Liro Forestry Solutions

PROJECT REPORT

PR - 90

2000

EFFECTIVENESS OF VEGETATION AND RIPARIAN BUFFERS IN REDUCING SEDIMENT TRANSPORT: A REVIEW

Pieter J B Fransen

Sala Street
Private Bag 3020
Rotorua
New Zealand
Phone
07 348 7168
Fax
07 346 2886

Leading Edge Forestry Solutions

Liro - Forestry Solutions
Private Bag 3020
Rotorua
NEW ZEALAND

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For information, please contact ***Liro – Forest Research,*** Private Bag 3020, Rotorua, New Zealand.

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Summary

Scientific knowledge on the effects of vegetation and riparian buffers on sediment movement was collated from New Zealand and mainly the United States to assist the New Zealand forestry and agricultural sectors in assessing environmental effects on water quality.

This report presents firstly a brief overview, and secondly a compendium of twenty-nine published accounts briefly describing characteristics of research sites, methodologies, and findings. Extrapolation of research findings to other areas should be treated with caution due to the site specific nature of physical and biological interactions, processes, and scale effects, and the type of research undertaken. However, an understanding of the physical effects of vegetation in reducing sediment loads by water erosion is an advantage for practical land and water management.

Research has shown that vegetation is generally effective in reducing sediment movement. A significant factor in sediment trapping effectiveness is the type and spacing of ground cover. Piles of logging slash or brush have been shown to significantly reduce sediment travel distance from forestry roads to less than 10 m. However, a significant proportion of sediment entering vegetation or riparian strips is trapped within 2 m. Where concentrated channel flow occurs, forest, shrub, or grass buffers are less effective or not effective at all. Riparian buffers may be a source of sediment depending on site conditions.

A positive aspect of logging on hilly terrain is the tendency for slash to accumulate on the lower slopes and gully bottom. Slash, along with other erosion control practices, will greatly reduce erosion and retain sediment on slopes. The implementation of riparian vegetation strips to reduce sediment from upslope may not be necessary. However, riparian vegetation buffers may be important at sites where stream banks are at risk from log-hauling disturbances and subsequent erosion of bared soils.

Introduction

Riparian buffers are that strip of land which separates upland soils (e.g. on forested and agricultural lands) from streams, rivers, lakes and wetlands (Gilliam et al., 1992). The riparian buffers provide shade, food and shelter for stream life, protects against excessive stream-bank erosion and reduces sediment inputs from upland areas. Natural riparian buffers commonly comprise a mixture of forest plants and trees, grasses and sedges, and wetland plants. Loss of vegetation in the riparian zone is generally viewed as a threat to the health of streams. Destruction of riparian vegetation and excessive soil disturbance in the riparian zone has occurred chiefly through forest removal by logging operations, land clearance by burning, and subsequent stock grazing in pastoral lands. With widespread decline in the quality of water and stream life, protection and restoration of vegetation in the riparian zone has become an important issue. In New Zealand, riparian management has been practised for a range of land uses for over 20 years (Quinn et al., 1993). An example is the protection and establishment of riparian vegetation in the Lake Taupo catchment in the 1970's by the local government agency (Smith, 1989) .

Riparian management continues to be a major issue. Some government agencies stress the need for catchment-wide protection of streams by establishing riparian vegetation buffer strips. This affects both agricultural and plantation forestry land owners. For the plantation forest industry there is at issue the need to establish riparian vegetation buffers, given that the land is managed for production forestry. It has been argued that establishing catchment-wide riparian buffers would cause a substantial loss of productive area and increased harvesting and roading costs. The result could be a negative environmental effect through increased forest road erosion due to additional roading with increasing riparian buffer area requirements (Visser and McConchie, 1993).

Scepticism about the effectiveness or applicability of riparian vegetation buffer zones arises from the lack of scientific research across a range of sites and the lack of standards or accepted methods for buffer zone design (Dillaha and Inamdar, 1997). Important issues regarding riparian buffers relate to their role, placement, size or width, vegetation type and effectiveness, the physical processes involved, and how often the buffer needs to perform (Barling and Moore, 1992; Quinn et al., 1993). Unless these are identified it will be impossible to determine whether a buffer strip is an appropriate management strategy for a given problem (Barling and Moore, 1992).

Research objectives

Determining the optimum design and protective function of riparian buffers was identified as a high research priority for sustainable production forestry in New Zealand (O'Loughlin and Warrington, 1997). To this end, ***Forest Research*** currently manages a riparian research programme that aims provide a set of management and planning tools to reduce potential impacts on the stream environment. One aim of this research is to examine the ability of riparian zone vegetation to filter sediments.

The reduction of sediment yields associated with harvested operations continues to be an important concern for forest managers. While a brief review of literature on riparian buffers in

New Zealand forestry was carried out by Gilliam et al. (1992), this report presents a comprehensive review of sediment trapping effectiveness of vegetation filters and riparian buffers. The report:

- collates and summarises scientifically researched findings
- identifies physical properties affecting the effectiveness of buffers to trap and filter sediments
- identifies information gaps on riparian buffer strips and their performance in relation to sediment movement

A range of studies have determined the reduction of sediment movement through buffers with varying widths and ground cover such as forests with associated litter, grasses, shrubs, and slash (Table 1). Although the main topic of interest is riparian buffers in forestry areas, much work has been carried out on agricultural lands, which may also have relevance to forestry riparian management. Most research has focused on riparian or lower slope areas with the exception of some vegetative filter plot studies. This review also covers studies on sediment movement from forest roads and the factors affecting the distance that sediment travels. The road sediment studies did not specifically test the effectiveness of riparian vegetation buffers. However, the studies did provide information on the potential impacts of roads to the riparian zone and streams and implications for planning of forest roads.

This review focuses on scientific studies, rather than riparian management guidelines with no supporting science-base evident (although some of these studies did go further to develop specific guidelines). Thus, specific riparian management decisions could evolve for New Zealand forestry interests using information from these studies.

Table 1. Number and type of sediment filtering studies.

Land Use	Forestry				Agricultural				
Buffer type	forest	slash	grass	various	grass	crop	forest	various	total
Catchment studies	7						1		8
Plot & hillslope studies	1		1		7	1		2	12
Sediment travel distance	3	2		2					7
Radio-isotope study							1		1
Interviews								1	1
									29

Overview

Catchment-scale studies

New Zealand research on the effectiveness of riparian buffers to reduce sediment in runoff from forest lands is limited to three catchment-scale studies in the Nelson-Westland region (Graynoth, 1979; O'Loughlin 1979, Pearce and Griffiths, 1980). Stream sediment concentrations or yield data were presented. O'Loughlin (1979) also included trapped sediment yields. No information exists in New Zealand on volumes of sediment trapped by vegetative buffers or minimum effective widths.

Experimental post-harvest riparian buffer widths were 20-30 m. Graynoth (1979) noted that the buffers were generally effective in protecting the stream from upslope sediment inputs, although these inputs were not measured. Graynoth (1979) and O'Loughin (1979) concluded that the buffers were not effective in reducing the amount of sediment carried in storm flows from skidder tracks and landings. Even a 150 m wide buffer could not prevent sediment laden flows from a skid site reaching the stream. However, in South Westland, no differences in suspended sediment concentrations were found during storm events between unprotected streams and a stream left with a 20 – 50 m wide undisturbed protection zone in selectively logged indigenous forest (Pearce and Griffiths, 1980).

Riparian forest buffers may also potentially be a source of sediment. As reported by Smith (1992) in New Zealand, and Daniels and Gilliam (1996) in the U.S. channelised storm flows within a forest buffer removed litter and exposed surface soil. However, Daniels and Gilliam (1996) showed that low sediment yields (from a U.S. agricultural study site) can be reduced in a sparsely vegetated forest buffer along an ephemeral channel.

In the U.S. most catchment-scale studies had stream-side forest buffer widths of 10-30m. Results showed that most of the time, riparian buffer strips were effective in reducing sediment concentrations and/or yields in storm flows, and when best management practices were applied to carefully manage logging and roading effects (Aubertin and Patric, 1974; Snyder et al., 1975; Lynch et al., 1985; Shaffer and Mostaghimi, 1997). Many of these U.S. catchments had lower average slope gradients (2 - 17°; *3.5 -30.5 %*) compared to the New Zealand studies (17-36°; *30.6 - 72.6 %*).

Optimum riparian buffer width has not been addressed using catchment-scale field studies to date. This may be due to limited site opportunities, logistic difficulties, and high research costs. In an alternative approach, Bren (1999) used a geographic information system (GIS) to study the effect of three geometric methods of buffer design at the catchment scale. Results showed that constant buffer widths, while simple, do not take into account the complexities of hydrologic loading. The more rigorous methods computed asymmetric and widely varying buffer widths. Riparian buffer widths increased upstream, and the shape of the buffer was dominated by the shape of the upslope catchment. Future buffer design methods and implementation will require a much better level of topographic mapping, GIS capabilities, a compromise between scientific methods and the need for simplicity of design by management, and political judgement (Bren, 1999).

Micro-catchment and plot studies

No accounts were found of hillslope-scale studies within harvested areas on the effectiveness of riparian buffers to trap sediment in New Zealand or the U.S. Only two accounts provide information for forested lands in the U.S.

Heede (1990) found that nearly all sediment was withheld by forest buffer strips regardless of vegetation type. Concentrated sediment deposits accumulated upslope of the buffer strips, which were up to 20 m wide, and decreased rapidly on entering the strips. Despite great variability in sediment delivery from bare source areas, there were still significant differences in sediment trapping ability between sites with and without buffers, and undisturbed forests (Figure 10, Appendix 1). On steep 30° slopes in chaparral a buffer strip of 2 m width was effective, but on 14° slopes in ponderosa pine the effective buffer width ranged from 7 to 25 m. Other factors were not described to explain this observation.

