

FUNCTION OF RIPARIAN VEGETATION IN RETAINING SEDIMENT IN WATERSHEDS

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Riparian areas are special vegetation zones that are frequently used as buffer strips to mitigate sediment movement from upland forest and agricultural management areas (Neary et al. 2010). These areas are often called streamside management zones. Understanding any concept and accompanying literature is ultimately based on knowledge of the descriptive terminology used. Therefore it is appropriate to discuss the terms used in the literature to describe since there is a lack of uniformity in how these near-stream landscape units are named. The most commonly used terms mentioned by Neary et al. (2010) are "riparian zones", "riparian buffers", "riparian management zones", "buffer strips", "filter strips", "wetlands", "greenways", "grassed waterways", and "streamside management zones". Various combinations of economic, ecological, and regulatory factors govern their size, shape, function, importance, and management (Williams et al. 2003).

The term "riparian zones" has variants in "riparian buffers", and "riparian management zones" that imply the same concept. Riparian zones are transition zones between upland and aquatic ecosystems that are under the influence of shallow groundwater (Mitsch and Gosselink 2007). Technically, riparian zones are those that meet the definition of "riparian". The riparian zone of a river, stream, or other body of water is the land adjacent to that body of water that is, at least periodically, influenced by flooding. Riparian zones are usually highly productive ecotones or transition zones between upland and aquatic ecosystems that are under the influence of flooding and shallow groundwater. They can vary from a few meters wide in steep terrain to hundreds of meters in coastal plains. Often, the term "riparian management zone" is used to broaden the concept beyond that of a buffer (Lowrance et al. 1985). Riparian management zones and buffers refer to management-designated areas that may or may not include all the components of the riparian zone and can also include some upland areas.

The transition between two different land uses where one land use, the buffer, mitigates the effects of

the other is referred to as a "buffer strip" (Karr and Schlosser 1978, Comerford et al. 1992). This transition zone allows runoff and its pollutant load to be reduced before reaching surface waters by filtering, deposition, infiltration, adsorption, uptake, and decay. The primary function of "filter strips" is on the filtering pollutants that leave upland portions of landscapes. Filter strips are usually viewed as zones to remove sediment from runoff (Cooper et al. 1987), but they will also filter out nutrients like nitrate nitrogen if they are wide enough (Lowrance et al. 1984). Filter strips are most often used at field edges but they can also function well along streams.

"Greenways and grassed waterways" are specialized grass or herbaceous plant zones along first- and second-order drainage areas in agricultural landscapes (USDA Agriculture Research Service 1987). They are sometimes used in forested areas but not frequently. In general, grassed waterways typically carry concentrated flows but have a high potential for reducing runoff volume and velocity, sediment transport, and chemicals coming from agricultural watersheds through sediment detention and water infiltration processes (Fiener and Auerwald 2003).

"Wetlands" are often used as an interchangeable term with the word riparian. This landform includes fifteen different, popular terms such as bog, fen, marsh, moor, swamp, bottomland, etc. (Mitsch and Gosselink (2007). Although it also describes land that is transitional between terrestrial and aquatic ecosystems, there are a number of distinctions which really set wetlands apart from other landscape units. Cowardin et al. (1979), in their classification of USA wetlands, defined the term as referring to lands where the water table is at or near the surface or the land is covered by shallow water. For the classification system that they used, wetlands have the following distinct attributes: (1) they support hydrophytic plants, (2) they contain predominantly hydric soils, and (3) they are water saturated or covered by water during part of the growing season. In the complete absence of active land management (e.g. wilderness, National

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Parks, special reserves, etc.), wetlands and riparian areas provide the functions that SMZs do in managed landscapes.

Streamside management zones can include riparian zones as well as upland areas (Phillips et al. 1999). The term encompasses all potential functions and management objectives for landscape units adjacent to streams. Thus, it is not tied to the hydrologically functional area of the riparian zone since it can include parts of upland areas, and it includes functions other than buffering. For these reasons, it is a preferable term to define the managed landscape units along stream courses.

Riparian zones have many functions. These include wildlife habitat, water source, recreation areas, climate moderation, and water quality protection. They are often recognized as important barriers or treatment areas that protect water resources quality from non-point source pollution sediment. The vegetation and the geomorphic characteristics of these buffer strips produce infiltration, filtering, and deposition of sediment-laden water flowing off of intensively managed forest and agriculture lands. The effectiveness of riparian vegetation in trapping sediment depends upon the velocity of water flow, size distribution of sediments, slope and length of slope above the riparian buffer, slope and length of the buffer strip, depth of water flow into the riparian zone, vegetation characteristics such as type, density, and height. Data on sediment removal by forest vegetation buffer strips suggest that two main actions occur. First, the forest edge environment promotes sediment removal from surface runoff. Second, the sediment is sorted as it moves through lower gradient zones of the riparian buffer. This paper examines these processes and illustrates them with examples from forest management and agriculture.

