Sound Watershed Consulting

Creating Functional Water Environments

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

Chapter 4

WATER EXCHANGE FUNCTIONS

for

The California State Board of Forestry and Fire Protection

September 2008

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4) WATER EXCHANGE FUNCTIONS

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

For

The California State Board of Forestry and Fire Protection

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September 2008

SWC Ref# 1013H

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SUMMARY OF TABLES & FIGURES

EXECUTIVE SUMMARY ON WATER

This document represents a comprehensive review of 18 scientific literature articles provided by the Board of Forestry to address a series of Key Questions relevant to riparian management for the protection of threatened and impaired watersheds in State and private forestlands in California. The review:

- summarizes recognized exchange function roles and processes as presented to us by the California Board of Forestry Technical Advisory Committee (CBOF-TAC 2008)
- responds to key questions posed by the Board
- describes key information gaps not covered within the reviewed literature
- discusses inferences for forest management to address water exchange functions

The literature on water exchange tells us that forest management activities in riparian areas might affect stream functions, although the effect is likely to be small, highly variable, and strongly influenced by the watershed context.

The predominant effect from management is the loss of riparian canopy, and changes in evapotranspiration associated with tree removal and subsequent regeneration. While there are some lines of logic that might suggest that riparian trees may have greater effects on water runoff processes than upslope trees, there is little direct evidence in the reviewed literature to support such concepts. Hydrologic effects have been studied for entire watersheds; riparian zones alone have not been studied.

Extrapolating to riparian areas suggests that effects from riparian management would likely be small (possibly undetectable) given the variability in runoff response and the ability to measure changes. The literature generally reports that the amount of change in water yield, peak flows and base flow associated with timber harvest is directly related to the amount of tree canopy removed, regardless of where in the watershed those trees are removed.

The effect of reduced canopy interception might be most significant in steep, zero-order basins, where hollows are filled with colluvium and the risk of slope failure can be influenced by levels of saturation. An intact canopy can moderate the intensity of short bursts of rainfall reaching the soil surface, and its removal may thus increase the potential rate of water input to the soil and the likelihood of slope failure. Such processes reflect highly complex soil physics relationships that were not a focus of this literature review.

There is evidence that soil compaction in riparian areas can negatively affect hydrologic processes. Soil compaction can occur when heavy equipment operates on soils at a time when water content in the soils makes them susceptible to compaction.

There is evidence that riparian stand complexity is beneficial for a number of hydrological processes associated with channel development, nutrient exchange, and other functions. Indirect hydrologic effects of riparian management can influence both channel morphology and aquatic ecology in headwater streams. Small increases in peak flow related to timber harvest operations have not generally been thought to adversely affect channel morphology. However, even modest increases in peak flows of the type observed in the literature can be important in some watershed contexts. For example, when such peak flow increases occur in steep channels with erodible substrates, they can potentially increase sediment production from headwater streams. Similarly, increased summer baseflows appear to benefit salmonid habitats by increasing the area of perennial flow in headwater channels.

In recent years, the ecological importance of hyporheic flows is becoming better understood, although the extent that forest management directly benefits or harms this environment is not yet clear. Hyporheic flows describe the flow of water that exchanges between the surface stream and shallow groundwater region immediately surrounding the stream.

There is very little in the reviewed literature that can used to directly address the issue of buffer strip delineation relevant to the water function. The extent of hydrologic saturation in riparian area is highly variable in time and space, and predicting its extent is extremely difficult. There are three dimensions that are important when considering the delineation of hydrologically-influenced riparian zones; lateral, longitudinal and temporal.

There are probably regional differences in the effects of forest management activities or disturbances, although the reviewed literature does not highlight them, since most of the studies are restricted to either Casper Creek (coastal Mendocino County) or other regions outside the state. Regional differences are likely to reflect regional geology, topographic variation, and dominant runoff mechanisms.

RECOGNIZED EXCHANGE FUNCTION ROLES & PROCESSES

Riparian vegetation in forested environments influences the roles and processes associated with storm runoff and other hydrologic processes that may affect aquatic conditions important to salmonids. Many of these important processes are governed by multiple interacting factors (biotic and abiotic) that have been described by CBOF-TAC (2008) and others, and which form the foundation of our review. These principles include:

Riparian zones in forested watersheds play a number of important hydrologic and water quality roles, whose importance far exceeds their relative surface area. These roles include:

Channel Structure & Morphology. Vegetation patterns influence how flows create both the primary channel morphology, as well as secondary preferential flow pathways in both surface and subsurface environments (Thorne et al, 1997; Swanson et al 1998; McDonnell 2003).

Runoff generation. During precipitation, riparian zones quickly become saturated, and are the first parts of a watershed to begin contributing runoff (McDonnell 2003). They account for most on the runoff on the rising limb of the hydrograph, whereas hillslopes contribute more on the falling limb. Three primary sources of groundwater exist (riparian, hollow and hillslope) and these sources are non-linear and distinct both chemically and isotopically (McDonnell 2003).

Moderating flood peaks. The high resistance to flow (friction) of riparian vegetation and woody debris slows water velocities, reduces peak discharge and affect flood synchronicity (Tabacchi et al, 2000; Nilsson & Svedmark, 2002)

Nutrient Exchange. Hydrologic conditions significantly affect the supply, availability and distribution of nutrients throughout the channel network (Tabacchi et al 2000).

