notes:

- h/F should be less than 0.75—increase the width of the crest (notch) to reduce h
- end sill height: ⅓ h
- upstream wing walls—minimum length: 3 h + 0.5 (m)
- downstream wing walls—minimum length: 2 times depth of flow
- minimum wing wall height at stilling basin—depth of flow + 0.3 m, tapering down to about 0.5 m.

Embedded floor blocks, if used, should occupy between 50% and 60% of the stilling basin width, and should be approximately square in plan, with sides the same dimension as the height of the end sill. Height of the blocks should be twice the height of the end sill.

If the structure is likely to be submerged, some rock protection may be necessary above the entrance to the notch.

Rock protection at chute outlets

Recommended mean (d_{50}) rock sizes and length, (L), of rock protection for minor chutes are presented in Tables 13.5 and 13.6, respectively. These rock sizes are based on information presented within ASCE (1992), rounded up to the next 100mm increment, with a minimum rock size set as 100mm (Catchments and Creeks 2010a).

Table 13.5: Mean rock size, d_{50} (mm), for batter chute outlet protection[1]

Depth of approach flow[2], y (mm)	Flow velocity at base of chute (m/s)						
	2.0	3.0	4.0	5.0	6.0	7.0	8.0
50	100	100	100	200	200	200	300
100	100	100	200	200	300	300	400
200	100	200	300	300	400	[3]	[3]
300	200	200	300	400	[3]	[3]	[3]

Notes:

1. *For exit flow velocities not exceeding 1.5 m/s*, and where growing conditions allow, loose 100 mm rock may be replaced with 75 mm rock stabilised with a good cover of grass.
2. *The flow depth at the base of the chute* as it approaches the outlet structure. The flow depth is based on the maximum depth, not the average flow depth.
3. *Consider using 400 mm grouted rock pad or a rock-filled mattress outlet.*

The pad lengths provided in Table 13.6 are suitable for temporary, rock-lined outlet structures only. These rock pad lengths will not necessarily fully contain all energy dissipation and flow turbulence; therefore, some degree of scour may still occur downstream of the outlet structure (Catchments and Creeks 2010a).

Table 13.6: Recommended length, L (m), of rock pad for batter chute outlet protection

Depth of approach flow[2], y (mm)	Flow velocity at base of chute (m/s)						
	2.0	3.0	4.0	5.0	6.0	7.0	8.0
50	1.0	1.5	2.1	2.6	3.1	3.6	4.2
100	1.3	2.0	2.7	3.4	4.1	4.8	5.5
200	2.1	2.7	3.4	4.3	5.2	6.1	7.0
300	2.7	3.6	4.3	4.8	5.8	6.8	7.9

Note:

1. The flow depth at the base of the chute as it approaches the outlet structure. The flow depth is based on the maximum depth, not the average flow depth

Design of grass (sod) chutes

The following information applies to the design of the face of a grassed chute, which is similar to that for a grassed waterway (see Chapter 9). An alternative approach to the design of a grassed chute is to use synthetic linings (see Catchments and Creeks 2010b).

The following are design requirements for a grassed chute:

- the discharge Q (m3/s)
- a safe velocity—see below for guidelines
- slope of the chute—the steeper the slope, the shorter the chute and the higher the velocities
- cross-sectional shape—usually a trapezoidal channel, side batters: 1:2 to 1:4 (V:H)
- amount of retardance provided by the grass—see Table 6.2 in Chapter 6.

Specifications will vary depending on how well the grass growth can be maintained on the chute. Grassed chutes require a lower slope and greater width than those made from more erosion resistant materials such as rock. The grade should be no steeper than 8%, i.e. 1:8 (V:H), but will depend on soil types and climatic conditions.

To accommodate the same flow, grassed chutes need to be much wider and flatter than erosion-resistant chutes such as those surfaced with rock. Related to soil types and percentage cover, guidelines for choosing the maximum velocity for a grassed chute are provided in Table 9.1 of Chapter 9.

In a vegetated waterway (or chute) under flowing water, depending on flow velocity, the roughness value of the vegetation changes, and this impacts on the Manning formula used in the design. The design of a chute may be simplified by using a waterway design chart as provided in Watt (1984). This publication contains tables suitable for the design of vegetated trapezoidal channels with side slopes of 1:3 (V:H), for C or D retardances and slopes up to 10%, and can be downloaded from the Queensland Government library catalogue.

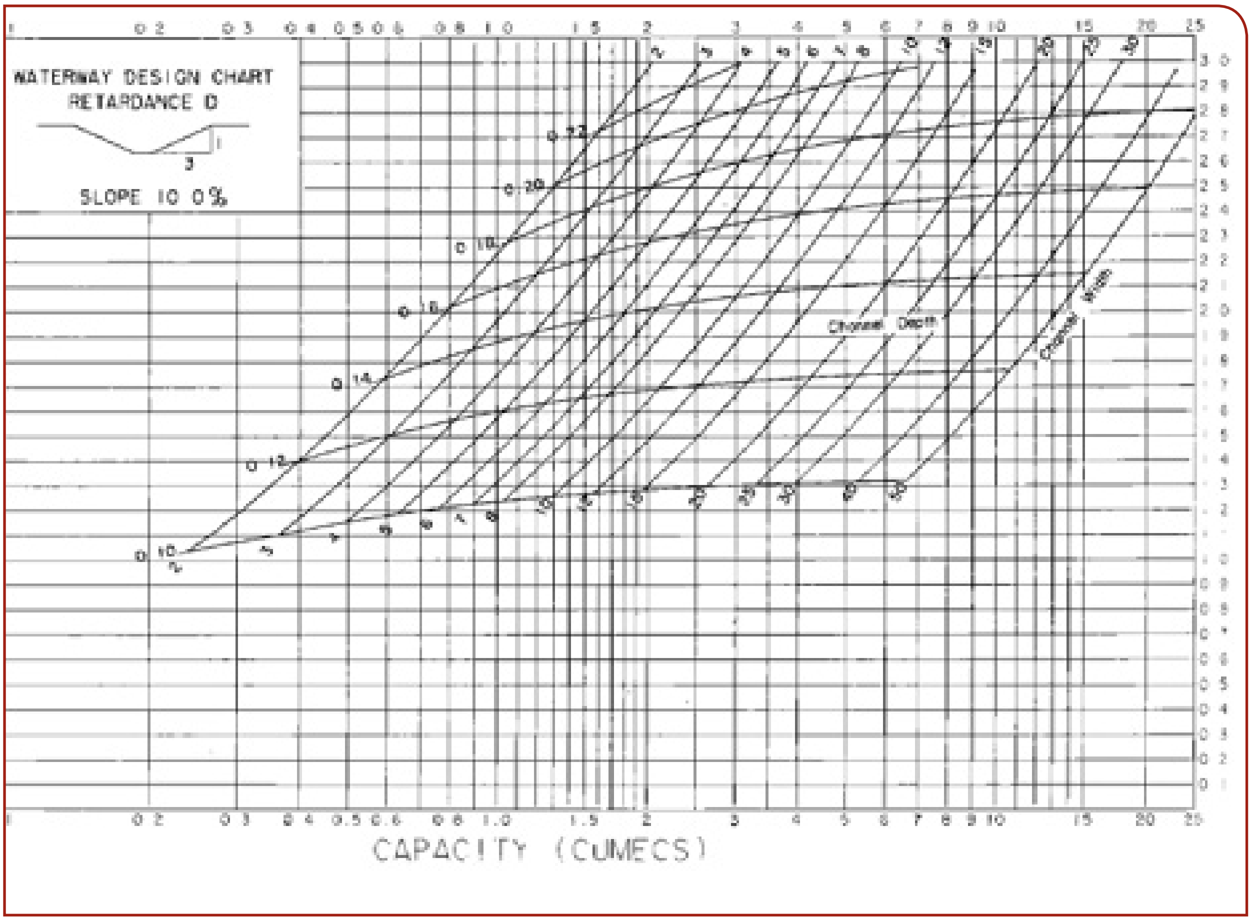
Alternatively, the computer program RAMWADE (downloadable from the same website as these guidelines) can be used to design such a vegetated channel by inputting values for discharge, velocity, slope, retardance and cross-sectional shape. The RAMWADE program is based on an Excel workbook providing for dimensions of channels with vegetal retardances of A to E.