SEDIMENT RETENTION PROCESSES

Surface Roughness

Surface roughness features include coarse-woody debris, live woody and herbaceous vegetation, emergent wetland vegetation, the soil organic horizon (litter), boulders, rock outcroppings, surface depressions, and land that slope away from the stream edge. In an agroforestry landscape, streamside management zones usually increase the surface roughness compared to adjacent tilled fields and pasture, which in turn reduces runoff velocity and thus enhances deposition of sediment particles and increases the opportunity for runoff to infiltrate into soils (Neary et al. 2010). Sufficient contact time between water, vegetation and soil is important to obtain a decrease in runoff velocity. Some of the other factors that interact with surface roughness include the width of the buffer zone, vegetation type (density, stiffness and height), and slope. These characteristics ultimately affect the trapping efficiency (Schultz et al. 2009).

Johnson and Buffler (2008) proposed a simple but useful classification system for surface roughness based on easily measurable or observable features (Table 1). The initial screening factor for their classification system is the percentage of the streamside management zone that contains recognizable surface roughness features. Examples of the three categories (low, moderate, and high). The Johnson and Buffler (2008) paper recognizes that surface roughness is not necessarily uniform and can be recognized and mapped. Figure 1 shows an example of an actual streamside management zone with sections characterized by variable surface roughness. This feature of can be fairly uniform or highly variable.

Table 1: Streamside Management Zone surface roughness classification system of Johnson and Buffler (2008).

Degree of Surface Roughness	Description
Low	• Less than 35% of the land surface contains surface roughness features. • SMZs with exposed mineral soils as a result of human use automatically have a low degree of surface roughness, as do managed areas (e.g. areas that are intensively grazed, mowed, or used for agriculture).
Moderate	• Between 35 and 65 percent of the land surface contains surface roughness features • For an open (non-forested) system, such as shrub-steppe or wet meadow, it must not be intensively grazed, mowed, hayed, or intensively managed • Usually, there will be clumps of woody vegetation establishing due to lack of mowing • Vegetation must be rough and dense. • There must be surface roughness features other than herbaceous vegetation, such as woody debris, boulders, or hummocky topography, over at least 5% of the land surface by aerial coverage. • The surface organic horizon (duff layer) is intact throughout the buffer unit.
High	• Greater than 65 % of the land surface contains surface roughness features. • The microtopography is complex with undulating topography resulting from previous geologic and hydrologic events. The land surface does not slope smoothly and consistently toward the stream. • The SMZ unit is forested or covered with dense stands of riparian scrub, shrub-steppe vegetation, or dense rush/sedge vegetation. • The surface organic horizon (duff layer) is intact throughout the buffer unit. Natural occurrences of mineral soils, such as tip-ups (trees that fall over bringing the root crown and attached mineral soils to the soil surface), may be present. In natural shrub-steppe plant communities, 35 percent exposed mineral soil is common and undisturbed sites may be covered with cryptogamic crust. • In forested areas, dead-and-down wood and rotting logs and stumps are common. Specifically, coarse woody debris (>25 mm.) is scattered about and older woody debris is being incorporated into the organic horizon. • There is a well-developed grass and forb layer. However, in shaded SMZ woodlands this will not always be the case. A dense grass-forb layer is not necessary, although it remains important for a high degree of surface roughness as long as other factors are present. • Boulders and exposed bedrock are common and, where present, add microtopographical complexity. This feature is not required.

Sediment Size

Often one of the main functions expected of riparian vegetation is to reduce sediment movement in runoff. A riparian buffer is meant to function as a physical filter by removing sediment that is being transported by water entering the zone. The effectiveness of vegetated areas in trapping sediments depends on a number of factors, the principal one being water velocity (Karr and Schlosser 1978). The size of sediment transported into and through streamside management zones is a function of water velocity, which is in turn affected by surface roughness (Comerford et al. 1992). Competance (see Equation 1) is the maximum size of sediment particles moved by water and is proportional to the sixth power of water velocity (Hewlett and Nutter 1969):

$$\text{Equation 1: } C = kV^6$$

where:

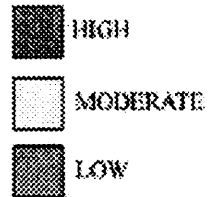
C = Competance

k = coefficient

V = water velocity

Small reductions in velocity can make drastic changes in the sizes of sediment particles carried in surface runoff. Sand-sized fractions of suspended sediment will usually deposit quite rapidly as velocity drops off (Figure 2). Silt-sized sediment is able to settle out if runoff water is detained in surface roughness and depression and velocities are dropped to near or <1 m sec⁻¹ (Hjulström 1939). Clay-sized sediment fractions do not readily settle out of a water column in even still water. The wider the buffer and the higher the surface roughness, the more likely that sediment trapping efficiencies will be high (Dosskey et al. 2008).

