Guidelines for Riparian Filter Strips for Queensland Irrigators

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CSIRO Land and Water, Canberra
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SECTION 1. INTRODUCTION

1. Objectives

These guidelines for riparian management were commissioned by the Queensland Department of Natural Resources. They are designed for use in a broader set of land and water management guidelines to be used in evaluating applications for water extraction licences for irrigation. The guidelines are intended both for new irrigation developments, where there is the greatest scope to implement best management practice, and for renewal or expansion of existing water extraction entitlements. The granting of water extraction licences takes into account the physical impact that the water use will have on streams, so that if the water is used for irrigated agriculture the impact of that agriculture on the physical character of the stream is considered.

Agricultural land use in riparian lands can influence two aspects of the physical character of streams. It can increase the delivery of sediments and nutrients to the stream and it can change the stability of the stream banks, both of which can change local stream morphology and adversely impact water quality.

Good management of riparian lands can allow them to trap sediment and nutrients eroded from upslope land and prevent them from being delivered to the stream. The aim of these guidelines is to provide a generic set of design procedures that can be used across Queensland for the purpose of designing filter strips to trap sediment and attached nutrients eroded from agricultural land.

2. Definition of Riparian Lands

We employ a functional definition of riparian lands. Riparian lands are that part of the landscape adjacent to streams which exert a direct influence on streams or lake margins and on the water and aquatic ecosystems contained within them. Riparian land includes both the stream banks and a variable sized belt of land alongside the banks. Riparian lands have a direct influence on the stream channel in several ways.   For instance, a riparian tree may fall into a stream, creating habitat in the middle of a stream, or riparian lands may be an important habitat or food source for water birds. In each case the zone of influence on the river varies.

Riparian lands have been defined in a legal context in some States as a fixed width along designated rivers and streams. This definition is less useful, as in places it will be too narrow to include the full zone influencing the stream, or, for some functions, it may be wider than is necessary.

Definition of the riparian zone based on landform can be used to help managers decide how the size of the zone varies from one location to another. In most cases, the complete floodplain is included in the riparian zone, and footslopes are included adjacent to small streams. However, there is no law of nature that defines the width of riparian land; this is solely a management decision. One of the aims of these guidelines is to provide a basis for informed choice of a suitable riparian filter strip width for the function of sediment filtering.

3. Riparian Functions

We can define several functions or ways in which riparian land influences streams. To this we can also add functions that affect land based ecosystems and additional functions of social or economic value. The main functions of riparian lands are to:

1. Stabilise banks against erosion
2. Reduce sediment delivery to streams
3. Modify water quality by filtering nutrients and other pollutants
4. Control plant growth in streams
5. Maintain in-stream habitat
6. Provide food for aquatic ecosystems
7. Provide terrestrial habitat and wildlife corridors
8. Provide aesthetic value and recreation
9. Provide economic value

Only functions 1 to 3 are physical functions that are considered in the context of water extraction licences. Function 1 is considered in a separate report (Abernethy and Rutherfurd, 1999) and thus only functions 2 and 3 are considered in detail here. Management aimed at achieving functions 1 to 3 will usually provide ancillary value toward achieving other benefits with little modification of management practice.

4. A Flexible Approach

There is a huge diversity of riparian land environments across Queensland and management guidelines need to reflect this diversity by allowing a flexible approach that reflects local conditions. It would thus be inappropriate to apply uniform constraints, such as uniform width of riparian set back of agriculture across Queensland. The aim here is to provide principles for designing riparian management appropriate to the local conditions. The difficulty with such an approach is that suitable information is not always available at each location to evaluate appropriate riparian management. Consequently, we have concentrated on outlining a consistent procedure for using local information to design riparian management so that those with the local information can make informed decisions about appropriate management for that set of circumstances. In addition, we have provided a set of first approximations of appropriate riparian management for the many cases where there is no additional local information and consequently design principles need to be extrapolated from where there is better information.

5. Riparian Research in Australia

There has been a large amount of research conducted overseas on the functions and management of riparian lands, but scant attention has been paid to these issues in Australia. The overseas research cannot be applied uncritically to Australia, because of the distinctive characteristics of Australian environments. Our vegetation is largely evergreen for example, and our soils are old and poor in nutrients.

The Land and Water Resources Research and Development Corporation (LWRRDC) commissioned a research program into riparian processes and management, beginning in 1995. At that time there were only a couple of Australian studies of physical processes in riparian lands. Since then various experiments have been conducted on sediment trapping as part of the LWRRDC program and these guidelines are based on these recent findings and earlier overseas research. Having started from such a poor background of information has meant that the research has focussed on the fundamental processes, to demonstrate the potential for riparian management, and much extrapolation is needed to apply these results across diverse environments.

6. Structure of the Guidelines

The two functions of sediment trapping and bank stability are treated in separate documents for three reasons:

1. In many locations one process far outweighs the other in terms of its significance for overall erosion or rate of sediment delivery to streams (Prosser, 1999). In the Johnstone River, Far North Queensland, for example, stream banks are naturally stable because of the low bank height, geo-technically strong soil materials and vigorous vegetation growth under all conditions. In contrast, there are substantial problems of sediment delivery from cropping lands because of relatively steep slopes, and high intensity rainfall. An opposite example is the Mary River catchment in SE Queensland where vigorous pasture growth reduces sediment delivery from the land but the river is incised with high, steep, banks that are subject to failure in each flood.

2. Hillslope and channel erosion entail quite different management approaches. Stream bank erosion is best targeted by managing stock access to streams, revegetating bare banks or using other bank stabilisation methods. Sediment delivery from agricultural land is best targeted by reducing source erosion, and by using riparian filter strips. Bank erosion is treated by focussing vegetation on the banks themselves, often using trees, whereas filter strips focus on the use of dense ground cover in the flatter streamside land before runoff reaches the banks.

3. Hillslope erosion can respond to short-term changes in land management, and trends are often reversible, whereas channel erosion reacts over longer time scales, and is mostly in response to the major clearing of vegetation upon introduction of modern land use. Channel erosion tends to go through a trend of rapid initial change and then gradual adjustment to a new equilibrium condition over many years or decades.

SECTION 2. PRINCIPLES OF FILTER STRIPS IN RIPARIAN LANDS

1. Introduction

Agricultural land use has accelerated rates of soil erosion beyond the very low rates experienced in Australia under natural conditions. Even under best management practices, there is occasional significant erosion when soil cover is low. Much eroded sediment was naturally trapped in riparian lands when these areas contained dense vegetation cover, but the role of riparian lands has not been appreciated until recent times and most riparian land is now denuded of vegetation cover. The restoration of riparian vegetation or the design of riparian filter strips can do a lot to restore the sediment and nutrient filtering function of riparian lands.

Sediment and nutrient delivery to streams needs to be minimised because excess sediment can drown aquatic habitat and promote weed invasion, and excess nutrients can cause eutrophication problems such as outbreaks of toxic blue-green algae. Excessive sediment delivery can also reduce channel capacity and increase flooding. Sediment derived from intense agriculture in the Johnstone River catchment of Far North Queensland, for example, has reduced the capacity of tributary streams from in excess of the 1 in 50 y flood to only one third of the 1 in 50 y flood (Bunn *et al*., 1998).

It should be noted that not all riparian land acts as a sediment and nutrient filter. It is only where sediments and nutrients enter the stream that the filter function can occur. Much of a river length may contain levees or other features where there is no surface drainage directly into the stream. Runoff will reach the stream somewhere though, at a break in the levee or through drains, and it is these areas that need protection with riparian filters.

While riparian filter strips can prevent sediment and nutrient delivery to streams they should be used as an addition to, and not as an alternative to, well-planned on-site erosion and nutrient control. On-site conservation practices keep soil and nutrients in the field, where they are valuable resources, while filter strips trap sediments below the field, where they are essentially lost to agriculture. It will be seen later that filter strips are only effective under low to moderate soil losses and can be defeated by excessive erosion rates.

There are three processes that make riparian lands effective controls of sediment and nutrient delivery to streams:

1. infiltration of runoff prevents pollutants from reaching the stream;
2. good vegetation cover can prevent erosion of riparian lands themselves; and
3. the vegetation cover can trap sediment and attached nutrients which are carried by the flow.

The first two processes are dealt with briefly before focussing this report, and the design guidelines, on sediment and nutrient trapping by vegetation, which is the most significant process.