Figure 13.44 is an example of a waterway design chart for retardance D on a 10% slope, and shows the solution for a flow discharge in a chute of 1.5 m3/s, with a velocity of 1.5 m/s, requiring the chute to be capable of a flow depth of 0.11 m for a bottom width of 9 m.

The width of the chute would normally be the same as the width of the weir at the crest of the chute, which can be calculated using the weir formula. To achieve this match, there are two options:

- Trial the use of different slopes for the face of the chute, and select a value that matches the width of the crest obtained from the weir formula.
- (Perhaps the simplest option)—Re-run the weir formula and select a crest width that matches a practical chute width then recalculate a new value for the flow head.

Figure 13.44: Waterway design chart for retardance D



Design of rock chutes

Critical design issues for rock chutes are maximum flow velocity on the chute and safe control of the flow discharging from the base of the chute. These require an understanding of the importance of placement of rock and rock size distribution in minimising the risk of movement of the rock material under high flows.

An understanding of energy dissipation at the outlet of the chute can minimise the risk of damage to the stilling basin and to the gully floor downstream from the chute.

The following information applies to the design of the face of a rock chute, and is similar to that for a grassed waterway. Much higher velocities are possible with rock chutes, and a critical issue is to ensure the rock face cannot move under high flows. Most of this information has been reproduced from material provided from the Catchments and Creeks website for Parts 3 and 5 (Catchments and Creeks 2010c, 2010e), and is intended for use by those experienced in hydraulic design.

Criteria to be determined in the design of a rock chute include the following:

- maximum allowable velocity down the face of the chute, dependent on slope of the chute, depth of flow and surface roughness related to the characteristics of the rock material
- type and size distribution of the rock used, which may depend on the source of the rock e.g. graded rock from a quarry, or natural rock from a streambed
- geometry of the chute identifying bed width and depth and slope of the side batters, dependent on flow discharge over the weir crest and the maximum allowable velocity.

Typical relative densities of various types of rock are provided in Table 13.7.

Table 13.7: Typical relative density (specific gravity) of rock

Rock type	Relative density (sr)
Sandstone	2.1–2.4
Granite	2.5–3.1, commonly 2.6
Limestone	2.6
Basalt	2.7–3.2

Selecting rock

The rock should be durable and resistant to weathering, and should be proportioned so that neither the breadth nor the thickness of a single rock is less than one-third its length. Generally, crushed (angular) rock is more stable than rounded stone

Rock used should be evenly graded with 50% by weight larger than the specified nominal rock size (d_{50}), and should have sufficient small rock to fill the voids between the larger rocks. The diameter of the largest rock size should be no larger than 1.5 times the nominal rock size.

Rock availability can therefore be a limiting factor, and designs are often hinged around that, rather than the needs of the site. The more variability in rock size, the greater will be the dissipation of energy and reduction of flow on the chute.

The selection and sizing of rock material may depend on whether the chute is to be a temporary or permanent structure, as well as on the level of risk associated with the structure. Table 13.8 is a guide to the level of risk used to determine rock size (Catchments and Creeks 2010e).

Table 13.8: Recommended safety factor for use in determining rock size

Safety factor (SF)	Recommended usage	Example site conditions
1.2	**Low-risk structures** Where failure of structure is most unlikely to cause loss of life or irreversible property damage. Permanent rock chutes with all voids filled with soiand pocket planted.	Embankment chutes where failure of the structure is likely to result in easily repairable soil erosion. Permanent chutes likely to experience significant sedimentation and vegetation growth before experiencing high flows. Temporary (< 2yrs) spillways with a design storm of 1 in 10 years or greater.
1.5	**High-risk structures** Where failure of structure may cause loss of life or irreversible property damage. Temporary structures that have a high risk of experiencing the design discharge while the voids remain open (i.e. prior to sediment settling within and stabilising the voids between individual rocks).	Waterway chutes where failure of the chute may cause severe gully erosion and/or damage to the waterway. Sediment basin or dam spillways located immediately upslope of a residential area or busy roadway where an embankment failure could cause property flooding or loss of life. Spillways and chutes designed for a storm frequency less than 1 in 10 years.

Table 13.9 provides a typical rock size distribution for use in preliminary design and is for general information only; it does not represent a recommended design specification.

Table 13.9: Typical distribution of rock size

Rock size ratio	Assumed distribution value
d_{100}/d_{50}	2.00
d_{90}/d_{50}	1.82
d_{75}/d_{50}	1.50
d_{65}/d_{50}	1.28
d_{40}/d_{50}	0.75
d_{33}/d_{50}	0.60
d_{10}/d_{50}	0.50

The thickness of the rock protection should be sufficient to allow at least two overlapping layers of the nominal (d_{50}) rock size. It must be also be sufficient to accommodate the largest rock size. In order to allow at least two layers of rock, the minimum thickness of rock protection (T) can be approximated by the values presented in Table 13.10.

Table 13.10: Minimum thickness (T) of rock lining

Minimum thickness (T)	Size distribution (d_{50}/d_{90})	Description
1.4 d_{50}	1.0	Highly uniform rock size
1.6 d_{50}	0.8	Typical upper limit of quarry rock
1.8 d_{50}	0.67	Recommended lower limit of distribution
2.1 d_{50}	0.5	Typical lower limit of quarry rock

Non-vegetated armour rock must be placed over a layer of suitably graded filter rock or geotextile filter cloth. The geotextile filter cloth must have sufficient strength and must be suitably overlapped to withstand the placement of the rock.

Armour rock that is intended to be vegetated by appropriately filling all voids with soil and pocket planting generally will not require an underlying filter layer, unless the long-term viability of the vegetation is questioned due to possible high-scour velocities or because of limited natural light or rainfall conditions.

Grades of rock chutes

The recommended maximum slope of a large rock-lined chute is 1:2.5 to 1:3 (V:H). However, side slopes as steep as 1:1.5 can be stable if the rocks are individually placed rather than being dumped. Allowing grass to grow between the rocks provides additional stability.

On steep gradients, rocks can slide down the chute, especially if they are sitting on hard compacted soil. There is also a chance that they can be 'plucked off' the chute by a fast flow.

However, the lower the slope, the more rock is required. A 1:4 (V:H) gradient requires twice as much rock has a 1:2 (V:H) gradient.

It is essential that rock-lined chutes have a gradient significantly less than the natural angle of repose of the rock, usually around 38º (1 in 1.3) for smooth round rock, to 41º (1 in 1.2) for angular rock.

Typical angles of repose for dumped rock are provided in Table 13.11.

Table 13.11: Typical angle of repose for rock

Rock shape	Angle of repose (degrees)	
	Rock size >100 mm	Rock size >500 mm
Very angular rock	410	420
Slightly angular rock	400	410
Moderately rounded rock	390	400

Having rock-lined chutes vegetated can significantly increase the stability of these soil conservation structures, but can also reduce their hydraulic capacity. Obtaining experienced, expert advice is recommended before establishing vegetation within drainage structures.