**SURFACE ROUGHNESS
LEGEND:**



**AVERAGED SURFACE
ROUGHNESS PER
BUFFER UNIT**

**TROUT CREEK
RIPARIAN BUFFER PROJECT**

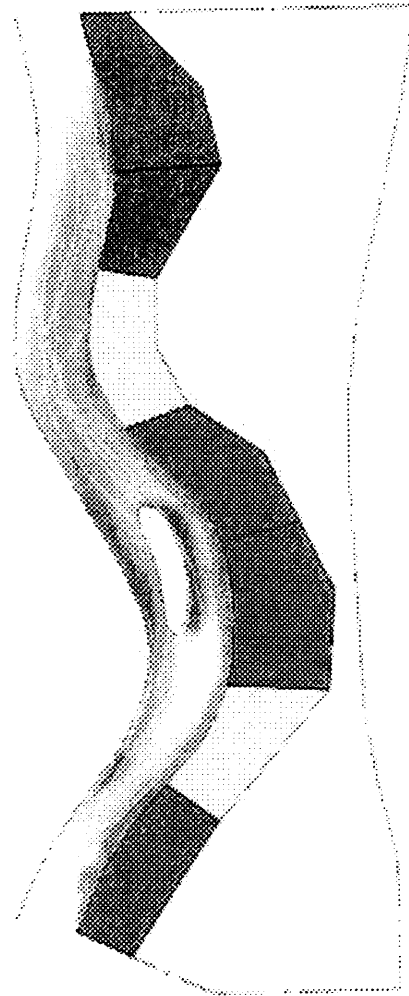


Figure 1. Surface roughness map for the Trout Creek riparian buffer streamside management zone (Adapted from Johnson and Buffler 2008).

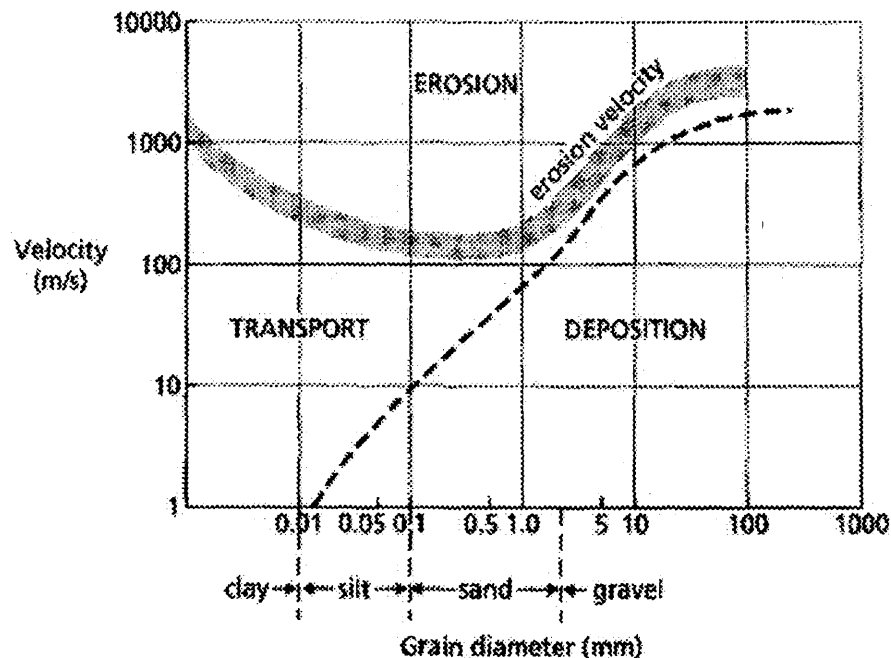


Figure 2. Relationship of suspended sediment size and transport velocity to erosion, transport, and deposition (Adapted from Hjulström 1939).

Water Velocity

Water velocity is an important concept influencing for sediment detention in riparian areas. Sediment transport in water is a function of water velocity and described in detail by Yalin (1977) and Haan et al. (1994). Any feature that reduces the velocity of water flowing into the buffer area will increase deposition of sediment. It will also provide additional time for infiltration of upland runoff into the soil, facilitating nutrient uptake and transformations (Schultz et al. 2009). Excessive water depths, especially in areas of concentrated flow, will reduce filtration functions since the water column will not interact with surface features. The sediment-laden runoff can then move directly into stream channels (Dosskey et al. 2002).

Slope Uniformity

Streamside management zones are often viewed to function by receiving relatively uniform sheet flow from uplands, and detaining the sediment and other pollutant loads carried in upslope runoff. However, hillslope geometry may force surface runoff into concentration points, increasing the velocity and depth of water flow into adjacent riparian areas. These

concentrated flows along natural or artificial drainage lines act more like point source inputs to streams and lakes rather than nonpoint ones. Roads frequently cause this sort of hillslope water flow pattern, but rock outcrops and coarse woody debris can produce the same effect. Streamside management zones are able to transform concentrated flow to sheet flow if the receiving area is wide enough, surface roughness is high, and drainage pathways are not well-defined. This situation is the most common cause of low buffer effectiveness since it routes upslope runoff straight through any streamside management zone, minimizing any filtering of pollutant-laden water. Sediment moving in surface runoff moves straight through the buffer rather than depositing within depressions (Figure 3).