In situations where there is significant soil loss, the majority of phosphorus is transported attached to sediment and thus the control of sediment also controls the movement of P (LWRRDC, 1999). Much particulate, organic nitrogen is also transported with soil particles but significant proportions of N also move as nitrates in soluble form, independent of sediment. In areas of continuous good cover and where P is added to the soil, such as intense dairying operations, significant P loss can occur in soluble form. Riparian lands are much less effective at removing solutes than they are at trapping sediment attached nutrients.

Trapping of the fine particles is important for nutrient trapping, such as silt and clay, for these tend to be highly reactive and enriched in P relative to coarser particles. Particulate organic matter, high in N, also behaves as a clay-sized particle, or is preferentially associated with clay particles.

2. Infiltration of Runoff in Riparian Lands

When overland flow from upslope areas infiltrates before, or in, riparian land the sediment and nutrient have lost their means of transport and cannot reach the stream. Whether, and how much, infiltration occurs is determined by soil properties, antecedent moisture conditions and the amount of runoff. During large runoff events which transport the majority of sediment and nutrient, infiltration volumes in the filter strips are likely to be negligible in comparison to the volume of runoff generated from upslope areas. Furthermore, riparian lands are the wettest parts of the landscape and may remain close to saturation for long periods, fed by soil moisture generated from upslope. Consequently in wet environments, such as coastal Queensland, riparian lands will be a source of runoff rather than absorbing runoff, as demonstrated by McKergow *et al*. (1999). It is only in the semi-arid areas of Queensland where soil moisture is low, that infiltration is likely to be significant in trapping sediment and nutrients. Calculations of the runoff absorbing abilities of riparian lands suggest that filters of the order of 10 to 30 m width are required to absorb runoff under dry antecedent conditions and greater widths are required where converging flow drains through a narrow zone of less than 20 m of riparian land (Herron and Hairsine, 1998).

Infiltration is important for filtering solutes, such as nitrates, for these are not trapped with sediment in surface flows. Infiltrated water must not, however, be allowed to quickly enter the stream, as solute delivery by rapid sub-surface flow is just as efficient as by surface runoff. The water needs to be stored in the soil for times of the order of days to weeks for effective filtering of nitrates. This is the time needed for denitrification and conversion to gaseous nitrogen, or for absorption by plants. Recent evidence has shown that much sub-surface water either bypasses riparian lands or is transmitted over such short time periods that there is little effective denitrification.

Consequently, infiltration in riparian lands as a mechanism for pollutant removal is likely to be limited to small volumes of runoff under dry conditions. If solute removal is of such concern that effective storage of water in riparian lands is needed, then Herron and Hairsine (1998) provide design guidelines based on volumes of runoff and riparian water storage potential. Forested riparian lands are the most effective at absorbing runoff.

Sediment and attached nutrient trapping by riparian vegetation generally occurs over shorter widths of riparian land than is needed for infiltration of runoff. Consequently, infiltration is not included as a design factor for sediment trapping in the rest of this report.

3. Erosion Protection

In some instances vigorous riparian vegetation is required to prevent erosion of riparian lands themselves rather than to trap sediment derived from agricultural land. There are two situations where erosion of riparian lands is likely to be a problem. The first of these is where riparian lands are relatively steep, and where runoff volumes are high. If these areas become degraded or are used for cropping they can pose a high erosion hazard with little opportunity for the eroded sediment to be redeposited before reaching the stream. Fortunately, these situations are not common in association with irrigation.

The second situation is where agriculture occurs on flood prone land. High velocities of flood flow can strip soil from large areas of this land and deliver it to the river. Flood flows are usually of such significant depth and volume that the usual sediment trapping role of a riparian filter is unable to make much impact on the sediment load, except for the coarsest particles. However, healthy riparian vegetation can slow the flow as it leaves the river and protect soil from scour, minimising damage to fields and the supply of additional sediment downstream. Additional vegetation perpendicular to the river, along fence lines, tracks and roads can also provide a barrier to flood flows, reducing their velocity and preventing soil loss from floodplain paddocks. This vegetation may also protect fences and tracks as long as it is maintained free of debris.

To protect against scour, the vegetation needs to be dense and strong over the height of expected flood flows. Thus, tall grasses, shrubs and dense stands of trees provide valuable roles on floodplains. Isolated trees provide little benefit as they form a vortex of flow which is highly erosive.

4. General Principles of Sediment Filtering

The entrainment of sediment by overland flow, its movement downslope and its deposition within riparian lands have been relatively well studied in the last few decades. Experimental results show that filter strips vary widely in their ability to remove sediment, reflecting such factors as vegetation type and density, soil type, and slope and placement of the filter. This variability prevents any general statement being made on filter strip performance or specification of a uniform optimal width for controlling sediment delivery to streams.

Sediment is trapped by riparian vegetation because when the flow enters a vegetated strip the velocity is reduced by the increased surface roughness or flow resistance of the vegetation. The decrease in velocity results in a decrease in the sediment transport capacity of the flow. Sediment is deposited if the resultant transport capacity is less than the incoming sediment load. The reduction in flow velocity within a filter is transmitted back through the flow to the area upslope. This gives rise to an area of deep, slow flowing water, known as a backwater (Figure 1).

Deposition occurs initially in the backwater, and progresses into the grass strip. During deposition, the grass stems and stolons that provide hydraulic roughness are progressively buried, which increases the capacity of flow to transport sediment through the filter. Eventually a steady-state is reached where the grass is buried to a sufficient extent that the flow can transport all the sediment it is carrying through the buried grass and the wedge of deposition moves forward through the vegetation. Eventually, the wedge may continue through the full length of the strip. By this time the filter strip has reached its full storage capacity and no longer traps any sediment (Karssies and Prosser, 1999). Fine suspended sediment may be transported well beyond the front of the sediment wedge because of its slow settling velocity. Therefore the sediment trapping efficiency of a filter may fall below 50 % well before the main depositional front reaches the end of the filter.

This concept of a wedge of deposition in the backwater and within the vegetation means that a filter has a limited sediment storage capacity beyond which it is no longer effective. We later use this concept of a storage limit in the strip to formulate design rules for strip widths across Queensland.

The storage capacity of a filter is constantly renewed by vegetation germination and growth on and through the trapped sediment. This renews the strip filtering capacity for future events. In warm climates we have observed dense grass cover to re-establish within three months of burial.

5. Factors Influencing Filter Strip Effectiveness

5.1 Filter strip vegetation

The important characteristics of filter strip vegetation are its structure, density and condition. Vegetation density at the ground surface is most important since deposition is achieved by reduction in flow velocity and by close spacing of stems within the flow. The greatest reductions in flow velocities are achieved by vegetation that is uniformly dense at ground level. Overland flow is rather shallow, in the order of 1 to 4 cm, and rarely flattens the grass in a filter strip. Because roughness at ground level is important, stoloniferous, creeping grasses such as kikuyu, couch and signal grass are a better trapping medium than tussocky grasses.

Forest floors are the least effective sediment filters because the structure of the large vegetation such as shrubs and trees hardly disperses the flow, while litter can be washed away during large events (Figure 2). For example, monitoring has shown that the litter layer in tropical rainforest filters work only as a temporary store. It traps sediment initially, but this sediment is flushed out in subsequent events, due to a limited ability to store sediment and due to the lack of vegetation growth on the deposit (McKergow *et al*., 1999). In contrast, deposits in grass filters are quickly colonised by fresh grass growth within a few weeks and rendered unavailable for subsequent re-entrainment. Furthermore, Mackenzie and Hairsine (1996) found that flow through forested riparian lands became concentrated into a few pathways of fast and deep flow that defeated filtering ability. Forested filter strips will be more effective where trees do not prohibit an understorey of dense grass through shading or competition. This is only likely in semi-arid and sub-humid environments where there is incomplete canopy cover.