Flow velocity down the chute is affected by the roughness of placed rock. Manning's (n) roughness for rock-lined surfaces can be determined from Table 13.12.

Table 13.12: Manning's (n) roughness of rock-lined surfaces

D_{50} =	200 mm	300 mm	400 mm	500 mm	200 mm	300 mm	400 mm	500 mm
Hydraulic Radius, R (m)	d_{50}/d_{90} = 0.5				d_{50}/d_{90} = 0.8			
	Manning's roughness, (n)				Manning's roughness, (n)			
0.2	0.10	0.14	0.17	0.21	0.06	0.08	0.09	0.11
0.3	0.08	0.11	0.14	0.16	0.05	0.06	0.08	0.09
0.4	0.07	0.09	0.12	0.14	0.04	0.05	0.07	0.08
0.5	0.06	0.08	0.10	0.12	0.04	0.05	0.06	0.07
0.6	0.06	0.08	0.09	0.11	0.04	0.05	0.05	0.06
0.8	0.05	0.07	0.08	0.09	0.04	0.04	0.05	0.06
1.0	0.04	0.06	0.07	0.08	0.03	0.04	0.05	0.05

Note: d_{50} = mean rock size, 50% of which are smaller; d_{90} = mean rock size, 90% of which are smaller

For 'natural' rock extracted from streambeds, the relative roughness value (d_{50}/d_{90}) is typically in the range 0.2–0.5. For quarried rock the ratio is more likely to be in the range 0.5–0.8.

Depth of flows, and mean rock size

The depth and diameter of rock depends on the chute slope and flow velocity. The ideal rock diameter can be calculated from a formula based on chute discharge and slope. Variation in rock size is desirable to create turbulence that assists in dissipating energy in the flow.

Table 13.13 shows values for grades ranging from 1:2–1:5, for rocks with a typical specific gravity 2.4; distribution d50/d90 equal to d50, and for structures requiring a 1.5 safety factor. For a range of Unit Flow Rates, this table provides values for chute flow depth, and mean rock size.

Table 13.13: Flow depth [1], y (m) and mean rock size, d_{50} (m) for SF = 1.5

Safety factor, SF = 1.5			Specific gravity, sr = 2.4			Size distribution, d_{50}/d_{90}=0.5		
Unit flow rate ($m^3/s/m$)	Bed slope = 1:5		Bed slope = 1:4		Bed slope = 1:3		Bed slope = 1:2	
	y(m)	d_{50}	y(m)	d_{50}	y(m)	d_{50}	y(m)	d_{50}
0.1	0.10	0.20	0.10	0.20	0.10	0.20	0.10	0.20
0.2	0.16	0.20	0.16	0.20	0.15	0.30	0.15	0.30
0.3	0.21	0.30	0.21	0.30	0.20	0.30	0.20	0.40
0.4	0.25	0.30	0.25	0.40	0.25	0.40	0.24	0.50
0.5	0.29	0.40	0.29	0.40	0.28	0.50	0.28	0.50
0.6	0.33	0.40	0.33	0.40	0.32	0.50	0.31	0.60
0.8	0.40	0.50	0.40	0.50	0.39	0.60	0.38	0.70
1.0	0.47	0.60	0.46	0.60	0.45	0.70	0.44	0.80
1.2	0.53	0.60	0.52	0.70	0.51	0.80	0.50	0.90
1.4	0.58	0.70	0.58	0.80	0.57	0.90	0.55	1.00
1.6	0.64	0.70	0.63	0.80	0.62	0.90	0.60	1.10

Note: 1. Flow depth can be expected to be highly variable due to whitewater (turbulent) flow conditions (Source: Catchments and Creeks 2010e)

Steps in the hydraulic design of rock-lined chutes

Step 1: Determine the design discharge (Q) for the chute.
(See Section 13.11.3 Design of chutes: Inlet design; Table 13.3 Inlet weir capacity, if head, H, is known—or weir formula, Equation 13.2.)

Step 2: Determine the slope (S) of the chute from the site geometry, from the crest to the base of the chute.

Step 3: Nominate the chute profile—typically trapezoidal.

Step 4: Determine the maximum allowable approach flow depth, relative to the inlet crest upstream of the chute, for the nominated design discharge.
(Note: where necessary, design and specify appropriate flow diversion works to appropriately control the approach flow to ensure any runoff does not bypass the chute.)

Step 5: Determine the required inlet geometry of the chute using an appropriate weir equation.
(Note: If the inlet channel is short, Equation 13.2 can be applied; Table 13.3 provides inlet weir capacities for typical trapezoidal chutes with 1:2 (V:H) side slopes. If the approach channel is long, and friction loss within this channel is likely to be significant, then an appropriate backwater analysis may be required.)

Step 6: Determine the design unit flow rate (q, $m^3/s/m$)—estimated by dividing the design discharge by the bed width determined in Step 5.

Step 7: Determine the density (specific gravity, sr), and a size distribution, (d_{50}/d_{90}), of the rock to be used on the chute.

Step 8: Determine the uniform flow depth, (y); and required size of the rock size, (d_{50}), for the chute from Table 13.13.
(Note 1: For flatter slopes and higher flow rates, additional rock-sizing tables are provided in Catchments and Creeks (2010c).

Note 2: Alternatively solve Manning's equation, [Q = A.V = (1/n) A. R 2/3. S ½], using values for Manning's n from Table 13.12, Manning's 'n' roughness of rock-lined surfaces.)

Step 9: Specify the required depth of the chute, being the greater of:

a. 300 mm—unless a lower depth is supported by expected flow conditions

b. 0.67(H) plus minimum freeboard of 150 mm—'H' determined from Step 4

c.the uniform flow depth, (y), plus a minimum freeboard of 150 mm, or the equivalent of the flow depth, whichever is smaller.

Step 10: Design the required outlet energy dissipation structure at the base of the chute.

(Note: For design of the outlet structure, see Section 11.3.3 Energy dissipation—stilling basins.)

(Source: Catchments and Creeks 2010e)

13.11.3 Construction of chutes

General principles

Backhoes are suitable for constructing smaller chutes, particularly where the site may require a chute gradient of 1:2 (V:H) or steeper, with vertical sidewalls. Bulldozers and/or scrapers are suitable for larger structures.

Topsoil should be removed and stockpiled prior to shaping the gully head. At the completion of construction the topsoil should be spread to a depth of 150 mm over the face and sides of the chute.

Chutes should be constructed by cutting soil from above the gully head and the sloped to the toe of the overfall in the gully bed. Ideally, the face of the chute should not contain fill.

The floor of the chute should be level from one side to the other to ensure an even flow of water down the face of chute. As necessary for artificial, vegetated waterways, there should be no side slope in the floor of the chute. When constructing the chute, allowance must be made for the additional depth of material such as topsoil and rock to be deposited on the excavated face.

As noted in the section on design, some form of energy dissipation such as a stilling pond is required at the base of the chute.

The following points for the construction of a chute are provided in New South Wales Soil Conservation Service (1992).

1. The chute should be aligned with the flow direction in the drainage line. Runoff must be able to enter the chute inlet directly and without constriction over a distance of at least 20 m to ensure that in the steep chute section, the flow will be parallel to the side walls.
2. Topsoil should be stockpiled at the beginning of the project.
3. The chute should be constructed on firm excavated soil rather than fill.
(Note: If a fill slope has to be used, ensure that the soil is adequately compacted for a width of at least 1 m each side of the chute to minimise the risk of erosion—otherwise protect the soil with suitable scour-protection measures such as turf or erosion control mats. Compaction of the subgrade to a condition that would prevent the turf from bonding with the subgrade should be avoided.)
4. The gradient of the chute depends on the method of stabilising the chute surface.
(See the sections on grass chutes and rock chutes for more information.)
5. Ensure the sides of the chute are no steeper than 1:1.5 (V:H).
6. Where necessary, install a geofabric over the chute surface.