The function of a streamside management zone in improving water quality depends on the assumption of an essentially uniform flow of water (above and below ground) through the zone. Channelized or concentrated flow at the surface or in the soil will reduce the water quality improvement effectiveness. In some landscapes, flow tends to be dominated by channelized flow towards the base of slopes (Nutter

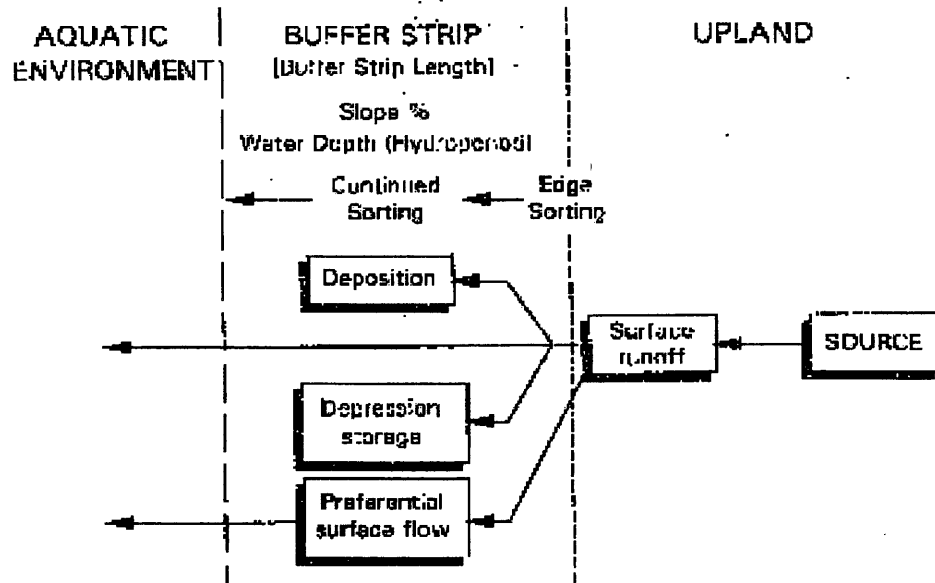


Figure 3. Schematic of sediment movement through a streamside management zone (From Comerford et al. 1992).

and Gaskin 1988). Rapid movement of water in ephemeral drainages and large soil macropores can quickly move sediments, nutrients, and pesticides across and through the riparian area and into stream channels. This reduces the time available for degradation and retention processes to occur. Flow routed into and through streamside management zones preferentially as concentrated surface runoff aggravates this situation.

Adjacent Slopes

Excessive slope can limit the effectiveness of riparian buffers. The steeper the slope the higher the velocity of surface runoff and, therefore, the greater the risk of concentrated flows breaking through an SMZ. As will be seen in the next section of this paper, most models for determining streamside management zone size factor in slope. Some researchers have argued the case that stream buffers should increase exponentially with slope (Nieswand et al. 1990) while others found that the width increase with increasing slope should be linear (Trimble and Sartz 1957, Swift 1986). There is a slope point at which buffers cease to be effective at all in containing runoff from adjacent uplands. Recommendations for this breakpoint range

from 10 to 40% (Cohen et al. 1987, Nieswand et al. 1990, and Wenger 1999).

Riparian Buffer Widths

The widths of streamside management zones reported in the literature are quite varied. There is no one-size-fits-all although many are in the 10 to 15 m range. The important feature of width is that it is flexible enough to meet the objectives functions of land managers (Minnesota Forest Resources Council 2005). Streamside management zone width is important since it allows sufficient time for water draining off uplands to contact vegetation, litter, and soil and decrease velocity, allowing for deposition of sediment. Width is important also in providing sufficient space for upland runoff, which might be entering as concentrated flow, to convert to sheet flow (Schultz et al. 2009).

Flow Conditions and Floods

If a riparian vegetation zone is not covered by water during most of the year, water depth and flow are minor considerations. However, if it is primarily wetland and frequently saturated, then the timing of surface runoff could influence the effectiveness of sediment filtration for water quality purposes. If high

flows or concentrated flows reduce contact time and interaction with surface roughness features, the beneficial effect of vegetation, litter, and coarse woody debris is greatly reduced (Comerford et al. 1992).

Vegetation Characteristics

Key vegetation characteristics that contribute to the effectiveness of riparian areas in retaining sediments entrained in runoff include the density, height, and lateral distribution of understory plants as well as the amount of coarse woody debris. Both contribute to the surface roughness characteristics of riparian zones. Greater sediment filtering is normally found with wide riparian zones typical of the larger river systems like the Colorado River, Salt River, Gila River, San Pedro River, and Rio Grande (Comerford et al. 1992). However, even these rivers have some reaches where riparian vegetation thins down to narrow strips (Baker et al. 2003).

