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Creating Functional Water Environments

Scientific Literature Review of Forest Management Effects on Riparian Functions for Anadromous Salmonids

Chapter 6

SEDIMENT EXCHANGE FUNCTIONS

for

The California State Board of Forestry and Fire Protection

September 2008

2201 Melvin Road, Oakland, CA 94602
(510) 927-2099
www.soundwatershed.com

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6) SEDIMENT EXCHANGE FUNCTION

Scientific Literature Review of Forest Management Effects on Riparian Functions for Anadromous Salmonids

For

The California State Board of Forestry and Fire Protection

Prepared by:

Mike Liquori

Dr. Lee Benda

with

Dr. Doug Martin

Dr. Robert Coats

Dr. David Ganz

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EXECUTIVE SUMMARY

The literature on sediment exchange tells us that there are a number of different mechanisms associated with forest management that are responsible for producing and delivering sediment to streams. These include surface erosion processes (rills and sheetwash), skid trails, yarding ruts, gullies, soil piping, roads, fire, mass wasting processes (e.g. landslides, earth flows, debris flows, etc.), bank erosion, windthrow and legacy forest management practices.

Associated with these production mechanisms are several mechanisms that contribute to the delivery of sediment to the stream network. Delivery is affected by mass wasting processes and concentrated surface runoff that have the capacity to mobilize sediment on hillslopes. Mass wasting processes can mobilize sediment over long distances, but generally, surface erosion processes only transport sediment short distances in the absence of concentrated runoff pathways.

Riparian buffers are effective at limiting sediment delivery to streams from surface erosion, skid trails, yarding ruts and bank erosion where buffers are employed (primarily on higher-order streams). In the absence of buffers, ground disturbances that are near streams have the potential to deliver sediment, and thus practices that minimize disturbances near the riparian environment are most capable of preventing sediment delivery. Several studies suggest that selective forest management within buffers will not substantially increase sediment production or delivery.

Riparian buffers are only somewhat effective in preventing sediment delivery from gullies, and mostly ineffective at preventing delivery from roads. Other processes like fire, mass wasting and soil piping were not sufficiently addressed by the reviewed literature. Buffers contributed to sediment production and delivery from windthrow in one study in California (Casper Creek in Mendocino County) and several studies in the Pacific Northwest.

The extent that riparian buffers along headwater streams are necessary to prevent sediment deliver is not clear from the reviewed literature. Several studies indicate that Best Management Practices (BMPs) that exclude equipment near streams, minimize soil disturbance, and prevent concentration of runoff in ditches, ruts and gullies should be effective. One study in Washington suggests that such non-buffer BMPs were not be effective, however that

study also indicates that these BMPs were either not implemented, or implemented poorly.

There are several factors that complicate the need for buffers in headwaters. Headwaters are dynamic systems where hillslope and channel processes are integrated and linked. Sediment functions in these areas are also dynamically linked with water and wood functions. The concept of disturbance cascades may help to provide an ecologically and geomorphically integrated framework for developing management practices guidelines in these landscapes. Such a framework might benefit by considering practices at larger spatial scales (i.e. sub-watershed to watershed) and longer time scales that recognize the recovery rates associated with various functional processes (see Figure 9).

Source distance relationships for sediment are described in Section 2.2.5. As with other exchange functions, the width for which sediment delivery to streams can be mitigated varies by process and landscape characteristics. The reviewed literature did not provide a sufficient guidance for the various landscape situations in California, although a more detailed analysis of data may lead to more definitive specifications for buffer width.

Road crossing decommissioning studies in California indicate that such practices contribute sizeable volumes of sediment. Such practices reduce the chronic sediment sources from roads, and reduce the risk of road crossing failures that can deliver very large volumes of sediment, and are thus beneficial over the long term. However, there may be opportunities for improvements in road crossing decommissioning practices that could reduce sediment delivery.

Recommended forest management objectives for sediment functions include mitigating harvest-related sediment, mitigating the hydrologic link to sediment delivery, mitigating road sediment, and mitigating for mass wasting impacts. Six specific considerations that would support these objectives are discussed, as well as two concepts for developing spatially-integrated buffer strategies. A summary of buffer dimensions used in regions throughout North America is also provided to help guide policy decisions.

SUMMARY OF TABLES AND FIGURES

1 RECOGNIZED EXCHANGE FUNCTION ROLES & PROCESSES

Riparian vegetation in forested environments influences the supply, delivery, routing, and deposition of sediment to stream environments. The relative importance of riparian forests in regulating sediment is governed by multiple interacting factors (CBOF-TAC 2007) and are summarized here:

- Erosion processes include 3 primary types:
  - surface erosion – including dry ravel, sheetflow erosion, and rilling processes
  - channelized erosion - including gullies, bank erosion and headcuts
  - mass wasting – landslides, slumps, earthflows, debris slides, rotational slides, debris flows, etc.
- The size of sediment delivered to aquatic environments is important.
  - Fine sediment – usually consists of sands, silts and clays, and generally has a negative influence on salmonid habitat if delivered in large volumes.. Fine sediment is generally measured as suspended sediment or turbidity.
  - Coarse sediment – usually consists of gravels, cobbles and boulders, and generally has a beneficial influence on salmonid habitats if delivered appropriately.. Coarse sediment is generally measured as bedload.
- Erosion occurs in conjunction with moving water, and deposition generally occurs where water movement stops or is slowed by hydraulic processes (e.g. gradient breaks, roughness, flow depth, etc.).
- Erosion also occurs in conjunction with mass wasting processes (e.g. landslides, debris flows, earth flows, etc) that occur near the stream environment.
- While erosion and deposition occurs throughout the channel network, headwater streams because of their dominant numbers in a watershed are significant sources

of sediment. Mid-gradient streams typically transport sediment, and low-gradient streams generally deposit and remobilize sediment.

- Sediment production in forested watersheds can vary substantially, depending on a wide array of factors, including natural soil erodibility, geology, climate, landform, gradient, vegetation, and relevant disturbance processes.

- Riparian communities influence sediment production, transport and storage by resisting erosion through root retention of soils, providing roughness elements that slows water, providing soil conditions that support infiltration of water.

- Poorly constructed or maintained roads have been implicated by many studies as the predominant source of increased fine sediment production from managed forest lands. Legacy road conditions can continue to be significant sources of sediment decades after construction. Even functioning road systems can be a potential and persistent source of sediment.

- The benefit of riparian buffers along fish-bearing streams has been widely accepted, although the characteristics of buffers (e.g. width, orientation, structure, permitted activities, etc) necessary to protect fish-bearing streams suffers from limited data, and has been widely debated.

- The necessity of buffers along headwater (e.g. non-fish) streams has also been widely debated, as scientific questions remain as to their value, benefit and risks.

2 RESPONSES TO KEY QUESTIONS

Sediment Best Management Practices (BMPs) typically address sediment primarily in three general ways:

Source controls: limiting the production of sediment from areas that are prone to erosion in response to forest management activities. This question is addressed in Section 2.1.

Runoff Controls: limiting the routing and delivery of sediment from source areas to stream environments. This question is addressed in Section 2.2.

Treatment Controls: mitigating sediment production and/or delivery through methods aimed at removing sediment from the stream environment. Examples include sediment traps, instream structures, filtration systems, treatment wetlands, etc. See Section 2.12.

To accommodate this approach, sediment production (source controls) and delivery (runoff and/or treatment controls) are separated within the Key Questions, even though the reviewed literature does not always address these different control approaches separately. There is likely to be some overlap based on the way that the Key Questions are covered and the way that the reviewed literature addresses these questions. At times this requires us to parse information from the literature in ways that may not have been intended, and which may result in some redundancy in how we address the Key Questions.

2.1 How do forest management activities or disturbances in or near the riparian zone affect the PRODUCTION of sediment over space and time?

There are several types of erosion processes that can produce sediment to streams (Figure 1). Most of these processes come from hillslopes (e.g. areas upslope of stream environments), although some may extend into riparian areas. Key sources include:

Surface Erosion

Surface erosion consists of dispersed erosion of sediment due to exposure to rain and runoff. It typically involves rilling and sheetwash processes. Sheetwash consists of unchanneled surface flow over compacted or saturated hillslopes. It is rare in forested soils, but common on and near roads. Rills are small, narrow, shallowly incised channels that are carved into hillslope soils as a result of erosion by overland flow (Selby 1993).

Surface erosion can occur in response to mechanical disturbance (e.g. skid trails, roading, etc.) or in association with other disturbances such as fires and intense precipitation events (MacDonald et al. 2004).

Skid Trails and Yarding Ruts

Skid trails and yarding impacts disturb the forest soils, often in long, straight pathways parallel to the hillslope. These areas can be source of hillslope sediment (Cafferata and Munn 2002; Rashin et al. 2006), although studies suggest that little sediment generally comes from these areas compared to other mechanisms (Euphrat 1992; Benda et al 2003; MacDonald et al 2004; others). In most studies, erosion from skid trails represents the only directly measured source of sediment from harvest activities due to the challenges in measuring sediment from surface erosion processes. Other studies infer surface erosion from measurements of instream sediment yield following timber harvest (Lewis 1998; Gomi et al 2005; others), although it is not always clear where such sediment is sourced.

Gullies

Gullies are enlarged rills that carve deep channels into hillslopes. Gullying is typically associated with roads and skid trails (CH2Mhill and WWA 1999; Cafferata and Munn 2002; Coe 2006; Rashin et al. 2006). Gullies require concentrated overland flow that generally is related to either soil compaction (by machinery), water repellant soils following fires, or directing concentrated flow onto soils (e.g. below road drainage culverts). Gullying can lead to extension of channel heads uphill into unchanneled swales (Swanson et al. 1989; Wemple et al. 1996). They can be a substantial source of sediment.

Soil Piping

Soil piping consists of concentrated subsurface water flows that can be a significant source of subsurface sediment erosion and transport. Soil pipes also influence mass wasting processes in steep landscapes. Forestry activities increase rates of soil piping through altered hydrologic runoff through increased infiltration and reduced canopy interception/evapotranspiration (Ziemer 1992).

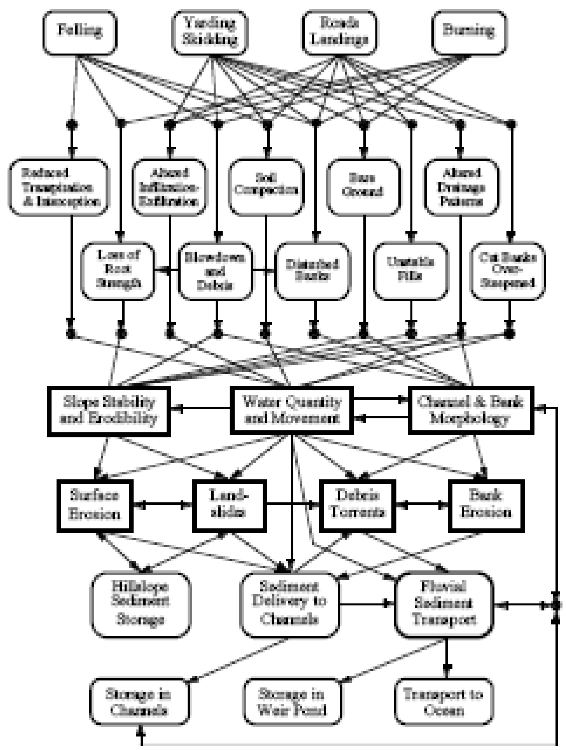

Figure 1) Conceptual pathways for forest management impacts on sediment production, delivery and transport (*from Lewis 1998*).

Roads

Roads are the most significant forest management activity that affects sediment production and delivery into streams in most California watersheds (Lewis et al 1998; Gomi et al. 2005; CBOF TAC 2007; others). Roads contribute sediment from exposed and unvegetated cutslopes, road tread, fillslopes, and drainage systems (WA DNR 1997). Sediment generated from roads can be delivered to streams via ditches and cross-draining culverts that concentrate and route runoff.

Road sediment production varies substantially . Key factors include the surfacing material (native v. rocked), road slope, mean annual precipitation, geology, road type, and road areas (Coe 2006; MacDonald et al 2004; Cafferata and Munn 2002; others).

Cited Study	***Type of Study***	***Location***	***Relevant Findings***
Benda et al. 2003	Sediment Budget	Southern Cascades (Judd Creek)	Estimated an average production of 0.038 tons/acre/year from roads within 200 feet of the stream
Cafferata & Munn 2002	Effectiveness Monitoring	Coastal and Inland California	Half or all road segments sampled had evidence of erosion downslope of roads; identified an average erosion from roads of 0.06 tons/road mile
MacDonald et al. 2004	Empirical Study	Central Sierras	Roads produced 4.0 tons/acre
Megahan & Ketcheson 1996	Empirical Study	Idaho Batholith	Road erosion rates varied from 4.8 tons/acre/yr to 39.7 m/ha/yr; 70% of erosion occurred during the 1st year after construction
Coe 2006	Empirical Study	Sierras	Native roads produced 12-25 times more sediment than rocked roads; native surfaces produced 0.00008 to 17.8 tons/ac/yr; the median production rate of rocked roads was 0.04 tons/ac/yr

Table 1) Summary of relevant road sediment production studies from reviewed literature.

Fire

The volume of sediment produced by fire can vary by several orders of magnitude. Severe wildfires have been documented to produce 4.9 tons/acre/year, while low-intensity prescribed burns produced only 0.004 tons/acre/year (MacDonald et al 2004). In humid to semi-arid landscapes, post fire erosion in the form of landsliding, debris flows and surface erosion can dominate the long term sediment budget (Figure 2) (Benda and Dunne 1997; Benda et al 2003).