Hyporheic flow. Flow through the hyporheic zone, which overlaps with the riparian zone, is important in regulation of stream water quality (Tabacchi et al 2000). Redox reactions in the hyporheic zone are important for immobilizing, transforming and releasing forms of nitrogen and phosphorus. It's been hypothesized, but not proven, that simplification of channels could reduce hyporheic interactions.

Interception and Transpiration. Vegetation in the riparian zone, especially hardwoods, seasonally transpires more water per unit area than upslope vegetation, and may have a strong influence on summer low flow and riparian microclimate (air temperature and relative humidity). Riparian conifers in the Sierra Nevada can reduce snow depth along stream channels through interception, reducing water available for runoff (Erman et al 1988 as cited by CBOF-TAC 2008).

Most of the forest management effects on hydrologic response occur in response to upland harvest, and have been well studied. It is less clear how management in riparian zones along contributes to these processes, and its presumed that they contribute in direct relation to the riparian area.

Water Exchange and transfer with the riparian floodplain zone are hypothesized but not particularly well studied. Some studies exist on larger unconstrained streams, but few studies on headwater streams. Trees in the riparian area are very effective at drawing water from this zone, as seen in the daily flux.

Taken as a whole, the perspective of CBOF-TAC (2008) and others is that timber harvest in riparian areas:

- Is unlikely to affect flows sufficiently to harm fish, although there is some suggestion from studies in Casper Creek that they might slightly benefit fish (Keppeller 1998).
- Can degrade water storage capacity and can increase runoff where mechanical disturbance (i.e. compaction) on riparian soils occurs.

These points provide a context for considering the following Key Questions.

RESPONSE TO KEY QUESTIONS

The following Key Questions were provided to the Sound Watershed Team by the Board of Forestry staff and a Technical Advisory Committee. The responses to these questions are based on our interpretation of the literature provided by the Board for us to review. To support some points, we added citations to other supporting literature with which we were familiar. We appreciate that other literature may be available that might also address these issues, and that in some cases, such literature may conflict with the general trends we report here.

In the case of the water exchange function, we found the 18 papers provided by the Board were only marginally helpful in addressing these questions. In general, the questions posed address issues for which limited information is available in the reviewed literature. The scientific community has focused on the hydrologic response from harvesting in watersheds, while the focus of this review was aimed toward addressing issues only in riparian areas. We've therefore applied our professional judgment to extract relevant trends for riparian areas from studies that did not address riparian processes directly.

1. How do forest management activities or disturbances in or near riparian zones/floodplains, and adjacent to small headwater first and second-order channels affect flow pathway and streamflow generation?

The information available in the selected literature suggests that riparian zones influence stream-generation functions in small headwater channels, and that disturbance processes substantially influence the condition and evolution of riparian functions. Timber harvest is but one type of disturbance that affects riparian zones. Other disturbance processes include flooding, mass wasting, fire, wind, infestation, disease, and competition mortality. Forest management practices also affect the frequency, timing and magnitude of these 'natural' disturbance processes.

Natural disturbances occur in response to natural drivers. A natural disturbance regime can be described by the frequency (how often), magnitude (how big), and duration (how long) that disturbances are expected to occur. For example, fires or large floods of a given magnitude occur with a statistical frequency probability in the absence of human manipulation of the watershed. Forest management, like most other land-use practices, can affect these natural disturbance regimes by altering their magnitude, frequency, duration or intensity (Beschta et al 2000; Swanson et al 1998; Dwire and Kauffman 2003; others). The extent that changes in disturbance regimes affect salmonids depends greatly on the watershed context, the signature of the disturbance, and how the disturbance processes affects the riparian structure and composition (Roby and Azuma 1995; Dwire et al 2006; Rieman et al 2003; others). Some large disturbances have modest effects (Swanson et al 1998), while others may have catastrophic effects (Minshall et al 1983; Young 1994; Roby and Azuma 1995).

Forest management activities can influence current and future riparian conditions in ways that can both increase and decrease risks to salmonids. The processes by which these disturbances affect headwater streams are highly variable, complex, dynamic and spatially distributed. Some of the effects from disturbance processes are essential for developing rich habitat conditions, both locally and in downstream reaches, which increases the benefits to aquatic species like anadromous salmonids (Swanson et al 1998; Tabacchi et al 2000). Other disturbance effects have the potential to degrade conditions. Generally speaking, smaller, frequent and varied disturbances increase the heterogeneity of flow pathways, leading to an environment that is more resilient, diverse and rich (Kaufman and Martin 1989; Malanson 1993; Tabacchi et al 2000; Everett et al 2003). The influence of moderate and frequent disturbance such as fire (Wright and Bailey 1982), insect (Mattson and Addy 1975) and disease-induced mortality (Matson and Boone 1984) may lead to minor reductions in the riparian canopy but more resilient and diverse habitat conditions that are generally described as beneficial for salmonids (Naiman and Bilby 1998). By contrast, disturbances that are large and infrequent tend to lead to more widespread changes that have larger and longer-lasting physical impacts (Young 1994; Roby and Azuma 1995). The affect of such large-scale disturbances on salmonids varies by disturbance type and location.