LITERATURE EXAMPLES

Sediment is an important water quality parameter, since higher than normal levels can harm aquatic organisms and habitats, and render water unacceptable for domestic or recreation purposes. Sediment yields after forest harvesting are highly variable depending on such factors as soils, climate, topography, ground cover, and watershed condition. Although sediment yields often increase after harvesting due to the physical disturbance that exposes soil to erosion processes, these increases are usually transient due to vegetation re-growth, and are mitigated by slash and litter retention and other aspects of surface roughness. However, the duration of sediment increases above pre-disturbance conditions can vary considerably. Beschta (1978) reported effects lasting 6 years after logging while Lynch and Corbett (1990) saw effects out to ten years. Neither study lasted long enough to document recovery to pre-disturbance conditions.

The largest increases in sedimentation documented in the literature have been associated with post-harvest mechanical site preparation in the absence of streamside management zones (Beasley 1979), or with slope instability (O'Loughlin and Pearce 1976), road construction (Swanson et al. 1986), or highly erosive soils (Beasley and Granillo 1988). Best management practices are most effective on sediment when properly planned and implemented prior to, during, and after harvesting. Most of these guidelines relate to designing, constructing, and maintaining major access

roads, logging roads, skid trails, and landings (Binkley and Brown 1993). These areas are the primary sources for 90 percent of the sediment generated by harvesting (Reid and Dunne 1984, Swift 1986). The underlying principles of BMP guidelines in this context are to minimize disturbances in riparian areas, reduce the erosive power of runoff from bare road surfaces, and to maintain the normally high infiltration capacity of forest soils.

Sediment movement to streams is an on-going environmental concern in managed forest watersheds, but it also occurs naturally without active management. Watersheds vary greatly in their natural sediment load characteristics. Both natural and anthropogenic sediment deposits can be re-entrained after initial deposition in ephemeral or perennial stream channels, and move downstream for long time periods (>100 years) and distances. The cumulative effects of erosion and sedimentation that occurred centuries ago from agriculture or forestry can present land managers with many challenges such as channel bank collapse, tunnel erosion, and channel sediment transport to sensitive water resources (Neary 2002, DeBano et al. 2005).

Erosion Rates

Reference sediment-yield baselines have been discussed by Neary and Michael (1996), Neary (2002), and DeBano et al. (2005). Natural erosion rates (geologic erosion) for undisturbed forests in the western United States of <0.01 to 5.53 Mg ha⁻¹yr⁻¹ are generally higher than eastern United States yields of 0.1 to 0.2 Mg ha⁻¹ yr⁻¹, but do not approach the upper limit of geologic erosion (15 Mg ha⁻¹ yr⁻¹, Schumm and Harvey 1982). Australia's geologic erosion rates range from 0.04 to 0.86 Mg ha⁻¹ yr⁻¹ (Wasson et al. 1996). The measured differences at both continental and local scales are due to natural site factors such as soil and geologic erosivity, rates of geologic uplift, tectonic activity, slope, rainfall amount and intensity, vegetation density and percent cover, and fire frequency. Landscape-disturbing activities such as mechanical site preparation (15 Mg ha⁻¹ yr⁻¹; Neary and Hornbeck 1994), agriculture (560 Mg ha⁻¹ yr⁻¹; Larson et al. 1983), and road construction (140 Mg ha⁻¹ yr⁻¹; Swift 1986, Binkley and Brown 1993) produce the most sediment loss and can match or exceed the upper rate of geologic erosion. Erosion rates can be as high as 1,000 Mg ha⁻¹ yr⁻¹ in small gullied basins, and along with channel banks they are the main sources of sediment for Australian rivers (Wasson 1994, Prosser

et al. 2001). Roads, including tree harvesting access roads and skid tracks, are particularly problematic and chronic contributors of sediments to streams.

Sediment Yield Variations

Variation in suspended sediment concentration can be quite large both within and between individual catchments and regions (Binkley and Brown 1993). Most undisturbed forested catchments have suspended solid concentrations $<5.0 \text{ mg L}^{-1}$ and stormflow peaks $>100 \text{ mg L}^{-1}$, but some routinely average higher than 20 mg L^{-1} . Storm runoff from steep watersheds with highly erosive soils can have average suspended solids concentrations $>400 \text{ mg L}^{-1}$ (Beasley 1979). Responses of forested watersheds harvested without SMZs can be in the range of <2 to 43 times reference or pre-treatment conditions (Binkley and Brown 1993).

The effectiveness of SMZs in filtering out sediment from storm runoff has been demonstrated in a number of studies (e.g. Arthur et al. 1998, Dosskey 2001, Helmers et al. 2005, Loch et al. 1999, McKergow et al. 2003 and 2006). Sediment removals of 90% or more have been measured, and reductions in flow weighted mean suspended sediment concentrations of an order of magnitude have been documented (148 to 13 mg L^{-1} , McKergow et al. 2003). So, it is very clear that SMZs can work well in protecting or improving water quality. The big question is: "Can tree stands in SMZs be harvested without causing a significant deterioration in water quality and other important functions?" There are a limited number of published studies that address this question.