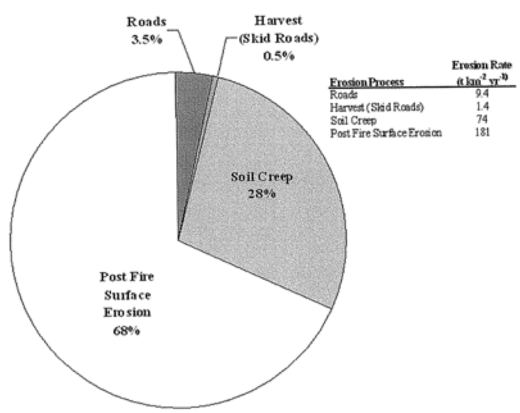

Figure 2) Estimated sediment production at Judd Creek (Southern Cascades). Soil Creep represents the "natural" rate of background sediment supply (*from Benda et al 2003*)

2.1.1 A) TO WHAT EXTENT AND WITH WHAT MECHANISMS ARE ZERO AND LOW-ORDER STREAMS (E.G., FIRST- AND SECOND-ORDER) AND THEIR RIPARIAN ZONES A SIGNIFICANT SOURCE OF SEDIMENT PRODUCTION IN UNMANAGED AND MANAGED FOREST AREAS?

Most sediment is reported to come from hillslope areas in the ways described above. Here, we summarize the reviewed literature with regard to sediment production (Table 2) and describe the dominant mechanisms that are primarily responsible for sediment production on hillslopes and near low-order streams. Sources of sediment

Overall, the extent of sediment production varies substantially by erosion process (e.g., Lewis 1998, Cafferata and Munn 2002, Rashin et al. 2006).

Cited Study	*Type of Study*	*General Location*	*Notes*
Benda et al. 2003	Sediment budget	Southern Cascades (Judd Creek)	Most sediment sourced from wildfire and natural background erosion. Roads and harvest activities generated <4% of the total sediment budget.
MacDonald et al. 2004	Sediment budget	Central Sierras	Unpaved roads and high-severity wildfire produced most sediment in forested landscapes (100 times and 1,000 times as much as background, respectively)
Cafferata & Spittler 1998	Empirical study	North Coast (Casper Creek)	Surface erosion from harvested units increased sediment production by 73 tons/acre. Post-harvest rills contributed ~2 tons/acre
Brandow et al. 2006	Effectiveness Monitoring	throughout California	Existing rules are highly effective in preventing erosion, sedimentation and transport to channels
Gomi et al. 2005	Literature Synthesis	Pacific Northwest	Sediment generation from windthrow can be significant, producing from 21 tons/mile (western Washington) to 32 tons/mile (Oregon coast range)
Benda et al. 2005	Literature Synthesis	Pacific Northwest	Background sediment rates range from 0.3-20 tons/acre/yr in steep headwater hillslope areas

Table 2) Summary of sediment production from various forest management activities as reported by the reviewed literature.

Harvest Management

Ground disturbance that occurs during logging activities within or near riparian areas can produce sediment (MacDonald et al. 2003, Kreutzweiser and Capell 2001, Rashin et al. 2006). Primary sources of sediment from harvest activities comes from skid trails and yarding corridors (Brake et al. 1997, Lisle and Napolitano 1998; Jackson et al. 2001, Gomi et al. 2005, Kreutzweiser and Capell 2001, MacDonald et al. 2004, MacDonald and Coe 2007, MacDonald et al. 2003).

One Oregon study (Hairston-Strang and Adams 2000) showed that harvest-related activities, including fire trails and cable corridors, were the largest single cause of exposed soil in buffers. The study also identified significant roles from other ground disturbance mechanisms including game trails, animal burrows, and windthrow. Some harvest-related activities in buffers, such as fire trail construction and site preparation, created continuous areas of exposed soil, but these were usually in the parts of the buffer farthest from the stream.

The variability of soil erodibility is important in establishing the risk of surface erosion (MacDonald et al 2004). Other key variables include geology, climate, and vegetation characteristics.

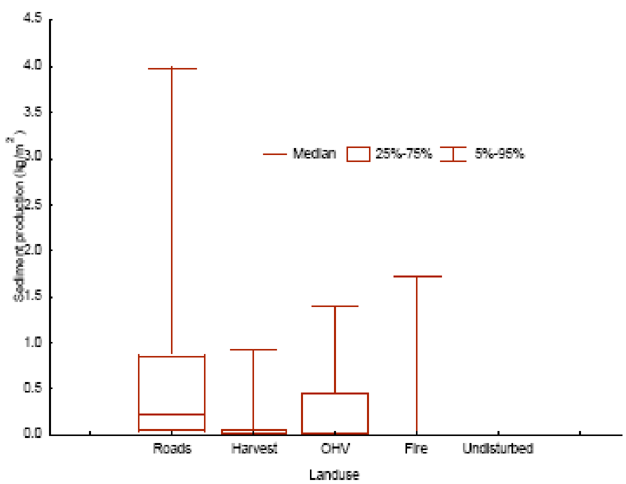

Figure 3— Sediment production by dominant land use for the 1999–2000 wet season.

Figure 3) Sediment production by land-use in the Sierras (*from MacDonald et al 2004*).

Mass Wasting Mechanisms and Extents

Mass wasting occurs from a number of erosion processes in forested landscapes, and is a major source of sediment in forested watersheds (CBOF-TAC 2007). Types of mass wasting include landslides, debris flows, earthflows, topples, and others. Mass wasting can be influenced by forest management through:

1. **altered hydrologic conditions** – which can increase the distribution of saturated soils, alter subsurface pore pressure dynamics, and change soil strength characteristics (Sidle et al 1985; others), and

2. **reduce root strength** – timber harvest activities can result in root mortality in some species, reducing the inherent ability for the hillslope to resist driving forces that result in mass wasting (Bishop 1964; Waldron 1977; Ziemer 1981).

Mass wasting can be a significant source of sediment from headwater areas (Figure 4), especially zero-order channels (hydrologically active unchanneled swales, also called 'hollows'). The areas most prone to mass wasting processes include steep, confined hillslopes and hillslope hollows (Dietrich et al 1986; Dietrich et al 1987; Crozier et al 1990).

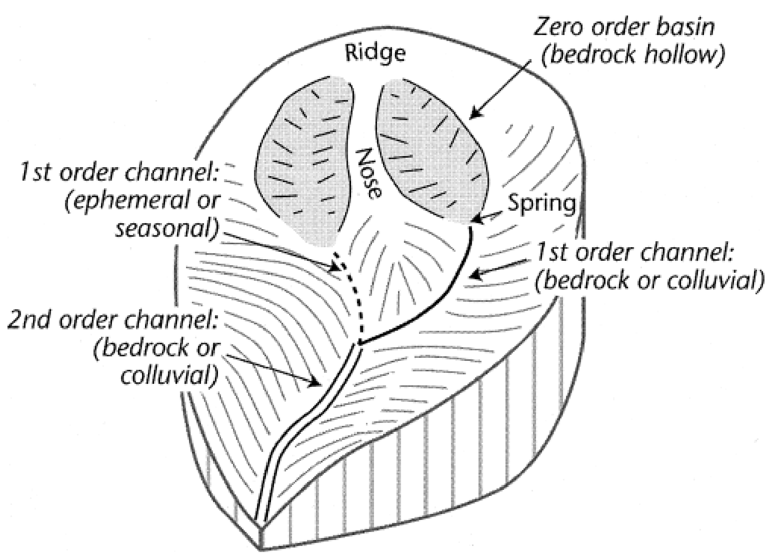

Figure 4) Anatomy of headwater drainage basins (from Benda et al 2005).

Mass wasting within inner gorges are a significant source of sediment from within riparian areas (Kelsey 1988). Such areas are typically found in geologic terrains with high uplift rates (e.g. north coast), and steep valley incision from fluvial (stream) erosion.

In California's North Coast region with sprouting coast redwood, Cafferata and Spittler (1998) found that the frequency of landslides is not substantially different between selective harvest and clearcut harvest, and the volume of sediment was similar between harvested and unharvested areas. However, May (2002) documented sediment dynamics associated with wood and sediment that occur in response to debris flow processes in low-order channels in managed and unmanaged landscapes and found that management influences the frequency, magnitude and characteristics of debris flows processes. The range in sediment volumes produced were highest in debris flows that originated from clearcuts and roads.

Most of the other reviewed literature offered did not substantially expand our understanding of mass wasting processes beyond that described by CBOF-TAC (2007), and thus insufficient information was available to fully describe the complex dynamics between mass wasting and sediment production and delivery in California forests.

Bank Erosion

Natural rates of bank erosion can be an important source of coarse-grained sediment to streams. Sediment provided by bank erosion supports channel morphology and spawning gravel supply functions (Hassan et al 2005). However, increasing bank erosion rates can degrade channel environments, and are generally considered undesirable. Stream banks store sediment over periods of time ranging from days to centuries (Benda et al 2005).

Direct disturbance in headwater channels can deliver sediment into the stream environment. Disturbance can include direct yarding impacts, mechanical disturbance of the banks, and introduction of debris into the stream (Jackson et al 2001; Rashin et al 2006). Cafferata and Munn (2002) identified only 4 eroded stream banks out of 37 erosion features in riparian areas in a study of 300 forest management sites. No volume estimates for bank erosion were provided in the reviewed literature.

Increased peak streamflow from reduced post-harvest canopy interception and/or snowmelt processes (within harvest areas) has also been implicated as one mechanism for increased bank erosion (Lewis 1998). However, the evidence in support of this mechanism is largely inferred from sediment yield studies, and has not been directly observed.

Riparian Windthrow

Another mechanism that may be locally important is the blow down of trees or windthrow. Uprooted trees can create new sediment production and where they occur adjacent to streams can deliver sediment to stream channels (Lewis 1998; Reid and Hilton 1998; Gomi et al 2005). Riparian buffers potentially increase windthrow rates adjacent to clearcuts because riparian stands don't develop wind-firm characteristics (Liquori 2006). Windthrow related sediment production from riparian areas can be responsible for delivering 21 to 32 tons of sediment per mile of stream (Gomi et al. 2005). Windthrow risks are generally considered a relatively minor issue in California, although Lisle and Napolitano (1998) and others report substantial blowdown on the North Fork Caspar Creek in selectively harvested buffers adjacent to upslope clearcuts**.**

Legacy Forest Management Practices

In some areas of California, the legacy effects of forest management continue to influence sediment production (CBOF TAC 2007). Such effects can be found in legacy roads, from increased bank erosion in incised stream channels, and from altered mass wasting characteristics (Cafferata and Spittler 1998; Gomi et al 2006).

2.1.2 B) HOW EFFECTIVE ARE CURRENT FOREST MANAGEMENT PRACTICES IN OR NEAR THE RIPARIAN ZONE IN MITIGATING THE PRODUCTION OF SEDIMENT IN HIGHER-ORDER STREAMS (E.G., THIRD-ORDER AND HIGHER)?

The reviewed literature discussed one primary aspect of forest management practices that mitigate sediment in higher-order streams; road crossings (Table 3) and harvest management practices. The reviewed literature generally does not distinguish between production and delivery in the context of mitigation practices.

There are important distinctions regarding erosion processes in low order versus high order channels due to allowable forest management activities in the different parts of a channel network and the different processes that occur in each. In general where riparian buffers are applied, erosion related to ground disturbance (by machinery) and skid trails are less likely and thus sediment does not recruit to the stream (Cafferata and Munn 2002, Brandow et al. 2006). In the absence of buffers along low-order streams, harvest activities in close association with channels are more likely to produce and deliver sediment to streams (Gomi et al. 2005; Rashin et al. 2006). Since mitigation generally implies addressing the delivery component, we discuss this issue more in Sections 2.2 and 2.2.5.

Road Crossings

In a study of road crossing decommissioning in Jackson Demonstration State Forest, Keppeler et al (2007) found that sediment generated after decommissioning was higher than expected, and that 50% of the measured sediment produced after decommissioning could be attributed to a relatively small number of sites (3 of 34 sites). Roads and water crossings with improper drainage due to improper design and/or maintenance of structures were the biggest sources of erosion and improper watercourse crossings were the largest contributor of sediment with both a high percentage of production and delivery to streams (Cafferata and Munn 2002).

In an extensive study of 275 stream crossing decommissioning projects in the North Coast region, PWA (2007) determined that the average sediment production following stream crossing decommissioning was 34 yd^3/site (~52 tons/site), a relatively large amount (approximately equal to 3 to 4 dump truck loads). Of the sites reviewed 58% did not meet decommissioning standards set by California Department of Fish and Game. Those sites that did meet the standards produced an average of 23 yd^3/site (~35 tons/site), while those that did not meet standards produced 42 yd^3/site (~64 tons/site).). Other California decommissioning studies include Klein (2003) and Madej (2001).

Study	***Type of Study***	***General Location***	***Number of Sites***	***Pertinent Finding***
PWA 2007	Empirical Study	North Coast, CA	275	small percentage of sites account for most of the erosion volume; avg. 34 yd^3/site (52 tons/site)
Keppeler et al 2007	Empirical Study	South Fork Caspar Creek Watershed, Mendocino, CA	34	small percentage of sites account for most of the erosion volume; avg. 30 yd^3/site (~46 tons/site)

Table 3) Summary of road crossing decommissioning studies in California.

2.1.3 C) TO WHAT EXTENT AND IN WHAT WAYS IS SEDIMENT PRODUCTION FROM CHANNELS, STREAMBANKS AND FLOOD-PRONE AREAS AFFECTED BY CURRENT FOREST MANAGEMENT PRACTICES?

Sediment production and delivery are not distinct in these settings. The reviewed literature generally treats production and delivery together in these settings. We discuss this Key Question in Section 2.2.3.

2.1.4 DOES PLANT SUCCESSION STAGE OR VEGETATIVE COMMUNITY HAVE ANY EFFECT?

Vegetative conditions in terms of stand density, species, ages, and stand structure (e.g., successional stage, see Liquori 2000; Rot et al 2000) may be an important influence on the potential for ground disturbance, surface erosion, and the delivery of sediment to stream channels in riparian zones. There was limited information in the reviewed literature that informed this question, however it is reasonable to expect that the vegetative community can influence sediment production and salmonid habitat conditions.