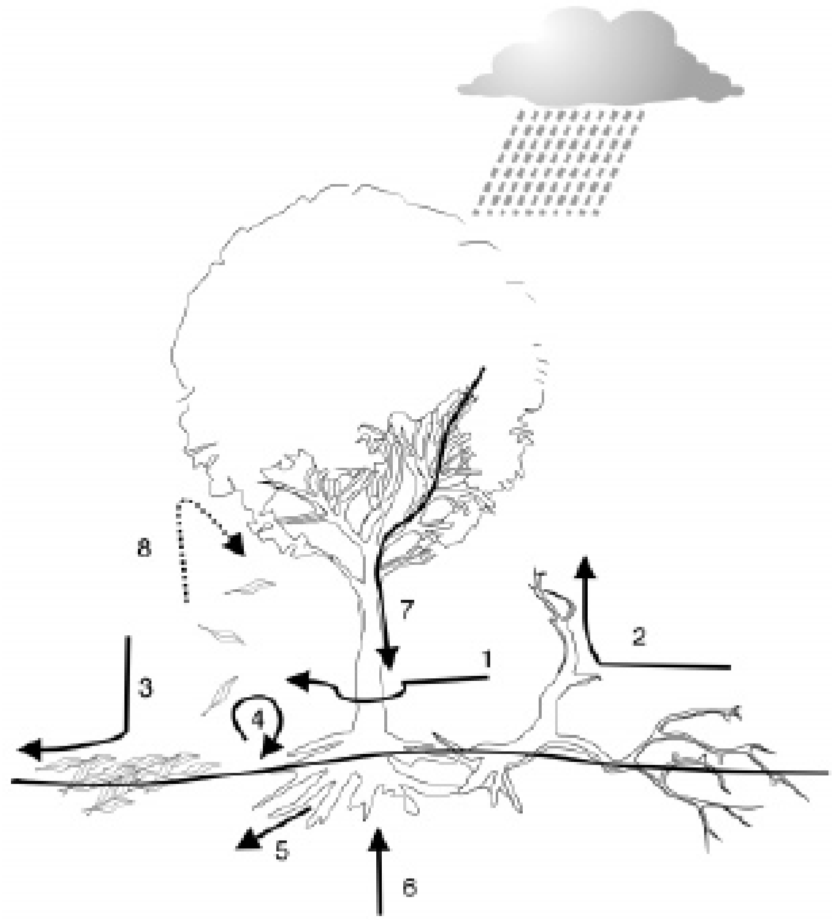

Figure 1) The main physiological impacts of riparian vegetation on water cycling: 1) interaction with over-bank flow by stems, branches and leaves; 2) flow diversion by log jams; 3) change in the infiltration rate of flood waters and rainfall by litter; 4) increase of turbulence as a consequence of root exposure; 5) increase of substrate macroporosity by roots; 6) increase of the capillary fringe by fine roots; 7) stemflow; 8) condensation of atmospheric water and interception of dew by leaves. (from Tabachi et al 2000)

A) HAVE FOREST MANAGEMENT ACTIVITIES IN RIPARIAN ZONES FOR HIGHER ORDER CHANNELS WITH FLOODPLAINS AND ADJACENT TO SMALL HEADWATER FIRST AND SECOND ORDER CHANNELS BEEN SHOWN TO ALTER WATER TRANSFER TO STREAM CHANNELS, AFFECTING NEAR-STREAM AND FLOOD PRONE AREA FUNCTIONS (E.G., SOURCE AREA CONTRIBUTIONS TO STORMFLOW, BANK INSTABILITY, LATERAL AND VERTICAL CHANNEL MIGRATION, FLOW OBSTRUCTION OR DIVERSION OF FLOW)?

Yes, forest management activities in these areas can affect stream functions, although the effect is likely to be small, highly variable, and strongly influenced by the watershed context. The key "variable source area" processes that are affected by riparian management are described in the water primer (CBOF-TAC 2008), but the reviewed literature does not provide sufficient coverage of the range of hydrologic, topographic and vegetation conditions to permit generalizations about the influence of these variables. MacDonnell (2003) expanded on the variable source area concept by suggesting that a) thresholds predominate, b) three primary sources of groundwater exist (riparian, hollow and hillslope) and that these sources are non-linear and chemically/isotopically distinct.

Water Transfer Effects from Riparian Management

The literature we reviewed primarily discussed the effects from timber harvest within the watershed on peak flow and water yields, and we can only infer impacts from riparian areas. Riparian areas typically dominate the early phase of runoff while hillslope drainage dominates the later phases of runoff (McDonnell et al 1998). The mechanisms for water transfer in riparian zones is predominantly associated with interception and evaporation (Ziemer and Lisle 1998), although there are a series of other minor processes that affect water cycling in riparian zones (Figure 1).

Removal of trees in the riparian area results in a loss of canopy interception and evapotranspiration, and as such, we should anticipate that harvest effects on water transfer are similar in scale to upland harvest, where the general scale of effects appears to be largest from clearcutting in smaller watersheds (Lewis et al 2001). There may also be effects related to biotic and nutrient transfer and hyporheic processes, but these are not yet understood (Moore and Wondzell 2005). In addition effects related to the loss of canopy interception and evapotranspiration, higher antecedent moisture conditions have been shown to affect runoff from watersheds (Lewis et al 2001), as since riparian areas typically have higher antecedent moisture conditions, it may be reasonable to assume that riparian tree removals might preferentially affect this mechanism. However, there are no studies that document this pattern, and it is unlikely that current hydrologic methods are sufficiently sensitive to measure such effects.