Pearce et al. (1998) used a rainfall simulator and introduced sediment to runoff to determine sediment trapping effectiveness of grass and sedge on 2-3° riparian slopes in a Colorado national forest. The simulated inputs of rainfall and sediment were greater than natural levels. The grass buffer plots of 2 and 10 m width respectively filtered 88 -98% and 99% of the incoming sediment. Pearce et al. (1998) also found that particle size distribution of sediment in overland flow directly influenced sediment yield; finer particles moved through riparian buffer zones better than larger particles. They concluded that assessment of particle size distribution of upland sediment helps to determine appropriate vegetation filter width.

Sediment from forest roads

Unsealed forest roads (arterial and those used during logging) are constantly exposed to erosive forces and are therefore a significant source of sediment. Sediment laden surface runoff from roads are diverted to drains, culverts and cut-outs and discharged downslope. Erosion increases when runoff is discharged over road and landing fillslopes and diverted into swales, gullies and streams. Research on sediment travel distance from forest roads has been mainly carried out in the U.S.

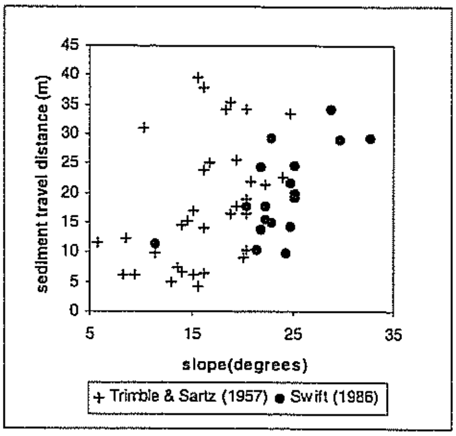

Figure 1. Sediment travel distances below culvert outlets. Data of Swift (1986) represents averages for various fillslope cover treatments.

Sediment travel distance data from road sources has been used to plan the location of new roads relative to streams. For discrete sediment sources (such as from culverts), the sediment travel distance essentially represents a default buffer width. Two early studies found wide variation but a general increase in sediment travel distance with increasing slope (Figure 1; Trimble and Sartz, 1957; Swift, 1986). Average sediment travel distances from roads ranged from 10 - 40 m for various regions in the US (Trimble and Sartz, 1957; Haupt, 1959; Swift, 1986) with maximum distances of up to 200 m. The probability of sediment travelling a designated distance has been proposed as a criteria for planning road positions relative to streams. For example, Burroughs and King (1989) found that 50% of culverts had sediment transport distances over 23m, and 80% had distances of at least 53m.

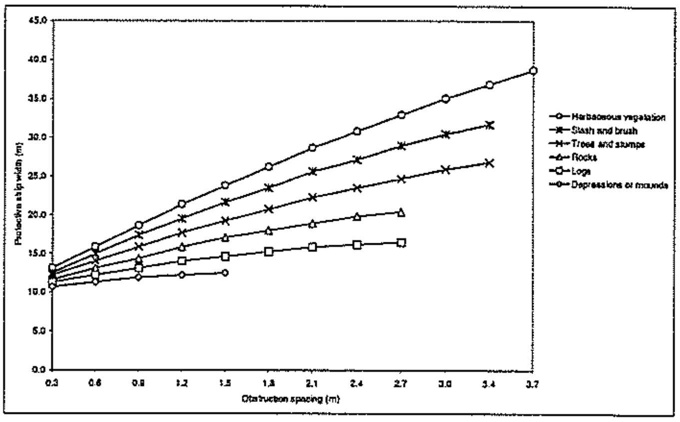

Figure 2. Protective strip widths (based on the average width plus one standard error of sediment travel distance from outlets of cross road drains, or 83.5% of sediment flows) downslope from the shoulders of logging roads built on basaltic soils, having 9.1 m cross drain spacing, 100% fill slope cover density, and zero initial obstruction distance under varying obstruction type (from Packer, 1967). See also page 19 in the Appendix I for additional effects on sediment movement distance.

Differences in sediment travel distances from road cross drain outlets occur between regions, type and density of obstruction or ground cover, and type of road management practice (Packer, 1967; Swift, 1986; Burroughs and King, 1989; Ketcheson and Megahan, 1996).

Obstruction type and spacing is a significant factor, accounting for 33% of the variation in sediment travel distance (Figure 2, Packer, 1967). Sediment transport distances from cross drain outlets increased as spacing between obstructions increased and as the sediment trapping effectiveness of obstructions decreased.

Slash or brush barriers and windrows were found to be very effective sediment traps compared to other types of road-fill treatment (Cook and King, 1983; Swift, 1986; Burroughs and King, 1989). Average travel distances of fill material below slash/brush barriers range from 1 to 11m. Packer (1967) also determined the effect of the proportion of soil aggregate size, cross-drain spacing, and road age, on sediment travel distance (see Appendix I).

In New Zealand, harvesting residue or slash, is potentially a significant obstruction to sediment movement on slopes and within riparian zones. Lower slopes and gully floors on cable logged settings have high concentrations of wood (up to 180 m^3/ha) compared to sideslopes (c. 60 m^3/ha), (Hall, 1999). Low sediment yields in a cable logged catchment without a buffer were attributed to sediment entrapment among thick slash within the stream channel (Table 3 - Appendix I; O'Loughlin, 1979).

Agricultural sites with buffers

New Zealand studies by Smith (1989, 1992) looked at the sediment trapping effectiveness of retired pasture-only buffers, and afforested buffers on pastoral land, in the Waikato and Nelson regions. The afforested buffer was 25-35 m wide and retired pasture buffer 10-12 m wide. The retired pasture buffer sites reduced suspended sediment concentrations by 50-60% (Smith, 1989). For the riparian afforested catchment study, Smith (1992) found that annual sediment exports were 31-60% less from the pasture only catchment. Higher sediment exports from the densely planted pine buffer site was attributed to a lack of ground cover and dried up wetland.

Research on agricultural lands (U.S.) has not covered a wide range of slopes, ground cover types and filter/buffer widths that are relevant to steep forested land. Most riparian buffer or vegetation filter strip (VFS) studies have been conducted on agricultural sites using natural or simulated rainfall-runoff plots. Research plots with filter strips ranged from 0.6 to 27.4 m wide on gentle to moderate slopes (1-11°). The performance of VFS is usually overestimated in plot experiments, but tend to be partially offset by the simulation of extreme rainfall events (Dillaha et al., 1989a). However, similar study site conditions are unlikely to be found in logged areas. Cultivated agricultural land is potentially a greater source of sediment compared to slash covered harvested forest land. Vegetation filters on steeper slopes would reduce sediment load, but to a lesser extent than easier slopes (Daniels and Gilliam, 1996). Grass filters 6m wide were found to be as effective as 13-18 m wide buffers comprising grass and riparian forest strips with access lanes (Daniels and Gilliam, 1996). Robinson et a.(1996) found 3m wide grass filters removed more than 70-80% of the sediment from runoff. Old grass was more effective in reducing erosion than young grass due to differences in grass density (Van Dijk et al., 1996). Investigating alternative pollution management treatments Young et al. (1980) showed that cropped buffer strips were effective in reducing feedlot runoff and solids.

Pertinent observations from agricultural studies about the effectiveness of riparian buffers in reducing sediment load are generally applicable to all slopes and land uses:

- forested riparian buffers generally reduce sediment from diffuse surface runoff (Schlosser and Carr, 1981; Peterjohn and Correll, 1984; Cooper et al., 1987; Daniels and Gilliam, 1996).
- forested riparian systems (with sparse forest groundcover) and VFS do not effectively reduce sediment loads from concentrated flow and consequently are ineffective for improving stream water quality (Dillaha et al., 1989b; Daniels and Gilliam, 1996; Smith, 1992)
- riparian buffers do not need to be very wide as a substantial amount of sediment is trapped at the upslope edge and decreases rapidly on entering the buffer (Neibling and Alberts, 1979; Cooper et al., 1987; Dillaha et al., 1989a,b; Heede, 1990; Daniels and Gilliam, 1996). The effective width indicated in the literature is about 1-3m.
- buffer effectiveness varies with the erosiveness of the catchment and storm intensity (Daniels and Gilliam, 1996)
- vegetative filter strips may become less effective in reducing sediment losses with time; as more and more runoff events occur, sediment accumulates and buries the VFS (Magette et al., 1989; Dillaha et al., 1989a,b)
- ephemeral riparian channels need a continuous vegetative cover to be effective filters (Daniels and Gilliam, 1996)
- riparian buffers and vegetative filters effectively reduce sediment particle size as it passes through the buffer strip (Cooper et al 1987; Pearce et al., 1998)
- wider or longer buffer strips may be important in lowland floodplain areas to trap suspended sediments (Cooper et al, 1987; Magette et al., 1989)
- the effectiveness of VFS diminishes as the ratio of vegetated to unvegetated area decreases or slope length increases (Magette et al., 1989; Dillaha et al., 1989a)
- poor land management practices reduce the effectiveness of VFS (Dillaha et al., 1989b)
- natural and man-made barriers - and practices to encourage rapid vegetative cover to reduce runoff - are effective in reducing sediment loads to riparian areas and streams

Conclusions

It is apparent from the review of research on the effectiveness of vegetative buffers in reducing sediment in runoff that;

- there is little information on the effective width of vegetative buffers for a range of steep slopes worldwide
- there is little information about the effectiveness of riparian buffers on harvested slopes
- vegetative filter strip plot studies with simulated rainfall indicate buffer widths of less than 10 m are effective in trapping sediment.
- windrows or slash barriers are very effective in preventing downslope transport of sediment
- riparian vegetation is potentially ineffective in reducing sediment loads in concentrated or ephemeral storm flows

Riparian management decisions need to be based on a consideration of local conditions for a range of environments. Riparian forest buffers of varying width have been established in the various plantation forests of New Zealand. However, with increasing concern about the need (or requirement) to advance post-harvest establishment of riparian buffer strips to first order streams, alternative solutions are being sought.