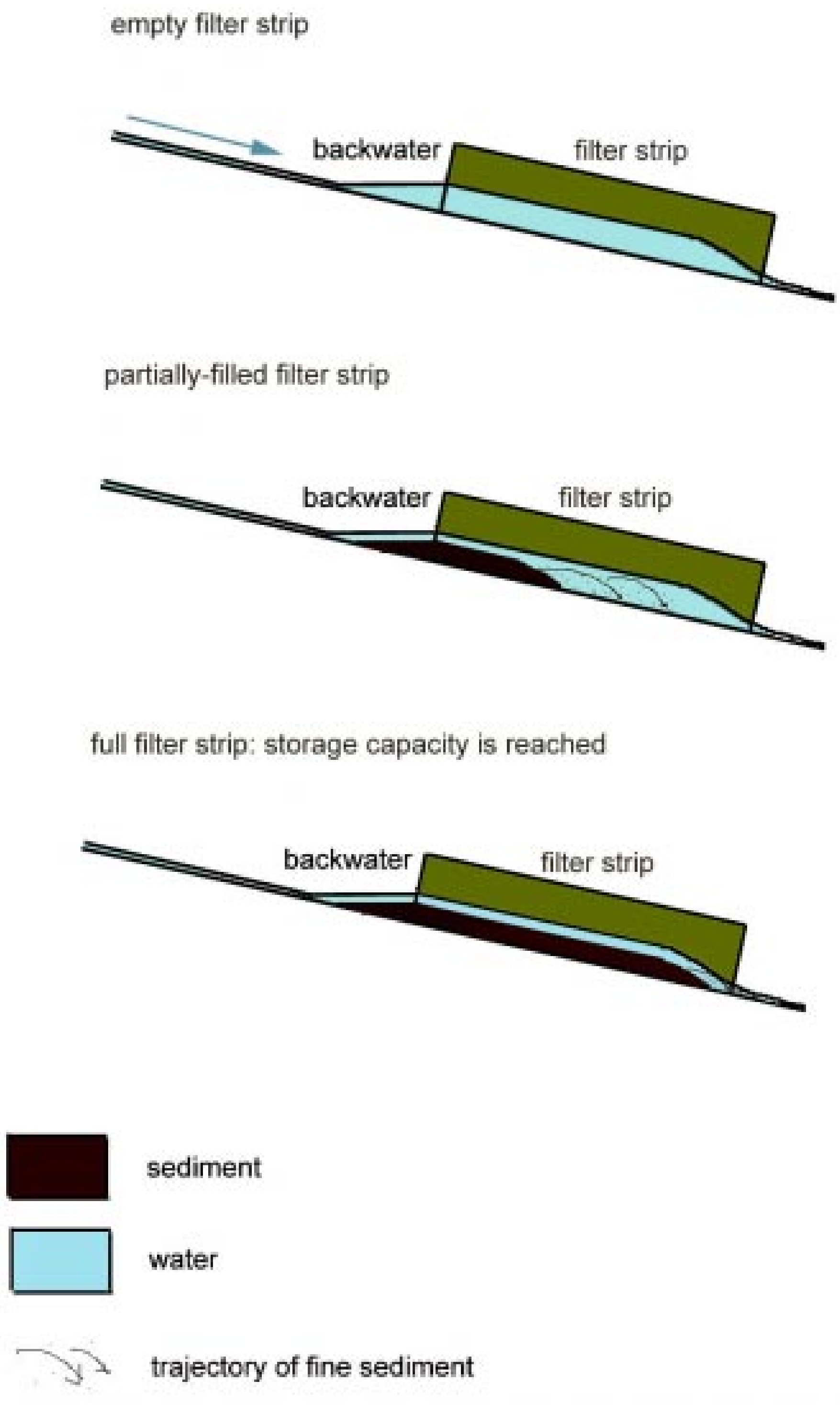

Figure 1. Grass filter showing backwater with forward growing deposit during trapping event.

A 100 % grass cover will trap sediment better than scarce grass because if grass is patchy the runoff can bypass the areas with a high roughness (Magette *et al*., 1989). Stock tracks are infamous in this respect, because they provide fast flow paths for runoff, usually straight down the hill towards the stream. Other important characteristics for grass filter species are to be perennial, resistant to flooding and drought, and able to keep growing after partial inundation.

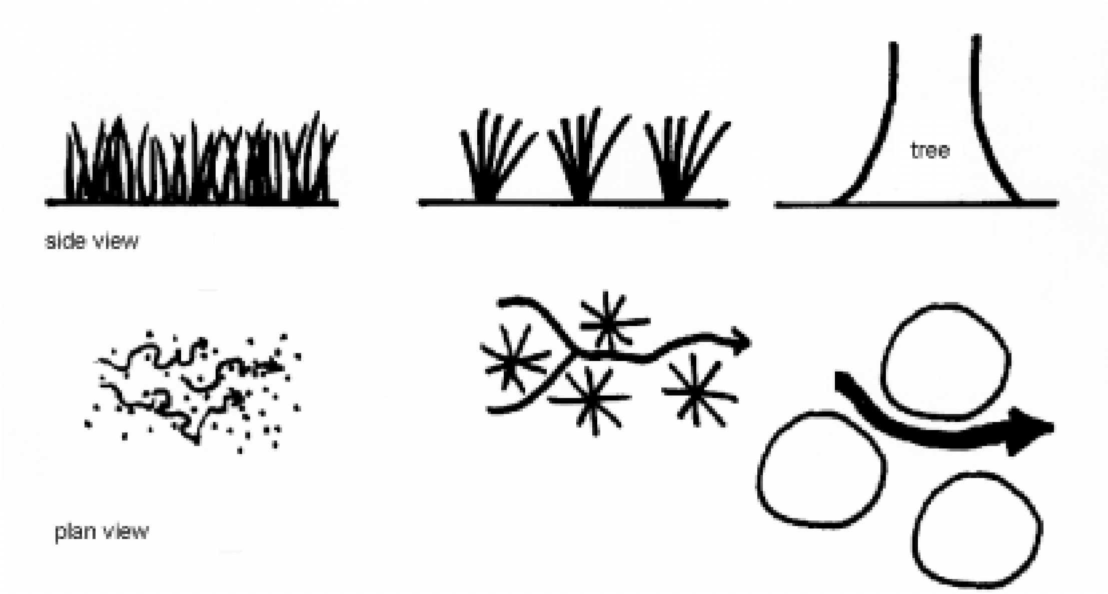

Figure 2. The vegetation density at ground level, and the way it can diffuse and slow down the flow are the main properties for filter strip vegetation. Dense, stoloniferous grass has the best properties for sediment trapping. (Thickness of arrow indicates flow velocity).

The height of the vegetation is important, since this affects the surface roughness. Heights of 10-15 cm have been recommended (Dillaha *et al*., 1986). Longer grass should not pose a problem, as long as the stem density near ground level is still high, and does not suffer from lack of light. Obviously, grasses that are highly invasive or are significant weed problems, such as para grass, should be avoided.

5.2 Sediment particle size

Filter strips are more effective at removing coarse sediment and aggregates than clay-sized or fine organic particles. Sand and large aggregates settle from the flow with a faster velocity and hence over a shorter distance. The very fine, often nutrient-enriched, clay particles have a much longer settling distance, because very little energy is needed to keep them in suspension. Fine particles can also be trapped by filtration of suspended solids and adsorption to plants and soil. These mechanisms are not well understood at this point (Lee *et al*., 1989) but provide additional trapping ability to that indicated by settling velocities.

The width of filter strip, *w*, required for sediment of settling velocity, *v*, to settle from suspension in a flow can be expressed by:

$$\frac{C_o}{C_i} = e^{-\left(\frac{v}{q}\right)x} \qquad (1)$$

where C_o/C_i is the ratio of the outgoing sediment concentration to the incoming sediment concentration, and *q* is the discharge per unit length of filter (Dabney *et al*., 1995). If a typical discharge through a strip is 1 litre per second per metre width, then simple settling theory indicates that 40 % of particles with a settling velocity of 0.001 m/s will be deposited in a 5 m filter and 99 % of particles with a settling velocity of 0.01 m/s will be deposited. This represents particles of fine silt to coarse clay diameter using Stokes Law to convert settling velocity to particle size.

Because filter strips are more effective at removing coarse sediment and aggregates than clay-sized or fine organic particles, increased filter capacity is necessary where the sediment is predominantly fine. This generally coincides with erodible soils which require wider filters overall. In situations where the clays travel in aggregate form the aggregates behave like coarse sand and high trap efficiencies are common. On-site conservation practices that preserve a good soil structure will diminish the width of the filters needed to trap fine sediment, and improve their overall effectiveness. In several filter experiments over 90 % of total sediment load was trapped, but only 10-80 % of total P was trapped, indicating that the fine particles with adsorbed P, are not trapped as efficiently as the coarser particles and aggregates (Hairsine, 1997).