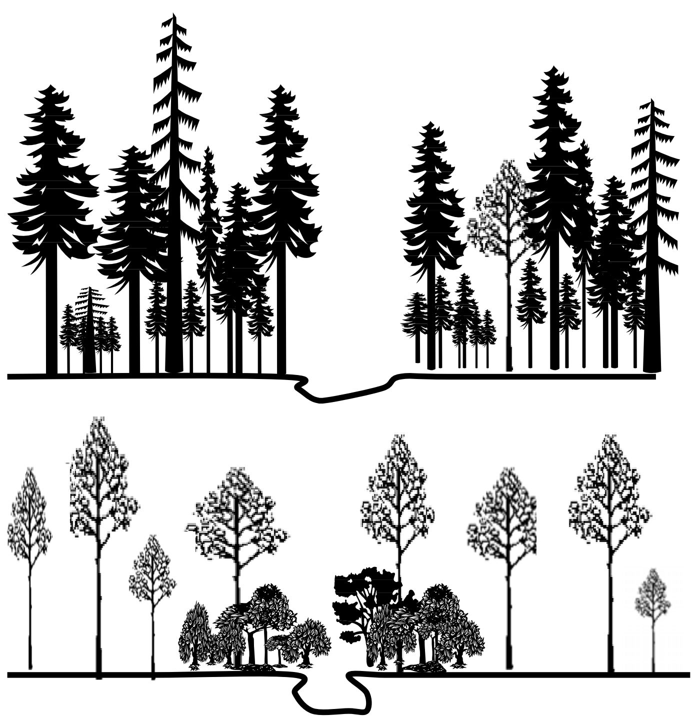

Figure 5) Schematic diagrams comparing a forested riparian area dominated by fir (top) as compared to a riparian community dominated by a scrub-shrub community(bottom). The scrub-shrub community requires an more open canopy, yet offers quality salmonid habitat conditions (from Liquori and Jackson 2001).

Liquori and Jackson (2001) surveyed first- to third-order streams in environments similar to many mixed fir forests in California, and found two distinct endpoints of riparian vegetation. Where the forest overstory is dominated by open stands of Ponderosa pine (Pinus ponderosa), channels are commonly bordered with a dense scrub-shrub vegetation community. Where fire suppression and/or lack of active riparian zone management have resulted in dense encroachment of fir forests that create closed forest canopies over the channel, scrub-shrub vegetation communities cannot compete, and are virtually absent near the channel (Figure 5). The scrub-shrub channels have more box-like cross-sections, lower width-to-depth ratios, more pools, more undercut banks, more common sand-dominated substrates, lower water temperatures and similar amounts of woody debris (despite lower tree density). These characteristics combine to describe quality salmonid habitat conditions in the scrub-shrub channels. The authors suggest that the scrub-shrub community was more common in the landscape prior to the 20th century, and may have been the dominant native riparian community for these stream types. Thus, managing these types of streams for dense riparian conifer might not mimic natural conditions, nor can dense riparian conifer provide superior in-stream habitat where scrub-shrub communities can become established.

Part of the success of the scrub-shrub communities may be in the higher root density provided by the denser vegetation. Root density has been shown to improve bank stability in many channel environments reducing the production of sediment from streambanks (Abernethy and Rutherfurd 1999; Simon and Collison 2002).

2.2 How do forest management activities or disturbances in or near the riparian zone affect the DELIVERY and STORAGE of sediment over space and time?

There are both internal and external sources of sediment to streams(Table 4). Internal sources include those processes that act within the channel, and external sources primarily address those that are active on hillslopes (e.g. areas outside streams or riparian areas)). Forest management practices can directly affect the delivery and storage of sediment primarily on hillslopes, although there are indirect effects from forest management on those processes that occur in streams.

	External Sources[1]
Infrequent	Landslide, debris flows, avalanche, slope failures, wind throw, earth flow
Frequent	Slope surface erosion (rain splash, sheet erosion, dry ravel, freeze/thaw), bank erosion, glacier discharge
Potential Effect of Logging	Road fill failures (mass movement), road surface, cut slope, fill, and ditch, slash burning, wind throw in riparian buffer, tree/wood death and decay, soil compaction, soil clearing by yarding
	Internal Sources[2]
Infrequent	Breakage of log jams, animal crossing, redd excavation by salmonids
Frequent	Channel substrate, sediment wedge, bank deposits (within bankfull width), headward channel extension, soil subsurface erosion (pipe flows)
Potential Effect of Logging	Changes in flow response, slash entrainment (channel roughness), in-channel storage (substrate and sediment wedge)

*Forest fire and wind throw both affect the occurrence of external suspended sediment sources.
[1]External sources are those located on hillslopes in headwaters and in the riparian zone outside the bankfull width, including zero-order basin.
[2]Internal sources are ephemeral and perennial channels.

Table 4) sources of suspended (fine) sediment found in small streams (*from Gomi et al. 2005*).

Concentrated water flows are a key ingredient in transporting sediment. Without concentrated water, sediment transport follows very slow, diffusive rates of transport, on the order of fractions of an inch per year (Ritter et al 1995). With concentrated flows, sediment can be transported as long as the flows remain concentrated, provided sufficient energy is available for transport. Sediment transport capacity is generally controlled by several factors, including the slope of flowing water, the depth of flow, and the size of the transported sediment grains (Knighton 1984).

The following section describes several important topics associated with sediment delivery and storage. Note that these occur in all areas regardless of stream order, although the characteristics associated with storage will vary in different settings.

Roads

Road studies generally do not describe the types of streams, so the general trends described below reflect all stream types.

Roads and skid trails represent a situation where flow and thus sediment transport can be concentrated due to ground compaction and hydrologic alteration (WA DNR 1997). Road related erosion is delivered from gullies below road drainage structures (e.g. culverts, waterbars, dips, etc.) through riparian zones, or can be directly routed into streams via inside ditches (Coe 2006; Rashin et al.

2006; others). Road fillslopes can also deliver sediment through disperse rilling and sheetflow processes when fillslopes are within about 65 feet of the stream (Megahan and Ketchinson 1996).

Cited Study	***Study Type***	***General Location***	***Relevant Findings***
Brandow et al. 2006	Effectiveness Monitoring	California	Approximately 7% of road segments surveyed delivered sediment to the stream
Cafferata & Munn 2002	Effectiveness Monitoring	California	24.6% of gullies and 12.6% of rills coming from roads delivered to streams; approximately 15% of all inventoried erosion features delivered sediment to channels
MacDonald & Coe 2007	Literature Synthesis	Central Sierras	The proportion of roads that deliver to streams can be reduced by about 40% through engineering drainage structures
Coe 2006	Empirical Study	Sierras	Road delivery to streams is proportional to the mean annual precipitation; 95% of sediment from cross-drain gullies was less than 138 feet
Megahan & Ketcheson 1996	Empirical Study	Idaho Batholith	95% of fillslope erosion traveled less than 65 feet; 95% of cross-drain routed sediment traveled less than 500 feet
Brake et al. 1999	Empirical Study	Oregon Coast Range	Downslope travel from cross-drain gulles ranged from less than 1 foot to 131 feet
Benda et al. 2003	Sediment Budget	Southern Cascades (Judd Creek	~50% of native surface road length delivers directly to streams; average estimated road erosion rate was 0.038 tons/acre/year

Table 5) Summary of road delivery results from reviewed literature.

Typical travel distances of sediment plumes downslope of culvert outlets (or other diversion structures) have been reported as follows:

- Average of 16-30 feet (5 to 9 m) and maximum of 75 to 131 feet (23 to 40 m) in Oregon (Brake et al. 1997),
- 20 to 121 feet (6 to 37 m) in the Sierras (Coe 2006), and
- within 100 feet (30 m) in other areas (Castelle and Johnson 2000).

Mitigating road and skid road generated sediment from reaching channels below drainage structures may not require vegetative buffers but rather requires diverting concentrated flows more frequently, or reducing outflow energy by discharging culverts onto high roughness elements such as rocks and downed woody debris (Brake et al. 1997; Coe 2006).

Skid Trails and Yarding Ruts

Disturbed hillslope soils that are created by skid trails, yarding ruts, ditches, gullies, or compacted swales can concentrate runoff and deliver sediment downslope toward stream environments. In these environments, sediment can be transported up to about 100 feet (Brake et al. 1997; Coe 2006; Castelle and Johnson 2000). In the absence of ground compaction or concentrated flow conveyances (swales, channels, ditches, rills, gullies, etc.), most sediment plumes from hillslope disturbances are captured by hillslope infiltration or vegetative roughness within about 16 – 32 feet (Benda et al. 2003 MacDonald et al. 2003; Kreutzweiser and Capell 2001). In either case, hillslope sediment transport distances can be influenced by the hillslope gradient, amount of surface roughness, and the infiltration capacity of the soils.

Forest ground cover can limit hillslope sediment transport distances. To mobilize, sediment generally must be carried by water. High infiltration capacity can disperse water and sediment into the forest floor. Sediment can also be captured by microtopography and other roughness elements (vegetative stems, debris, etc), which can pond water and trap sediment.

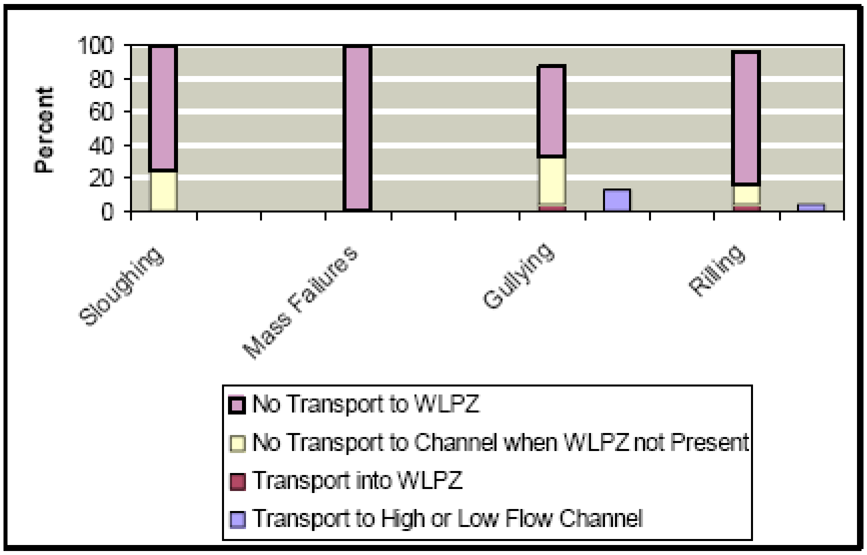

Figure 6) proportion of erosion features observed during dry season surveys of skid trails that deliver to streams and riparian areas (*from Cafferata and Munn 2002*). Note that only a small fraction of sites delivered to the stream channel (short bars next to Gullying and Rilling).

To reduce sediment delivery, vegetative buffers may not be necessary along streams. In one study in the southern Cascades of California, erosion generated along skid trails only traveled several meters (at most) before being intercepted by downed woody debris and micro surface topography (Benda et al. 2003). As long as mechanical disturbance of ground cover was located away from stream channels, riparian buffers may not be needed (MacDonald et al. 2000). However, at least one specific study suggests that non-buffer BMPs used in headwater streams in Washington state may not be effective in preventing sediment delivery (Rashin et al 2006).

Equipment exclusion zones of 15-35 feet (5 to 10 meters) or more adjacent to streams have been identified by several studies as a potential mitigation practice (MacDonald et al. 2003; Young 2000; Gomi et al. 2005; Kreutzweiser and Capell 2001). However, a study of 13 equipment exclusion zone sites in Washington suggests that they may not be effective at preventing sediment delivery to streams (Rashin et al 2006).

2.2.1 A) TO WHAT EXTENT AND WITH WHAT MECHANISMS IS SEDIMENT DELIVERED TO ZERO AND LOW-ORDER

STREAMS (E.G., FIRST- AND SECOND-ORDER) IN UNMANAGED AND MANAGED FOREST AREAS?

As described in Section 2.2, the mechanism for delivering sediment generally require a source of sediment and sufficient conveyance capacity provided by flowing water or mass wasting processes to mobilize that sediment.

The complexity and variability of channel-hillslope interactions, makes it difficult to rigorously link upstream sources of sediment to downstream areas of impact (Hassan et al 2005; MacDonald and Coe 2006), thus the extent of hillslope sediment sources that deliver to zero and low-order stream was only qualitatively described by the reviewed literature. Several papers describe general mechanisms for delivering sediment, and they are generally the same processes that are responsible for producing sediment (Benda et al 2005; Gomi et al 2005; Hassan et al 2005; Rashin et al 2006; others). Key processes include surface erosion (rills and sheetwash), skid trails, yarding ruts, gullies, soil pipes, roads, and mass wasting processes.

Headwater areas are particularly prone to delivery because of generally steeper slopes, higher stream density, and greater confinement (MacDonald and Coe 2006; Benda et al 2005; others). When ground disturbance processes are active near streams, or in the unchanneled hollow axes immediately upstream of the channel, they pose a generally high risk of delivering sediment to the channel network (Figure 7). These areas play in important role in generating and moderating storm runoff, especially on the rising limb of the flood hydrograph (Gomi et al 2006). Typically, as a storm progresses, the bed and banks in these areas become increasingly saturated and the area with active surface flows expands both upstream, and laterally. This “hydrologic zone of expansion”[1] provides the conveyance capacity required to mobilize (and thus deliver) sediment.

[1] *The “hydrologic zone of expansion” is not a technical term, but one that is consistent with the Variable Source Concept, which is the predominant theory in hillslope hydrology (see Chapter 4). We use this term to avoid confusion with the technical jargon.*

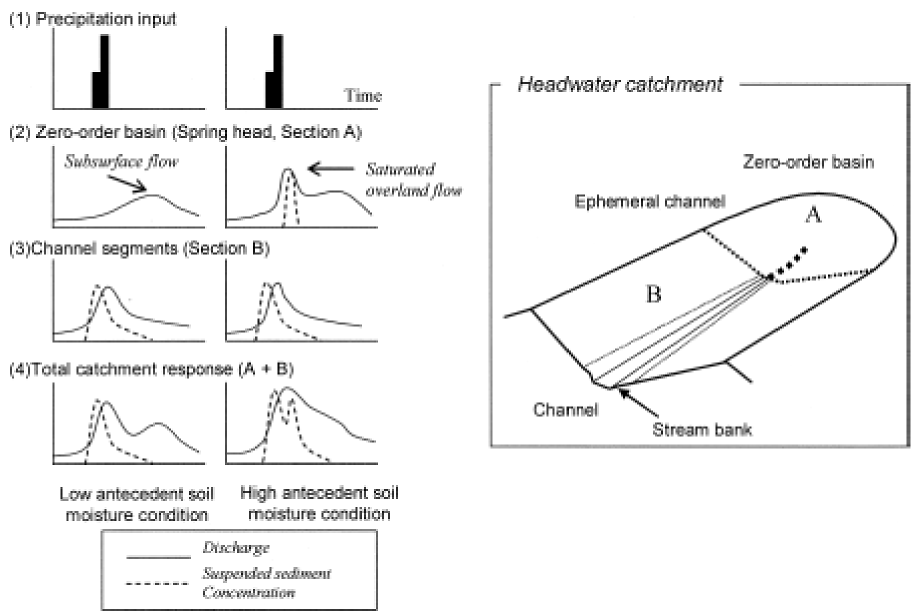

Figure 7) Hypothetical hydrologic response and suspended sediment concentrations in a zero-order (hollow) and 1st-order (channeled) catchment during low and high antecedent soil moisture conditions. The X-axis shows time and y-axis represents relative magnitude (*from Gomi et al 2006*).