The abundance of harvesting residue or slash retained on slopes may significantly prevent soil erosion and in the riparian zone reduces sediment delivery to streams. Erosion studies have been initiated by ***Forest Research*** to test the effectiveness of slash cover compared to vegetative buffers.

Acknowledgment

This project was funded through the Public Good Science Fund by the Foundation of Research Science and Technology, under contract CO4806.

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Appendix I – Compendium of research

A compendium is presented below of published accounts on the subject of sediment trapping by vegetation and riparian buffers. The compendium is presented by subject group and in chronological order of publication, firstly for New Zealand and then the United States. Briefly described are the characteristics of research sites, methodologies, and findings. This will facilitate the reader to compare these characteristics with other sites of interest. Use of research findings to other areas for which there is little information must be done with caution due to the site specific nature of physical and biological interactions, processes, and scale effects, and the type of research undertaken.

New Zealand Research

Existing New Zealand research on sediment movement through riparian forest buffer strips is limited with only three studies conducted in forestry areas by Graynoth (1979), O'Loughlin (1979) and Pearce and Griffiths (1980), and two studies by Smith (1989, 1992) in agricultural areas with and without a riparian forest buffer.

Forest harvesting with riparian forest buffers

Graynoth (1979) studied the effect of logging operations on the stream environment in Golden Downs Forest, Nelson District from August 1973 to June 1974. Four catchments with different treatments were compared (Table 2).

Table 2. Characteristics of study catchments in Golden Downs Forest, Nelson (Graynoth, 1979).

Catchment	Area (ha)	Vegetation
control	232	31% *pinus nigra*, 58% *Nothofagus* beech, 11% open / roaded
buffered	47	150 m buffer - 38 % beech, 62 % initially clearcut (incl. roads) 30 m riparian buffer - 10% beech, 90% final clearcut
logged - no buffer	185	51 % indigenous, 36 % regenerating, 13 % clearcut to stream edge
logged - no buffer	2030	14% indigenous, 61% radiata pine and Douglas fir, 25% of upper catchment clearcut to stream edge; lower reaches and valley floor shaded by willow, gorse and some pine

Slopes were 17 - 22° with clay loam soils. Logging was by rubber-tyred skidders using contour tracks. The annual rainfall was about 1300 mm. Stream water samples were manually collected twice per week and during flood flows.

The low flow suspended sediment concentrations were not markedly different between the four treatments and reflect mainly in-stream influences rather than buffer effectiveness (Table 3).

Table 3. Suspended sediment concentrations (g/m^3) in stream flows from catchments in Golden Downs Forest (Graynoth, 1979). Buffer widths were on both sides of the stream.

Catchment		Control (11 % open)	Buffer (62 -90% open)	No buffer (13% open)	No buffer (25% open)
Low flow	mean	6	14	12	7
	range	1 - 14	6 - 22	6 - 20	2 - 16
Storm flow			150m buffer		
Aug - Nov 1973					
	mean	7	11	306	160
	range	2 - 22	2 - 31	16 - 862	13 - 452
			during logging		
18th Dec 1973		-	124	31	26
			30 m buffer		
5th Apr 1974		7	23	134	32
16th Apr 1974		16	-	197	593

Mean storm sediment concentrations in the forested control and logged 150 m buffer catchments were similar, and two orders of magnitude lower than the catchments with no buffers. However, during logging and consequent reduction of the 150m buffer zone to 30 m, storm sediment concentrations were much higher than the non-buffered catchments.

Graynoth concluded that the forest riparian buffer strip was generally effective except where incorrect placement and construction of a skid site and a log-bridge resulted in sediment passing through the buffer. Not much could be said about the effectiveness of the 30 m buffer because of limited storm flow data. However, the proportion of streambed sediment (sand and silt) in *unaffected* parts of the buffer strip was similar to the control stream, indicating no additional inputs of sediment through the forested riparian buffer from upslope sources.

O'Loughlin (1979) assessed two harvesting methods on sediment yields in a paired catchment study in North Westland. The mixed multi-tiered beech/podocarp/hardwood forest catchments were logged by down-hill cable-hauling and ground-based skidder. Slopes averaged 36° with slope lengths from 70 to 150 m. The parent soil is clayey conglomerate mantled by well-drained humus topsoil. A soil disturbance survey indicated 36-37 % total disturbance for the logged catchments. Deep soil disturbance was 20% for the cable logged catchment (along haul paths and spurs), and 18% for the skidder logged catchment which had contour tracks.

A 20 m wide buffer was left in the skidder logged catchment. Both catchments were burnt after felling was completed. The catchments did not have pre-treatment monitoring. Suspended sediment was collected using automatic samplers (600 samples from each catchment). Channel trapped sediment was collected every 4 -5 months.

O'Loughlin (1979) concluded that the 20 m riparian forest buffer failed to prevent large quantities of suspended sediment entering the stream in the skidder logged catchment. Specific sediment yields were 5- 6 times higher from the skidder logged catchment (contour tracked) than the cable logged catchment (Table 4). Sediment was sourced from track surfaces and track sidecast which, during storm flow, was diverted via cutoffs and cross-track rills into first order

(Table 4). Maimai Experimental Catchment sediment yield data, 1977 - 79. (O'Loughlin, 1979).

Catchment treatments	Undisturbed indigenous forest	Cable logged; no buffer; burnt	Tracked; skidder logged; 20 m wide riparian forest buffer; burnt
Area (ha)	1.6	4.1	8.3
Study period (days)	730	911	545
Suspended Sediment (m^3)	0.7	3.8	26.6
Trapped sediment (m^3)	0.3	1.1	5.9
Total sediment (m^3)	1.1	4.9	32.5
Mean Sediment yield rate ($m^3 km^{-2} yr^{-1}$)	33	47	264

gullies and flowed through the riparian protection zone into the main stream. Track surfaces accounted for 60% of the sediment yield.

A confounding factor in the cable logged catchment was that sediment movement was restricted in streams by woody debris accumulations (post-burning) which acted as sediment traps. The riparian buffer zone in the skidder logged catchment prevented the accumulation of logging debris in the stream.

O'Loughlin (1979) cautioned that the sediment yield rates (Table 4) have large errors for small catchments. The short term, 1.5 -2.5 year results through the harvesting period were probably atypical because of the lower than normal annual rainfall (2000 mm). Thus, in a normal rainfall year (2500 mm/yr) sediment yields could have been larger.

Water quality parameters were monitored during selective logging of indigenous podocarp forest in Okarito, south Westland (Pearce and Griffiths, 1980). Twenty-five percent of the standing volume (98%) of rimu trees (*Dacrydium cupressinum*) was felled and hauled along narrow lanes in a radial pattern to two landings. A high-lead cable system operating from a 20 m log spar was used; the maximum haul distance was about 500 m. Three streams drained the harvest area, with the largest set aside as an unlogged riparian protection zone 20 m to 50 m wide on either side of the stream. Approximately 500 m of the 1 km stream in the logged area was unprotected and crossed by one hauler lane. This stream was sampled c. 400 m and just downstream of the unprotected reach. The two smaller streams were sampled at sites near the edge of the logged area downstream of several hauler lane crossings on each stream.

Stream water samples were collected weekly from March to October 1978. In addition samples were collected at 30 minute intervals for several hours during two heavy rainstorms (170 mm and c. 300 mm depth). The outstanding feature of the data is that differences were not found between the suspended sediment concentration during low flows and during storm flows, between the sites with riparian protection and those without, nor during times when parts of the area were only partially logged. The weekly samples contained no visible suspended sediment, and thus had sediment concentrations less than 10 ppm. It was noted by Pearce and Griffiths (1980) that insufficient storms samples were collected during the rising limb and at or near the peak flow rate where sediment concentrations are likely to be greatest.

Pasture with riparian forest buffer

Smith (1992) studied the effect of riparian zone afforestation on catchment hydrology and stream water quality in the Moutere hills, near Nelson. Three pasture (sheep and cattle farm) headwater catchments were compared for 9 years before and 9 years after riparian afforestation of two catchments. The upper reaches were ephemeral, and the mid to lower reaches - intermittent.

(Table 5). Suspended sediment concentrations (g/m^3) and estimated exports ($t/km^2/yr$)in stream flows from pasture catchments in the Moutere hills, Nelson region (Smith, 1992).

Catchment		Pasture control	Riparian pine buffer		Significant differences 95%
		C2	C3	C4	
Area (ha)		6.9	2.8	2.7	
Low flow	median	15	31	39	
	range	1 - 82	4 - 174	10-167	C2 < C3 = C4
Storm flow	median	61	573	254	
	range	10 - 1112	36 - 2114	22 - 1755	C2 < C4 < C3
Exports	mean	21	67	32	C2 ≈ C4 < C3
	95% C.I.	15 - 27	57 - 76	22 - 43	

In 1978, a 25 -35 m wide strip that enclosed the stream channel/riparian area and lower slopes was fenced off and planted in radiata pine (20% of a 2.7 & 2.8 ha catchment area). Trees were planted at 1400 stems ha^{-1} and thinned to 500 stems ha^{-1} at 5 yrs. Light stock grazing occurred under trees at year 8. Under pines at year 8 the ground cover was 51 % bare soil or pine litter (< 2 mm size), 8 % pine slash or litter (> 2 mm size), and 41 % pasture and weed species. Soils were silt-sandy loam with gleyed clay loam subsoils.

Hillslopes were 6-17°, with slope lengths of 70 - 85 m. The upslope source areas were in mixed ryegrass, browntop, white clover, and cocksfoot; and grazed all year round and fertilised in late summer or autumn. Contour plowing occurred in the first year of the 9 year pre-treatment monitoring of the riparian forest catchment.

Suspended sediment samples were collected automatically at 7.5 - 15 minute intervals for storm flows and at 2- to 4-weekly intervals during winter and spring low flows. Summer and autumn flows were intermittent and sampling was infrequent. The long-term annual rainfall was 1050 mm.