The reviewed literature does not address differences between low-order headwater channels and higher-order channels. However, as the proportion of flow is directly related to the total upslope contributing area, we can infer that the relative increase in flows from low-order headwater riparian areas is likely to be greater than from higher-order channels.

Forest management activities in a watershed (road building and tree removal) have been shown to increase peak runoff, with the effect diminishing as the frequency of the event decreases (Ziemer and Lisle 1998). The effect is generally greater in the fall, when the difference in soil moisture between cut and uncut areas is greatest (Moore and Wondzell, 2005; Beschta et al., 2000). At Caspar Creek, the average percentage increase in peak flow for a 100% clearcut area was 27 percent for the 2-yr event (Ziemer, 1998 as reported in Lewis et al, 2001). In snow-dominated landscapes in Colorado, peak flow increases ranged from none detected to 87% and total water yield increased by up to 80% in small catchments using various treatments (Moore and Wondzell, 2005). At E. St. Louis Creek in Colorado, the increase was 25 percent for events with recurrence intervals (RI) of 2-5 yrs. In terms of sediment transport (and possibly channel erosion) these would be significant increases (Moore and Wondzell, 2005). . Lewis et al (2001) found that increases in suspended sediment loading following harvest in headwater watersheds corresponded to the area harvested, suggesting that hillslope sources of sediment were at least as important as any channel sources.

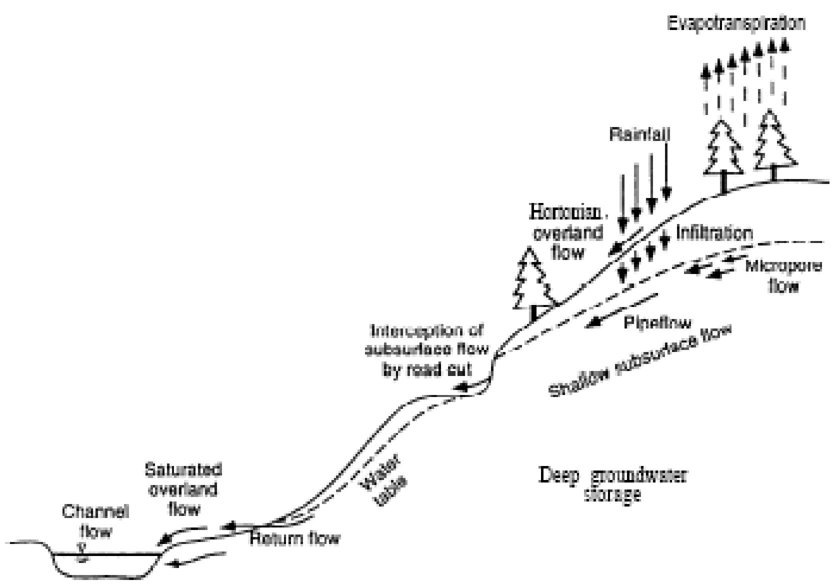

Figure 2) Distribution of hydrologic processes on an idealized hillslope in the Pacific coastal ecoregion (Ziemer and Lisle 1998).

Note that the hydrologic effects described above are for the entire watershed; effects from riparian zones alone would be considerably smaller, and possibly undetectable given the variability in runoff response and the ability to measure changes.

Functional Response in Channels

It's unlikely that the magnitude of large floods is significantly influenced by forest management activities in riparian areas alone, although the limited number of observations may be a factor (Moore and Wondzell 2005). Disturbances from large floods are highly heterogeneous and support a complex mosaic of riparian and aquatic habitats (Swanson et al 1998). In many cases, the flood disturbance signature will reflect the riparian conditions at the time of the flood. Large floods (floods with a 5+ yr recurrence interval) which are not affected by forest management) can recruit, entrain and mobilize woody debris, reorganize channel morphology, and transfer sediment from hillslopes to riparian zones through mass wasting.

Functional Response in Riparian Areas

In the literature that we have reviewed, there is only one study dealing with hydrologic impacts of activities confined to the riparian zone. A study on impacts of fuel reduction in a "Stream Environment Zone" (SEZ)[1] of the Tahoe basin looked at impacts on the saturated hydraulic conductivity (Ksat) of soils in an area thinned (of lodgepole pine) with a low-ground-pressure CTL forwarder/harvester. The average Ksat across the area, including areas outside of the harvester tracks, was reduced by over 50 percent, even though the loamy coarse sand soils were dry at the time (Norman, et al., 2008). The reduction in Ksat was attributed to horizontal spreading of applied pressure (due to equipment vibration) through layered soils. Because the SEZ was relatively flat, and the initial Ksat was high (5.5 in/hr) the reduction in Ksat in this instance would be unlikely to cause surface erosion. In an Australian Eucalyptus forest, Croke et al (1999) documented reductions in Ksat of approximately 50% following riparian logging, although the method of logging is not clear. In other circumstances, such a reduction could increase surface erosion and modify flow pathways, since riparian areas are known to be vulnerable to soil compaction and physical disturbance due to areas of high moisture and low soil strength (Dwire et al., 2006). These findings emphasize the need for exclusion of heavy equipment from the riparian zone.