As described above, extensive disturbance or compaction of the soils in steep hollows or near streams can produce sediment that is available for transport by surface runoff (Jackson et al 2001; Rashin et al 2006; others).

It is also important to recognize that there are disturbance cascades (Figure 8) that occur in headwater areas that affect downstream reaches (Nakamura and Swanson 2003; Hassan et al 2005). The concept of disturbance cascades is important in setting the context for the role of sediment in forested watersheds (Hassan et al 2005; Nakamura and Swanson 2003; others). A disturbance cascade is a framework that describes the way that mass and energy pass through the watershed hillslope, riparian and channel network. A series of interlinked physical processes transfers sediment, wood and water downslope and downstream in ways that influence the characteristics and processes in the landscape. Because these systems and processes are coupled, they are inherently interdependent.

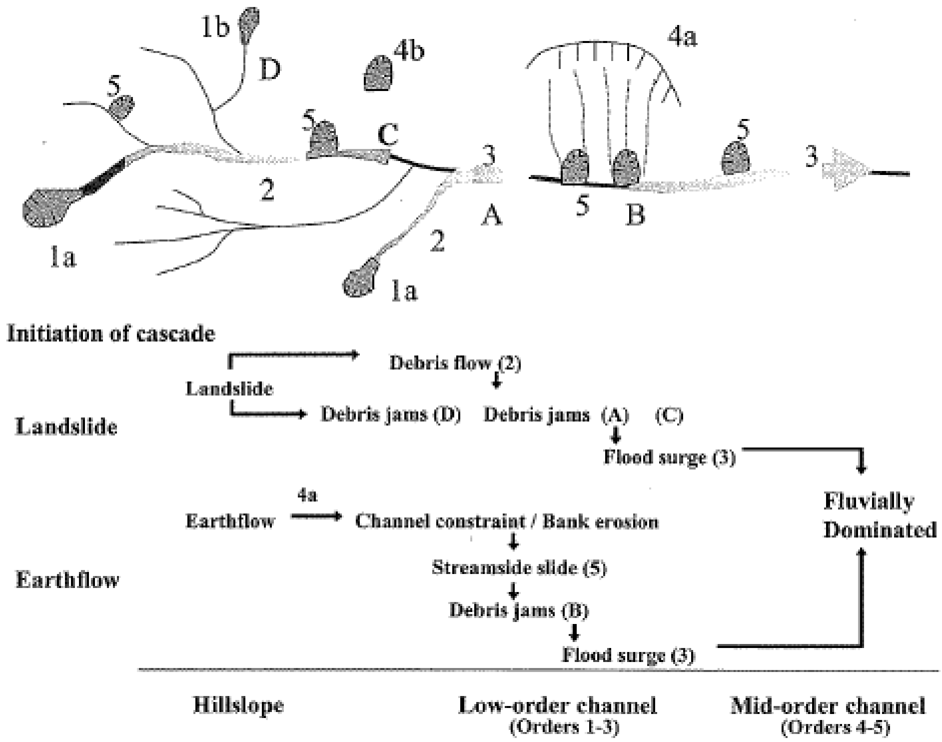

Figure 8) Example schematic diagram of a disturbance cascade, showing how processes over a channel network translate into different disturbances types as the disturbance moves downstream. For example, a landslide from a hollow (1a) becomes a debris flow in the first-order channel (2) causing a flood surge in the 3rd-order channel in which it deposits (*from Nakamura and Swanson 2003*).

Because of the large number of headwater streams in a channel network, sediment delivery has the potential to contribute substantial amounts of sediment to the stream network (Benda et al 2005; Rashin et al 2006; MacDonald and Coe 2006; others). The concern over sediment introduction into headwater streams may depend on whether sediment is routed downstream and impacting other beneficial uses such as water quality and fish habitat (MacDonald and Coe 2007; Gomi et al. 2005). The complex nature of headwater channel morphology (e.g., filled with rocks, brush, woody debris, etc.) and ephemeral flow (intermittent dry or dewatered areas) generally acts to limit downstream sediment transport and enhance sediment deposition near the site where sediment enters (Jackson et al. 2001; Robison and Runyon 2006). Nevertheless, studies have documented that fine sediment can be routed effectively through headwater streams to larger fish bearing channels (Gomi et al. 2005). Sediment delivery to small streams may also have impacts to amphibians and other species important to the aquatic community (Jackson et al 2001; Rashin et al 2006), although specific biological studies were not described within the reviewed literature.

2.2.2 B) HOW EFFECTIVE ARE CURRENT FOREST MANAGEMENT PRACTICES IN MITIGATING THE DELIVERY OF SEDIMENT IN HIGHER-ORDER STREAMS (E.G., THIRD-ORDER AND HIGHER)?

This question is addressed in Section 2.2.5.

2.2.3 C) TO WHAT EXTENT AND IN WHAT WAYS IS SEDIMENT PRODUCTION AND DELIVERY FROM CHANNELS AND STREAMBANKS AND STORAGE ON FLOOD-PRONE AREAS AFFECTED BY CURRENT FOREST MANAGEMENT PRACTICES?

Stream channels in forested areas are highly dynamic systems that respond morphologically to inputs of fine sediment (sands, silt and clay particles), coarse sediment (gravel, cobbles and boulders), large wood, smaller organic debris and water (Wohl 2000). Understanding the effects from management can be difficult given the complexity of these systems, the natural variability in key processes, and the wide variety of landscapes in which functions are important. Additionally, measuring or modeling sediment in these landscapes can be complicated by persistent instream structures that temporarily store and moderate sediment signals (Hassan et al 2005).

The concept of disturbance cascades is important in setting the context for the role of sediment in forested watersheds because they represent a series of spatial linked processes that change in the downstream direction in response to changes in the geomorphic structure of the hillslope and channel network (Hassan et al 2005; Nakamura and Swanson 2003; others).

In managed landscapes, sediment is produced on hillslopes and delivered to streams via road networks, mass wasting processes (landslides, earthflows and debris flows), management-induced hillslope erosion, and natural erosion processes (e.g. rainsplash, creep, frost-heave, etc). In headwater channel environments, hillslope processes dominate the form and function of stream environments because sediment and wood are the predominant materials. Fluvial (stream) processes gradually increase in importance downslope, as the volume of water increases.

Management can affect these processes in many ways:

- Roads generate sediment and alter hydrologic flowpaths in ways that affect sediment delivery (Megahan and Kidd 1972;

Montgomery 1994; Wemple and Jones 1996; Luce and Black 1999; Coe 2006; others);

- Harvest activities generate sediment and can locally concentrate water by disturbing hillslope soils through skid trails, yarding ruts, compaction and general site disturbance (Jackson et al 2001; Rashin et al 2006; others);

- Harvest activities affect hydrologic processes in ways that modestly increase the storm peak associated with small to moderate floods (Chapter 4), which influences the way the sediment is routed through the channel network (Lewis 1998);

- Forest management practices can alter the natural disturbance regime, affecting the frequency and magnitude of natural disturbance processes that act to produce and deliver sediment and wood in ways that affect ecosystem processes in watersheds (Liquori 2000; Young 2000; Dwire and Kauffman 2003; Nakamura and Swanson 2003; Reiman et al 2003; Bisson, Reiman et al 2003; Hassan et al 2005; Gomi et al 2005; others);

- Riparian management activities, including harvest and silvicultural practices, influences the timing and characteristics of wood recruitment to streams

- Forest management of roads and harvested areas can trigger landslides and other mass wasting processes before they would be triggered from natural processes.

The net (or cumulative) effect of these management impacts are difficult to define in a general context. Many of these impacts from forest management have minimal impact on aquatic environments; others can have major impacts. The distinguishing factor as to whether an impact is minimal or major depends on a) the regional and watershed-scale context for the site, and b) any dynamic interactions among and between processes and functions that can elevate the relevant impact from any single management practice.

Channels

To evaluate the net effect from management practices, several studies have evaluated the increase in sediment yield in stream environments (Table 6). Sediment yield measurements and models are difficult to develop for a variety of technical reasons; there are many factors that must be considered. But they can provide an integrated measure of the effectiveness of forest management in terms of sediment production and delivery. The reviewed literature did not directly study sediment sourced from channels, although several studies evaluated changes in sediment yield following harvest activities. Such studies are an indirect measure, in that sediment sources from such studies can only be inferred.

Cited Study	*Type of Study*	*General Location*	*Pertinent Finding*
Macdonald et al. 2003	Empirical Study	Sub boreal forests, BC	Elevated total suspended sediment concentrations returned to preharvest levels (or lower) within 3 years or less.
Hassan et al. 2005	Synthesis of Regional Literature	Pacific Northwest	Variations in sediment yield reflect temporary sediment storage and variations in sediment transport capacity in complex headwater stream environments
Gomi et al. 2005	Synthesis of Regional Literature	Pacific Northwest	Suspended sediment increases were observed in several studies following roading, harvest, and broadcast burn practices. Recovery varied.
Lewis et al. 2001	Empirical Study	Caspar Creek Watershed, Mendocino, CA	Suspended sediment during storms was 89% higher in small watersheds following harvest with buffers following California Forest Practice Rules (circa 1990s). Mainstem showed no impacts.
Lisle & Napolitano 1998	Empirical Study	North Fork Caspar Creek Watershed, Mendocino, CA	No changes in bedload yeild were detected following harvest, although changes in stored sediment and pool volume were noted, primarily in association with increased woody debris inputs. 42-56% of annual sediment yield came from landslides
Lewis 1998	Empirical Study	Caspar Creek Watershed, Mendocino, CA	Sediment load increases are correlated with flow increases after logging; suspended sediment in streams increased 2.4-3.7 times due to harvesting. Suggested that some of the observed increased in sediment was from increased bank erosion associated with higher storm peaks following harvest.
Keppeler et al. 2003	Empirical Study	Caspar Creek Watershed, Mendocino, CA	Annual suspended sediment increases were smaller in buffered and clearcut watersheds as compared to unbuffered watersheds. Peak flow increases recovered within 12 years following harvest, but sediment yields remained elevated.

Table 6) Summary of post-harvest sediment yield studies in reviewed literature.

There are typically two types of sediment yield measurements. Suspended sediment tracks the delivery of fine sediments (generally sands, silts and clay particles). Bedload measurements reflect delivery and/or mobilization of coarse sediment (sands and gravel particles). Bedload is more important in affecting channel morphology processes, while suspended sediments may be more important in predicting biological impacts in aquatic environments.

Studies following harvest indicate that elevated sediment yields occur, even where buffers are employed in larger (typically higher-order) streams (Macdonald et al. 2003; Hassan et al 2005; Gomi et al 2005; Lewis et al 2001; Lisle & Napolitano 1998; Lewis 1998; Keppeler et al 2003). While such studies are generally unable to identify specific sources of sediment following harvest, authors speculate that elevated sediment yields may come from roads (Gomi et al 2005), increased bank erosion (Lewis 1998), hillslope erosion (Lewis 1998; Gomi et al 2005; others), increased mass wasting (Lisle and Napolitano 1998; Gomi et al 2005; Hassan et al 2005), and increased wood recruitment to streams (Reid and Hilton 1998; Lisle and Napolitano 1998; Gomi et al 2006; others).

In a review of sediment yields from unmanaged forests, California ranks highest in observed sediment yields (Gomi et al 2005). In coastal California, studies of post-harvest sediment from Casper Creek (Jackson Demonstration State Forest) have documented annual sediment loads that increased 123-269% in the tributaries, but at main-stem stations, increased loads were detected only in small storms and had little effect on annual sediment loads (Lewis et al 2001; Keppeler et al 2003). Much of the increased sediment load in North Fork tributaries was attributed to increased storm flow volumes associated with clearcut timber harvest of upslope areas. As hydrologic effects recover in the years following harvest, flow-related increases in sediment load will return to pre-harvest levels (Lewis et al 2001: MacDonald et al 2003). Sediment effects appear to persist for at least 12 years after harvest, even though flow increases appear to be recovering (Keppeler et al 2003).

Recovery of associated increases in sediment yield following harvest vary, and may reflect differences in instream storage, sediment sources, or other factors. General recovery trends are suggested by Gomi et al (2005) (Figure 9).

The capacity to transport sediment from headwater streams to downstream reaches is a function of channel type, transport processes, transport capacity, and sediment particle size (MacDonald and Coe 2006; Hassan et al 2005).

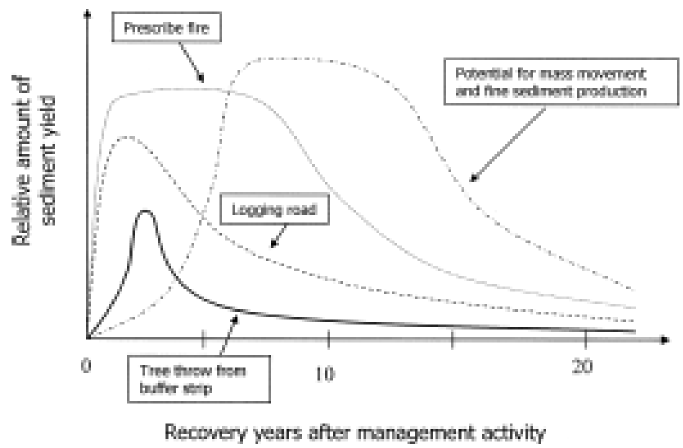

Figure 9) Relative duration and recovery rates of increased suspended sediment yield associated with forest harvesting and other disturbances (*from Gomi et al 2005*).