Smith (1992) found that the sediment concentrations were higher in the riparian afforested catchments than the control pasture catchment in low flows and storm-flow events (Table 5). Estimated annual sediment exports from the pasture catchment was 31 -60 % of those from the riparian afforested catchments in spite of a higher water yield.

The relatively poor water quality in afforested catchments was attributed to the lack of riparian wetlands, in-stream vegetation and close riparian ground cover. After large storm events, runoff channels commonly formed in the riparian forest strip with the loose pine litter swept downslope into the channel, and exposing soil.

Riparian pasture buffers

Smith (1989) also studied the effect of riparian pasture (intensive sheep and cattle farm) retirement on sediment yield in channelled surface runoff, central Waikato District, North Island, NZ. Flow-proportional sampling of surface run-off was collected over a 22 month period. Annual rainfall was 1165 -1447 mm. Soils comprised silt - sandy loam topsoil to gleyed clay loam subsoils. Slopes selected were a 15°, 230m long south-facing slope and a 20°, 94m long north-facing slope. The retired pasture strips were 10-13 m wide. Pasture and buffer slopes were covered in ryegrass and white clover, with the buffer also comprising fescue and paspalum.

Smith found that median suspended sediment concentrations were about 50% lower at retired sites (Table 6). Pasture retirement had little impact at low sediment concentrations. At high initial concentrations retired pasture strips removed a substantial and often major fraction of the sediment. Higher concentrations in runoff from north facing slopes suggests a basic difference in soil stability (slips were more numerous also). Flow-weighted means and large differences between average treatment means indicate retirement reduced surface runoff loads substantially.

Table 6. Suspended sediment concentrations (g/m^3) in surface runoff from grazed and retired (R) pasture catchments (Smith, 1989).

	South facing sites (6% retired)				North facing sites (11% retired)		
	1	2	3R	4R	5R	6R	7
median	30	28	16	14	33	29	64
range	9 - 535	7 - 496	4 - 134	2 - 42	7 - 203	8 - 347	6 - 1083
flow-weighted mean	47	68	37	31	36	35	268
Flow-weighted mean at retired sites as a percentage of average means at grazed sites				59	13		

United States Research

Studies on vegetation filtering and riparian zone trapping of sediments have mainly been carried out in the US in both the forestry and agricultural. Studies in forested areas have focused on sediments delivered by natural processes. In contrast the agricultural research sector has commonly employed plot studies using simulated and natural rainfall runoff events.

Forest harvesting with riparian forest buffers

Aubertin and Patric (1974) concluded that protective strips were effective most of the time and where logging roads were carefully managed. They found no significant differences in average turbidity of storm flows in two catchments in West Virginia. The catchments were:

1) a 34 ha catchment tractor-arch logged with a 750 m long, 10 -20m wide, protection strip on each side of a perennial stream. Large trees in the strip were selected and logs winched up to the road; there was little soil disturbance.
2) a 38 ha forested control catchment.

Soils were silt loams on slopes commonly 11 - 17° (max. 33°). Average annual precipitation is about 1470 mm. The forest was a mix of oak, maple, poplar, black cherry and beech. While logging roads were in active use, high turbidities (550 JTU[1] compared to 25 JTU upstream) were recorded during a severe storm, where road runoff flowed 30 m through the protective strip to the stream. At this time erosion control structures were damaged by logging, or were absent. In non-roaded areas their was little evidence of overland stormflow or soil erosion during or after clearcutting.

[1] JTU – Jackson Turbidity Unit; is roughly equivalent to an NTU - Nephelometric Turbidity Unit (USEPA, 1983)

In northern Idaho, Snyder et al. (1975) measured stream water quality to determine the effectiveness of forest buffer strips in controlling sediment following clearcutting and burning within cedar-hemlock-grandfir forest. They found significant differences (P = 0.05) in mean filterable solid concentrations between upstream and logged sites and no significant differences between upstream and downstream sites (Table 7).

Table 7: Mean suspended solid concentrations for drainage sites monitored weekly from Sept. 1970 to July 1972 (Synder et al. 1975).

Site		Activity	Soil	Drainage	Mean filterable solids (Mg/l)		
	Buffer				Upstream (control)	On-site (logged)	Downstream
1.	0m on true right 60m on true left, trees	44 ha clearcut 1969, no logging across stream - burned 1970	silt loam	ephemeral - snowmelt and storm flows	4.6	6.5	4.7
2.	61m, trees	2.6 ha tractor logged - slash windrowed and burned 1970	silty clay loam	spring fed - subsurface - main channel (atypical)	9	35.7	12.6
3.	30m, 100 yr old trees	23 ha clearcut and burned 1970, 3 ha partial cut	loam - silt loam	spring-fed and joins main stream; two sub-sites # 1 & 2	2.7	16.5 (#1), 8.5 (#2)	3.9

Flow dilution affected downstream results at study sites 1 and 3, whereas at study site 2 flow concentration processes prevailed. Increases in filterable solids at the logged site was attributed to soil disturbance caused by logging and by lack of soil protection after burning. Interestingly, filterable solids measured in rainfall exceeded by 2-8 times the natural losses from undisturbed land to stream water. Snyder et al. (1975) could not quantify the utility of buffer strips as sediment traps, despite noting that the forest floor acted as an effective micro-barrier to sediment laden water.

Lynch et al. (1985) evaluated the effectiveness of best management practices (BMP) to control water quality. Three catchments (43 - 123 ha) in central Pennsylvania were monitored for 2 years after harvesting. A 104 ha catchment, had 43% clearcut with a 30 m buffer strip left on each side of the stream in which selected logging of high-value or undesirable trees was allowed. The buffer strip did not extend the full length of the channel, and the exposed reach subsequently had windblown uprooted trees that eroded sediment into the stream. Impacts were compared with an adjacent clearcut herbicide-treated catchment (research purpose only) and a forested control catchment. Average slopes were 10°, with a maximum of 20°. Soils were primarily silt loams and stony loams. Forest cover was oak, hickory and maple. Results (Table 8) show annual average suspended sediment yield in the logged - riparian buffer catchment was less than on the clearcut-herbicide catchment which was affected by channel cutting, bank

Table 8. Post-harvest annual average (range) of stormwater suspended sediment concentration (mg/l), (Lynch et al., 1985).

Catchment Treatment	1977	1978
Unharvested	1.7 (0.2 - 8.6)	5.1 (0.3 - 33.5)
43% clearcut with 30 m buffer	5.9 (0.3 - 20.9)	9.3 (0.2 - 76.0)
Clearcut with herbicide	10.4 (2.3 - 30.5)	78.7 (1.8 - 38.0 sic)

erosion and slumping. The riparian buffer was probably effective in preventing bank erosion, but effectiveness in trapping upslope sediment was inconclusive.

Three small (8-10 ha) watersheds in the Virginia coastal plain were monitored to evaluate the effectiveness of BMP's on stream sedimentation (Shaffer and Mostaghimi, 1997):

1) The watershed with BMP's was harvested and left with a 15 m buffer on either side of the stream. Within the buffer about one-third of large diameter trees were removed with minimum ground disturbance. Rubber-tyred feller-buncher/ grapple skidder systems were employed during logging, with manual felling in streamside areas. Waterbars were installed on primary skid trials immediately after harvest and landings were seeded with grass.
2) Another watershed was clearcut without BMP's with a similar sized streamside buffer retained.
3) The third watershed was an uncut control.

Slopes in the watershed range from 1-1.7° over most of the area, to 17° along deeply incised stream channels. Timber consisted of loblolly pine with mixed hardwoods along the stream bottoms. Differences in pre-harvest (27 month period) and post-harvest total suspended solids

Table 9. Comparison of pre- and post-harvest total suspended solids concentration and loading (Shaffer and Mostaghimi, 1997).

Watershed	Pre-harvest mean	Post-harvest mean	% change (pre - post)	% minimum detectable change
	TSS concentration (mg/L)			
no BMPs	890	1910	116	+78
With BMPs	210	150	-29	+49
Control	110	170	59	+60
	TSS loading (kg/ha/yr)			
no BMPs	4489	11502	156	+91
With BMPs	659	704	6	+52
Control	300	680	126	+82

concentration and loadings were determined at watershed outlets (Table 9).
Sediment concentrations and loadings in the watershed harvested with BMP's and the riparian buffer were not significantly different from the control. Harvesting without BMP's and riparian buffer significantly increased loadings and concentrations of total suspended solids.

Sediment travel distance from forest roads

Recognising that forest roads are major sources of sediment, researchers in the United States focused on determining the effects on sediment transport and delivery from road-based sources. Most of these studies examined the effects on sediment travel distance downslope from the road, rather than the effectiveness of riparian buffers per se. Results were used to develop guidelines to reduce the passage of sediment to streams. Packer (1967) developed criteria for locating and designing secondary logging roads.

Trimble and Sartz (1957) reported on measured sediment trails from the outlets of open-top log culverts in relation to slope gradients (Figure 1, Page 5). Their study was in northern hardwood forest, White Mountains, New Hampshire. Ground cover was composed of litter, humus, and mineral soil (sandy loam). During summer storms (1956) sediment travelled up to 40 m over slopes ranging 5-25°. Sediment travel distances were influenced by hollows, breaks in slope, slash and windthrown limbs and trees.

Haupt (1959) advanced buffer width research with the development of a prediction equation for sediment travel distance below forest roads on granitic soils in Idaho. Sediment trail distances were measured from the toe of fill slopes to determine the length of slope required to dissipate sediment flows from logging road drainage. Sediment flow distance averaged 19 m (range 1 - 112 m), with 67% of the flow distance from 3 to 36 m. A multiple regression analysis determined that slope obstruction index was highly related to sediment flow distance. This was followed in order by cross ditch spacing squared, fill slope length, and cross ditch spacing x road gradient. Lower side-slope gradient and road cut height were not significant parameters influencing sediment movement. The four main road and slope characteristics were incorporated into a regression equation to determine the safe width of buffer strips to protect lower roads or stream channels from sediment discharges.