7. Some form of energy dissipation should be provided at the base of the chute—rocks, rock mattress, or a flat concrete bed with a sill.

8. At the completion of the chute, wing banks should be constructed to ensure that all runoff is directed to the crest of the chute and not able to bypass it.

9. Good subsoil drainage and foundations are required to stabilise the chute lining.

10. Ensure the chute is straight from its crest to the toe of the chute.

11. Ensure water leaving the chute and the outlet structure will flow freely without causing undesirable ponding or scour.

12. Stabilise all disturbed areas with vegetation immediately after construction.

(Note: Where geotextile fabric is used, it should be placed directly on the prepared foundation. If more than one sheet of fabric is required to cover the area, the edge of each sheet should be overlapped by at least 30 cm, and anchor pins placed at a minimum of 1 m spacing along the overlap. The upper edge of flexible linings such as filter cloth must be well secured, that is, pinned and buried, in an anchor trench. Porous fabrics such as filter cloth should not be used on dispersive soils.)

Cut-off trenches

Cut-off trenches may be required to secure geotextiles above and below the structure or to install a drainage system above the structure. They may also be required to install a rock or concrete cut-off wall above or below the structure.

A cut-off wall above the drainage line would prevent surface flows from seeping underneath a concrete- or rock-faced chute. A cut-off wall below the structure can protect the chute from being undermined by a gully head that may advance up the drainage line.

A cut-off trench is required at the top of the chute to prevent any seepage moving through the soil reaching the back of the chute, although this is not necessary for a grass chute. Upstream and downstream trenches should be located where the masonry or other material meets the soil. They should be a minimum of 1 m deep under the apron and 50 cm deep under the wing walls.

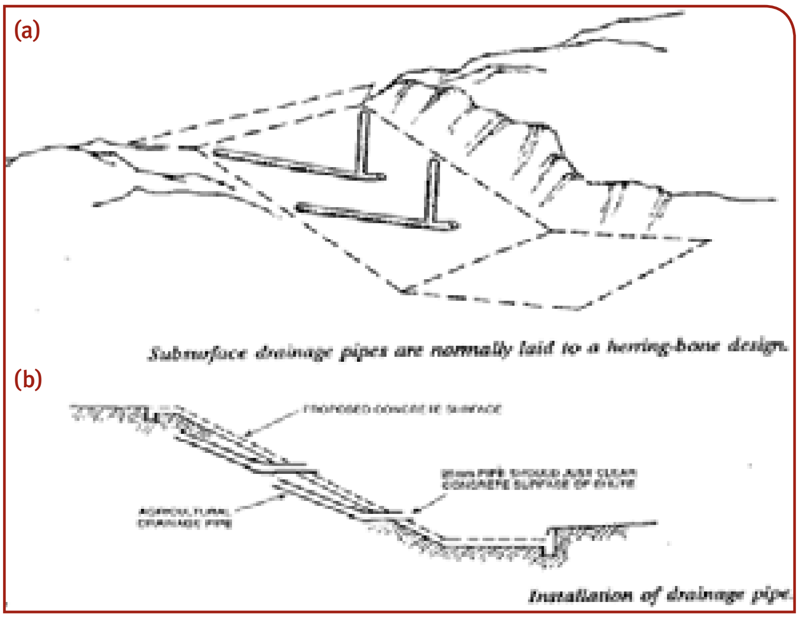
The depth of the trench depends on the amount of overfall. The greater the depth, the more effective will be the trench in intercepting groundwater flows. In a report on a study tour of New South Wales, Crothers et al. (1990) found cut-off trenches varying in depth from 0.3 m to 1 m, but were also told that 2 m deep trenches should be provided in some cases.

Subsurface drainage

Agricultural drainage pipe wrapped in filter cloth may be placed on a bed of coarse aggregate or sand in a trench that would normally be dug in a herringbone pattern as shown in Figure 13.45. A 50 mm diameter flexible agricultural drainage pipe can be laid in the trench, and the trench then filled with previously excavated soil. With the aid of a reducing connector the 50mm agricultural drainage pipe can be connected to a 25 mm polythene pipe cut to a size that will permit it to drain at the chute surface.

There should be some method of dissipating the energy of the water flowing out of the pipe, such as rocks or vegetation, a small stilling basin or an outlet riser.

Figure 13.45: Subsurface drainage of a chute: (a) plan view; (b) section view



Cut-off walls, or collars, should be placed along the length of the pipe to prevent seepage water flowing along the outside of the pipe. These collars can be formed by concrete using Masonite formwork. A rubber ring or sealant around the pipe helps maintain a seal between the concrete and the pipe.

Bentonite is a clay material with great capacity to absorb water and swell, and may be used in cut-off trenches. Thoroughly mixed with the backfill material, bentonite may be compacted in the cut-off trench surrounding the pipe, or used along the entire length of the pipe. The appropriate mix of bentonite and backfill should be obtained from the supplier of the product.

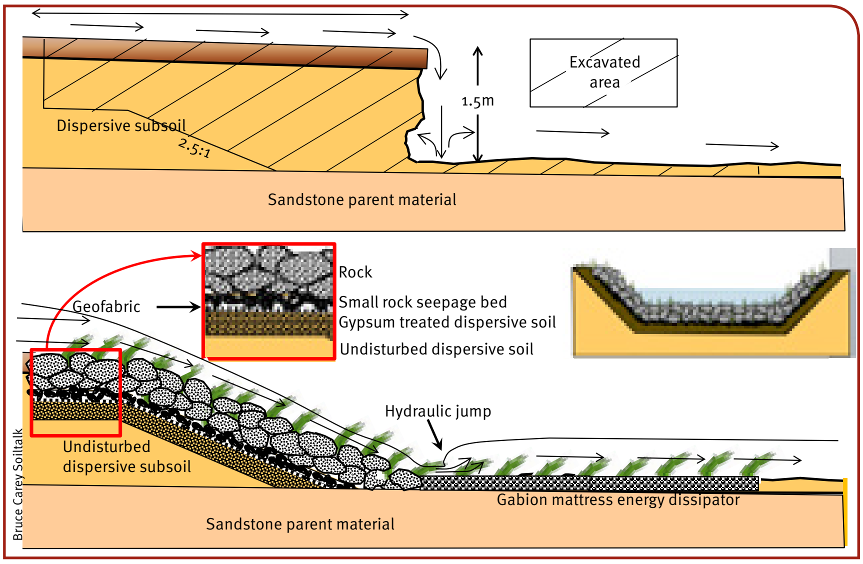
Managing dispersive soils

Gullies often occur on dispersive soils where chutes are vulnerable to failure by soil erosion, and special precautions may be required. Seepage can lead to tunnel erosion and the undermining of structures.

To avoid this, 20–30 cm of non-dispersive soil should be placed on the excavated batter. This soil may be topsoil, dispersed soil with a gypsum amendment, or a compost blanket (Figure 13.46). A geofabric could be placed over the topsoil, followed by a layer of small rock that provides a seepage layer. A compost blanket blown into the bottom layer of rock would assist in the establishment of vegetation on the chute.