Increased peak flows by altered canopy removal or snowmelt runoff regimes can lead to increased stream bank erosion and to increased in-channel erosion of previously stored sediments (Lewis et al 1998; MacDonald et al. 2003). The extent of this process outside of Casper Creek is unknown although it is likely to be most significant (if at all) in small streams given the hydrologic dilution effects in larger watersheds (MacDonald and Coe 2005).

In the North Fork of Casper Creek, downstream suspended load increases were no greater than would be expected from the proportion of area disturbed (Lewis et al 2001). Lewis et al. suggest that most of the increased sediment produced in the tributaries was apparently stored in the mainstem and has not yet reached the mainstem stations. Effects of multiple disturbances on storm discharge peaks, water yields, and sediment yields are approximately additive, and there is little evidence for magnification of effects downstream (Lewis et al 2001).

Bank Erosion

Bank erosion can be a dominant source of sediment to stream channels, a process that can be accelerated by certain forest management activities. Stream bank erosion can be increased in response to harvest-related woody debris (Jackson et al 2001), mechanical ground disturbance (Jackson et al 2001; Rashin et al 2006), increased peak streamflow and/or flow duration (Lewis 1998; Lewis et al 2001; Kepeller et al 2003), loss of rootstrength from vegetation (Cafferata et al 2005), and post-harvest windthrow (Lisle and Napolitano 1998; Reid and Hilton 1998; MacDonald et al 2003; Liquori 2006; Rashin et al. 2006).

Compared to other major erosion processes in managed watersheds (e.g., mass wasting and road erosion), dispersed bank erosion remains relatively undocumented in the reviewed literature and uncertainty surrounds the increase in fine sediment production by enhanced channel erosion of sediment via increased flows, even outside of California (Gomi et al. 2005). Bank erosion rates are difficult to measure, and reports of increased bank erosion are generally inferred from observed increases in post-harvest sediment measurements. Increased sediment production from stream bank erosion in low-order channels have been measured in eastern Canada (MacDonald et al. 2003) and interpreted from suspended sediment data in California (Lewis 1998).

Buffer strips may reduce the potential for bank erosion in areas where tree roots intersect banks (Abernethy and Rutherfurd 1999; CH2Mhill and WWA 1999). In a detailed engineering study of bank stability from riparian vegetation, Simon and Collison (2002) identified a 32% increase the stability of stream banks through root reinforcement and a 71% increase from hydrologic reinforcement during dry antecedent conditions. In studies of unbuffered headwater channels, bank erosion following disturbance from yarding was extensive (Rashin et al 2006).

The extent to which enhanced bank erosion, including headward migration of channel heads by headcut processes, was not documented by the reviewed literature. The controls on headcut processes may be affected by the type and mode of stream disturbance from forest management activities, the existing channel type and condition, and the overall climatic regime.

Storage on Flood-Prone Areas

Flood-prone areas include areas adjacent to streams where flooding is possible. They differ from a floodplain, in that floodplains are typically flooded under relatively frequent intervals (about 50 times/century or so). Sediment storage in flood-prone areas can occur in the areas outside the channel banks that are prone to flooding.

In general, storage in flood-prone areas was not covered by the reviewed literature in any meaningful way. Cafferata et al (2005) discuss effects from forest management practices in flood-prone areas (see Section 2.24), but do not discuss storage functions, other than broadly describing flood-prone areas as depositional environments.

2.2.4 D) ARE THERE FOREST PRACTICES THAT CAN REMOBILIZE THE SEDIMENT DEPOSITED WITHIN THE RIPARIAN ZONE AND FLOOD-PRONE AREAS AND REDELIVER INTO THE STREAM SYSTEM?

Cafferata et al (2005) describe in considerable detail the ways that forest management may affect the production and delivery of sediment from flood-prone areas to stream channels. Sediment production can occur via overland flow processes where excessive soil compaction associated with equipment entry into flood-prone areas occurs (Norman et al 2007). Ground disturbance that occurs during harvesting can expose soil to runoff if sufficient surface flows (or floods) occur. The fate of such sediment is not entirely clear from the reviewed literature.

Flood-prone areas are subject to considerable change in response to frequent disturbance, primarily from flooding, but also from alluvial deposition, channel avulsion, debris-flow deposition, channel scour, and other fluvial processes (Cafferata et al 2005). Forest management practices that cause ground disturbance in flood-prone areas can potentially increase the risk of accelerated natural channel dynamics, and the level of risk depends on the dominant channel type and active geomorphic processes (Hassan et al 2005).

Cafferata and Munn (2002) report that very few erosion features were observed in WLPZs, which included some flood-prone areas (Figure 10). In an extensive survey of 300 THPs and NTMPs between 1996 and 2001, only 37 erosion features were observed, about half of which were related to mass wasting, and most of the mass wasting features predated the current Forest Practice Rules. However, most of these erosion features delivered to streams, primarily due to the proximity of the feature to the stream.

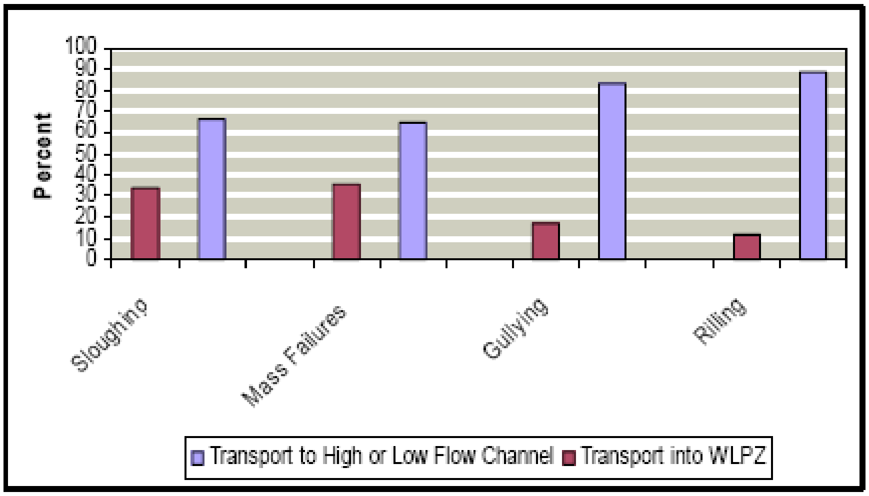

Figure 10) Percent of erosion features in riparian buffers observed during dry season surveys that deliver to streams (from Cafferata and Munn 2002). Note that in each case, most erosion features in buffers deliver to streams. However, only 37 erosion features in riparian zones were observed in 300 project sites.

Areas at greatest risk of accelerated disturbance are often biological hotspots, because of the ecological value of diversity and niche habitats that tend to accompany such areas (Benda, Poff et al 2004). Such areas can include:

- Alluvial fans;
- Immediately downslope of confined canyons;
- Debris fans (debris flow and landslide deposits in flood-prone areas);
- Tributary junctions;
- Areas with relict, abandon, or secondary channels;
- Off-channel habitats (ponds, wetlands, etc.).

Channel avulsion is a natural process of channel movement. Instead of gradual migration of meanders, avulsion processes result in channels that "jump" from location to location across the flood-prone area (Ritter et al 1995; Knighton 1984). Risks of channel avulsion and diversion in response to forest management are described by Cafferata et al (2005), although descriptions are qualitative, and not supported by direct measures. Channel avulsion processes are typically influenced by sediment and wood loading (Schumm 1985; Kellerhals and Church 1989; Knighton and Nanson 1993; Nanson 1996; Cafferata et al 2005; others), so practices that increase wood and sediment recruitment to streams in substantial amounts can affect avulsion processes. However, in systems that are prone to avulsion, bank stability provided by tree roots immediately adjacent to channels is thought to be important in preventing accelerated avulsion processes.

Gullies that form in flood-prone areas can deliver fine sediment to stream channels from upslope sources. (e.g. roads – See Section 2.2). Gullies typically form in response to concentrated flow, which can develop in response to road drainage structures (e.g. cross-drains and water bars), yarding ruts, and skid trails.

To the extent that selective harvest and equipment operation take place in flood-prone areas, the potential for delivery of sediment generated by ground disturbance to streams should be considered given the periodic overbank flows that would occur in such areas (Cafferata et al. 2005). However, flood prone areas are generally considered a sediment “sink” or a depositional environment due to high vegetative roughness and low gradient conditions that generally support sediment deposition over erosion.

Forest practices that can remobilize sediment produced or deposited within riparian and flood prone areas include concentrated discharge linked to roads, skid trails, or ditches (Brake et al. 1997, Coe 2006). Thus the discussion that applies to road related erosion and runoff and skid trails that are located close to streams applies to this question.

2.2.5 B) HOW EFFECTIVE ARE CURRENT FOREST MANAGEMENT PRACTICES IN MITIGATING THE DELIVERY OF SEDIMENT IN HIGHER-ORDER STREAMS (E.G., THIRD-ORDER AND HIGHER)?

AND

E) HOW EFFECTIVE ARE RIPARIAN BUFFER ZONES IN PROVIDING A SEDIMENT FILTERING FUNCTION IN UNMANAGED AND MANAGED FOREST AREAS?

In order to incorporate information from studies outside California, our discussion focuses on general types of forest practices (riparian buffers, selective harvest practices, use of mechanical equipment, yarding practices, etc.) and their implications for mitigating sediment delivery to channels. Specific information about California Forest Practice Rules is available in other studies (Brandow et al 2003; Cafferata and Munn 2002; Cafferata et al 2005). There are a number of practices employed during timber harvest activities that act to minimize sediment production and delivery. Such practices include riparian buffers, as well as a wide array of Best Management Practices. The reviewed literature does not systematically distinguish between specific practices, and thus we report here the overall effectiveness of forest management practices as measured in several studies.

As summarized in Table 7, there is general consensus in the literature that stream buffers are effective at mitigating sediment delivery to streams (CH2Mhill and WWA 1999; Cafferata and Munn 2000; Castelle and Johnson 2000; Brandow et al. 2006; Gomi et al. 2005; Rashin et al. 2006; Newbold et al. 1980; others).

In general, sediment filtration functions occur within short distances, as long as the water that carries sediment is not concentrated into persistent flows. Rashin et al (2006) documented that 95% of the sediment delivery occurred when erosion source areas were located within 30 feet (10 m) of the channel. This agrees in general with a study in California that found that 64 to 89% of hillslope erosion sites that delivered to channels were located in close proximity to stream banks (Cafferata and Munn 2002).

Sediment that is transported from disturbed areas by rills, sheetflow, or short gullies that are not connected to streams can be quickly captured by roughness elements on the ground including local depressions in the topography, logs, and other vegetative debris including branches and needles (Brake et al. 1997, Benda et al. 2003). Transport in this manner is captured as a) the flows that carry sediment are infiltrated into permeable soils and b) sediment is filtered through ground vegetation, microtopography, leaf litter and debris. This pattern of short hillslope transport of sediment is consistent in both unmanaged and managed forest lands, even though managed lands tend to expose more sediment from roads and hillslopes. Low order and high order channels are similar with respect to erosion and sediment delivery processes (see above). Low-order channels tend to be more influence by landslides and debris flow processes, while larger streams tend to be more influenced by fluvial (stream) processes.

Cited Studies	*Type of Study*	*General Location*	*Pertinent Finding*
Cafferata & Munn 2002	Effectiveness Monitoring	California - North coast, Cascades, and central Sierra	a review of 300 forest management sites found that forest practice rules are effective in the 90% of sites that where implemented correctly
Brandow et al 2006	Observational	California - North coast, Cascades, and central Sierra	Existing rules are highly effective in preventing erosion, sedimentation and transport to channels; surface erosion was uniformly prevented when groundcover exceeded 70%.
Reid & Hilton 1998	Experimental	North Fork Caspar Creek Watershed, Mendocino, CA	90% of sediment introduced directly by windthrow originated within 50 feet of the channel
Gomi et al 2005	Synthesis of Regional Literature	Pacific Northwest	Streams with buffers of 30 to 100 feet had relatively small increases in sediment yield, except where impacted by mass wasting or road erosion
CH2MHill & WWA 1999	Synthesis of Regional Literature	Idaho, Oregon, Pacific Northwest	sediment filtration source distances from several studies show a rapid rise in effectiveness in short distances and a leveling off at longer distances (up to about 150 feet)
Castelle & Johnson 2000	Synthesis of Regional Literature	Pacific Northwest	75% of sediment is removed within 16-200 feet of erosion source
Rashin et al 2006	Observational	Washington State	stream buffers were effective at preventing chronic sediment delivery to streams; unbuffered streams were ineffective at preventing sediment delivery
Kreutzweiser & Capell 2001	Observational	Turkey Lakes Watershed, Ontario, Canada	no significant sediment delivery associated with selective harvesting in riparian areas at up to 50% removal; large volumes of sediment delivered from tractor ground disturbance near streams

Table 7) Summary of riparian effectiveness studies from reviewed literature.

Low order and high order channels are similar with respect to erosion and sediment delivery processes (see above). Low-order channels tend to be more influenced by landslides and debris flow processes, while larger streams tend to be more influenced by fluvial (stream) processes.

Source distances curves (Figures 11 and 12) have been established for sediment by several studies (FEMAT 1993; CH2MHill and Western Watershed Analysts 1999; Castelle and Johnson 2000). Similar to the wood source distances, the shape of individual curves reported in the literature vary according to characteristics and processes responsible for sediment delivery (see Chapter 7). Steep, confined hillslopes, areas with shallow soils, and finer-grained sediment sources are likely to require a farther distance. Smaller watersheds, areas with low antecedent soil moisture conditions, and soils with high infiltration capacity generally require less distances. Variations in curves are also likely to exist based on dominant geology and soil types found within the watershed. There are also likely to be variations in source-distances between lateral (buffer width) and longitudinal (buffer length along the stream – particularly within zero-order channels).