5.3 Placement of filter

To be effective, a filter strip needs to be established or maintained at points where overland flow enters the stream. For effective sediment trapping the flow through a filter strip needs to be shallow, uniform and slow, and to disperse evenly through the filter. Filters can be quickly overloaded where overland flow concentrates within the catchment into narrow, fast flow. In these situations, flow only experiences a narrow zone of filter and the narrow filter thus receives a disproportionately large amount of sediment. The increased trapping requirement at sites with converging flow can be accommodated by installing wider filters that intercept the flow upstream before it concentrates (Figure 3). This leads to varying filter widths along a stream, depending on the amount of runoff and sediment received per metre length of riparian land. Where convergence is so strong that a natural drainage way forms before a stream, the entire area where flow concentrates should be a well-grassed waterway. Spring heads or areas where depressions, farm dams or disposal basins connect to the stream are such areas. In many instances the erosion of soil in drainage ways can produce as much, if not more sediment than is generated by the flow on adjoining agricultural land (Barling *et al*., 1988). In this case, a better method to reduce the amount of sediment leaving these areas would be to reduce on-site erosion as well as establish grassed waterways to safely convey the runoff water to the field outlet (Flanagan *et al*., 1989). In a similar way, in areas where little or no overland flow enters the channel, such as where there are natural levees, no filter strip is required for the purposes of sediment trapping.

5.4 Slope

For dense grass strips, it has been observed that the storage capacity within a grass filter is not noticeably affected by the slope of the filter, because the effect of slope on flow velocity within the grass filter is smaller than that of the high roughness of the dense grass strip (Karssies and Prosser, 1999). However, the storage capacity of the backwater decreases with increasing slope, as shown in Section 6 below, as the backwater extends further upslope at low gradients.

5.5 Filter strip width

A filter has reached full storage capacity when the grass is buried to sufficient extent that the flow can transport all the sediment it is carrying through the strip and no longer traps sediment. Wider filters logically have more area of grass that can be buried, thus the total amount of sediment that can be stored increases with filter width (Dillaha *et al*., 1988; Magette *et al*., 1989; Hairsine, 1997). The filter width required depends on the amount of sediment that needs to be trapped, and thus on soil loss rates and the actual length of filter over which that sediment is spread. Locations with high loads of sediment, either because of locally high soil losses or because flow has been concentrated, will require increased storage capacity and thus wider filter strips. Wider strips are also needed for fine sediment to settle from suspension.

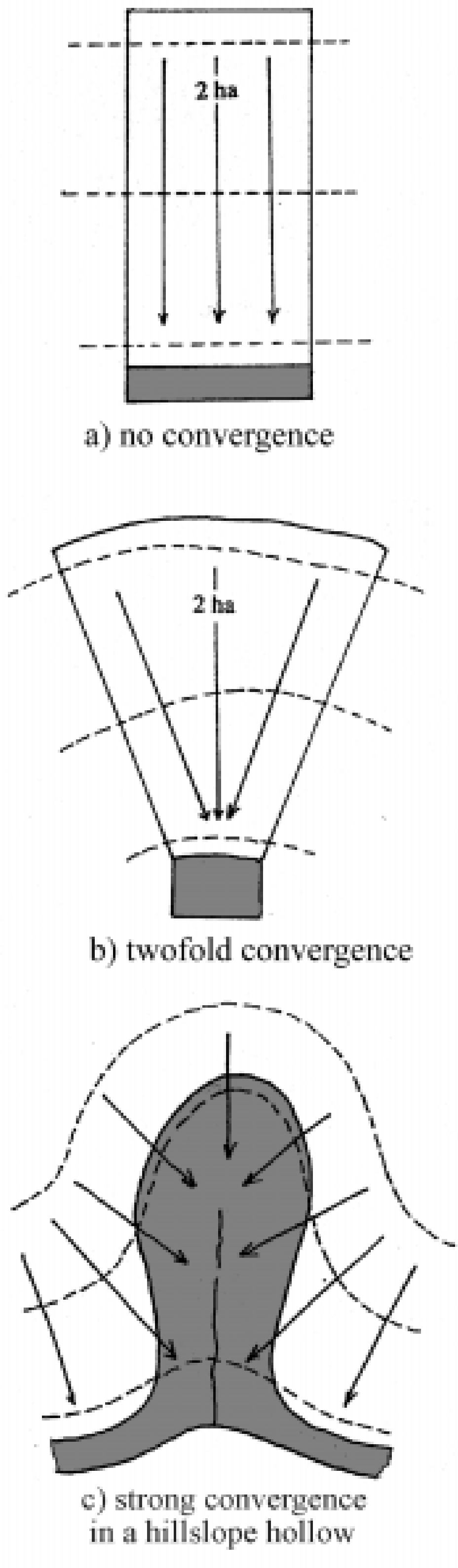

Figure 3. Convergent areas in the landscape require extra width.

6. CSIRO Experiments on Sediment Storage Capacity of Grass Filters

The design guidelines that we give below use sediment storage capacity of backwaters and grass strips measured in a set of flume experiments conducted at the CSIRO Land and Water over the last two years. To our knowledge they are the only filter strip results aimed at measuring storage capacities and thus are the best data for the designs. They are of course limited by the range of experimental conditions that were applied.

The experiments used dense grass strips of Kikuyu grass with a grass height of 15 to 30 cm. Flow resistance through the grass was similar to that obtained in other published grass strip experiments. The sediment applied was from a kraznozem soil used for potato cultivation. The soil was well aggregated with 10 % of material finer than 0.063 mm in diameter. Discharge was applied to the grass at a rate of 1.0 l/s across a one metre wide flume.

Results of the early experiments are given in Karssies and Prosser (1999). The average sediment storage capacity in the grass across all experiments with a 2 metre wide filter was 0.063 t/m^2 of grass strip. The sediment accumulated to an average depth of 9 cm in the grass. We found that particles smaller than 0.063 mm diameter were trapped effectively over a period of 2 hours in a 2 metre wide filter.

Sediment in the backwater formed a triangular wedge with a horizontal surface. Thus sediment storage in the backwater increases with decreasing gradient at the leading edge of the filter (Figure 4) varying from 0.035 t/m length for 18 % slopes and 0.160 t/m length for 6 % slopes. The average height of the wedge at the grass front was 13 cm, and the sediment deposit had a bulk density of 0.9 t/m^3.

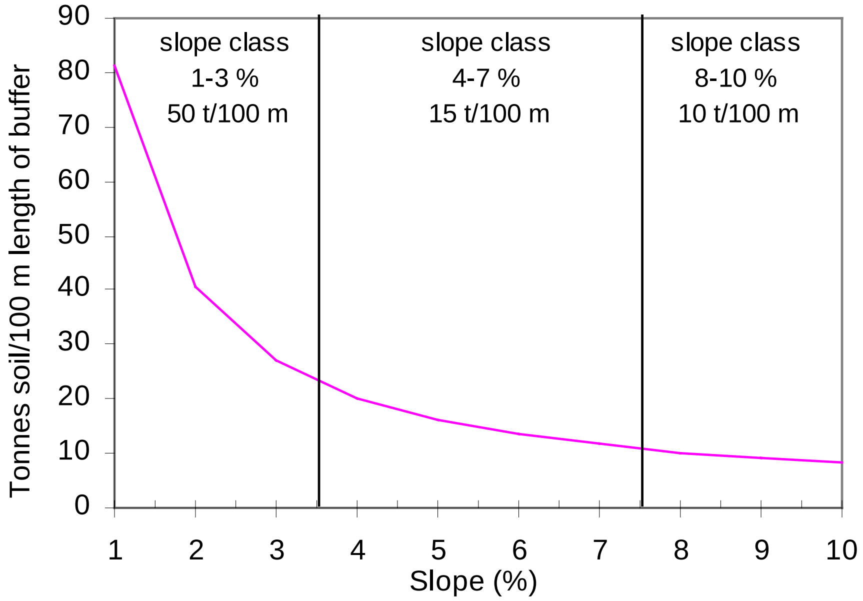

Figure 4. Backwater storage changes with slope of the grass filter. Based on unpublished experiments at CSIRO Land and Water, February 1999.

SECTION 3. DESIGN GUIDELINES FOR GRASS FILTERS IN QUEENSLAND

1. Introduction

The approach taken here to filter strip design, is to estimate the amount of soil loss that needs to be trapped at a location, and then design the filter to accommodate that soil loss. Average annual soil losses often occur during single erosion events. Gradual recovery of grass filters between erosion events guarantees a long-term effectiveness. Incorporation of sediment in the filter will not raise its height significantly within a generational time-span.

Indicative values of both soil loss and associated filter widths are provided across six biogeographical regions, encompassing varying soil type, rainfall, land use and topography within each region.

This section also describes the design procedure, so that for any location an effective filter width can be calculated given sufficient information on soil loss rates, paddock size, slope gradient, and the effective length of the filter strip.