Minnesota

Hemstad et al. (2008) reported on fish habitat changes after several thinning treatments in a mixed hardwood forest with a SMZ. Reference areas had no tree felling at all. Riparian reference sites had upland areas that were clear-felled with a shortwood cut-to-length (CTL) system, but they retained a 30 m no-cut buffer zone (Mattson et al. 2000, Palik et al. 2000). Cut-to-length logging is a mechanized harvesting system in which trees are delimbed and cut to specified lengths (usually 3 m) directly at the tree stump. CTL is typically a two-machine operation with a harvester felling, delimbing, and cutting trees and a forwarder transporting the logs from the felling to a landing. The CTL riparian thinning treatment involved upland clear-felling and riparian zone harvesting to a

residual basal area of $12.3 \text{ m}^2 \text{ ha}^{-1}$. The final treatment was a whole tree-length (WTL) harvesting where the adjacent upland was clear-felled and the streamside management zone was thinned to the same residual basal area as the CTL treatment. In WTL logging trees are felled, delimbed, topped, and moved to a landing without being cut into smaller lengths. Hemstad et al. (2008) measured a small (15%) increase in streambed fine sediments and gravel embeddedness after harvesting. However, the sediment increase was catchment-wide in all stream reaches and involved the uncut reference reaches as well as the stream reaches that had SMZ harvesting. The effect was attributed to sediment washing off roads and stream crossings and into stream channels, not sediment derived from harvesting operations. This result points out the role of roads in producing much of the post-harvest sediment yield observed in forested catchments. Roads have been broadly recognized as important contributors to stream sediment loads (e.g. Beschta 1978, Swift 1986, Ziemer et al. 2000).

North Carolina

In another study, a coastal plain swamp (riparian zone) forest in North Carolina was clear-felled in May, 1998, leaving a 10 m wide uncut portion of the riparian zone as a buffer (Ensign and Mallin 2001). The harvested area was along the lower end of a 479 km^2 catchment. A significant increase in total suspended solids was measured in the harvested catchment during rainfall in June, July, and August after harvesting. Compared to a nearby uncut reference catchment, suspended solids were consistently 3 to 10 mg L^{-1} higher in the logged catchment during that 3-month period. One peak of 111 Nephelometric Turbidity Units (NTUs) was measured in the treated catchment during the first month after clear-felling. In contrast, extreme rainfall during Hurricane Bonnie in late August 1998 did not produce a notable effect on total suspended solids in either catchment. Stream samples collected 8 days after the hurricane landfall and 85 mm of rain did not show any notable impact to total suspended solids as a result of the storm. Turbidity in the harvested area was not significantly different from the uncut reference catchment although it did rise from 6 to 14 NTUs due to the hurricane. This was not a significant rise in NTU level, but it demonstrates that harvesting in wide riparian zones can lead to at least small and transient increases in turbidity even if BMPs exclude SMZ harvesting.

Malaysia

Gomi et al. (2006) studied the effects of logging lowland tropical rainforest in Butik Tarek Experimental Watershed in Malaysia that included 20 m riparian buffers. Catchments (14 to 38 ha) included a reference site with no harvest (C1), a 20 m buffer (C2), a 20 m buffer with a high road density and in close proximity to the riparian area (C2T), and a riparian partial harvest (C3). Catchment areas outside the streamside management zone were clearcut and logs extracted by skidders and log trucks. There was no significant difference in sediment delivery to the Butik Tarek stream in catchments C1 and C2. Catchments C2T and C3 produced 6 and 5 times the sediment volume into channels, respectively, than the C1 catchment. Roads and skid trails in C2T and C3 with steep gradients (>20%) and a high degree of connectivity to the catchment channels were responsible for the high sediment delivery to the Butik Tarek stream, not the tree-felling operation per se, as observed, for example, by Sidle et al. (2004).

Mississippi

Logging with and without streamside management zones in twelve mixed hardwood forest catchments with highly erodible loess soils in Mississippi, USA, was evaluated by Keim and Schoenholtz (1999). Treatments consisted of: 1) unrestricted cable- and skidder-harvesting including the streamside management zone, 2) cable-yarding only harvesting in a streamside management zone of 30 m width, and unrestricted cable- and skidder-harvesting of outside the streamside management zones, 3) no-harvesting within a 30 m-wide streamside management zone and unrestricted cable- and skidder-harvesting of other areas, and 4) a no harvesting reference watershed. Streams in catchments without any streamside protection had mean total suspended solids (TSS) concentrations 2.9, 3.2, and 1.8 times the concentration of the reference watershed stream with a buffer and no harvesting (mean TSS of 244.2, 272.0, 147.4, and 83.7 mg L⁻¹ for treatments 1, 2, 3, and 4, respectively). While this indicated the water quality protection value of streamside management zones, the responses of treatments 2 and 3 indicated the importance of minimizing soil disturbance within riparian areas. The results suggest that the streamside management zones did not function in trapping sediment originating in harvested areas outside the

buffer. Instead, the reduced sediment input into streams was achieved by creating less soil disturbance within the streamside management zone. The authors concluded that riparian zone prescriptions should focus on eliminating machine traffic within 10 m of streams.