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[1] SEZs in the Tahoe Basin are defined as biological communities that owe their characteristics to the presence of surface water or a seasonally high ground-water table.

B) HAVE FOREST MANAGEMENT ACTIVITIES IN RIPARIAN ZONES FOR HIGHER ORDER CHANNELS WITH FLOODPLAINS AND ADJACENT TO SMALL HEADWATER FIRST AND SECOND ORDER CHANNELS BEEN SHOWN TO RESULT IN CHANGES IN TREE CANOPY/VOLUME THAT SIGNIFICANTLY AFFECTS EVAPOTRANSPIRATION AND/OR INTERCEPTION, WITH RESULTANT CHANGES IN WATER YIELD, PEAK FLOWS, LOW FLOWS, ETC.?

It is not clear if there are significantly different effects from canopy removal in riparian zones. Removing riparian trees is likely to reduce canopy interception and evaporation, thus increasing total water available for runoff from harvested areas. Interceptions losses in north coastal California have been reported at about 20% over the season (Lewis et al, 2001), and more broadly ranges from 10-30% across most landscapes (Moore and Wondzell 2005). The literature generally reports that the amount of change in water yield, peak flows and base flow associated with timber harvest is directly related to the amount of tree canopy removed, regardless of where in the watershed those trees are removed. However, our understanding of fundamental hydrologic processes suggests that tree removal in riparian zones might impart different effects than upslope tree removal in its response to runoff (McDonnell et al 1998; Moore and Wondzell 2005). For example, additional water availability in riparian areas may differentially affect peak flows, water yields and baseflows relative to timber removal from upslope areas. The expected hydrologic response to riparian tree removal is complex. The reviewed literature contained only speculation as to this effect, and to our knowledge, specific effects have not been directly studied. Thus the magnitude and direction of net effects on water yield, peak flow and low flows are subject to debate.

Peak Flows

The direct peak flow response from reduction of tree canopies in riparian zones has not been directly studied. The degree of forest removal and type of harvest applied can help explain the wide variability in peakflow and stormflow volume increases described in the reviewed literature from harvested watersheds (Ziemer and Lisle 1998). Factors like forest type, harvesting method, antecedent soil moisture conditions, and precipitation magnitude all influence the magnitude of the response, and the varying nature of forest regrowth affects the duration that responses can be measured.

However, the largest increases in peak flows observed in clearcut watersheds usually follows generally small storms with the driest antecedent conditions, when riparian zones are likely unsaturated (Ziemer and Lisle, 1998; Beschta et al, 2000; Lewis et al, 2001), suggesting that the relationship between riparian canopy removal and peak flows is more complex.

Runoff from large storms are unlikely to be affected by clearcutting (Beschta et al 2000) and runoff associated with large precipitation events (or events with an already saturated canopy) are unlikely to be affected by riparian canopy removal. Dunne and Leopold (1978) state:

> "*The subtraction of intercepted water from gross precipitation becomes insignificant during very large rainstorms. Interception, therefore, has little effect upon the development of major floods*".

To our knowledge specific studies of the response from riparian areas alone are not available, in part because statistically valid measurement of responses from riparian timber harvest alone are extremely difficult to obtain.

The effect of reduced interception might be most significant in steep, zero-order basins, where hollows are filled with colluvium and at risk for slope failure even when unsaturated. An intact canopy can moderate the intensity of short bursts of rainfall reaching the soil surface, and its removal may thus increase the potential rate of water input to the soil and the likelihood of slope failure. Such processes reflect highly complex soil physics relationships (e.g. Torres et al 1998; McDonnell, 2003) that are not well understood, and were not a focus of this literature review.

Water Yield & Summer Baseflow

Water yield increases following timber harvest have been well documented (Ziemer and Lisle, 1998; Lewis et al, 2001; Moore and Wondzell, 2005) and are attributed to reduced transpiration. Generally, the reduction in transpiration resulting from tree removal makes more water available for flow during the summer, and in some circumstances, this can be beneficial to aquatic organisms. However, where harvest of conifers in the riparian zone results in conversion to deciduous species, summer low flow may be reduced (Moore & Wondzell, 2005). Total water consumption is known to vary dramatically by species, even in similar soil moisture and climate conditions (Tabacchi et al, 2000).

Table 1) Summary of reported water yield response from treated watersheds[2]

Location	Watershed	Watershed Size (ha)	Treatment Area	Treatment Type	Increase in Summer Yield
Coastal CA	SF Casper Ck	484	67%	Selection	120%
	NF Casper Ck	473	12%	Clearcut	150%
	NF Casper Ck	473	42%	Clearcut	200%
					Annual Yield
Oregon Cascades	HJ Andrews 6	13	100%	Clearcut	30%
	HJ Andrews 7	15.4	100%	Clearcut	22%
	Coyote Creek	69.2	100%	Shelterwood	8%
	Coyote Creek	68.4	30%	Patchcut	14%
	Coyote Creek	49.8	100%	Clearcut	43%
Oregon Coast Range	Needle Branch	70.8	82%	Clearcut	26%
	Deer Creek	30.4	25%	Patchcut	insignificant
					Annual or Seasonal Yield
Colorado Rockies	Wagon Wheel Gap	81	100%	Clearcut	15%
	Fool Creek	289	40%	Patchcut	45%
North-Central Idaho	Horse Creek 12	84	33%	Patchcut	80%
	Horse Creek 12	62	27%	Patchcut	79%
	Horse Creek 12	28	21%	Patchcut	51%
	Horse Creek 12	86	29%	Patchcut	52%

The classic paper by Hewlett & Hibbert (1961; cited in CBOF-TAC 2008) describes a study at Coweeta Hydrologic Laboratory in North Carolina which found that complete felling of a strip of riparian vegetation produced only very minor increases in water yield. Although impacts in a Mediterranean climate might be different, the environmental constraints on vegetation removal from riparian zones in California limit the potential for increasing water yields.