2. Soil Loss

The average annual soil loss upslope determines the sediment loading supplied to the filter strip. We used the Universal Soil Loss Equation (USLE) to assess the average annual soil loss for a location (Wischmeier, 1978; Rosewell, 1993). Other models exist and may be more appropriate depending on the location, and local data from erosion monitoring should always be used in preference to a model such as USLE. However, monitoring results only cover a limited range of conditions and the results of monitoring across Queensland have not been synthesised and are not widely available. For these reasons, assessment across large diverse regions needs to be based on a predictive model. Comparisons of available data on annual soil loss in Queensland and our calculated values from the USLE suggest that the predictions yield realistic regional patterns of soil loss. Average annual soil loss (A) is a product of rainfall erosivity (R), soil erodibility (K), slope length and gradient (LS), cover and crop management (C) and the level of supporting practices applied (P):

$$A = RKLSCP \quad (2)$$

For the purpose of regional filter strip design we needed a range of typical values. Within each region we chose two to three typical values for *R*, *K*, and *S*. No regional information on P is available so this factor was set to a value of 1. Predictions were made for a slope length of 200 m and for two annual cover factors: C = 0.2, indicative of poor pasture or traditional tillage cropping; and C = 0.01, indicative of minimum tillage cropping systems or well-maintained pasture. Details of parameter selections used for predicting soil loss are given in Appendix 1. The regional patterns of soil loss predicted are given in Table 1.

3. Design of Filter Strip Width

Here we outline a procedure to design grass filter strips that can trap the average annual soil loss from a paddock. We use average annual soil loss as an indicator of the intensity of a typical large erosion event, as soil loss in any season is focussed in a few events at most. Such filters will be effective sediment traps over most conditions but will not be effective for extreme events such as 1 in 100 y recurrence interval events. Much wider filter strips are required for such purposes, as soil losses from extreme events can be many times the mean annual soil loss and can reach high levels, of the order of 300 to 700 t/ha (Edwards, 1993). For a cropping area in NSW, Hairsine *et al*. (1993) found that a 1 in 100 y event had a soil loss of almost ten times the average annual soil loss, while in the 20 years before that period the largest single event had been half the average annual soil loss.

To design a filter strip to trap the annual soil loss requires consideration of three factors:

1. The amount of sediment that gets stored in the backwater before the grass strip;
2. the width of grass required to store the remaining sediment; and
3. an additional width of un-impacted grass to trap as much of the fine suspended sediment as possible.

The width of riparian filter strip required for a paddock will depend upon the area of the paddock (a, ha), its annual soil loss (A, t/ha) derived from the USLE or other methods, and the length of riparian land into which the sediment is deposited (l_s, m). The total amount of sediment delivered to the riparian land is Aa (Figure 5).

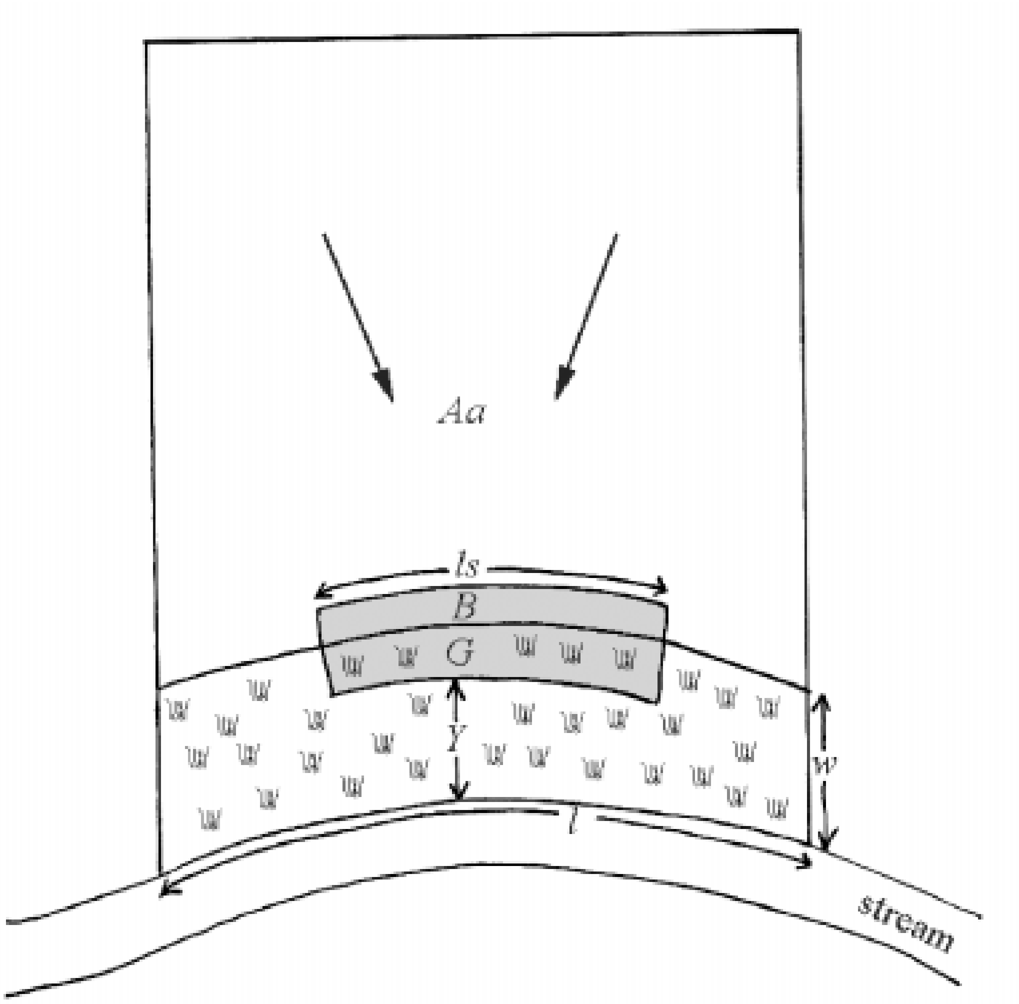

Figure 5. Definition of riparian filter strip at the bottom of a paddock of area *a*, with annual soil loss *A*. *B* = backwater sediment mass; *G* = grass sediment mass; *w* = filter width; *l* = filter length; l_s = length of deposit and *Y* = additional width required for settling sediment.

Sediment stored in the backwater forms a triangular wedge with an approximately horizontal surface. Consequently, the storage volume increases with decreasing gradient at the filter edge (θ, measured in degrees). The mass of sediment stored in the backwater (*B*, t) is the volume of the wedge multiplied by the average bulk density of the deposit (ρ_s, t/m^3). This can be expressed as

$$B = \frac{l_s \rho_s H^2}{2 \tan \theta} \qquad (3)$$

where *H* (m) is the sediment depth at the front of the grass.

Sediment encroaches into the grass as a depositional wedge. It buries the grass until a stage is reached when all sediment is transported over the deposit to the front of the wedge. Consequently, the wedge grows forward over time as the sediment storage capacity of each metre of grass is reached. We found the sediment storage capacity to be 0.063 t/m^2 of grass. It should be noted that the sediment density of deposits in grass is lower than that for most sediment deposits because of space filled by grass and entrapped air. The storage capacity within a grass filter (*G*, t) is:

$$G = 0.063 l_s w \tag{4}$$

where *w* is the width of the filter.

The total storage capacity of the backwater and grass must at least balance that of the supplied annual mass of sediment:

$$Aa = B + G \, . \tag{5}$$

Substituting equations (3) and (4) into (5) gives

$$Aa = \frac{l_s \rho_s H^2}{2 \tan \theta} + 0.063 l_s w \, . \tag{6}$$

Equation (6) can be rearranged to calculate the required width of filter strip. To this we add an additional width (*Y*, m) for trapping of fine suspended sediment beyond the sediment wedge. We used a value for *Y* of 2 m on low and moderately erodible soils, and 5 m for highly erodible soils with a high clay content. Rearranging equation (6) and adding *Y* gives

$$w = Y + \frac{1}{0.063}\left[\left(\frac{Aa}{l_s}\right) - \left(\frac{\rho_s H^2}{2 \tan \theta}\right)\right]. \tag{7}$$

The length of riparian land over which sediment is deposited is often much less than the total length of riparian land (*l*, m) along a paddock edge because of convergence of flow. This may result from topography or concentration of flow in plough furrows, stock tracks or other features. Thus we can express a convergence ratio (*c*) defined as

$$c = \frac{l}{l_s}. \qquad (8)$$

Substituting equation (8) into (7) gives the complete equation needed to design filter strip widths:

$$w = Y + \frac{1}{0.063}\left[\left(\frac{cAa}{l}\right) - \left(\frac{\rho_s H^2}{2\tan\theta}\right)\right]. \qquad (9)$$

In our experiments we found H = 0.13 m, and ρ_s = 0.9 t/m^3. For the purposes of designing indicative filter strip widths across Queensland we assumed a typical situation to be a 2 ha paddock draining into a 100 m long riparian filter at the bottom of the paddock and a convergence ratio of 2. Using these values and Y = 2 m, equation (9) reduces to

$$w = 2 + 0.636A - \frac{0.12}{\tan\theta}. \qquad (10)$$

This expresses the design width purely in terms of the predicted or measured annual soil loss and the gradient at the foot of the paddock. Values of filter width predicted by equation (10) are given for a range of typical soil losses and gradients in Table 2. Equation (9) can be used for other paddock configurations if these are known locally.