Tasmania, Australia

A study was conducted in northwest Tasmania, Australia, to evaluate the water quality benefits of establishing a riparian streamside management zone and the effects of tree harvesting in this zone (Neary et al. 2010). This case study consisted of a 20-year-old *Eucalyptus nitens* pulpwood plantation in a streamside management zone of an intermittent stream that was harvested according to the Tasmania Code of Forest Practice. A machinery exclusion zone immediately adjacent to the stream limited machinery traffic. Ground cover and water quality pre- and post-harvesting were measured to identify the major sources of sediment in this headwater catchment, and to determine the effect of tree harvesting. Tree harvesting in the Tasmanian study resulted in minimal mineral soil exposure and increased surface roughness. Post-harvesting turbidity levels in streamflow were similar to pre-harvest levels (<2.5 Nephelometric Turbidity Units (NTUs) exiting the catchment) (Figure 4). Much more significant sources of sediment were a road, a dam that was accessible to cattle, and a cultivated paddock. These sources led to turbidities of c. 300 NTUs in a dam immediately below these points and above the harvested stream reach during a storm in late June 2009. In-stream dams installed many years earlier to store water for stock and irrigation, acted as very effective sediment traps. The riparian buffers and other BMPs used in these landscapes were effective at protecting water quality. This demonstrates that forest-harvesting operations can be conducted in riparian zones without increasing stream turbidity, if existing BMPs are followed.

Slope and Riparian Buffer Size

Helmers et al. (2005) reported on the mean sediment reduction with riparian vegetation zones of <5 to 20 m and slopes of 2 to 16% (Table 2). Mean sediment reduction was best with over 10 m in width. However, even riparian zones <5 m in width can be effective at trapping over 77% of sediment inputs.

Table 2: Mean sediment reduction on different slopes with riparian buffer widths of <5 to >20 m (Helmert et al. 2005).

Buffer Width	Slope Range		Mean Sediment Reduction	Sediment Reduction Range	
	Minimum	Maximum		Minimum	Maximum
m	%	%	%	%	%
<5	2	16	77.5	45	97
5 to 10	2	16	83.3	57	100
10 to 15	2	16	96.3	84	100
15 to 20	6	16	96.2	85	100

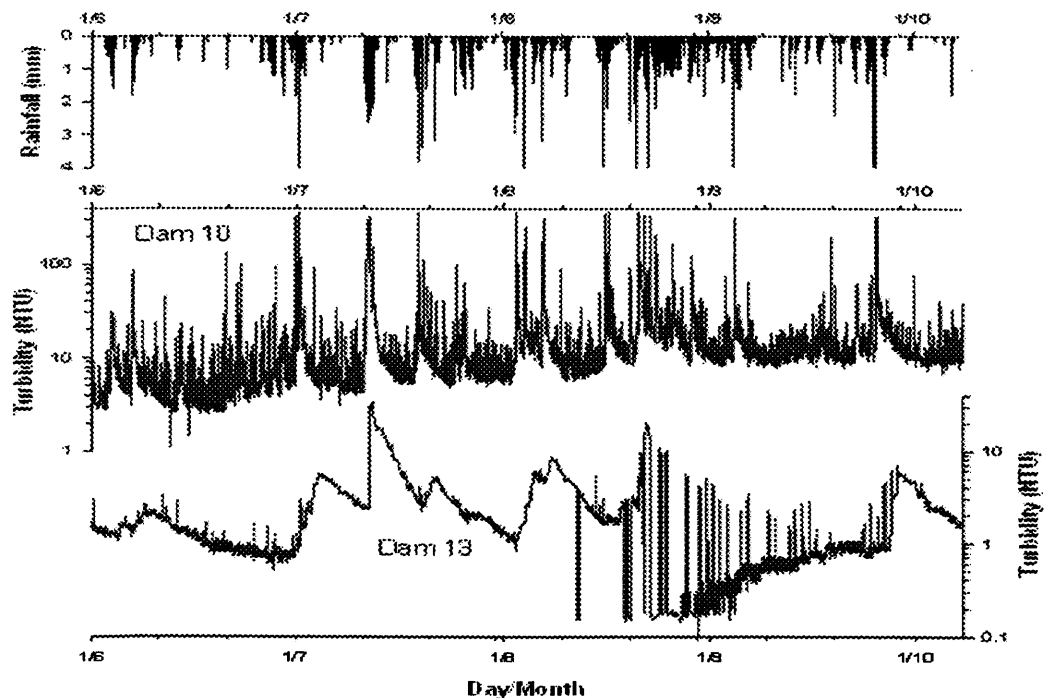


Figure 4. Rainfall in mm on the Pet River tributary catchment during the 2009 winter rainy period, and continuous turbidity measurements at D10 and D13 in mm per 15-minute intervals from 27 May 2005 to 9 October 2009. Y-axis units for Dams 10 and 13 are in NTUs on a log scale (From Neary et al. 2010).