To avoid tunnelling along a drainage pipe in dispersive soils, gypsum can be mixed with the backfill at a rate of 1 kg per cubic metre of backfill. The backfill should be compacted in layers as the trench is filled.

Figure 13.46: Placement of a non-dispersive soil on a chute to avoid tunnel erosion



Constructing rock chutes

Constructing a rock chute is not as simple as haphazardly dumping rocks in the bed of a gully. Such attempts invariably end in failure, as seen in Figure 13.47. It is essential that runoff is directed over the rock rather than around it. If the rocks at the entrance to the chute are above natural ground level they will divert runoff to one or both sides of the chute. This will lead to erosion around the edges of the rock and failure of the structure. The centre of a rock or rock mattress chute should be 'dished' so that the centre is about 150 mm lower than the edges.

Figure 13.47: Haphazardly placed rocks fail to control erosion

Chute failure often occurs when runoff does not enter the chute properly. It is critical to control potential leaks and flow bypassing, especially at the chute entrance. Rocks should be held in place with wire netting; particularly on steeper grades (see Figure 13.48).

Figure 13.48: Field example of a failed rock chute; sidewalls not stabilised; geofabric used, but no wire netting to hold the rocks in place

The following is an outline of steps used in the construction of a rock chute. The channel should be cut to a depth equal to the specified depth of rock plus the depth required accommodating the design flow.

1. The gully head and walls are battered to form the chute with a maximum grade not steeper than 1:2(V:H). Excavate a further 30 cm deep at the top of the chute to provide an approach sill at least 1 m long for the width of the chute.
2. Create an apron at the foot of the chute for a distance of at least 1.5 times the depth of the gully (see note below), and for the width of the chute. Excavate the apron area 30 cm lower than ground level to allow for the depth of rocks.
   (Note: The length of the dissipater apron should depend on the design relating to grade, length and surface cover of the chute—1.5 times is an arbitrary minimum.)
3. Dig cut-off trenches 50 cm deeper than the excavation at the upstream end of the approach sill and at the downstream end of the apron.
4. If necessary, lay a geofabric over the area to be covered by rocks to prevent fine soil particles washing away from beneath the rocks and causing undermining. The fabric should be placed directly on the prepared foundation.
   (Note: If more than one sheet of fabric is required to cover the area, the edge of each sheet should be overlapped at least 300 mm and anchor pins placed at minimum of 1 m spacing along the overlap.
   Ensure the geotextile fabric is protected from punching or tearing during installation of the fabric and the rock. Any damage should be repaired by removing the rock and placing another piece of filter cloth over the damaged area, overlapping the existing fabric a minimum of 300 mm.
   Where necessary, a minimum 100 mm layer of fine gravel, aggregate or sand should be placed over the fabric to protect it from damage.)
5. Drive steel pickets in at 1 m x 1 m intervals over the area to be covered by rock. The pickets should be driven in to a depth so that the top of each is level with the top of the rocks to be placed in the chute.
6. Pack rocks tightly into both cut-off trenches.
   (Note: If the soil is dispersive, the cut-off trenches should be filled with concrete and, if necessary, measures taken to allow disposal of saline groundwater.)
7. Cover the chute, approach sill, and apron with rocks of an appropriate mixed size to a depth of 30 cm. The rock should be placed to its full thickness in one operation. It should not be placed by dumping through chutes or other methods that cause segregation of rock sizes.
   (Note: The finished surface should be free of pockets of small rock or clusters of large rocks. Hand-placing may be necessary to achieve the proper distribution of rock sizes to produce a relatively smooth, uniform surface. The finished grade of the rock should blend with the surrounding area. No overfall or protrusion of rock should be apparent.
   Where specified, fill all voids with soil and vegetate the rock surface in accordance with the approved plan.)

8. To reduce the chance of rock movement, secure the netting tightly over the rocks and tie to the top of the pickets.
9. Construct wing banks, as necessary, to ensure the flow is directed through the chute—the chute will fail if water is allowed to go around, or under, the chute.

(Source: Geoff Faulkner, personal communication)

Constructing sod (grass) chutes

The earthworks required in constructing a sod chute is similar to that for a rock chute, as described above, except that the grade of the chute should not exceed 1:8(V:H). This will depend on soil and climatic conditions that affect the likely success of maintaining a complete vegetal cover of the chute face.

Consideration should also be given to the need for including cut-off trenches and subsurface drainage measures.

Establishing vegetation on a sod chute

As it may take up to two years for the vegetation to become well established, it could be necessary to divert runoff to temporarily exclude it from the chute—provided a suitable discharge area is available.

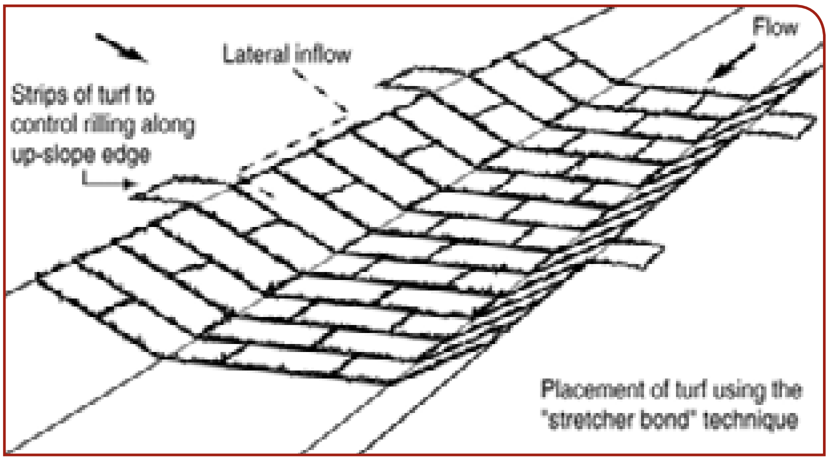
If irrigation water is available, an initial application of water to establish the cover is an advantage, especially during dry periods. The most suitable time to install a sod chute is generally in autumn, while conditions are still warm enough to promote growth but after the risk of high-intensity rains has lessened. In northern areas, however, the best time to establish a sod cover may be before the beginning of the wet season.

Application of a mixed fertiliser is recommended.

For small chutes, laid turf or sods planted close together is the best method of planting (Figure 13.49). The sod or turf should be planted on the floor of the chute, side slopes and wing-banks and above and below the chute. Creeping grasses such as couch, kikuyu, African star grass, Indian bluegrass or pangola are recommended.

Local experience should be sought to determine the most appropriate species for a particular location.

Figure 13.49: Placing turf in a chute (Source: Catchments and Creeks 2010d)



Some watering may be necessary to assist establishment especially during dry periods. A mixed fertiliser is recommended to promote establishment of vegetation.