For the conditions simulated, table 2 shows that filter strips alone are not effective techniques alone to manage high soil losses (> 70 t/ha/y). If soil loss is reduced below 10 t/ha/y, however, design widths are not onerous impositions on agricultural land and aid in effective sediment management.

Equations (9) and (10) will give values less than *Y*, and in some cases negative values, where annual soil loss is less than the storage capacity of the backwater. For these cases *w* should be set equal to *Y*, the distance required to settle suspended particles.

4. Recommended Filter Widths

Filter widths for Queensland were calculated using equation (10) and indicative soil losses for each of six bio-geographical regions (Table 1). For highly erodible soils, *Y* was set to 5 m rather than 2 m. A filter width of 30 m was considered the maximum practical value. Two sets of predictions are shown in Table 1: those for C = 0.2 appropriate for degraded pasture and traditional tillage practises, and C = 0.01 appropriate for well maintained pasture and minimum tillage systems.

Table 1 predicts filter strips >30 m wide are needed in most cases where poor cover is associated with high rainfall intensity, steep slopes, or highly erodible soils. In these cases it is clear that installing a grass filter strip is not a practical method for controlling water pollution. It is interesting to note that if cover is improved then soil loss is reduced by up to an order of magnitude, and a filter strip of 10 m or less is satisfactory in most circumstances. This dramatic effect of improved soil management is supported by field evidence. Prove *et al*. (1995) found that soil erosion from conventionally cultivated ratoon canelands was 47-505 t/ha/yr, with an average of 148 t/ha/yr. Improved tillage practices reduced this erosion to < 15 t/ha/yr.

All values in Table 1 are based on the assumption of a convergence factor of 2. In areas of extreme convergence such as hillslope hollows, even a wide filter will not be a sufficient measure. Again, this is supported by field monitoring. McKergow *et al*. (1999) measured riparian filter strip performance in a situation where an area of 5 ha drained through a 1 metre long strip, indicating very strong convergence before the flow had reached the riparian land. No sediment was trapped in the filter strip and in some events the strip scoured and was a source of sediment. Our predictions indicate that a >30 m wide filter would be needed in that case, confirming the inadequacy of filters in such situations. For strongly convergent flow the filter strip needs to extend to the top of the hollow so that sediment is trapped before flow converges (Figure 3c).

Table 1. Indicative soil losses and design filter widths for the six bio-geographical regions of Queensland, for varying rainfall erosivity, soil erodibility, slope and land cover.

region (annual rainfall) (mm/y)	rainfall erosivity[1]	soil erodibility[2]	slope[3]	poor cover soil loss[4] (t/ha/y)	filter width (m)	good cover soil loss[4] (t/ha/y)	filter width (m)
WET TROPICS 800-5000	high	medium	low	17	7	1	2
			medium	41	26	2	2
			high	74	>30	4	2
		high	low	25	15	1	5
			medium	61	>30	3	5
			high	112	>30	6	7
	v. high	medium	low	29	15	1	2
			medium	71	>30	4	2
			high	130	>30	7	2
		high	low	44	27	2	5
			medium	107	>30	5	7
			high	195	>30	10	10
	extreme	medium	low	38	20	2	2
			medium	92	>30	5	2
			high	167	>30	8	2
		high	low	57	>30	3	5
			medium	138	>30	7	7
			high	251	>30	13	12
BURDEKIN 500-1200	high	low	low	8	2	0	2
			medium	20	13	1	2
			high	37	24	2	2
		medium	low	17	7	1	2
			medium	41	26	2	2
			high	74	>30	4	2
		high	low	25	15	1	5
			medium	61	>30	3	5
			high	112	>30	6	7
	v. high	low	low	15	5	1	2
			medium	36	23	2	2
			high	65	>30	3	2
		medium	low	29	15	1	2
			medium	71	>30	4	2
			high	130	>30	7	2
		high	low	44	27	2	5
			medium	107	>30	5	6
			high	195	>30	10	10

Table 1. continued

region (annual rainfall) (mm/y)	rainfall erosivity[1]	soil erodibility[2]	slope[3]	poor cover soil loss[4] (t/ha/y)	filter width (m)	good cover soil loss[4] (t/ha/y)	filter width (m)
BRIGALOW	medium	medium	low	8	2	0	2
500-1200			medium	20	13	1	2
			high	37	24	2	2
		high	low	13	7	1	5
			medium	31	22	2	5
			high	56	>30	3	5
	high	medium	low	17	7	1	2
			medium	41	26	2	2
			high	74	>30	4	2
		high	low	25	15	1	5
			medium	61	>30	3	5
			high	112	>30	6	5
SOUTH EAST	medium	medium	low	8	2	1	2
800-2000			medium	20	13	1	2
			high	37	24	2	2
	high	high	low	8	2	1	2
			medium	20	13	1	2
			high	37	24	2	2
		medium	low	17	7	1	2
			medium	41	26	2	2
			high	74	>30	4	2
		high	low	25	15	1	5
			medium	61	>30	3	5
			high	112	>30	6	5
WEST	low	low	low	2	2	1	2
150-500			medium	4	3	1	2
			high	8	6	1	2
		medium	low	4	2	1	2
			medium	9	5	1	2
			high	16	11	1	2
	medium	low	low	4	2	1	2
			medium	10	6	1	2
			high	19	12	1	2
		medium	low	8	2	1	2
			medium	20	13	1	2
			high	37	24	2	2

Table 1. continued

region (annual rainfall) (mm/y)	rainfall erosivity[1]	soil erodibility[2]	slope[3]	poor cover soil loss[4] (t/ha/y)	filter width (m)	good cover soil loss[4] (t/ha/y)	filter width (m)
CAPE	high	low	low	8	2	1	2
500-2000			medium	20	13	1	2
			high	37	24	2	2
		medium	low	17	7	1	2
			medium	41	26	2	2
			high	74	>30	4	2
	v. high	medium	low	29	15	1	2
			medium	71	>30	4	2
			high	130	>30	7	2
		high	low	44	27	2	5
			medium	107	>30	5	6
			high	195	>30	10	10

1. Rainfall erosivity R: low = 850, medium = 2000, high = 4000, very high = 7000, extreme = 9000 (see Table A1).
2. Soil erodibility K: high = 0.045, medium = 0.030, low = 0.015 (see Table A4).
3. Slope S: high = 9 %, medium = 6 %, low = 2 % (see Table A5).
4. Poor cover C = 0.2; good cover C = 0.01 (see Appendix).

5. Procedure for Assessing Riparian Filter Strips

The most important properties of riparian filter strips are the vegetation structure, the filter location and the filter width. Existing riparian zones should all be assessed on these principles.

5.1 Vegetation structure

Uniformly dense ground cover is essential, which is best provided by grass. If riparian lands are forested there only needs to be a grass strip between paddock and the edge of the forest. The grass should be stoloniferous, and have rhizomes, and cover the soil completely so that no soil can be seen between the stems. Examples are signal grass (*Urochloa decumbens*), kikuyu grass (*Pennisetum clandestinum*) and couch grass (*Elytrigia repens*). The grass density should be high, and the grass height should be over 15 cm. Uniform, shallow, slow flow is needed for filter strips to be effective.

5.2 Placement of filter

It is essential for any filter that it intercepts the flow of water and sediment coming down the slope. Be wary of convergence such as caused by cross slopes, because that can guide the

Table 2. Recommended grass filter strip widths (m) for typical values of annual soil loss and filter gradient under conditions of dispersed overland flow.

soil loss	filter strip slope (%)									
(t/ha/y)	1	2	3	4	5	6	7	8	9	10
1	2	2	2	2	2	2	2	2	2	2
2	2	2	2	2	2	2	2	2	2	2
5	2	2	2	2	3	3	3	4	4	4
10	2	2	4	5	6	6	7	7	7	7
20	3	9	11	12	12	13	13	13	13	14
30	9	15	17	18	19	19	19	20	20	20
40	15	21	23	24	25	25	26	26	26	26
50	22	28	30	>30	>30	>30	>30	>30	>30	>30
60	28	>30	>30	>30	>30	>30	>30	>30	>30	>30
70	>30	>30	>30	>30	>30	>30	>30	>30	>30	>30

water to one corner of the field, and cause the flow to bypass most of the filter. Dillaha (1989) advised that filters on incised hillslopes, where channelization occurs, are not useful. Slightly elevated filters also defeat the purpose, as they will not be able to intercept the flow.