In national forests of Idaho and Washington, Packer (1967) sediment travel distance was measured below cross-drain outlets and the road shoulder. Variables included ground cover characteristics, rock type, soil texture, aspect, topographic position, and road grade. A regression equation was used to estimate the average width of buffer strips required to protect streams and other sites from sediments.
Obstruction type and spacing accounted for 33% of the variation in sediment-movement distance (Figure 2, Page 5). Distance of sediment movement ranged between 10 - 36 m for logging roads built on basaltic soils, having 9.1 m cross drain spacing, 100% fill slope cover density, and zero initial obstruction distance under varying obstruction types.

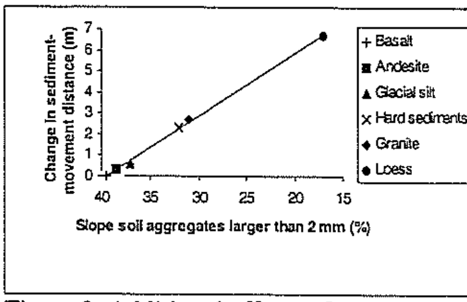

Figure 3. Additional effects of proportion of soil aggregate and parent material on sediment movement distance (Packer, 1967).

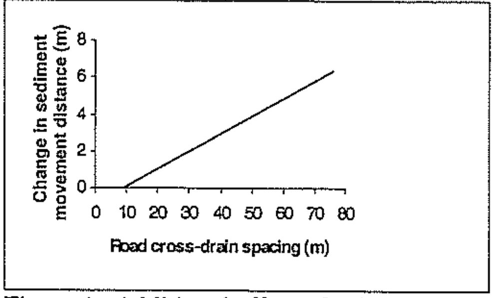

Figure 4. Additional effect of culvert spacing on sediment movement distance (Packer, 1967).

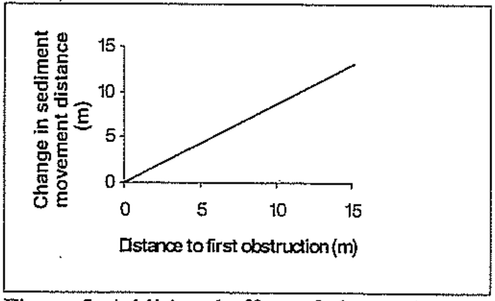

Figure 5. Additional effect of obstruction distance on sediment distance (Packer, 1967).

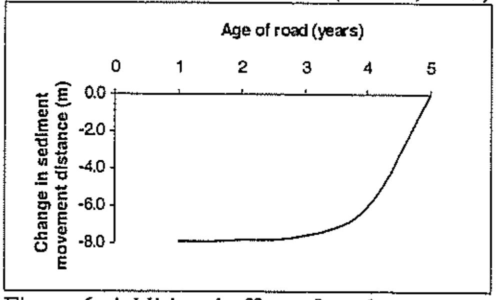

Figure 6. Additional effect of road age on sediment distance (Packer, 1967).

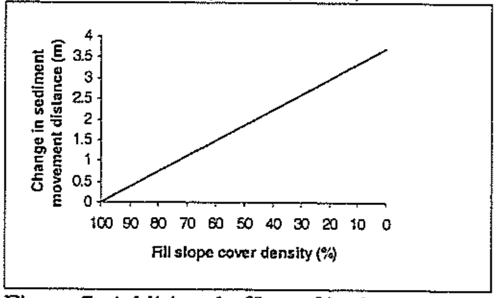

Figure 7. Additional effect of herbaceous and litter cover density on sediment transport distance (Packer, 1967).

Sediment transport distances increased as spacing between obstructions increased and as the sediment trapping effectiveness of obstructions decreased. Additional effects included:

- increasing sediment distance up to 7 m with decreasing proportion of soil aggregates larger than 2 mm dependent on soil parent material (Figure 3)
- increasing sediment distance up to 8 m as cross drain spacing increases (Figure 4)
- increasing sediment distance up to 15 m as distance from cross drain outlet to first obstruction increases (Figure 5)
- decreasing sediment distance up to 8 m as the age of road increased from 1-5 years. (Figure 6)
- increasing sediment distance up to 4m as density of ground cover on fill slopes decreases (Figure 7). The effect of minor herbaceous vegetation and litter is greater on fill slopes than it might be elsewhere because only a few obstructions occur on fill slopes.

Other site factors exerting important effects but not included in the analysis of variance are: soil depth and water holding capacity; amount, intensity and distribution of precipitation; amount, rate and time of snowmelt runoff; and shape and angularity of soil particles (Packer, 1967).

Cook and King (1983) determined the effectiveness of filter windrows (2-3 m wide and up to 1m high compact piles of logging slash) on fill slopes of newly constructed roads adjacent to streams by:

1) measuring sediment volume collected in troughs placed below windrow and non windrowed slopes, and
2) measuring sediment transport distance below windrows.

The study was conducted in a northern Idaho forest dominated by Grand fir. Soil texture was silty sand grading to silty gravel. Fill slopes were seeded, hydro-mulched and fertilised in the autumn following construction.

Windrows were found to be inexpensive and effective treatments for preventing road fill material entering streams. Approximately 99% of the eroded fill was deposited within the windrow (Figure 8). Over a three year period the windrows reduced the amount of sediment leaving the slopes by 4.6 m^3 for 3m high fillslopes, and 13.2 m^3 for 3-6 m high fill slopes. Only a small fraction of fillslope sediment passed through the windrow and reached the stream 3 out of 7 instances. Average transport distance below windrows was 1.2m, compared to 7.4 m (no slumping), and 12.6m (slumping) below unprotected fillslopes. Sediment trapping efficiency from rills was estimated at 75 - 85 %.

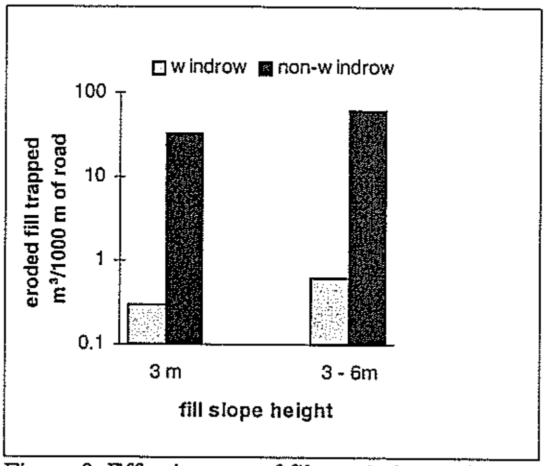

Figure 8. Effectiveness of filter windrows during 3 years following road construction (Cook and King, 1983).

Swift (1986) similarly measured sediment transport distances below forest roads fillslopes with various cover treatments in the Appalachian Mountains, western North Carolina. In particular, brush (slash) barriers 1 - 2m high by 3 m or more wide were constructed at the lower edge of the forest road edge. Soil texture was mainly sandy loam. Swift found that the sediment travel distance:

- increased with increasing hillslope (Figure 1, Page 5)
- averaged 10 –18 m for grassed fills with or without other treatments (Table 10)
- through forest floor litter averaged 20 m
- was effectively reduced by brush barriers

Table 10. Down-slope movement of sediment from road fills with various roadway and slope conditions (Swift, 1986).

			Distance (m)		
Fill treatments	No. sites	Mean slope (deg)	Mean	Max	Min
Bare fills	9	29	34	94	12
Mulched fills (straw + asphalt)	16	33	29	96	11
Grassed fills	63	22	18	60	1
Grass fills and forest litter with brush with culvert	4	11	11	13	9
Grass fills and forest litter with brush without culvert	12	24	10	45	1
Grass fills and forest litter without brush with culvert	7	20	18	27	9
Grass fills and forest litter without brush without culvert	23	23	15	45	1
Brush barrier	26	25	14	48	1
No brush barrier	62	25	25	96	1
Culvert	21	22	24	96	9
Forest floor litter	71	25	20	96	1
Forest floor burn	17	23	29	60	10
All sites	88	25	22	96	1

Sediment travel distances below fillslopes were determined one year after road construction for a range of treatments in the weathered gneiss and schist terrain of northern Idaho by Burroughs and King (1989). Slash windrows were 85 - 95% effective in reducing sediment transport distance on side-slopes of 17-22°, compared to other treatments (Table 11). Excluded from the results were rills and gullies that potentially contribute sediment to streams. However, eroded sediment was typically transported *over* the windrows in spring when they were still buried by snow rather than through the windrow.

Table 11. Sediment transport distances of eroded fill material with different treatments (Burroughs and King, 1989).

Treatment	No.	Mean (m)	Maximum (m)
Slash Windrow	45	1	10
No windrow, no slumps, no road drainage,	112	8	26
No windrow, no slumps, roadway drainage, no culverts	25	18	26
No windrow, slumped and non-slumped, culverts	25	22	38
No windrow, slumped, no culverts	30	24	32

Burroughs and King (1989) also measured the effect of obstruction density on sediment transport distance below road fillslopes. Obstruction density was a qualitative index from 0 to 6, with 6 representing high density obstructions such as slash, shrubs and depressions (the other index values were not defined). The maximum sediment travel distance was less than 7 m for the lowest obstruction index, and decreased to less than 1 m for obstruction index of 6 (Figure 9).

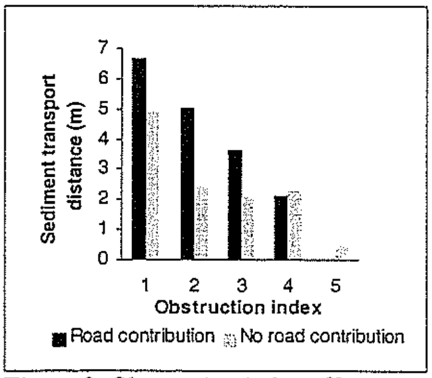

Figure 9. Obstruction index effects on average sediment transport distances below fillslopes (Burroughs and King, 1989).