13.11.4 Management of chutes

The following practices should be adopted to ensure chutes will function effectively:

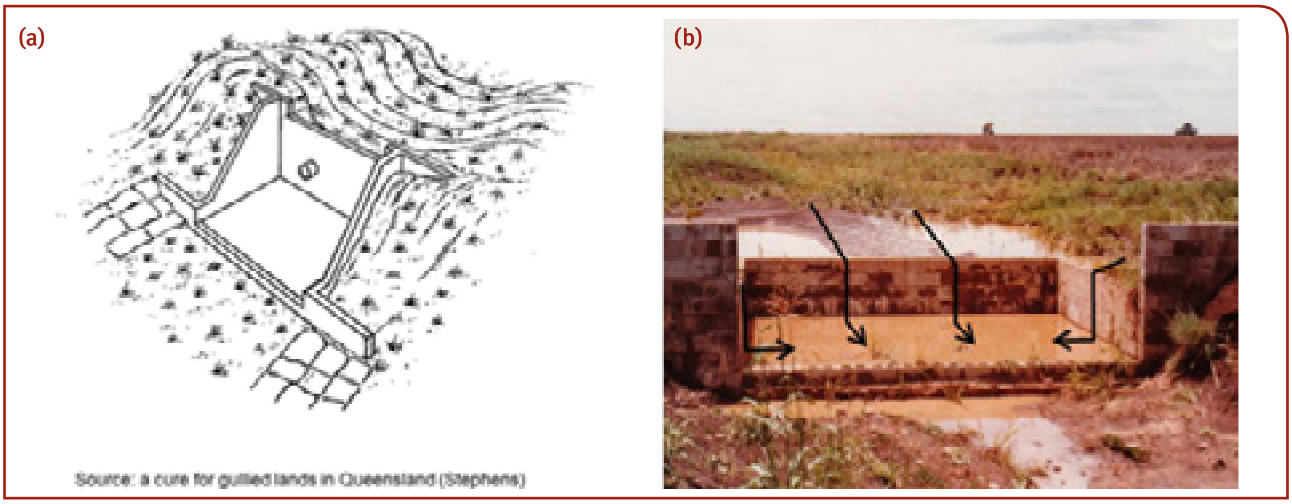
- Exclude stock from chutes—solar-powered electric fences are useful for fencing off small areas in isolated locations. However, an occasional grazing is desirable to assist in promoting a close-growing and vigorous growth.
- In spring apply a mixed fertiliser, and again in mid to late summer with a nitrogen-based fertiliser.
- Encourage vegetation growth above and below the chute to trap sediment.
- Repair any damage to the chute and surrounding areas as soon as possible—check for piping failure, scour holes or bank failures.
  - Erosion at the base of the chute may indicate that a more effective energy dissipation work is required.
  - Severe rilling along the sides of the chute may show that lateral inflows are deflected by the edge of the chute.
- Maintain a healthy stand of vegetation on the face of the chute as well as the areas above, below and on the sides of the chute, as it is vital to the stability of a sod chute.

13.12 Drop structures

Drop structures are vertical structures that convey runoff from a higher level to a lower level (Figure 13.50), and are commonly used in road cross-drainage structures. This section describes their role in the control of gully erosion.

Drop structures are constructed from concrete, concrete blocks, gabion mattresses, steel sheets, concrete in sand bags, or timber. They require some form of energy dissipation at their base to help dissipate the energy gained when runoff flows over the structure.

Figure 13.50: Box inlet drop structure: a) diagrammatic; b) field example



Source: a cure for gullied lands in Queensland (Stephens)

Where a gully head has an overfall greater than 1.0 m, New South Wales Soil Conservation Service (1992) advised that chute structures are preferred to drop structures.

The information in this section has been sourced primarily from an unpublished report, A cure for gullied areas in Queensland, prepared for the Queensland Department of Primary Industries by R. M. Stephens in 1989.

The most common drop structure is a straight wall placed across the line of the water flow. The wall commonly has a lower section called the notch, designed to pass the flow at a predetermined depth, and an apron or stilling basin in which the energy of the fall is dissipated.

Drop structures are usually placed right at, or near to, the gully head. If this location is not feasible, such as if the gully is too narrow or too steep at that point, the structure may be placed some distance below the gully head. In this event, the relative difference in height between the gully head crest and the notch of the structure should be based upon the gradient at which the watercourse—or similar watercourses in the area—appear to be satisfactorily stable.

This method is only satisfactory if there is sufficient sediment being carried down the watercourse to silt up the area above the structure within two or three years. If grass establishes in the trapped sediment behind (i.e. upstream) the structure it will in turn trap more, and the floor and sides of the gully—and eventually the overfall, will be completely stabilised. The same principle is employed if a chain of sediment traps is used to build up the floor of an eroding watercourse or waterway.

If insufficient sediment is being carried down the system, there is a risk that the gully head will continue retreating at a rate faster than the rate of sedimentation, and subsequently, that another structure will need to be established at the gully head.

As with chute structures, it is essential that the approach channel be straight and the structure placed at right angles to the flow direction, with the notch centrally located.

A box inlet drop structure, as in Figure 13.50, has the following advantages where a large volume of water has to be passed down a narrow channel:

- • Since the flow through a weir is proportional to the length of the crest, a greater volume of runoff can be conveyed through a box inlet compared to a straight wall of equivalent outlet width.
- Energy dissipation is effectively carried out in the box as the water impinges upon itself from three directions.
- If tied together well, the structure is immensely strong and needs less buttressing.
- There can be a considerable saving in earthworks as the box can be placed in the head of the gully.

The main disadvantage of a box inlet is that the exit flow is confined to a narrow opening and channel velocities will be high unless a flow-spreading structure can be incorporated in the downstream section of the watercourse. The lack of a spreading structure is apparent in Figure 13.50b as erosion is evident at the outlet of the structure

Like chutes, very few drop structures have been constructed on rural properties in Queensland. Wilkinson (1986) described the use of two structures made to stabilise an eroding waterway on black cracking clay soils in the Central Highlands. One was made from steel sheeting while the other was made from concrete blocks and incorporated a box inlet drop, as in Figure 13.50. Constructing the box inlet on a cracking clay soil required significant foundation preparation. Problems occurred in keying the wing walls safely into the black soil. Repair work was required on a number of occasions to fill in tunnel erosion through the earth embankments. After these initial problems, the structure appeared to settle into equilibrium, possibly as a result of the silt accumulation.

Drop structure design

Equation 13.4

$$Q = CbH^{1.5}$$

Where:

Q = calculated discharge (m3/s) for the selected ARI

C = a coefficient related to flow conditions to the chute—value of 1.7 for a sharp-crested weir

b = length of the crest (width of the flow), (m)

H = the total energy head of the approach flow, (m).

The design for most drop structures can be based on that used for sharp-crested weirs. The major difference between a broad-crested weir and a sharp-crested weir is that with the former, the water follows the surface of the structure continuously, and with the latter, water is thrown clear and forms a 'nappe'.

The dimensions of drop structures can be determined by use of the weir formula (see below and Section 6.6 in Chapter 6), using sharp-crested weir conditions with vertical sides, that is, a rectangular cross-section. The design of drop structures is related to the critical depth of flow over the inlet sill of the structure. For the range of soil conservation structures the critical depth is approximately equal to two-thirds the flow head.

The weir formula, based on a rectangular cross-section that is typical for drop structures, is reproduced in Equation 13.4.

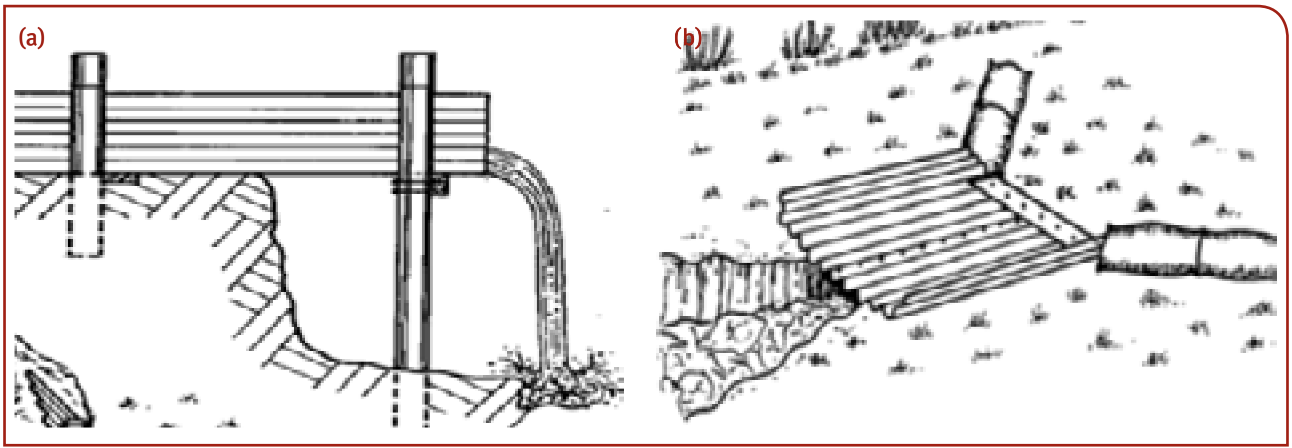
The design of a drop structure should also include an energy dissipater at the outlet, in order to return the flow to non-erosive velocities at the downstream end of the structure. This can take the form of a non-erosive apron or a stilling basin.