5.3 Filter width

The minimum filter width in areas where any soil loss occurs is 2 m. The required width increases with the amount of soil loss, which in turn increases with slope, soil erodibility, soil erosivity and the amount of time that the soil is bare. To assess the width of existing riparian zones it is important to compare them with a designed filter width (see design procedure and Table 1 for indicative widths).

6. Best Management Practices

The various best management practices all relate to keeping up the desirable properties of a dense grass filter through time, but especially when erosion events can be anticipated. They are closely related to the properties that are assessed in existing filters.

Controlled stock access can avoid development of direct pathways for runoff from the paddock into the stream (stock tracks) as well as bank trampling. Benefits of controlled stock access include:

- improvements in water quality which can prevent toxic algal blooms and the spread of bacteria
- improvements in bank stability
- enhanced productivity: on-farm trials have shown improvements of up to 20 % in weight gain for stock drinking from piped water sources

- creation of a fodder reserve which can be utilised periodically and in times of drought (Bourchier, 1996).

Where stock access is controlled, all or most of the stream bank is fenced off, leaving a filter strip alongside the stream to trap sediment and limit the supply of sediment and nutrients to the stream. One or more off-stream watering points (using piped water) or restricted access points can be constructed (Figure 6). Fences allow control of the timing, intensity and duration of grazing on the banks (Department of Natural Resources, 1998). This so-called crash grazing in grass filters will not cause any permanent damage, but try to avoid it in periods of high rainfall and erosion potential, as the deterioration of the grass will temporarily make the filter less effective.

Occasional slashing is important to keep a uniform dense grass cover in non-grazed areas. A high stem, leaf and litter density at ground level is crucial, so leave the litter on the surface, where, wedged between grass stems, it forms an extra barrier for overland flow, that improves the quality of the filter.

Control weed growth. Weeds compete with the grass, and often do not provide a good filter, as their near-ground plant density is not as high as that of grass. Occasional slashing can assist with weed control.

Install grassed waterways up to the top of the hollow in areas of extreme convergence (Figure 3c).

Use accepted soil management techniques on all paddocks to maintain cover, good soil structure, and reduce erosion throughout the year.

Retain as much runoff on-site as possible. Runoff or sediment retention ponds are useful for this purpose. Essentially the aim is to increase the residence time of water in the basin to at least that of the time it takes sediment to settle out from suspension. For fine sediment this requires residence times of 24 hrs or more. Converting the basin into a constructed wetland by encouraging or planting wetland species such as rushes, reeds and sedges helps retain sediment and nutrients by further reducing flow velocities and by adhesion of fine sediment to the plant stems. There is a vast literature on the effectiveness of constructed wetlands for sediment and nutrient control. Wetlands are effective at trapping P bound to sediment but are less effective at trapping the more soluble forms of N.

A controlled overflow structure is needed for retention basins and this should be designed as a grass filter strip to prevent scour and encourage further sediment trapping. The design should follow the same principles as those outlined above. The flow should be spread over the greatest width possible and be conducted from the pond at low gradient.

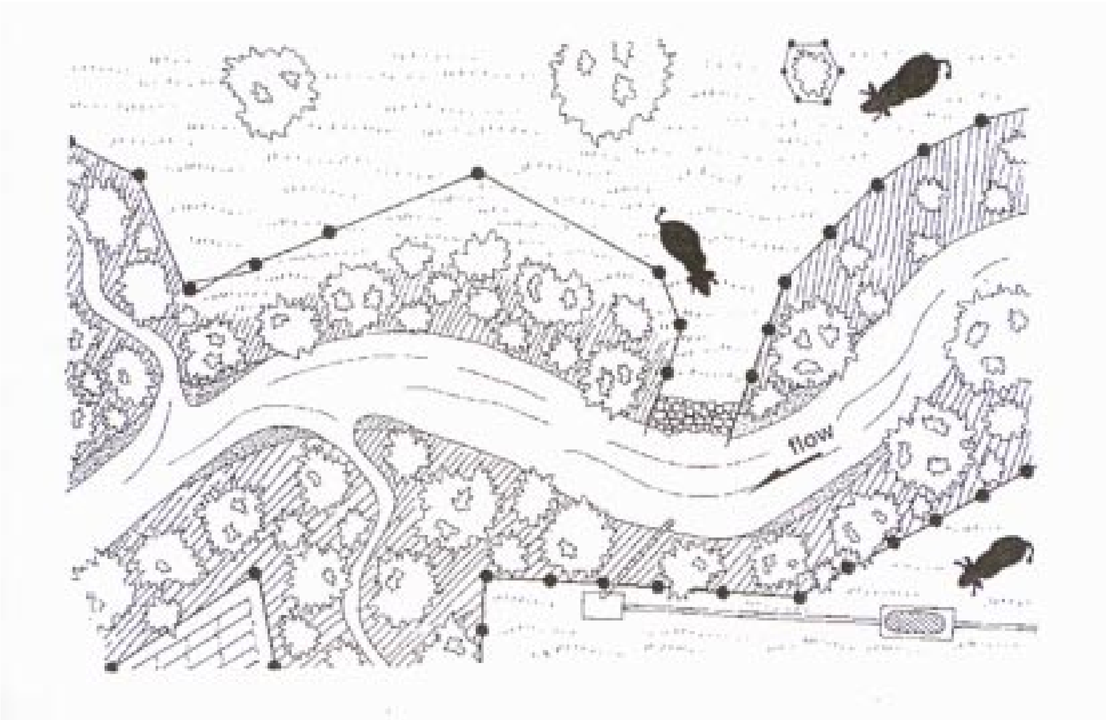

Figure 6. Two types of controlled stock access: a restricted access point (top of diagram) and an off-stream watering point (bottom of diagram). (DNR, 1998).

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APPENDIX 1
CALCULATION OF SOIL LOSS USING THE USLE

1. Average Annual Soil Loss

Average annual soil loss (A) is a product of rainfall erosivity (R), soil erodibility (K), slope length and gradient (LS), cover and crop management (C) and the level of supporting practices applied (P):

$$A = RKLSCP\,. \qquad \text{(A1)}$$

2. Rainfall Erosivity Factor

R is determined by the amount of rainfall and the kinetic energy with which it falls. It is calculated from the maximum 30 minute intensity, as this is an appropriate timescale for generating erosion. Rainfall erosivity, in MJ.mm/(ha.h.year), was derived from the isoerodent maps provided by Rosewell (1993; Figure A1). Typical values of R for each region were used as shown in Table A1.

Table A1. Rainfall erosivity factors used in this document (Rosewell, 1993)

Region	Annual rainfall (mm/yr)	Range of rainfall erosivity used in MJ.mm/(ha.h.yr)
Wet Tropics	800-5000	4000, 7000, 9000
Burdekin	500-1200	4000, 7000
Brigalow	500-1200	2000, 4000
South East	800-2000	2000, 4000
West	150- 500	850, 2000
Cape	500-2000	4000, 7000

The values mentioned above were based on 2-year, 6-h rainfall intensity data (Rosewell, 1993). This approach does not allow determination of the seasonal distribution of rainfall erosivity. For tropical sites, rainfall erosivity is highly seasonal with a single peak in February. Summer months (November-April) typically contribute about 90 % of the R factor. A daily erosivity model performs better in these cases, but requires long term daily rainfall data which is often not available (Yu, 1998). The R factors of Rosewell (1993) are a good approximation, but deviations will occur in places.