The authors cautioned that the results may be oversimplified, and suggested that gully size may also affect the contributions of drainage from the roadway. Roadway drainage to fills resulted in longer sediment transport distances.

In a four year study, Ketcheson and Megahan (1996) quantified and related sediment deposit volumes and measured travel distances on hillslopes below newly constructed roads in southwestern Idaho. Annual precipitation averages about 890 mm. The light coloured granitic sediments were mapped at sites where there were no nearby streams to transport sediments, and in swales so that sediment did not move out of the area. They found that sediment delivery varied significantly by road source type. Considering only unimpeded sediment deposits contained on slopes, average deposition volumes were greater from cross drains than from any other source (Table 12).

Table 12. Frequency of occurrence and size of unimpeded sediment deposits by source type (Ketcheson and Megahan, 1996).

Source	No.	Mean Volume (m^3)	Mean Length (m)	Maximum length	Total runoff area (ha)
Cross drain	26	11.4c	49.6c	184	3.34
Landing	4	3.2b	20.8b	106	-
Berm drain	6	1.7b	14.0b	54	0.06
Rock drain	17	0.3a	8.7a	34	0.28
Fill	264	0.2a	3.8a	66	0.04

Values with different letters are statistically different ($P < 0.05$)

The sediment from cross drains travelled farthest and tended to funnel into the bottom of swales. In contrast, the diffuse nature of sheet and rill erosion on fill slopes resulted in short sediment travel distances and deposits were elongated along the base of the fill slopes. One of the reasons for greater runoff from cross drains is the larger source area for runoff, both from the road prism and from upslope watershed areas. Logs and other obstructions on the hillslope surface below the road stored sediment and sometimes caused changes in sediment flow direction, depending on the orientation of the obstruction. Ketcheson and Megahan (1996) found that all sediment deposits rapidly decrease in volume as they move downslope.

About 70% sediment deposition occurred in the first year after road construction, and marked reductions occurred in subsequent years (Table 13). Summer storms increased erosion in the forth year. However, few changes in sediment flow length occurred. Most of the sediment in the second and subsequent years was deposited on top of the original sediment deposit. Sediment accumulates because of normal deposition processes, and because the storage capacity of the surface is rejuvenated to some degree by vegetation growth on and through the sediment, and by the accumulation of new forest debris on the surface.

Table 13. Road erosion rates (Ketcheson and Megahan, 1996).

Year	m^3/ha
1	96
2	17
3	9
4	16

Cumulative frequency distributions for sediment transport distance was considered a useful tool for planning road distances from streams. Burroughs and King (1989) found that over 50% of the relief culverts had sediment transport distances over 23m, and 80% had distances of at least

53m. Ketcheson and Megahan (1996) determined a 50% chance of cross drains having sediment transport distances over 50m. The different findings relate to differences between the two study areas in Idaho. Differences in sediment travel distances may be attributed to the density of obstructions on the soil surface. In northern Idaho much of the reduced travel distances can be attributed to a greater density of obstructions than in southwestern Idaho (Ketcheson and Megahan, 1996; Burroughs and King, 1989; see also Packer, 1967).

Micro-catchment and plot studies on forest land

In north and east Arizona, Heede (1990) carried out a pilot study to investigate natural forest vegetation types as barriers against surface soil movement. Annual rainfall of the study sites ranged from 395-1100 mm/yr. The forest land had been used periodically since the early 1900's for selected timber harvesting, fuel wood cutting, and cattle grazing. Three forest types were studied: ponderosa pine, pinyon-juniper, and chapparral; all with litter buffer strips from 2 to 25 m wide. In the pinyon-juniper and chaparral catchments buffer strips were defined as denser clusters of trees compared to the rest of the forest. Collector toughs trapped sediment in overland storm flow in selected micro-catchments on hillslopes ranging 6° - 30 ° and up to 130 m long. Comparisons were made with adjacent open areas of bare ground dominated by clay loam to sandy clay loam soils.

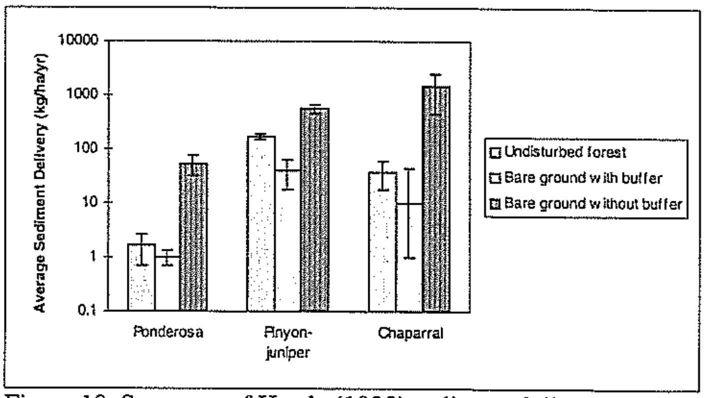

Figure 10. Summary of Heede (1990) sediment delivery results (log scale and standard error bars shown).

Heede (1990) noted that nearly all sediment was withheld by buffer strips regardless of vegetation type. There was great variability but significant differences in sediment delivery among the small number of sites (Figure 10). Where buffer strips were missing, 61, 18 and 277 times more sediment was delivered in ponderosa, pinyon-juniper and chaparral forests respectively. Concentrated sediment deposits accumulated upslope of the buffer strips, decreased rapidly on entering the strips. Litter, mull and soil layers contributed to a reduction in overland flow through increased infiltration and vegetation type. Interestingly, effective buffer width was 2m on steep (30°) slopes in chaparral, and 7 and 25 m on 14° slopes in ponderosa pine.

A riparian zone study in national forest in Colorado was carried out by Pearce et al. (1998) using rainfall/ runoff simulation and introduced sediments in runoff. The study treatments were: 3 vegetation heights (0, 10 cm, and natural vegetation height), 2 riparian vegetation communities (sedge and a grass-sedge complex), 2 plot sizes (0.6 x 2m and 3 x 10m), and 2 types of introduced sediment (sandy loam soil in year 1, and a ground silica product in year two) of known particle size distribution. Vegetation cover, vegetation density, litter cover, species composition, surface roughness, bare ground, slope, and rock cover were measured factors. The sediment volumes (equivalent to 10,000 kg/ha) were double the actual levels of sediment that might reach the riparian areas. The study therefore represented an extreme case. To simulate runoff and sediment delivery from an upland area to the riparian zone, rainfall was applied at 60 mm/hr for 30 minutes on pre-wetted soils. A uniform runoff was also applied, at

25 mm/hr to the upper end of the plot. Sediment yields were measured for 18 minutes. Slopes were 2 -3°.

Buffer width (plot size) and sediment type had significant effects on sediment yield. The 10m buffer plots had no differences in sediment yield between the two sediment types (< 200 kg/ha). However, more silica sediment was produced (c.1200 kg/ha) than soil sediment (c.50 kg/ha) from the 2m plots. The difference was attributed to the higher proportion of fine silica particles (68% silt and clay) compared to the soil (47% silt and clay). Sediment filtering was more than 99% efficient for soil sediment in the 10 m plots and 88 - 98 % efficient for the silica sediment in the 2m plots. Nearly 50% more sediment was transported through the sedge community (ave. 427 kg/ha) than through the grass community (ave. 306 kg/ha). The higher density and more uniform spacing of the grass may have created a more effective filter than the sparsely spaced sedge tussocks.

Particle size distribution of sediment in overland flow directly influences sediment yield. Finer particles move through riparian buffer zones better than larger particles. Pearce et al.(1998) suggested that assessment of particle size distribution of upland sediment helps to determine appropriate vegetation filter width. They also comment that regression models with more than 7 variables do not have utility for land managers, and that models with 3 or 4 variables could not be developed from the data.

Agricultural land with forest buffer

Water quality was monitored for 17 months during base flow periods in Illinios agricultural catchments to evaluate the impact of riparian vegetation on suspended solids and other indicators (Schlosser and Karr, 1981). Over 80% of the land use was in corn and soybeans. In the areas without riparian vegetation, both instream algal production and seasonal low flows appeared to be major determinants of suspended solid concentrations (Figure 11). During summer, suspended solids increased significantly in streams without riparian vegetation, but did not change throughout the year in areas with permanent flows and riparian vegetation. Streams with riparian vegetation and intermittent flow also had significant increases in suspended solids during summer. However, a significant decrease occurred in autumn.

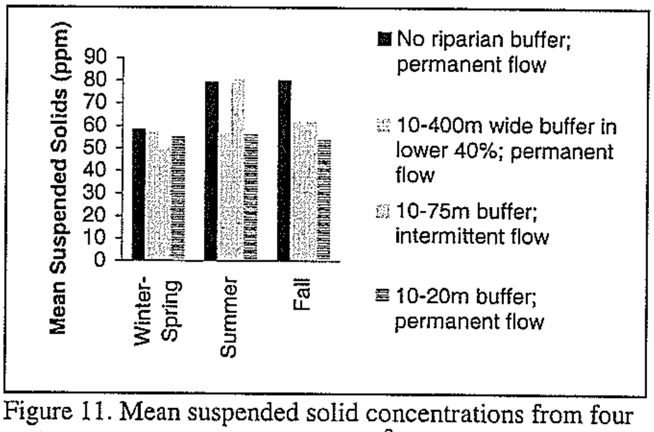

Figure 11. Mean suspended solid concentrations from four agricultural watersheds (35 - 85 km^2) without point inputs (Schlosser and Karr, 1981).

The role of riparian forest in trapping or releasing suspended particulates from agricultural land was assessed by Peterjohn and Correll (1984). The study was located within the mid-Atlantic Coastal Plain, Maryland, in a 16 ha catchment of which 10 ha was planted in corn. From surface runoff that had passed through approximately 50 m of riparian deciduous forest an estimated 4.1 Mg/ha (4 t/ha) of suspended particulates was removed during the study year. The annual concentration of total suspended particulates entering the riparian forest was 6480 mg/L; at 19 m concentrations reduced to 661 mg/L; and upon leaving the forest at 50 m, 419 mg/L. Soils were a fine sandy loam on slopes of 3°. Peak concentrations of suspended particles from the cropland corresponded with intense storm activity in spring and summer, and also became less pronounced 19 m into the riparian forest.