For the design of the length of a stilling basin (and height of an end sill if included), see Equation 13.3 in Section 13.11.1.

Verandah chutes

Verandah chutes are really a particular form of drop structure that creates a 'natural' stilling pond in the floor of the watercourse (Figure 13.51). They are designed is to carry the runoff flow over the gully head to prevent the cutting-back action. The flow is dispersed in a hole, or splash pool, made in the gully floor, which serves as a stilling basin to dissipate the energy in the flow.

Figure 13.51: Diagrammatic representations of verandah chutes (Stephens 1989)



A field example of a verandah chute is shown in Figure 13.52.

Figure 13.52: Field example of a veranda chute

Trials of a number of these structures were carried out in south-east Queensland in the 1980s with varied success. They are relatively cheap to construct and can be made from second-hand materials, such as galvanised iron, that can be riveted or bolted together. Water troughs, or 200 L drums cut in half, provide an alternate source of materials. The main support beams need to be strong enough to handle the weight of several cubic metres of flowing water.

Subsurface flows—particularly in dispersive soils—can lead to failure, with the flow undermining the structure. The installation of slotted PVC drainage pipe about 50 cm deep and 2 m upstream from the head will help to intercept this flow and dry out the critical area.

As a verandah chute comprises mainly timber and sheeting that will deteriorate over time, these structures should be considered for temporary gully control only, perhaps while more permanent measures are put in place. In grazing lands, the timber components may be vulnerable to damage by fire used as a strategy for management of timber regrowth. The structure should be fenced to prevent stock damage, and monitored frequently to ensure the timber or metal components have not deteriorated.

13.13 Revegetating disturbed areas

All gully erosion control projects will require the planting of some vegetation to complete the project.

Topsoil should be spread over any subsoil exposed by construction activities before planting. On roadside batters, compost blankets can be applied by a blower onto inaccessible exposed surfaces to provide an excellent medium to support plant growth.

Where rapid revegetation growth is required on exposed surfaces, season-dependent cover crops such as oats for winter or millet for summer can be used to provide protection while other species are being established. Erosion control blankets, mats or mesh may be useful, and hydromulching or hydroseeding can also provide protection until the permanent vegetation is fully established.

If it is available, some form of irrigation may be useful to assist in the establishment of vegetation. An initial application of a mixed fertiliser aids in rapid establishment of an effective cover.

The aspect of different surfaces in relation to sunlight needs to be considered. South-facing surfaces in the Southern Hemisphere are not conducive to plant growth as they receive little or no sunlight in winter, depending on latitude. On the other hand, northerly or westerly slopes can dry out rapidly.

13.14 Further Information

References

Alt, S., Jenkins, A. and Lines-Kelly, R. (2009) *Saving soil—A landholder's guide to preventing and repairing soil erosion*, Northern Rivers Catchment Management Authority and New South Wales Department of Primary Industries, Sydney.

ASCE (1992) *Design and construction of urban stormwater management systems*, ASCE Manuals and Reports of Engineering Practice No. 77, and Water Environment Federation Manual of Practice FD-20, American Society of Civil Engineers, New York.

Bhattarai, R., Kalita, P. K., Yatsu, S., Howard, H. R. and Svendsen, N. G. (2011) Evaluation of compost blankets for erosion control from disturbed lands, *Journal of Environmental Management*, 92(3), 803–812.

Catchments and Creeks (2010a) *Chutes part 1: General information*, fact sheet, Catchments and Creeks Pty Ltd, Brisbane, ‹catchmentsandcreeks.com.au/M-fact_sheets-ESC.html›, accessed 14 July 2015.

Catchments and Creeks (2010b) *Chutes part 2: Geosynthetic linings*, fact sheet, Catchments and Creeks Pty Ltd, Brisbane, ‹catchmentsandcreeks.com.au/M-fact_sheets-ESC.html›, accessed 14 July 2015.

Catchments and Creeks (2010c) *Chutes part 5: Rock linings*, fact sheet, Catchments and Creeks Pty Ltd, Brisbane, ‹catchmentsandcreeks.com.au/M-fact_sheets-ESC.html›, accessed 14 July 2015.

Catchments and Creeks (2010d) *Chutes part 3: Grass-lined*, fact sheet, Catchments and Creeks Pty Ltd, Brisbane, ‹catchmentsandcreeks.com.au/M-fact_sheets-ESC.html›, accessed 14 July 2015.

Crothers, R. B., Wilkinson, W. F., Gray, H. J. and McLatchey, J. F. (1990) *Gully stabilisation techniques used by the Soil Conservation Service of New South Wales*, Queensland Department of Primary Industries, Study Tour Report, QS 90002.

Department of Environment and Resource Management (2011) *Managing grazing lands in Queensland*, Queensland Department of Environment and Resource Management, Brisbane.

Department of Natural Resources and Water (2006) *Gully erosion*, fact sheet L81, Queensland Government, ‹qldgov.softlinkhosting.com.au/liberty/opac›, accessed 16 July 2015.

Department of Natural Resources, Mines and Water (2006) *Farm dam construction*, fact sheet W10, Queensland Government, ‹qldgov.softlinkhosting.com.au/liberty/opac›, accessed 16 July 2015.

Hardie, M. (2009) *Dispersive soils and their management*, Technical Reference Manual, Sustainable Land Use, Department of Primary Industries and Water, Hobart, Tasmania.

Hazelton, P. and Murphy, B. (2007) *Interpreting soil test results—what do all the numbers mean?* CSIRO Publishing, Canberra.

Horton, A. J. and Jobling G. A. (Eds) (1984) Farm water supplies design manual, Rural Advisory Services, Client Advisory Services Division, Queensland Water Resources Commission, Brisbane.

Hudson, N. W. (1995) *Soil conservation*, B. T. Batsford Limited, London.

Institution of Engineers Australia (1996) *Soil erosion and sediment control: Engineering guidelines for Queensland construction sites*, The Institution of Engineers, Australia (Queensland Division), Brisbane.

Jones, M. R. (2006) *Cenozoic landscape evolution in central Queensland*, Australian Journal of Earth Sciences 53, 433–444.

Keller, R. J. (2003) *Guidelines for the design of rock chutes using CHUTE*, CRC for Catchment Hydrology, Brisbane, toolkit available at ‹toolkit.net.au/chute›, accessed 16 July 2015.

Kroon, F., Turner, R., Smith, R., Warne, M., Hunter, H., Bartley, R., et al. (2013) Chapter 4: Sources of sediment, nutrients, pesticides and other pollutants in the Great Barrier Reef catchment, *2013 Scientific consensus statement*, Reef Water Quality Protection Plan Secretariat, Brisbane.