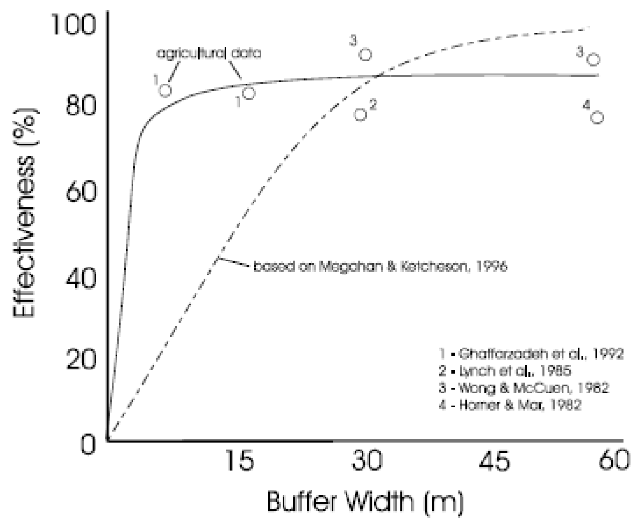

Figure 11) Source-distance relationship for sediment as reported by Castelle and Johnson (2000).

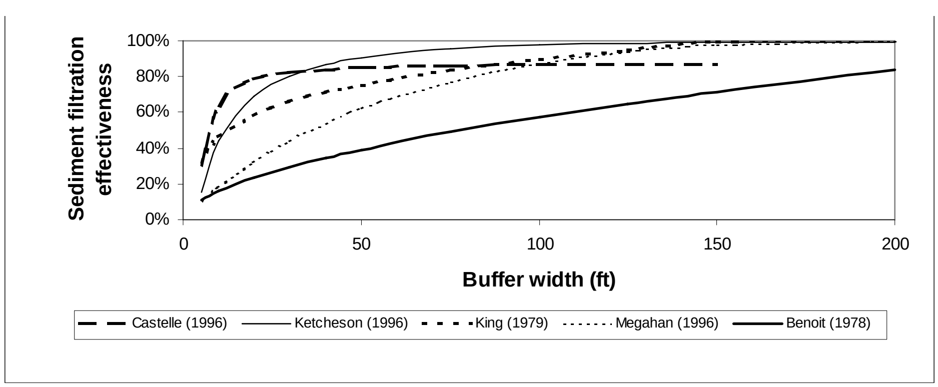

Figure 12) Source-distance relationship for sediment as reported by CH2MHill and Western Watershed Analysts (1999).

The mitigation of sediment from mass wasting processes was not sufficiently covered by the reviewed literature, as there are a number of pertinent studies that evaluate this function that were not part of this review (Benda and Cundy 1990; Coho and Burgess 1994; Gomi et al 2001; others). May (2002) identified a correlation between the volume of sediment generation and the runout length of debris-flows, which is a function of the stream channel gradient and tributary junction angles (Benda and Cundy 1990). Debris flows that are generated from roads tend to result in longer runout and more sediment than non-road related sources (May 2002). A more thorough review of the literature is appropriate to fully address this issue.

In a study of randomly selected non-federal timber harvest projects throughout California, Cafferata and Munn (2002) showed that individual practices currently required by California's Forest Practice Rules are effective in preventing hillslope erosion features when properly implemented. Harvest-related activities that had the greatest potential to produce sediment, such as fire trail construction and site preparation, were usually mitigated in riparian buffers in the areas farthest from the stream (Hairston-Strang and Adams 2000). Compliance and effectiveness monitoring programs within California have consistently demonstrated that no significant ground disturbance, sediment production, or delivery occurs within selected WLPZs along Class I and II streams (Cafferata and Munn 2002; Brandow et al. 2006). However, several papers suggest that excluding equipment, skid trails and yarding ruts near streams and zero-order channels (hollows) may be sufficient in preventing sediment delivery to streams, even in the absence of buffers (Kreutzweiser and Capell 2001; MacDonald et al. 2003; Gomi et al 2005).

Rashin et al (2006) found that riparian buffers in Washington State were similarly effective at mitigating sediment production around both fish-bearing and non-fish streams. They also report that both ground-based and cable-based yarding in unbuffered streams were mostly ineffective at preventing sediment generation, even where disturbance limiting BMPs (equipment exclusion and requirements to fall trees away from the channel) were applied. In each of the unbuffered sites that were rated as ineffective, extensive instream sedimentation and channel disturbance was observed, even though no evidence of sediment delivery from skid trails or yarding ruts were noted beyond the first year. Three of the 13 sites rated as ineffective were harvested using cable systems, although yarding ruts running across streams caused substantial disturbance resulting in chronic sediment delivery, extensive fine sedimentation in the stream, and increased bank erosion. In general, the study reported that most BMPs were either not implemented, or not followed correctly.

Various selective harvest methods employed along unbuffered low-order streams in eastern Canada (Figure 13) were also shown to have minimal affect on sediment conditions in streams (Kreutzweiser and Capell 2001).

Fig. 2. Inorganic fine sediment bedload (mean ± SE, n = 10) at sample sites collected in the spring (s) and fall (f) of each year. The vertical arrow indicates when harvesting occurred. The broken lines on the reference graph indicate measurements taken from the two alternate reference sites.

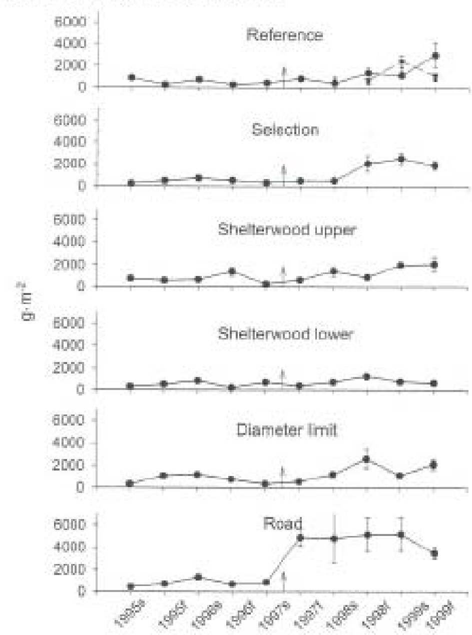

Figure 13) Sediment concentrations associated with various types of harvest treatments in low-order channels without riparian buffers (*from Kreutzweiser and Capell 2001*).

One potentially conflicting issue in extending riparian buffers into headwater streams is an increased risk of sediment generated from windthrow processes in some California landscapes (Ried and Hilton 1998; Lisle and Napolitano 1998; Liquori 2006; others). Windthrow risks are probably higher near the coast, and within buffers adjacent to clearcuts.

2.3 Based on the results of the above, what riparian zone delineation or characteristics (e.g., cover, plant species and structure, etc.) are shown to be

needed to ameliorate sediment production and delivery from managed forests?

It may be helpful to consider riparian buffer widths for other jurisdictions in answering this key question. Lee et al (2004) reviewed riparian management practices across the United States and Canada. They found wide variations in the critieria used for buffer protections, but generally found a common distinction between fish-bearing and non-fish streams (Figure 14), and between no-harvest buffers and selectively managed buffers (Figure 15). Note that these buffer widths were not based only on sediment controls, but in meeting all desired riparian functions. Variations are also employed based on stream size, and in some cases, stream type.

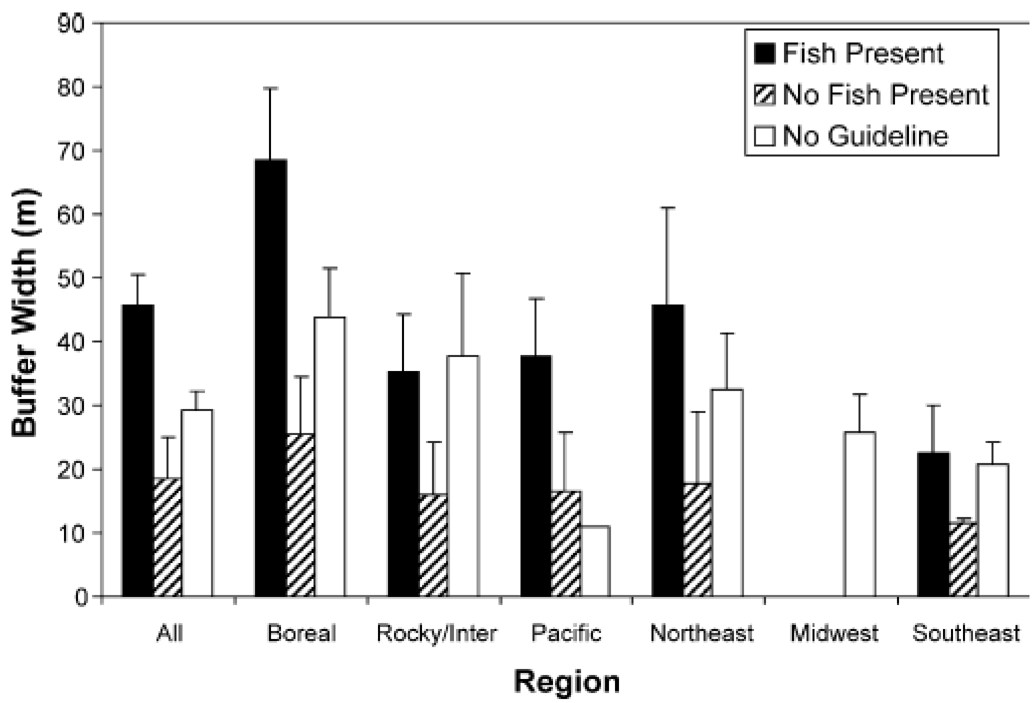

Figure 14) Mean buffer widths of large streams with fish (first bar) and without fish (second bar) for jurisdictions with fish guidelines, and jurisdictions without fish guidelines (third bar). Error bars represent standard error. (*From Lee et al 2004*).

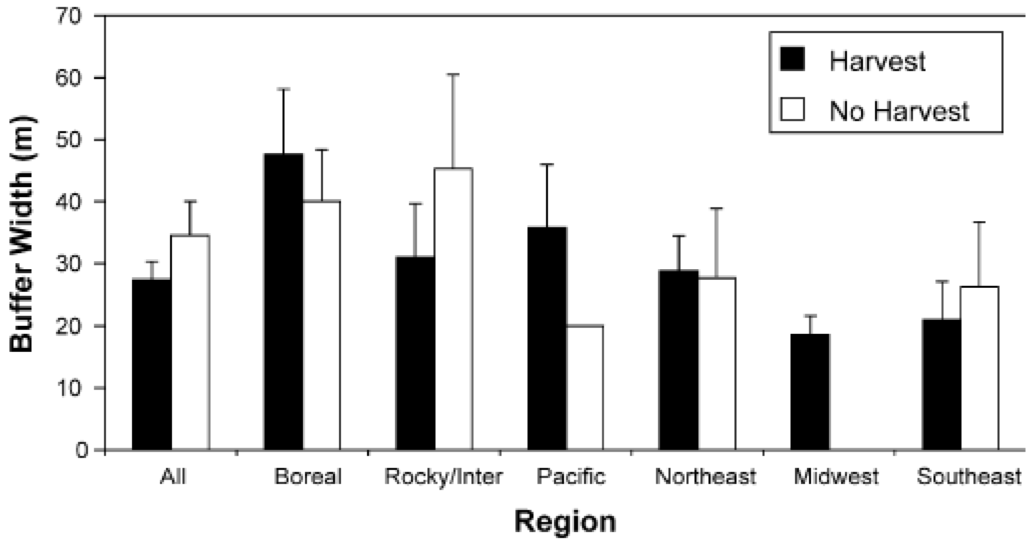

Figure 15) Mean buffer widths on large streams for jurisdictions with selective harvest (first bar) and jurisdictions without selective harvest (second bar). Error bars represent standard error (*From Lee et al 2004*).

Riparian buffers are often employed using a uniform width that extends continuously up the channel network. Width variations typically occur at specific transitions between channel types. Alternatively non-uniform and discontinuous buffers that are based on an integrated ecological framework might be equally effective if designed carefully (Figure 16). Such buffer strategies could more precisely target specific functional values recognizing the spatial variability inherent in natural ecosystems (Bisson, Rieman et al 2003; Nakamura and Swanson 2003; others). Such a concept could extend into headwater protections as well. Similarly, Bren (1998) describes a faceted buffer strategy that employs a constant buffer percent across the landscape, independent of the number of streams (Figure 17). Such an approach can offer operational and economic certainty.

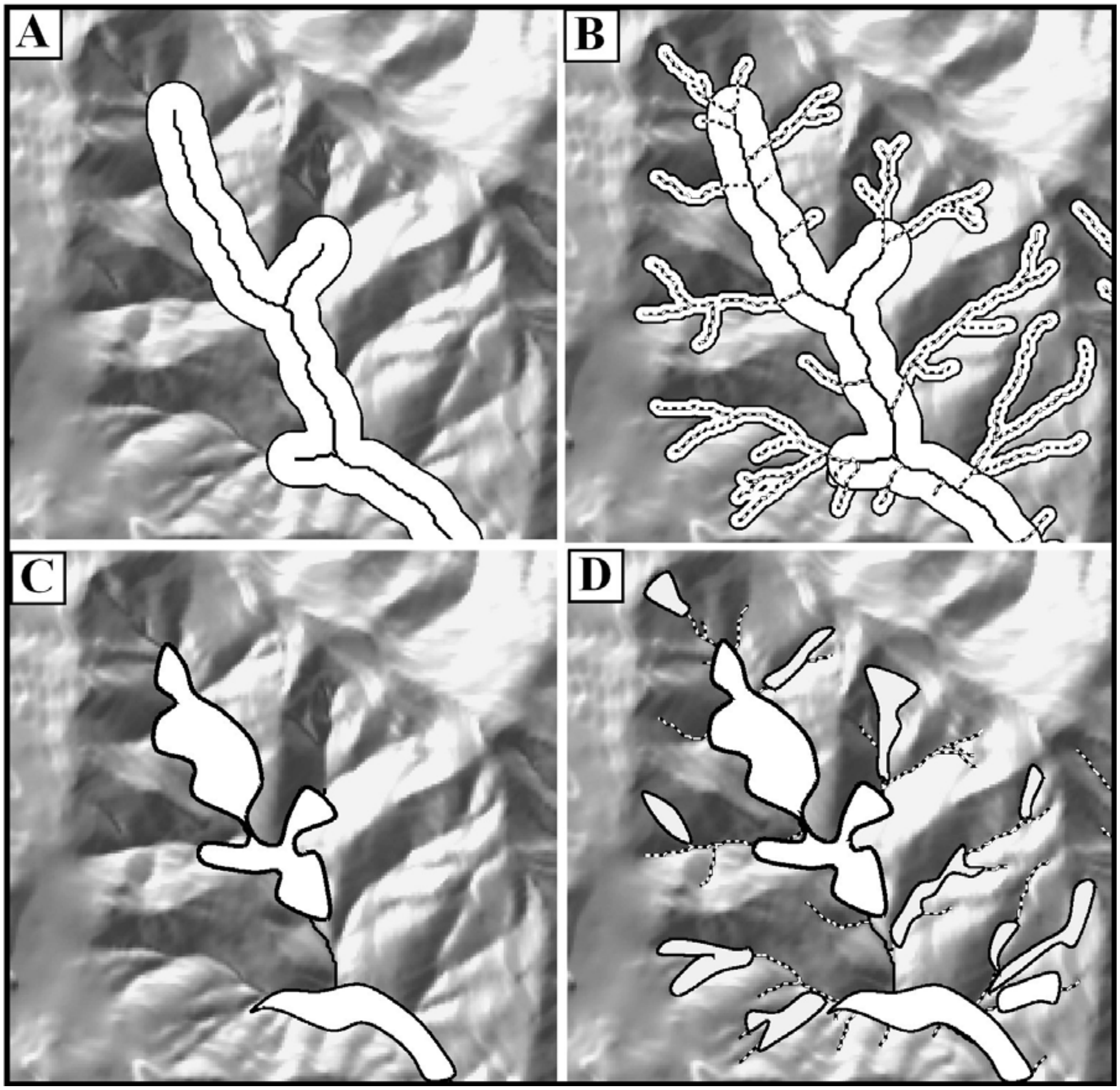

Figure 16) Example of a spatially-integrated ecological framework for riparian management. Traditional buffer approach: (A) continuous, uniform buffer, on primary streams (B) including headwaters. Spatially-integrated approach: (C) variable, discontinuous buffers on primary streams (D) and including headwaters.