Only one study examined the effect of riparian forest buffers on sediment accumulation over a long timeframe. Cooper et al. (1987) traced clay absorbent Cesium-137 in soil samples on traverses across drainage systems in the coastal plain of North Carolina. Peak fallout of ^{137}Cs from nuclear weapon testing (1963-64) provided a geologic dateline that was used to estimate subsequent sediment deposition over 20 years. The downward movement of ^{137}Cs in soil was estimated by gamma-ray activity distribution with depth. Ground cover included 50% cultivated upland on slopes less than 4°, 50% undisturbed natural forest on 11° side-slopes, and floodplain swamps in the lower part of the catchments. Soils were a loamy sand to silt loam.

Results showed that the thickest (15-50 cm) accumulations of sediment were at the edge of the upland cultivated field/ forest. At many locations the turning action of the plow at the field edge produced a berm and dense vegetation provided a barrier to runoff. Ephemeral stream sites had lesser thicknesses (5-15 cm) of accumulated Cs-enriched sediment, and on floodplains of 2nd to 4th order streams, sediment accumulations were similar (5 -20 cm). There was less than 5 cm of Cs-enriched sediment on the floodplain swamp, indicating slow soil accumulation rates over 20 years.

Cooper et al. (1987) estimated that more than 75% of the ^{137}Cs sediment had been deposited upstream of the floodplain swamp, with >50% being deposited 100 m downslope from the field-forest edge. The cultivated uplands were 2-3 km from the floodplain swamp implying considerable sediment reduction and storage time. However, in another catchment a larger amount of sediment deposited on the floodplains and in the swamps resulted from the close proximity of the cultivated fields on upland areas and the narrow riparian forest areas between.

Floodplain swamps are important for trapping silt and clay particles - the dominant soil texture. These particles are more likely to pass through upstream riparian areas. In flood prone areas, the riparian buffer zone width needs to increase downstream as inputs enter higher order streams and the opportunity for deposition decreases while transport capacity increases (Cooper et al., 1987). This finding contrasts with that of Bren (1999) whose geometric buffer design methods suggest narrower buffer widths with increasing distance downstream. The apparent contradiction may be attributed to reduced sediment yields from upland slopes to the riparian buffer verses overbank flooding into the riparian buffer zone.

Daniels and Gilliam (1996) determined the amount of sediment removed by natural and planted filters over a 2 yr period. They collected sediment laden runoff at the edges of cultivated crop fields and at various locations within vegetative buffers in the North Carolina Piedmont. Soils were sandy loam and silt loam to silty clay. Slopes through the vegetative buffers ranged from 1 - 6° with upland slopes of less than 9°, and 48 - 86 m long.

Runoff from four selected sites flowed through a narrow strip of fescue (80 - 100% cover), across a field lane, and then (for 2 sites) into either a groundcover of weeds and vines or a cover of mixed hardwood and pine trees. Collectors were placed 0, 3, and 6m downslope from the field/buffer edge. Below fescue only sites the runoff continued through a grassed waterway with mixed weeds and shrubs and then into a riparian forest with a continuous layer of litter.

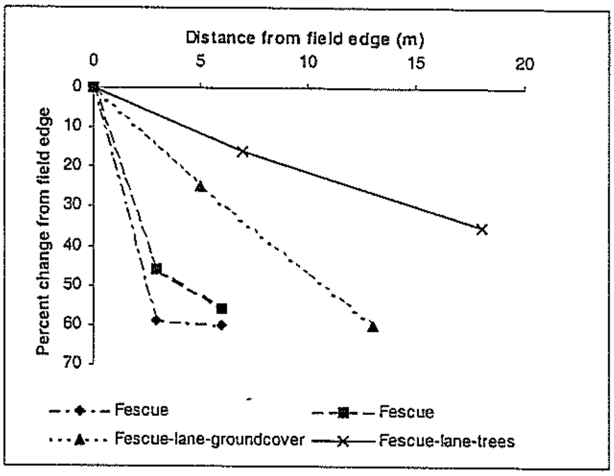

Figure 12. Sediment reductions through buffer strips (Daniels and Gilliam, 1996).

The weight of sediment measured in the runoff varied considerably from storm to storm but usually decreased with distance from the field edge where sheet flow was dominant (Daniels and Gilliam, 1996). The vegetative filters reduced total sediment by 30 to 60 % (Figure 12), but when eliminating the effect of a 60 mm storm event, total sediment delivered to the field edge was reduced by 55 to 82%. Grass filters with a width of 6m receiving sheet flow were as effective as grass and riparian forest filters with greater widths (Figure 12). Traffic on the field lanes between the grass and riparian filters served as a secondary sediment source. The removal of sand was greater than the removal of silt plus clay, and as the filter width increased so did the removal of silt and clay.

Additionally, Daniels and Gilliam (1996) measured storm sediment loads in an ephemeral channel that bisected a cultivated field. The filter areas had sparse vegetation cover of grass and weeds near the entry point, but only leaf litter and scattered plants downstream into the baseflow area. Ten to twenty metres downstream from the field edge were patches of bare soil and channel incision. Storm induced channel scour within this zone, resulted in a significant increase in total sediment load. However, sediment weight subsequently decreased as the storm water flowed through the 75m long filter area (Figure 13).

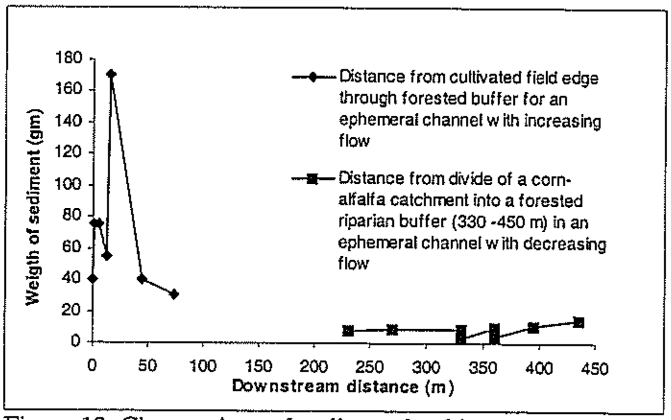

Figure 13. Changes in total sediment load in concentrated runoff in two catchments of 10 to 20 ha (Daniels and Gilliam, 1996).

At another site, sediment loads in storm flow increased downstream in the forested area (due to bed scour during heavy flows (Figure 13). Sparse vegetation and litter in the ephemeral channel offered little resistance to flow.

Daniels and Gilliam (1996) concluded that:

1. Buffer effectiveness varies with the erosiveness of the catchment and storm intensity.
2. Ephemeral riparian channels need a continuous vegetative cover to be effective filters.

3. Forested riparian systems associated with upland ephemeral channels do not effectively reduce sediment loads from concentrated flow (with sparse forest ground cover) except in streams where flow decreases and seldom reaches the main stream.

Agricultural land with grass and crop filters

Neibling and Alberts (1979) measured the amount and particle size distribution of naturally eroded sediment retained by several widths of sod buffer strips under sheet flow conditions. Plots were located on silty loam cropland soils near Miami. Slopes were 4°. Two replicate plots of one control and one treatment (1.8 x 6 m) with strip widths (treatments) of 0.6, 1.2, 2.4 and 4.9 m were plowed, disc harrowed, levelled, and smoothed before sowing a bluegrass filter. Sediment was generated using a rainfall simulator, and surface flow collected via flumes with stage recorder and sampler. Rainfall simulations of 127 mm over two days comprised 63 mm/hr applications; a 1 hr dry-run followed by a 24 hr wait, and then two 30 minute wet-runs with a 30 minute wait.

Findings by Neibling and Alberts (1979) were:

- strip widths greater than 0.6 m provided little additional benefit regardless of particle size (Figure 14)
- soil loss decreased as width increased (Table 14)
- all four strips reduced total sediment discharge rates by more than a factor of ten
- most sediment was deposited above the strip with only the finer fractions entering the strip. The majority of sediment deposited appeared to be independent of strip width.
- as strip width increased the velocity of flow decreased (a dye front was monitored in the runoff)

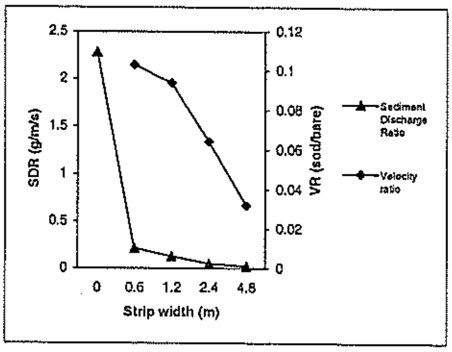

Figure 14. Sediment discharge rate (SDR) passing through a sod strip of different widths, and overland flow velocity ratio (sod vs bare plots) (Neibling and Alberts, 1979).

Table 14. Sediment discharge rates in vegetative filter strips (Neibling and Alberts, 1979).

Strip Width (m)	Particle size (mm)	Sediment entering $g\ m^{-1}\ s^{-1}$	Sediment leaving $g\ m^{-1}\ s^{-1}$	% reduction
0.6	<0.002	0.090	0.057	37
1.2	clay	0.121	0.027	78
2.4		0.110	0.020	82
4.9		0.089	0.015	83
0.6	0.002 - 0.01	0.227	0.093	56
1.2	silt	0.218	0.066	70
2.4		0.293	0.016	94
4.9		0.241	0.013	95

Young et al.(1980) tested the ability of cropped buffer strips to control runoff from an active cattle-feedlot in west-central Minnesota. A rainfall simulator was set up over six plots located at the lower edge the feedlot. Plot lengths (feedlot plus treatments) were 41 m in the 1st year and 33m in the second year. A variety of ground cover treatments were used: corn, orchardgrass, sorghum-sudangrass, and oats. The untreated feedlot was 14m long. Slopes were 2 °. It was found that runoff was reduced through the crop filters by an average 67%, with total solids reduced an average 79%. Larger reductions in soil and runoff from corn plots may have been caused by the corn rows - which were planted across the slope - retarding runoff (Table 15).