The increase in summer low flow that results from reduced transpiration in an entire watershed may be substantial from even

[2] *Data compiled from Ziemer & Lisle (1998); Moore and Wondzell (2005) and includes entire watershed (not just riparian areas)*

modest treatments (Table 1), but generally decline to an insignificant level after a few years (Moore and Wondzell, 2005; Ziemer and Lisle, 1998). Some consider these increases to be beneficial to juvenile fish by expanding the range of summer rearing habitat, although such relationships are only inferred by the increased length of perennial flow and increased depth of flows observed in low-order streams (Keppeler 1998).

C) CAN FOREST MANAGEMENT ACTIVITIES IN RIPARIAN AREAS ALTER WATER YIELD, PEAK FLOWS OR LOW FLOWS SUFFICIENTLY TO AFFECT CHANNEL MORPHOLOGY OR THE AQUATIC ECOLOGY OF HEADWATER STREAMS?

While large floods and mass wasting are the primary mechanism for creating the structural foundation for diverse aquatic habitat mosaics within the headwater channel network (Swanson et al 1998; Wondzell and Swanson 1999; Nilsson & Svedmark 2002), the indirect hydrologic effects of riparian management can influence both channel morphology and aquatic ecology in headwater streams (Moore and Wondzell 2005). These relative impacts from such effects are mixed, and depend on the watershed and regional context, including such key factors as site gradient, valley confinement, regional geology, elevation, dominant riparian tree species, location within the watershed, and riparian stand condition.

Channel Morphology

Pioneer vegetation can encroach upon sand and gravel bars during low flows, which can affect flow hydraulics, thus influencing both local channel morphology and aquatic habitats (Tabacchi et al 2000). Water yield and summer baseflow conditions can affect the distribution of riparian species that become established in riparian zones, especially in the years immediately following disturbances (Wondzell and Swanson 1999; Dwire et al. 2006; Nilsson and Svedmark, 2002). Homogenous riparian stands generally offer lower habitat quality than more heterogenous stands formed from disturbance-initiated vegetative dynamics (Tabacchi et al 2000).

For example, Nilsson and Svedmark (2002) describe successional variations in riparian vegetative response that are associated with variations in local flow pathways and erosion processes. These varied vegetative environments can for example, produce localized canopy gaps in conifer stands that promote hardwoods, which can improve local nutrient dynamics and trophic response (Kiffney and Roni, 2007) in ways that benefit salmonids. Tabacchi et al (2000) similarly describe the role of riparian vegetation in accessing lateral structures (oxbows, remnant channels, flood channels, etc), and report that

> *"the hydraulic role of the later stages of riparian vegetation depends upon the density and transverse profile of successive cohorts."*

Tabacchi et al (2000) also report that riparian stand complexity provides a higher stem density and more woody debris that increases turbulence during peak flows, which results in more complex channel conditions, more habitat diversity, and greater resilience. These patterns are important in both lateral and downstream directions.

The indirect effect of increased peak flows specifically from riparian timber harvest on headwater channels has not been directly studied, due to the extreme difficulty of isolating the effects of timber harvest on hillslope and riparian zone contributions to the runoff hydrograph. For example, Moore and Wondzell (2005) outline at least 18 different papers that infer the importance of "forest harvest activities" on channel morphology. Most of these inferences are with regard to wood supply and sedimentation, presumably from harvest activities and upslope erosion.

Lewis et al (2001) identified significant increases in suspended sediment yield from treated headwater watersheds in Casper Creek, and demonstrated that these increases are strongly correlated to increased volume of streamflow during storms after logging. Median suspended sediment yields generated from individual storms in partial cut watersheds increased by 64% over pre-harvest yields, and 107% in clearcut watersheds. Annual suspended sediment yields increased by 73% and 212% respectively. Sources of sediment were identified to include roads, riparian windthrow, and erosion from unbuffered streams (particularly in those watersheds that were broadcast burned after harvest). However, increased peak flows were implicated in affecting observed bank erosion, headcutting, and soil pipe enlargements.

Small increases in peak flow related to timber harvest operations have not generally been thought to adversely affect channel morphology (Grant et al. 1999; Ziemer 1998). There is evidence, however, that even modest increases in peak flows of the type observed in the literature (e.g. Lewis et al 2001, Moore and Wondzell, 2005, etc) can be important in some watershed contexts. When such peak flow increases occur in steep channels with erodible substrates, they can potentially increase sediment production from headwater streams (Lewis et al 2001; others). Similarly, increased flow duration in erodible landscapes can also affect stream sediment production by extending the period during which sediment transport thresholds are exceeded. Steep headwaters are particularly sensitive to increased shear stress during modest flows. Such effects can potentially be ameliorated by increased roughness provided by woody debris, steps, and riparian vegetation. This relationship between peak flow increases and sediment production from fluvial processes in headwater streams deserves more research.