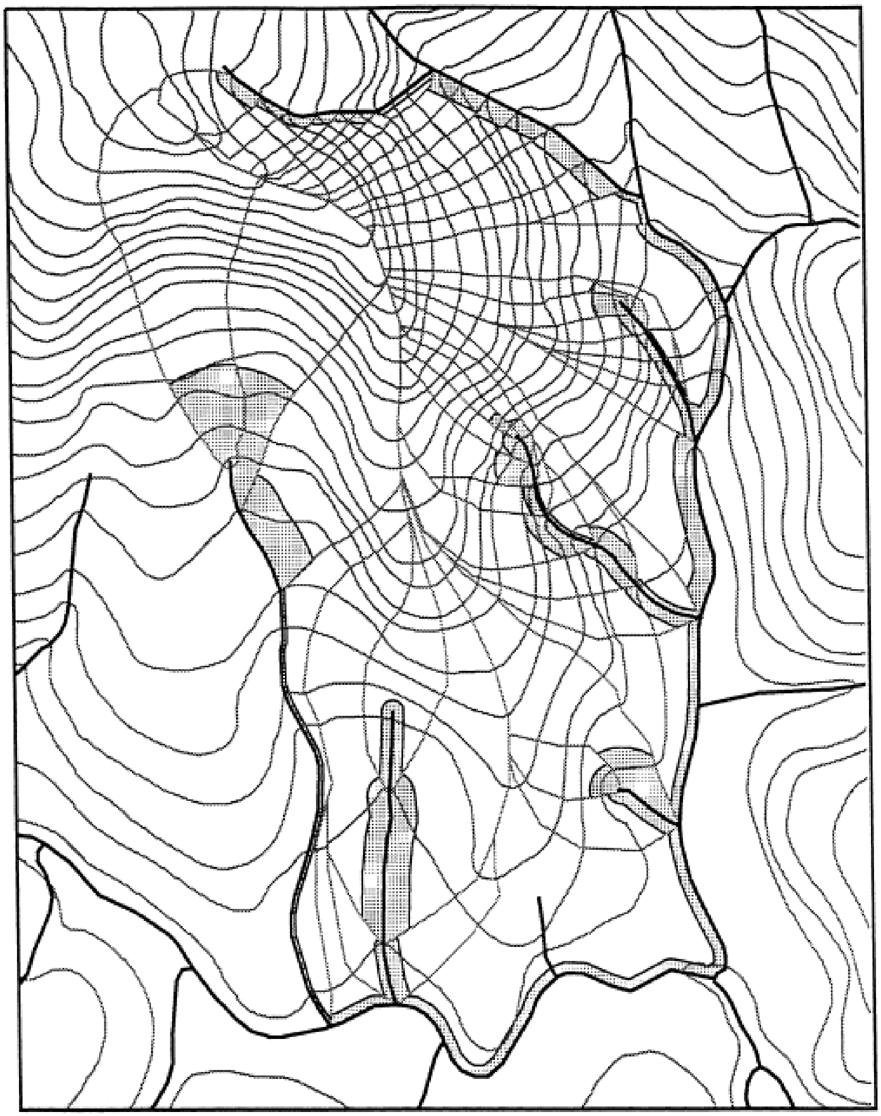

Figure 17) Example of a constant-buffer loading design that consumes 20% of the land area *(from Bren 1998*).

The overall purpose for riparian management of sediment depends in part on the management objectives for riparian areas. Possible objectives include:

Mitigating Harvest-Related Sediment – small buffers required if skid trails and yarding ruts avoided. Consider strategies for zero-order impacts from forest management (hydrologic and disturbance).

Mitigating the Hydrologic Link to Sediment Delivery – Hillslope sediment transport distances are limited if infiltration capacities are preserved on hillslopes, and are limited where soils remain undisturbed in the portions of hollows and low-order streams prone to saturation during runoff events (see section 2.2.1 and Chapter 4). Since the soils of riparian zones (including the small channels) tend to be vulnerable to compaction and loss of hydraulic conductivity, it is important that they be protected from extensive operation of heavy equipment (Norman et al 2007). Skid trails, roads and yarding impacts should be avoided in these areas, either through the use of buffers or other Best Management Practices (Rashin et al 2006).

Mitigating for Road Sediment – Road sediment delivery is largely independent of riparian conditions, as it depends primarily on the drainage structures associated with the road system, and how they are connected to the stream environment (Montgomery 1994). Strategies that disconnect roads from the stream network have been shown to be highly effective (WFPB 1997; Coe 2006; MacDonald and Coe 2007; others). Methods for disconnecting roads from stream networks include relocating roads away from streams, decommissioning stream crossings, increasing the number of cross-drains on the approach to stream crossings, rocking the approach to streams, diverting cross-drains onto hillslope ridges instead of hollows, using dips and waterbars, and reducing gullies below cross-drains, etc. (Weaver and Hagans 1994; Coe 2006; others).

Mitigating for Mass Wasting Impacts – This is by far the most significant potential risk for low-order streams. The approach required to address this issue is beyond the scope of this report. However, factors that should be considered include localized hydrologic effects on slope saturation and pore pressure dynamics, impacts from harvest on rootstrength, and concentration and diversion of normal hillslope runoff patterns (both surface and subsurface patterns).

Characteristics

The primary considerations for riparian zones include:

1. Preserving soil infiltration capacity by minimizing the disturbance associated with soil compaction from heavy equipment (Norman et al 2007).

2. Minimizing soil disturbance associated with tree felling, skid trails and yarding ruts (Rashin et al 2006).

3. Minimizing activities that concentrate and direct runoff from road drainage and harvest activities, including skid trails, yarding ruts, ditches, outfall gullies, etc. Such practices should seek to disconnect these potential sediment sources by a) disrupting the flow conveyance pathways that route sediment to the channel network, and b) minimizing the number of such sources near streams.

4. Manage disturbance risks where management practices alter the natural disturbance regime.

5. Establishing practices that are appropriate to the geographic region, including factors like the dominant geology, and the associated disturbance processes that contribute to sediment production and delivery (e.g. landslides, fires, etc).

6. Establishing practices that recognize the hierarchal nature of stream networks, including variations in dominant processes and functions in hollows (zero-order channels), headwaters (low-order channels), and larger channels (higher-order). Such variations should consider factors like hillslope confinement and gradient.

Mechanical disturbance from forest management activities (skid roads, yarding ruts, etc.) within about 30 feet will generally produce and deliver sediment to the stream, although the width of this sensitive zone may depend in part on the slope of the hillside, the confinement of the channel, and the orientation of disturbance relative to the hillslope gradient (Kreutzweiser and Capell 2001; MacDonald et al. 2003; Rashin et al 2006; Gomi et al 2005). Outside of 30 feet, sediment delivery rates drop rapidly with increasing distance from the channel. Note that unlike other riparian exchange functions (i.e. heat, water, biotic/nutrient and wood), sediment filtration functions in riparian areas are not dependent on the structural characteristics of riparian vegetation.

There remains some uncertainty with regard to the need for vegetated riparian buffers for reducing sediment production and delivery to streams since ground surface roughness elements appear to reduce or eliminate sediment delivery to streams (MacDonald et al. 2003). The primary benefit to sedimentation functions that is achieved by vegetated riparian buffers is that buffers limit timber falling, yarding and ground disturbance near the stream (Rashin et al 2006). Yet, a wide array of sediment BMPs are available that do not require vegetated riparian buffers, and such BMPs appear to be effective when properly implemented (Cafferata and Munn 2002).

In the only study to test such BMP effectiveness in non-fish, low-order (headwater) channels, 12 of 13 sites had excessive ground disturbance, in-stream sedimentation, and bank erosion following harvest activities (Rashin et al 2006). However, while non-buffer sediment BMPs (equipment exclusion, falling and yarding restrictions, etc) were required at those sites, the study reports that such BMPs were either not implemented, or implemented incorrectly.

A conflicting risk in extending riparian buffers into headwater streams in some California landscapes is the potential sediment generated from windthrow processes (Ried and Hilton 1998; Lisle and Napolitano 1998; Liquori 2006; others). Windthrow risks are probably highest near the coast, and within buffers adjacent to clearcuts. There may also be a risk differential associated with the tree species occupying the riparian area, with deeper rooted trees less vulnerable to windthrow (Liquori 2006).

2.3.1 A) IS THERE A THRESHOLD OR DEGREE OF EFFECTIVENESS BASED ON BENEFIT (E.G., CHANNEL AND STREAMBANK STABILITY, UPSLOPE FILTRATION, SURFACE STABILITY IN FLOODPRONE AREAS, SEDIMENT STORAGE DUE TO HYDRAULIC ROUGHNESS)?

The reviewed literature does not identify thresholds of effectiveness. Lateral source distance relationships are described in Section 2.2.5. Longitudinal source distance information is only qualitatively described in the reviewed literature.

2.3.2 B) HOW DOES EFFECTIVENESS VARY BY GEOGRAPHICAL REGION, GEOLOGY, SIZE OF WATERSHED, VEGETATION, STREAM REACH, FOREST PRACTICES WITHIN AND NEARBY THE ZONE, ETC.?

Geographic Region (including Geology and Climate)

There are strong geographical variations in California in the ability of ground disturbance on hillslopes, riparian zones zones and from roads that can produce and deliver sediment to stream channels.

Several studies have demonstrated that mean annual precipitation is a relatively precise indicator of sedimentation potential in California (Anderson et al 1976; Coe 2006; CBOF-TAC 2007; others). Snow-dominated landscapes also appear to reduce sedimentation (Coe 2006), probably by reducing the energy associated with runoff, since snowmelt peak flows are usually much lower than rainfall. For example, the length of roads that can deliver sediment directly to stream channels varies with mean annual precipitation. Twenty percent of a road network can deliver sediment to stream channels in areas with 20 inches per year average precipitation compared to 50% of the road network when precipitation exceeds 120 inches per year (Coe 2006). In addition, the ability of ground disturbance to generate and deliver sediment to stream channels should vary with precipitation regimes, although this factor has not been specifically evaluated across California's diverse regions by the reviewed literature.

Steep, confined topography in areas with naturally high fine sediment production is characteristic of the North Coast and Klamath regions (coinciding with areas of higher precipitation). Disturbance processes that generate soil in these areas are also dominated by mass wasting processes. The dominance of road-related erosion that exists throughout the state can be eclipsed by mass wasting in the humid coastal ranges, which can deliver orders of magnitude more sediment than surface erosion processes (Benda et al 2005; Gomi et al 2006; others). Similarly, fire-related erosion (sheetwash and gullying) in more arid areas (Klamath Plateau, Sierras) can overwhelm sediment production and delivery (Benda et al 2003; MacDonald et al 2004; Gomi et al 2005; others).

Geology can be an important control on various types of erosion in a watershed including related to ground disturbance in riparian zones and to roads. Soils that are a derivative of underlying rock type should affect erosion processes but they have not become a predictive variable in several models (Brake et al. 1997, Coe 2006).

However, variations in geology have been implicated in differences in erosion rates and erosion processes. For example, there have been reported variations in road erosion from native surface roads and rocked road (Coe 2006; WFPB 1997). While decomposed granite, sandstone and clay-rich soils all profoundly influence the effectiveness of management practices aimed at controlling sediment delivery to streams, the reviewed literature does not offer sufficient basis for drawing specific geographic differences.

Watershed Context & Stream Type

Watershed context refers to the spatial variability in the various physical factors that influence surface erosion potential and gullying including hillslope gradient, hillslope convergence, vegetation density, soil types, lithology, drainage density and road density (Young 2000; Benda et al 2005; Gomi et al 2005; Hassan et al 2005; Gallo et al 2005; others).

In the channels studied in Hassan et al (2005), sediment inputs were derived directly from adjacent hillslopes and from the channel banks. Morphologically significant sediments move mainly as bed load, mainly at low intensity. The larger clastic and woody elements in the channel form persistent structures that trap significant volumes of sediment, reducing sediment transport in the short term and substantially increasing channel stability.