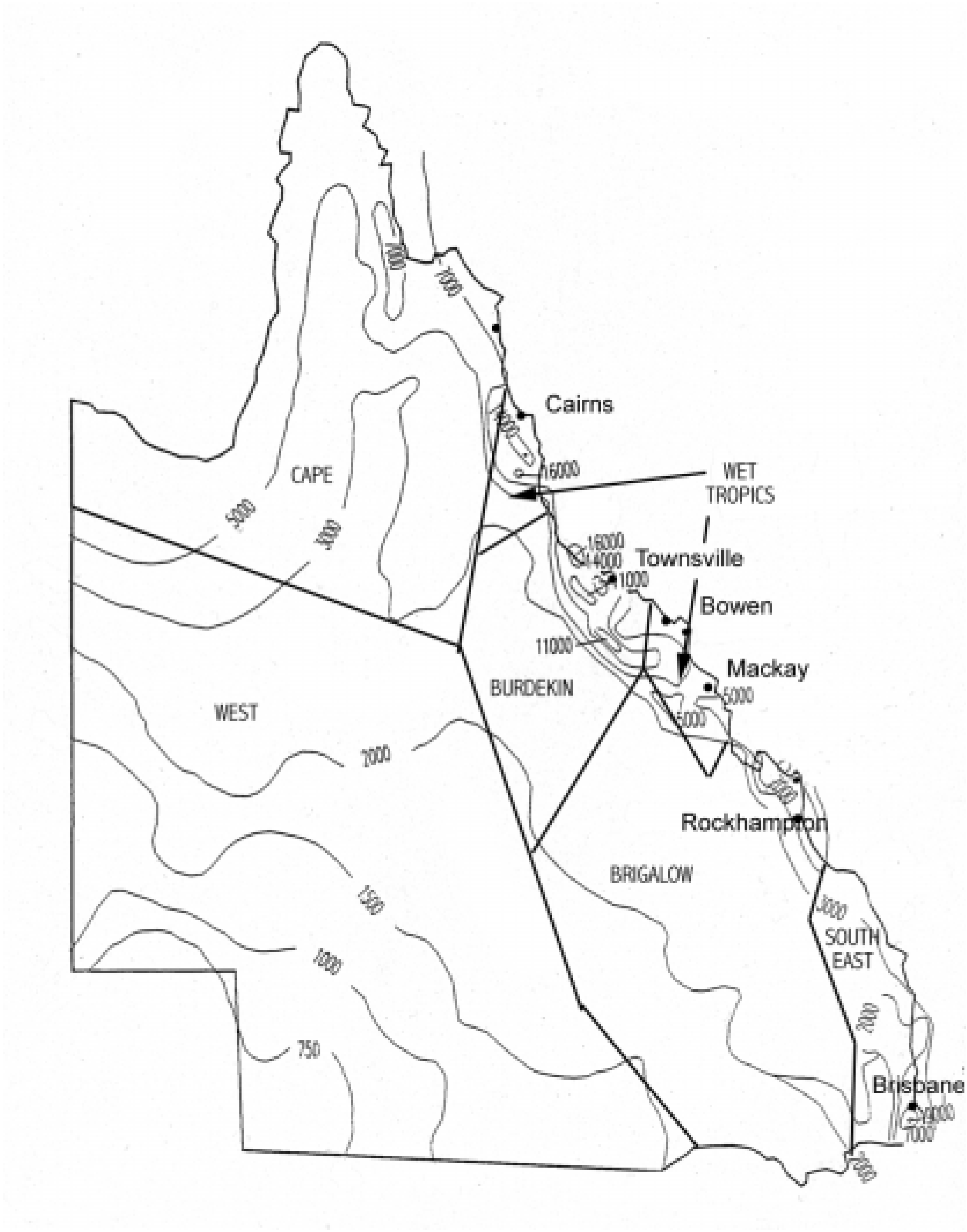

Figure A1. Rainfall erosivity factor R for Queensland in MJ.mm/(ha.h.yr) (Rosewell, 1993).

3. Soil Erodibility Factor

K is very important for assessing soil losses. The soil texture determines how easily the dislodged soil particles can be transported by overland flow. Fine particles such as clay are the most easily transported. Soil structure controls drainage and water storage. Well-structured soils that have high infiltration capacity and water storage capacity are less likely to cause runoff then poorly structured soils. If well-aggregated soils erode, the size of the aggregates will determine the ease with which they are transported and trapped. Some aggregates readily break down when wet, and these erode easily. Soil organic matter content affects the strength of the bonds within aggregates, and a higher organic matter content means stronger aggregates and lower soil erodibility. The K factor in the USLE is an overall measure of the resistance to soil of sheet and rill erosion. For Australian soils, soil mapping units from the Atlas of Australian Resources-Soils (Division of National Mapping, 1980), have been assigned a K factor on the basis of an assessment of surface soil texture, organic matter content, surface soil structure and profile permeability of the dominant soils in the mapping unit (Rosewell, 1997). Table A2 shows some examples of soil types and their associated K factors.

Table A2. Soil erodibility factors (Division of National Mapping, 1980; Rosewell, 1997)

Soil type	K factor
black and red brown earths	0.05
duplex soils	0.05
cracking clays	0.05
solodic soils	0.03
shallow loam soils	0.03
massive earths	0.03
podzol	0.03
non-calcic brown soil	0.02
structured earths	0.02
structured loam soils	0.02
saline soils	0.01

An alternative method to estimate K, is to base it on surface soil texture and assume an appropriate organic matter content (Table A3). Soil texture data are not available on a widespread scale (Rosewell, 1993). In this document three erodibility classes have been considered, using soil groups and their assigned K factor values (Table A4; Rosewell, 1997). Direct measurement of the K factor is both costly and time-consuming and has been done only for a few sites in Queensland (Loch, 1984).

Table A3. Estimating USLE K factor from soil texture (based on Rosewell, 1993)

Soil texture	Suggested K Factor
sand	0.015
clayey sand	0.025
loamy sand	0.020
sandy loam	0.030
fine sandy loam	0.035
sandy clay loam	0.025
loam	0.040
loam, fine sandy	0.050
silt loam	0.055
clay loam	0.030
silty clay loam	0.040
fine sandy clay loam	0.025
sandy clay	0.017
silty clay	0.025
light clay	0.025
light medium clay	0.018
medium clay	0.015
heavy clay	0.012

Table A4. Erodibility factors (K) used in this document

Ranking	Average value used in USLE
low	0.015
moderate	0.03
high	0.045

4. Slope Length and Gradient Factors

L and S are topographic factors that influence soil loss. Soil loss increases with slope steepness and hillslope length, as sediment is transported faster on steeper slopes, and longer hillslopes allow more soil to be eroded. The slope length and gradient factor LS was derived using a nomograph developed by Wischmeier (1978).

For filter strip design a standard hill slope length of 200 m was used, as there is no information available on patterns of hillslope length in each region (Table A5). Because the focus of this exercise is on irrigation areas, only slopes from 1 to 10 % were considered. Much irrigated land is on floodplains with very low slopes, where slope and hillslope length are relatively unimportant. Even in these areas, the place where runoff drains into the stream, can still cause stream pollution. These vulnerable areas need to be recognised, and should contain filter strips.

Table A5. Slope steepness and length factors (LS) used in this document, assuming a 200 metre long hillslope.

Normative value	Slope	Average value used in USLE
low	1-3 %	0.7
moderate	4-7 %	1.7
high	8-10 %	3.1

5. Cropping Phase and Productivity Level Factor

C refers to the role of vegetation in protecting the soil. Cover acts as a blanket so that most of the erosive energy of rainfall is dissipated before the soil is affected. A bare soil has a maximum susceptibility to erosion, while any degree of cover, including stubble retention, protects the surface. In most cropping areas the soil is bare for at least part of the year. Pasture provides a very effective protection from erosion. In irrigation areas the pasture will likely be of good quality, and sheet erosion is unlikely. The cropping phase and productivity level factor (C) is one of the most complicated factors in the USLE. It is defined as the ratio of soil loss from land maintained under specified conditions to the corresponding loss from continuous tilled bare fallow. It measures the combined effect of all the interrelated cover and crop management variables. The value of C is usually expressed as an annual value for a particular cover and crop management system but is calculated from the soil loss ratios for short periods of time over which the cover and management effects are relatively uniform. For annual crops the most crucial aspect is whether the time of year when the soil is bare coincides with high rainfall erosivity.

For a detailed method of estimating the C value, the user must have knowledge of the distribution of erosivity throughout the year, and must use information on stubble management methods, type of machinery, cultivation and sowing dates, crop type and potential yield (Rosewell, 1993). This level of detail is beyond the scope of this document, and for illustrative purposes an average annual C of 0.2 has been used. This is based on traditional tillage practices, with the soil being bare for some periods, partially covered with a crop the remainder of the year. Importantly this value can be lowered to close to 0.01 when improved tillage practices are used. The C factor for permanent pasture may be estimated from the long term average ground cover e.g. a cover of 80 % has a value of 0.01, a cover of 40 % has a value of 0.1. We have used annual C values of 0.2 and 0.01 as indicators of soil loss for good and poor cover management respectively in each region.

6. Practice of Cultivation

P refers to the presence of contour banks and other earthworks that are designed to reduce soil loss. No supporting practices were considered in the construction of Table 1 and thus a P factor of 1 was used.