Aquatic Ecology

Riparian tree growth appears to benefit by increased baseflows (Disalvo and Hart, 2002), which may explain the more robust vegetative conditions observed in riparian zones. Lateral soil moisture increases can also affect zonation of riparian vegetation (Nilsson and Svedmark, 2002).

Aquatic species generally recover quickly from even severe flood disturbances, usually in as few as 1-3 years (Swanson et al 1998).

During extended dry periods, portions of headwaters channels become dry when the transpiration water losses from riparian vegetative exceeds streamflow and hillslope contributions to the riparian zone (Moore and Wondzell ,2005). Increases in summer water yields from upslope timber harvest may decrease the length of dry reaches, effectively extending the perennial channel network and providing additional habitat availability (Keppler, 1998; Liquori, 2003), which affect the species distribution and richness of macroinvertebrates (Price et al, 2003).

D) CAN FOREST MANAGEMENT ACTIVITIES ALTER WATER QUANTITY IN RIPARIAN ZONES FOR HIGHER ORDER CHANNELS WITH FLOODPLAINS SUFFICIENTLY TO AFFECT OVERFLOW/SIDE CHANNELS THAT SERVE AS REFUGIA FOR FISH DURING FLOODS?

The answer to this question is "probably not," for two reasons. First, as noted above, the effect of timber harvest activities on peak flow is greatest for small storms and those in the fall. An increase in discharge for small storms could increase the frequency of flow in overflow/side channels, in some situations, depending on floodplain and channel morphology Site-specific surveys and water surface profile calculations would be needed to test this hypothesis, and to our knowledge this has not be done. Second, the streams with overflow channels and defined floodplains are likely to be 4th or 5th order channels draining a relatively large area. Lewis et al. (2001) showed that complete clearcutting of a catchment can cause in increase of 27 percent in the peak flow magnitude of the 2-yr event in relatively small watersheds (e.g. ~50 acres), however the potential for peak flow effects decreases significantly in larger basins (Thomas & Megahan 1998), largely due to asynchronization of flow timing from contributing basins (Ziemer and Lisle, 1998).

As described above, increases in summer flows following upslope timber harvest is well documented, and at least one study described increased habitat availability, but without any increase in aquatic invertebrate biomass (Keppeler 1998). Thus the extent that such treatments benefit salmonids remains unclear.

Also, as noted earlier, deciduous riparian vegetation can have higher summer transpiration than conifer species, and thus the distribution of riparian vegetation could influence any net flow benefit from upslope treatments.

Heavy equipment operation in the riparian zone could modify flow in side channels, but equipment is usually excluded from the riparian zone by existing forest practice regulations.

E) DO FOREST MANAGEMENT ACTIVITIES IN RIPARIAN ZONES FOR HIGHER ORDER CHANNELS WITH FLOODPLAINS AND ADJACENT TO SMALL HEADWATER FIRST AND SECOND ORDER CHANNELS SIGNIFICANTLY AFFECT HYPORHEIC EXCHANGE FLOWS?

Hyporheic flows describe the flow of water that exchanges between the surface stream and shallow groundwater region immediately surrounding the stream (Figure 3). In recent years, the ecological importance of hyporheic flows is becoming better understood, although the extent that forest management directly benefits or harms this environment is not yet clear.

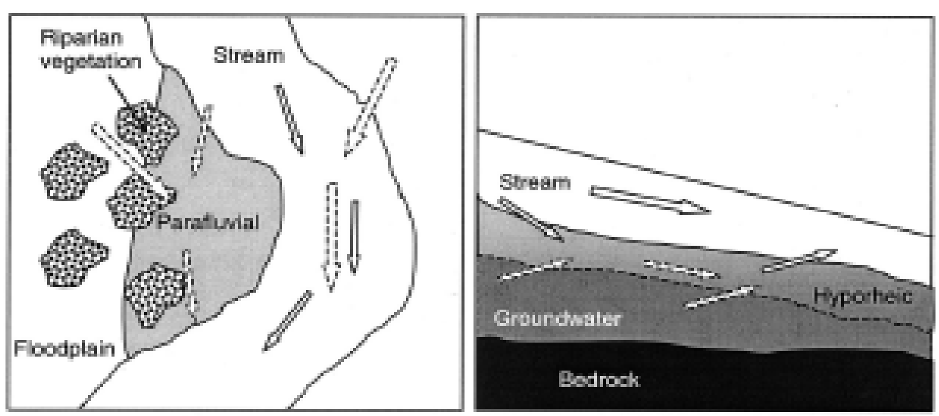

Figure 3) Aerial and side view of the hyporheic and parafluvial zones showing connections with the stream, groundwater, riparian and floodplain systems (Hancock 2002).

As described in the biotic/nutrient section, the supply and uptake of nutrients is strongly influenced by riparian vegetation through its controls on primary productivity and litter nutrient concentration. Physical/chemical and microbiological controls on stream nutrient concentrations include adsorption and co-precipitation (chiefly of phosphorus) with organic matter and iron oxides (Froelich 1988; Newbold, 1987), and nitrification/denitrification (Triska et al 1993). The hyporheic zone in forest streams is characterized by steep gradients in oxidation-reduction potential, and as water moves through the zone, nutrient concentrations are modified (Allan, 1995). The hyporheic zone thus acts as a water quality buffer, sometimes immobilizing pulses of nutrients released by fire or timber harvest, and at other times releasing nutrients back to the stream. Thus, activities that reduce hyporheic exchange may have an adverse effect on the stream ecosystem (Hancock, 2002).