Small, headwater streams and hollows can experience excessive sedimentation and bank disturbance from logging activities (Jackson et al 2001; Rashin et al 2006; others). In larger streams, sediment transport capacity is greater, and sediments can be reworked into the alluvial substrate in ways that affect salmonid spawning and rearing habitat (Figure 18). The mechanisms and processes by which sediment support (or impacts) salmonid habitat can be loosely defined by stream type (Hassan et al 2005; Montgomery and Buffington 1997; others). Generally, sediment tends to be stored in steep channel types like cascades and step-pool channels behind boulder and wood obstructions. In lower gradient channels, sediments can become sorted into pools and spawning locations dependent on the level of instream wood loading, slope gradient, and a wide variety of other factors (Benda et al 2005; Gomi et al 2006; others). The full range of instream geomorphic responses to sediment should be informed through a wider array of literature than was included within this review.

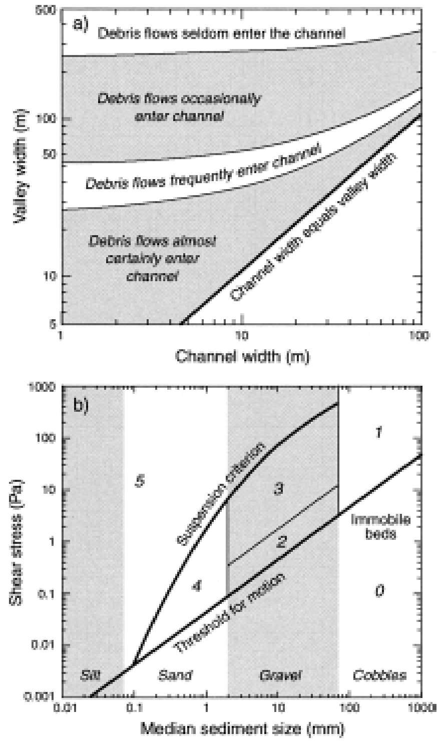

Figure 18) Process-based stream classification system characterizing the degree of hillslope interaction with the channel and the transport capacity of sediment within the channel (*from Hassan et al 2005*).

Robison and Runyon (2006) report that the channel conditions found where fish-use ends has variable watershed area (ranging from 7 to 837 acres) and variable stream channel gradients (3% to 44%). Similar results were presented for studies conducted in Washington State (Liquori and Barry 1997; Liquori 2002). The primary reason for this variation is that various parts of the watershed are affected by different processes and disturbance cascades that influence habitat conditions. Thus the impact from sedimentation varies over the landscape as the dynamics between the channel, riparian areas, and hillslopes respond to the spatial structure of the river network (Nakamura and Swanson 2003; Benda et al 2005). Thus the watershed-scale context is important, and requires consideration of a wide array of factors. Establishing a science-based ecological framework that incorporates the various watershed-scale functions can provide managers with such a context (see Chapter 7).

Vegetation

The relative presence or absence of ground cover vegetation appears to be a stronger influence on surface erosion and sediment delivery than riparian canopy structure. Vegetation in terms of stand density, species, ages, and stand structure may influence the potential for ground disturbance, surface erosion, and the delivery of sediment to stream channels in riparian zones, although specific studies were not available in the reviewed literature (and may not exist). The most direct benefit to riparian trees appears to be that they limit ground disturbances associated with forest management practices, although it is not clear if tree are required to limit such disturbances (Rashin et al 2006).

While there was not direct evidence of the importance of canopy structure in affecting sediment functions, the riparian structure is important for addressing sediment within the channel, since riparian vegetation influences bank stability (Bilby 1984; CBOF-TAC 2007; others). There is also an abundance of literature regarding the role of instream wood in storing sediment delivered to the channel network that was not provided as part of this review (Keller and Swanson 1979; Megahan 1982; Nakamura and Swanson 1993; Young 1994; Abbe and Montgomery 1996; Jackson and Sturm 2002; Gregory et al 2003; others).

The dynamics between wood and sediment are complex, and are beyond the scope of this study. However, they are important in understanding the context for the interactions between sediment and wood riparian exchange functions. For example, Gomi (2002) examined the influence of woody debris on sediment movement and storage in relation to timber harvesting and episodic sediment supply in headwater streams. He found that the availability of sediment and woody debris alters the threshold for sediment entrainment, transport processes, and sediment storage. Similarly, the response of a channel to external sediment supply depends on flood history (i.e., magnitude and sequence) and the sediment supply history (Hassan et al 2005).

2.3.3 C) WHAT ARE THE TYPES OF EROSION EVENTS FOR WHICH BUFFER ZONES ARE NOT EFFECTIVE IN PREVENTING OR REDUCING SEDIMENT DELIVERY AND THOSE FOR WHICH THEY ARE RELATIVELY EFFECTIVE?

The effectiveness of buffers in addressing the various types of erosion mechanisms is described in the answers to the Key Questions described above. We've classified the general level of effectiveness for each mechanism as described by the reviewed literature (Table 8). The characterization of buffer effectiveness is based on our subjective interpretation of the reviewed literature.

Erosion Mechanism	*Relevant Report Section*										*Effectiveness of Buffers*
	2.1	*2.1.1*	*2.1.2*	*2.1.3*	*2.1.4*	*2.2*	*2.2.1*	*2.2.3*	*2.2.4*	*2.2.5*	
Surface Erosion	■	■			■					■	Effective
Skid Trails and Yarding Ruts	■		■		■	■	■	■	■	■	Effective
Bank Erosion		■		■	■	■	■	■	■	■	Effective
Windthrow		■						■		■	Varies
Gullies	■					■			■	■	Somewhat Effective
Road-Related Sediment	■	■	■			■	■	■	■	■	Somewhat Ineffective
Fire	■	■			■					■	Insufficient Information
Mass Wasting		■					■	■	■	■	Insufficient Information
Soil Piping	■										Insufficient Information

Table 8) Summary of buffer effectiveness. The relevant report section identifies where more detailed discussion (and citations) can be found for each mechanism.

3 INFERENCES FOR FOREST MANAGEMENT

The reviewed literature generally supports the concept that the primary requirement for preventing the production and delivery of sediment to headwater (e.g. first- and second-order streams) is the limitation of disturbance and/or compaction adjacent to the channel and upslope for some distance along the valley axis (within a zone of hydrologic expansion in hollows). The impacts from ground disturbance adjacent to the channel have been well documented by the reviewed literature (Jackson et al 2001; Rashin et al 2006; others), but other processes important in hollows (zero-order channels) could use additional review. One of the most certain ways to minimize disturbance near these areas is to require riparian buffers, since buffers are effective at limiting disturbance (Rashin et al 2006). However, the reviewed literature did not resolve uncertainties regarding the effectiveness of non-buffer Best Management Practices in headwaters. Because surface erosion in near stream areas requires mechanical disturbance, equipment exclusion zones or other Best Management Practices may be effective at eliminating this form of management related erosion and sediment delivery to streams.

Riparian buffers on higher-order streams are effective at limiting sedimentation in streams (Cafferata and Munn 2002; Rashin et al 2006; others), and in general, sediment production from harvest activities are relatively low when compared to other sources. However, forest management practices associated with roads, and the indirect potential to increase sediment production via mass wasting or fire risks are areas where managers should be concerned. These sources of sediment are generally much more significant (Benda et al 2003; MacDonald et al 2004; others).

The reviewed literature is consistent with regard to the amount of forest management that can be preformed within a designated riparian zone without accelerating sediment production and delivery. Forest management practices should not create ground disturbance (exposing mineral soil) nor should it lead to compacted areas immediately adjacent to streams. Exactly how much activity can exist within a buffer is not clear, although several partial cut buffers with relatively heavy removal appear to have had minimal sediment yield increases or evidence of sediment delivery (MacDonald et al 2003; Kreutzweiser and Capell 2001; others).

The width of riparian buffers necessary to prevent sediment delivery vary somewhat, most likely in response to variations in factors like slope, confinement, geology, climate and vegetation characteristics (see Section 2.25). However, sufficient information to develop specific guidelines using these factors as input variables would require more detailed analysis, and perhaps additional data. Available source-distance curves from the reviewed literature were generally from areas outside California.

Recommendations for riparian management strategies that address sediment are described in Section 2.3.

4 INFORMATION GAPS

The physics that underlie sediment functions are similar across various physiographic regions. Thus, the body of studies that extend across western North America can be helpful in drawing conclusions about the relationships between forestry and watershed environments for the purpose of crafting regulatory guidelines. Based on the reviewed literature, there are a several data gaps that would help establish or refine management practices to address sediment functions. These include:

- The reviewed literature did not sufficiently address the role of riparian management in affecting the production and delivery of sediment from mass wasting (see Section 2.1.1). There is additional literature available to address this issue, and a review similar to this one could help resolve important policy questions, particularly in headwater areas.

- There remains uncertainty as to the effectiveness of non-buffer BMPs in headwater streams (see Section 2.3). Research into this area might also consider study designs that help to develop or improve non-buffer BMPs, and to specifically identify conditions in which variable responses can be observed (Gomi et al 2006), for example:

    - confined channels versus unconfined channels,

    - cohesive versus non-cohesive alluvial banks,

    - banks buttressed (by embedded logs) and/or armored (by cobble/boulder) versus unprotected banks, and

    - unconfined channels with significant rates of channel migration and undercutting versus those with slow rates.

- Studies evaluating the effectiveness of road crossing decommissioning consistently indicate that substantial volumes of erosion follow such activities (see Section 2.1.2). Such rates of erosion would be considered quite high in current stream restoration practices outside of the Forestry sector, and thus there appears to be some room for improvement in such practices. Stream restoration design practices offer many tools for establishing hydraulic and geomorphic channel design criteria (width, slope, depth, etc.) that may help improve road decommissioning practices and reduce post-decommissioning erosion. Developing a set of improved road crossing decommission design guidance tools should be considered.

- Post-harvest studies consistently show increases in sediment yields, but have yet to identify the sources of such material (see Section 2.2.3). Hypotheses that suggest that hydrologic changes result in increased channel scour and/or bank erosion should be tested to either confirm or refute this concept. We note that it may be difficult to resolve this issue given the challenges associated with accurate hydrology and sediment measurements.

- Vegetative communities can influence erosion and sedimentation processes near streams, as well as instream habitats (see Section 2.1.4). However, it is not entirely clear to what extent riparian management may affect the vegetative succession along streams. In some environments, riparian conditions may be somewhat different than natural conditions because of the management preference to certain species, the effects of fire suppression, and alterations in natural disturbance regimes associated with management. Such changes may have resulted, for example, in sites that have over time transitioned from pine to fir-domination, or from hardwood to conifer domination, etc. Such transitions may be reducing important ecological diversity that may be important for aquatic communities. This may be especially important near the transitions in ecotypes. Liquori and Jackson (2001) showed this effect in Washington State, in a setting very similar to environments in California.

- It is unclear how far upstream a hydrologic zone of expansion may exist (see Section 2.2.1). While technically a hydrologic function, it is primarily important for sediment delivery functions. The hydrologic zone of expansion would be helpful in establishing the upslope distance along the valley axis upstream of the channel that may be vulnerable to sediment delivery if disturbed.

- Source distance relationships for sediment do not appear to be as well developed as for other exchange functions (see Section 2.2.5). The reviewed literature indicates that source distances vary according to many factors. However, it would be valuable to know precisely which factors affect source distance relationships in which direction so that site specific prescriptions can be generated based on empirical data.

- Much of the information about regional variation in this review is quite general and qualitative (see Section 2.3.2). A more detailed meta-analysis of existing data, perhaps including a regional geospatial analysis, would help shed more insight into regional variations, and how they could inform specific prescriptive variations.

- Studies that evaluate the effectiveness of headwater riparian buffers in mitigating risks from mass wasting. Mass wasting can be a major source of sedimentation, but its not clear what effect riparian buffers may have in preventing or mitigating sediment (and wood) delivery.

5 GLOSSARY

Bankfull stage	is the river elevation and depth that occurs when discharge fills the entire channel cross section without significant inundation of the adjacent floodplain, and generally occurs with a frequency of 1.5 to 2 years for natural, undammed rivers
Flood-prone Area	the area adjacent to a watercourse or lake that is periodically covered with water and contributes to the interchange between terrestrial and aquatic components of the watershed
Bankfull depth	is the average vertical distance between the channel bed and theestimated water surface elevation required to completely fill the channel
Bankfull width	is the channel width at bankfull discharge
BMP	Best Management Practice. A set of practices that can be employed to minimize or mitigate undesired management effects.
Stream terraces	are abandoned floodplain areas constructed by the river underdifferent climatic or tectonic conditions, or in response to changes in land managementpractices. Terraces are infrequently inundated by floodwaters associated with thecurrent climactic period
Channel migration	are areas where the active channel of a stream is prone to move, resulting in a potential near-term loss of riparian function and associated habitat adjacent to the stream, except as modified by a permanent levee or dike. For this purpose, near-term means the time scale required to grow forest trees that will provide properly functioning conditions.

Channel avulsion	is when large-scale switching of the main flow occurs and new channels are cut or older ones are reoccupied.
Channel zone	includes the bankfull channel and floodplain, encompassing the area between the watercourse transition lines (WTLs)
Headwaters	a generalized term for small-order streams, typically inclusive of hollows through 2nd-order streams. Note, the specific definition of headwater streams varies widely in the literature.
Higher-Order Streams	in this report, 3rd-order or higher
Hollow	a confined, unchanneled valley immediately upslope of a first-order channel. Hollows are source areas for water and sediment. Steep hollows are prone to debris flows at scale of centuries to millennia. Also called a zero-order channel (which is a misnomer, since they by definition do not have a channel)
Hyporheic Zone	is defined as the region beneath and adjacent to streams and rivers where surface and groundwater mix
Low-Order	in this report, first- and second-order streams, sometimes inclusive of hollows (zero-order streams)
Mainstem	the trunk branch of a stream network, relative to another (usually smaller) tributary or side-channel
Rill	A rill is a narrow, shallowly incised channel that is carved into hillslope soils as a result of erosion by overland flow
Riparian forest	is defined as extending laterally from the active channel to include both the active floodplain and adjacent terraces
Roughness	refers to flow resistance in channels and on floodplains. For floodplains, major roughness is caused by trees, vines, and brush. In channels, its caused by the bed forms (ripples,

	dunes, etc), channel form, boulders, wood, steps, falls, and hydraulic jumps
Zero-Order	see hollow

6 REVIEWED LITERATURE

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