Landloch (2002) *Studies of hydromulch effectiveness*, report prepared for the National Centre for Engineering in Agriculture, University of Southern Queensland, Toowoomba, June 2002, NCEA Publication NCEA 1000437/1, Landloch Pty Ltd, Toowoomba.

Landloch (2004) *Standards for the supply and application of hydromulch products, Stage 1—critical shear testing*, report prepared for the Queensland Department of Main Roads, October 2004, Landloch Pty Ltd, Toowoomba.

Local Government Association of Queensland (2006) *Introductory erosion and sediment control guidelines for Queensland councils*, Local Government Association of Queensland, Brisbane.

McDonald, L. A., Stone, P. C. and Ingles, O. G. (1981) 'Practical treatments for dams in dispersive soils,' In *Proceedings of the 10th International Conference on Soil Mechanics and Foundation Engineering*, Stockholm, 15–19 June, Vol. 2, pp. 355–366.

Milton, L. E. (1971) *A review of gully erosion and its control*, Soil Conservation Authority, Victoria.

New South Wales Soil Conservation Service (1991a) Unit 5, *Soils*, Earthmovers training course, NSW Department of Primary Industries, Parramatta.

New South Wales Soil Conservation Service (1991b) Unit 9, *Farm dams*, Earthmovers training course, NSW Department of Primary Industries, Parramatta.

New South Wales Soil Conservation Service (1991c) Unit 10, *Construction of farm dams*, Earthmovers training course, NSW Department of Primary Industries, Parramatta.

New South Wales Soil Conservation Service (1991d) Unit 15, *Gully filling and shaping*, Earthmovers training course, NSW Department of Primary Industries, Parramatta.

New South Wales Soil Conservation Service (1991e) Unit 18, *Pipes in earthworks*, Earthmovers training course, NSW Department of Primary Industries, Parramatta.

New South Wales Soil Conservation Service (1992) Unit 19, *Flumes and chutes*, Earth Movers Training Course, NSW Department of Primary Industries, Parramatta.

Prosser, I. P. and Dietrich, W. E 1995, Field experiments on erosion by overland flow and their implications for a digital terrain model of channel initiation, *Water Resources Research*, 31(11): 2867–2876.

SEQ Catchments (2015a) *Gully erosion repair*, available for download at ‹seqcatchments.com.au/resources-fact-sheets.html›, accessed 16 July 2015.

SEQ Catchments (2015b) Gully erosion repair: Case studies, available for download at ‹seqcatchments.com.au/resources-fact-sheets.html›, accessed 16 July 2015.

Shellberg, J. and Brooks, A. (2012) *Alluvial gully erosion: A dominant erosion process across Tropical Northern Australia*, Tropical Rivers and Coastal Knowledge (TRaCK) report, Charles Darwin University, Darwin, available at ‹track.org.au/publications/registry/track1843›, accessed 16 July 2015.

Shellberg J. G. and Brooks A. P. (2013) *Alluvial gully prevention and rehabilitation options for reducing sediment loads in the Normanby Catchment and Northern Australia*, final report for the Australian Government's 'Caring for Our Country' reef rescue initiative, Australian Rivers Institute Griffith University, Nathan.

Skinner, A. F., Gillies, C. C. and Milton, L. E. (1972) *An erosion survey of the Upper Nogoa catchment*, Technical Bulletin, Division of Land Utilisation, Queensland Department of Primary Industries, Brisbane.

Stephens, R. M. (1989) *A cure for gullied areas in Queensland*, unpublished report, Queensland Department of Primary Industries, available at ‹qldgov.softlinkhosting.com.au/liberty/opac›, accessed 16 July 2015.

Thorburn, P. J. and Wilkinson S. N. (2013) Conceptual frameworks for estimating the water quality benefits of improved agricultural management practices in large catchments, *Agriculture Ecosystems & Environment*, 180: 192–209, see ‹dx.doi.org/10.1016/j.agee.2011.12.021›.

Vacher, C. A., Loch, R. J. and Raine, S. R. (2004) *Identification and management of dispersive mine spoils*, final report for the Australian Centre for Mining Environmental Research, Kenmore, Queensland.

Watt, M. O. (1984) *Waterway design tables*, Miscellaneous Publication Series QM 84010, Queensland Department of Primary Industries, Brisbane, can be downloaded from the Queensland Government Library at ‹qldgov.softlinkhosting.com.au/liberty/opac/search.do›, accessed 15 July 2015.

Wilkinson, S. N., Bartley, R., Hairsine, P. B., Bui, E. N., Gregory, L. and Henderson, A E. (2015) *Managing gully erosion as an efficient approach to improving water quality in the Great Barrier Reef lagoon*, report to the Department of the Environment, CSIRO Land and Water, Australia, available at ‹publications.csiro.au›, accessed 16 July 2015.

Wilkinson, S. N., Kinsey-Henderson, A. E., Hawdon, A. A., Ellis, T. W. and Nichols, D. M. (2013) *Gully erosion and its response to grazing practices in the Upper Burdekin catchment*, report to NQ Dry Tropics for the Paddock to Reef program, CSIRO Water for a Healthy Country Flagship, Australia, available at ‹publications.csiro.au›, accessed 16 July 2015.

Wilkinson, W. (1986) *Gully control—the Central Highlands experience*, Division of Land Utilisation Technical News, August 1986, Department of Primary Industries, Brisbane.

Other information

Brodie, J., Waterhouse, J., Schaffelke, B., Kroon, F., Thorburn, P., Johnson, J., Fabricius, K., Lewis, S., Devline, M., Warne, M. and McKenzie, L. (2013) Land use impacts on Great Barrier Reef water quality and ecosystem condition, 2013 *Scientific consensus statement*, Reef Water Quality Protection Plan Secretariat, Brisbane.

Brooks, A., Spencer, J., Borombovits, D., Pietsch, T. and Olley, J. (2014) Measured hill slope erosion rates in the wet dry tropics of Cape York, northern Australia: part 2, RUSLE-based modelling significantly over-predicts hill slope sediment production, Catena 122: 1–17.

Carey, B. (2014). Understanding dispersive soils, available for download at Landcare Queensland website, ‹landcare.org.au/wp-content/uploads/2013/01/Understanding-dispersive-soils.pdf›, accessed 16 July 2015.

Department of Primary Industries (1977) *Soil conservation handbook*, Soil Conservation Branch, Queensland Department of Primary Industries, Brisbane.

Northern Territory Government (2006) *Gully rehabilitation and stabilisation fact sheet*, Land Note ASLN-02, Natural Resource Management Division, Alice Springs, Northern Territory.

Rose, C. W., Bofu, Yu B., Ward, D. P., Saxton, N. E., Olley, J. M. and Tews, E. K. (2014) The erosive growth of hillside gullies, *Earth Surface Processes and Landforms*, Vol. 39, Issue 15 (December 2014), pp. 1989–2001.

United States Department of Agriculture (2007) *Gullies and their control*, National Engineering Handbook Part 654, Technical Supplement 14P, United States Department of Agriculture, Washington DC.

Department of Water (2001) Understanding critical flow, Chapter 7 in: *Managing and enhancing our waterways for the future*, Government of Western Australia, Perth, see ‹moodle.unitec.ac.nz/file.php/1319/pdf/Understanding_Critical_Flow.pdf›, accessed 16 July 2015.

Zund, P. R. and Payne, J .E. (2014). *Mapping erodible soils in Burdekin Dry Tropics grazing lands: User guide to the datasets*, Department of Science, Information Technology, Innovation and the Arts, Queensland Government, Brisbane.