Table 15. Summary of runoff and sediment transported from cattle feedlots and cropped buffer strips (average of two replications) (after Young et al., 1980).

	antecedent soil moisture %	runoff cm	sediment kg/ha	sediment reductio n %
	1977			
Feedlot (13.7 m long)				
Dry run	32	6.9	643	
Wet run	35	7.7	1473	0
Corn (27.4 m buffer)				
Dry run	22	0	0	
Wet run	36	0.2	139	90
Orchardgrass (27.4 m buffer)				
Dry run	25	0.4	368	
Wet run	31	2.4	344	76
Sorghum - Sudangrass (27.4 m buffer)				
Dry run	24	1.5	127	
Wet run	34	4.1	256	82
	1978			
Feedlot (13.7 m long)				
Dry run	68	7.1	2413	
Wet run	66	7.2	1706	0
Corn (21 m buffer)				
Dry run	31	1.2	279	
Wet run	38	3.7	508	70
Oats (21 m buffer)				
Dry run	44	3.1	392	
Wet run	50	5.4	645	62

¶ Percentages were calculated from this table and not those reported by Young et al.

Magette et al. (1989) conducted rainfall simulation tests on a series of plots treated with liquid urea and chicken litter compared to a bare (fallow) control in Chesapeake Bay, Maryland. The vegetative filter strip (VFS) cover was fescue, on a 2° slope, comprising sandy loam. Suspended sediments were collected from plots 4.6 and 9.2 m in length. The composition of the suspended material while not determined, but probably comprised a mix of soil and broiler litter solids. Magette et al. (1989) found that:

- longer filters were more effective in trapping suspended material (Table 16 and 17).
- large variability occurs in solids losses in runoff
- the mass of solids lost from bare plots was much greater than that from VFS plots
- the VFS appeared to be less effective in reducing suspended solids losses in runoff as more and more runoff events occurred
- the performance of VFS diminishes as the ratio of vegetated to unvegetated area decreases

Table 16. Summary results of Magette et al., 1989: Average performance ratios (% loss of suspended solids) for VFS relative to bare plots during individual tests.

Plot	Filter width (m)	Urea ammonium nitrate	Broiler litter	Total
1	9.2	25	15	20
4	9.2	11	11	11
7	9.2	44	43	44
Mean		27	23	25
2	4.6	32	39	35
5	4.6	60	8	34
8	4.6	62	88	75
Mean		51	44	48

Table 17. Summary of cumulative losses and performance ratios of solids in runoff from all tests (Magette et al., 1989).

Plot	Filter width (m)	Total suspended solids (kg)	Performance ratio (%)
1	9.2	19	19
2	4.6	29	29
3	0	102	
4	9.2	20	5
5	4.6	84	23
6	0	372	
7	9.2	82	30
8	4.6	142	51
9	0	277	
Ave.	9.2		18
Ave.	4.6		34

Dillaha et al. (1989a) evaluated the effectiveness of vegetative filter strips in reducing sediment losses from cropland in Virginia. They used plot studies and rainfall simulators, and collected suspended sediment in surface flow to flumes with stage recorder and sampler. The VFS comprised orchardgrass and a source area of bare compacted silt loam soil. Plots were 18 m long by 5.5 m wide with slopes of 3°, 6°, and 9°. The results are shown in Table 18.

Dillaha et al. (1989a) found that:

- most of the sediment removed from the source area was deposited just upslope or within the first few meters of the VFS
- the effectiveness of the VFS decreased with time as sediment accumulated
- VFS plots receiving concentrated flow were generally as effective as plots with uniform flow; however, the VFS plots with concentrated flow on 3° slopes were more effective than the 9° slope uniform flow plots and only slightly less effective than the 6° flow uniform flow plots

Table 18. Flow weighted mean concentration of total suspended sediment, sediment yield, and % reduction for all simulation runs (Dillaha et al., 1989a). The 3° slope plots had a 2° cross slope which concentrated flow to one side of the plot.

Slope (deg)	Filter length (m)	FW Mean TSS (mg/L)	reduction (%)	TSS Yield (Mg/ha)	reduction (%)
3	0	3538		2.10	
3	4.6	1792	49	0.36	83
3	9.1	582	83	0.14	93
6	0	5513		3.93	
6	4.6	676	88	0.56	86
6	9.1	354	93	0.10	98
9	0	15929		8.94	
9	4.6	6063	62	4.22	53
9	9.1	3404	79	2.71	70

Dillaha et al. (1989a) stressed that experimental field plots (with borders) do not exactly duplicate field conditions. The most significant difference is that real cropland will have larger areas upslope of the VFS contributing to runoff. Surface runoff in fields with longer slopes will tend to concentrate and cross the VFS in a few localised areas. Filter strips are not expected to be effective under these concentrated flow conditions which tend to have a greater sediment load than experimental plots. Consequently, bordered experimental VFS would tend to be more effective than the open field VFS with the same rainfall. However, this over-estimation of VFS performance in plot experiments will tend to be partially offset by the simulation of extreme rainfall events (> 100 yr return period or a 200 mm rainfall with an intensity of 50 mm/hr over a seven day period) which will produce more runoff than would be expected under normal conditions. Concentrated surface runoff was found to be more of a problem in hilly areas than flatter areas (Dillaha et al., 1989a).

Dillaha et al. (1989b) surveyed on-farm effectiveness or maintenance of vegetative filter strips (VFS) to document management practices and site conditions affecting VFS performance in Virginia. The survey included interviews, site visits (five at 3 month intervals), and a mail survey. VFS ground cover ranged from planted or indigenous vegetation to grass/pasture plants. Features inspected for problems or characteristics that would enhance or reduce VFS effectiveness were; width, slope, and vegetation cover; use of adjacent land; estimation of % concentrated flow entering VFS; maintenance programmes; and owner attitudes. Results from the field visits were:

- features reducing VFS effectiveness
  - majority were ineffective for water quality improvement because most flow was concentrated; hilly areas had the highest proportion of concentrated flow
  - stabilised gullies allowed runoff to pass through VFS as channel flow
  - narrow filter strips where valleys, woods and natural drainageways projected into fields; these areas are where VFS should be widest because flows naturally concentrate in these areas
  - lack of repair and reseeding of eroded areas
  - drift or misapplication of herbicides; herbicide application and wet ground affected 2 of 33 sites
  - no mowing and excessive weed growth; tall weeds shade desirable grasses and reduce cover at ground level
  - poor cover, severe damage (bare & compacted) due to machine tracking or turning
  - cattle hoof damage
  - certain tilling techniques and width reduction each time the field was tilled
  - planting/seeding during periods of drought resulting in poor survival/germination
  - competition from other (weed) species
  - sediment build-up
- features enhancing VFS effectiveness
  - filter strips in smaller fields where flow could not concentrate
  - natural levees or man-made barriers to runoff
  - mowing and proper fertilisation
  - high seeding rates
  - water quality improvements only under shallow sheet flow conditions

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Robinson et al. (1996) assessed the effectiveness of 18m grass filter strips on sediment concentration and soil loss from an 18 m continuous fallow strip on a 4° and 7° slopes. Soils were silt loams in northeast Iowa. Collectors were placed at six intervals within the VFS and recorded data from thirteen rainfall events from 10-72 mm. In all storms, the initial 3m of the VFS removed more than 70% to 80% of the sediment from runoff, while 9 m of the VFS removed 85%. Little decrease in sediment concentration was observed with greater VFS width. The 7° slope had greater runoff and soil losses at all VFS widths than the 4° slope. Three storms accounted for 65% of the total soil loss and eight storms accounted for 93% of the total soil loss. Greatest sediment concentrations occurred at the edge of the fallow/VFS. However, increasing sediment concentration or soil loss from the source area did not correspond with increasing storm intensity (Figure 15).

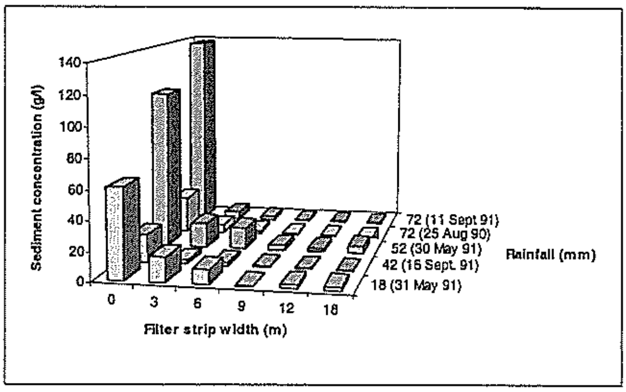

Figure 15. Sediment concentrations along a grass filter receiving 3.5 to 26.6 Mg/ha of soil from 7° sloping fallow strips (Robinson et al., 1996).

Netherlands

On loess soils in the south Netherlands, Van Dijk et al. (1996) conducted field plot experiments to simulate runoff carrying loess sediment through grass filter strips of different widths, grass age, and agricultural management. Results showed that grass strips were effective in filtering out sediment from surface runoff as long as concentrated flow was absent. Outflow sediment concentrations could be described as a function of inflow concentrations and strip width (r^2 = 0.90 & 0.95 respectively). Reductions in sediment discharge varied between 50-60, 60-90, and 90-99% for strips of 1, 4-5 and 10m width respectively. Old grass, extensively used as pasture, was more effective in reducing erosion than young grass, which was often accessed by tractors for mowing. Differences in water retention between both young and old grass appear to be caused mainly by differences in grass density.