WHERE RIPARIAN VEGETATION BUFFERS DON'T WORK

There are situations where riparian buffers do not function well in trapping sediment derived from

adjacent upland landscapes (Comerford et al. 1992). These involve processes that produce focused, directional routing of sediment-laden water into and through riparian zones, or situations where the normal sediment detention mechanisms are not functional.

The chief causes are roads, non-uniform slopes, flood inflows, scarce vegetation, and channel sediment sources. Some of these causes are unique and others interact to produce cumulative sediment loss effects.

Roads

Roads are the leading cause of runoff that breaks down the filtering function of riparian vegetation (Swift 1986). If roads are not designed properly, runoff can concentrate on road surfaces and deliver large volumes of water directly into streams. The Variable Source Area Concept (Hewlett and Hibbert 1967) describes how the perennial channel system expands during precipitation as areas at the head of and adjacent to perennial channels become saturated during storm events. Roads result in the expansion of

effective drainage network in a catchment. High levels of soil disturbance (e.g., physical exposure, removal, site preparation, and road construction) can shift more water originating from precipitation into overland flows and surface stormflows that produce damaging stream flows and concentrated flows through riparian vegetation and directly into stream channels (Neary 2002). High velocity water flows detach road surface sediments and lead to road fill and side slope gully erosion. Over-dense road networks also contribute to this problem. Gomi et al. (2006) reported that tree harvesting in Malaysia using a 20 m vegetation buffer increased stream sediment depositions by 3-fold, but adding roads into the mix increased sediment by an additional factor of 6.

Non-Uniform Slopes

This condition was discussed previously as a contributing factor to reduced sediment filtration in riparian zones. It sets up conditions for rapid movement of water into and through riparian buffers (Comerford et al. 1992). Rapid movement of large volumes of water into the riparian zone buffer reduces the amount of sediment deposited within the riparian zone or in depressions (Figure 3).

High Rainfall and Flood Inflows to Riparian Areas

High amounts of rainfall and subsequent runoff can have the same effect on sediment filtering as concentrated flows from roads or non-uniform slopes (Comerford et al. 1992). Substantial amounts of coarse and fine sediments carried in flood flows are often deposited in riparian areas during these inundation events, but significant amounts are also moved through riparian systems either further

downstream or into adjacent uplands. Riparian vegetation is able to trap sediments up to a variable failure point determined by water flow velocity and sediment load (Dosskey et al. 2002).

Channel Sediment

Some channel sediments can be temporarily stabilized by riparian herbaceous and woody vegetation. However, fluvial dynamics during flood events can easily remobilize these sediments (Baker et al. 2003). Vegetation is often viewed as a good mechanism for stabilizing bank and first terrace sediments (Medina et al. 1996). The main exception to this rule is the presence of vertical banks due to channel degradation (Neary et al. 2001). Vertical banks are major sources of sediment and will only be stabilized by vegetation when the angle of repose of the banks declines below a stability angle ($<45^\circ$) determined by the sediment texture and moisture content (Bell 1998). Bank collapse occurs as a result of streamflow undercutting or animal activity.

SUMMARY AND CONCLUSIONS

Riparian areas are special vegetation zones that are frequently used as buffer strips to mitigate sediment movement from upland forest and agricultural management areas. These areas are often called streamside management zones. They are strips of land along rivers or lakes that are given special management consideration. Various combinations of economic, ecological, and regulatory factors govern their size, shape, and management. Riparian zones function as and are often recognized as important barriers or treatment areas that protect water resources from non-point source sediment. Vegetation and the geomorphic characteristics of these buffer strips produces infiltration, filtering, and deposition of sediment-laden water flowing off of intensively managed forestry and agriculture lands. The effectiveness of vegetation in riparian areas for trapping sediment depends upon the velocity of water flow, size distribution of sediments, slope and length of slope above the riparian buffer, slope and length of the buffer strip, depth of water flow into the riparian zone, and vegetation characteristics such as type, density, and height. Data on sediment removal by forest vegetation buffer strips suggests that two main actions occur. First, the forest edge environment promotes sediment removal from surface runoff. Second, the sediment is sorted as it moves through lower gradient zones of the riparian buffer. This paper

examined these processes and illustrated them with examples from forest management operations and agriculture. In most instances, vegetation is quite effective in detaining sediments derived from uplands. However, the use of Best Management Practices on forest and grassland watersheds is really the first "line of defense" in reducing sediment input into streams. There are situations where even vegetation buffer strips can't cope with sediment movements. These situations are poorly designed roads, non-uniform slopes, flood flows, and channel sediments, especially vertical banks.

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