Forest management activities may affect hyporheic exchange flows by affecting instream wood loading conditions, although not necessarily in response to hydrology effects from riparian management. The primary factors controlling hyporheic exchange are the channel and valley shape, porosity of the streambed, and wood loading (USFS-PSW, 2004). The interaction between streamflows, ripiarian areas, and hyporheic areas is complex, and the science on this topic is somewhat immature. Another potential forest management factor is the input of fine sediment to the stream enough that the open pore space in gravel becomes clogged and inflow at point-bars and step-pools is reduced (Hancock, 2002). Litter mats from deciduous trees can retard hyporheic exchange by seasonally limiting inflows, even as they increase nutrient availability to the aquatic community through litter decomposition processes (Tabacchi et al 2000).

Hydrologically speaking, Wondzell and Swanson (1999) showed that extremely large floods, like the 1996 flood in the H.J. Andrews Experimental Forest, radically altered the structure of the hyporheic zone, changing flow-paths and residence time. While a flood of that magnitude is unlikely to be affected by timber harvest activities (Thomas & Megahan, 1998; Beschta et al, 2000), the manner in which forest management affects the riparian zone may indirectly influence the qualities and characteristics of wood and sediment recruitment in was that can locally affect hyporheic response and recovery (Wondzell and Swanson 1999), although the spatial heterogeneity of disturbances at the river network scale tends to buffer against net impact (Swanson et al 1998).

Transpiration by riparian vegetation can modify hyporheic exchange. Nilsen and Svedmark (2002) describe increases in capillary fringe associated with riparian evapotranspiration processes. While transpiration rates vary significantly by species (Tabacchi et al 2000), a mixed hardwood stand transpires water from soils at rates that vary from less than 1 foot over a summer season (Wullschleger, Hanson and Todd, 2001) to as much as 4 feet in extreme arid environments. On the conservative side, compacted soils might have a porosity of 20-30%, suggesting that typical riparian transpiration can lower the water table surface elevation by 2 to 5 feet in mixed hardwood stands over the course of an entire summer season, or as much as 12-20 feet in more arid environments. If one assumes that hyporheic exchange is at least partly influenced by water table elevations, it would follow that riparian conditions could influence hyporheic flows. However, it is not clear if removal of riparian vegetation increases or decreases hyporheic exchange, as no direct studies are known to exist.

Hyporheic flows can also affect riparian vegetation, although the interactions between riparian communities and hyporheic conditions are not well understood (National Research Council, 2002). Harner and Stanford (2003) found that cottonwood (*Populus trichocarpa*) growth in a gaining reach was twice that of a losing reach, and that nitrogen was 16% higher relative to carbon in the gaining reach. Hinkle et al (2001) observed hyporheic exchange fluxes of 5-10% of the streamflow at reach-scales. McDonnell et al (1998) identified higher dissolved organic carbon delivery from hill slopes when riparian groundwater levels were higher.

2. What bearing do the findings of the reviewed articles have on riparian zone buffer strip delineation (area influencing water transfer/exchange function) or characteristics (cover, plant species and structure, etc.)?

There is very little in the reviewed literature that can used to directly address the issue of buffer strip delineation relevant to the water function. Therefore, what follows are some general concepts and interpretations extracted from the conclusions drawn from the reviewed literature.

It appears appropriate here to make a clear distinction between a riparian zone and a riparian buffer. Here, we use the term "*riparian zone*" to describe the area of hydrologic influence adjacent to the stream, and note that this zone is highly dynamic both in space and time. We use the term "*riparian buffer*" to describe a management zone that is typically defined by specified criteria, and which are typically static in space and time. We also note that the structure, distribution and operational guidelines in riparian buffers may be more important than the delineation of the buffer.

The reviewed literature did not specifically discuss the delineation of the hydrologically-influenced riparian zone. Dunne (1978) originally described spatially dynamic expansion of riparian saturation in response to storms and watershed conditions that probably remains valid today. These delineation characteristics are highly variable in time and space, and their prediction is extremely difficult. Basically, there are three dimensions that are important when considering the delineation of hydrologically-influenced riparian zones:

Lateral – The lateral dimension describes the width of the zone that is influenced by hydrologic functions. The width that is hydrologically-defined riparian area can extend from a few feet to hundreds of feet, largely dependent on the gradient, confinement and hydraulic conductivity (which is a function of soil type).

Longitudinal – The longitudinal dimension describes the upstream extent of the channel network that influences hydrologic functions. The primary variables that control this dimension include total precipitation, runoff mechanism (snowmelt v. rainfall), drainage density, gradient, confinement and hydraulic conductivity. This dimension responds dynamically to timber harvest as water yields increase the length of perennial flow in headwater channels for several years following harvest.

Temporal – The temporal dimension describes the amount of time that the riparian zone is influenced by hydrologic functions. Zones of influence can range from hours (during storms) to years (e.g. the perennial stream network). The primary variables that control this dimension include the upslope stand characteristics, as well as those variables that describe the longitudinal dimension.

It appears from the literature that hydrologic functions are not highly sensitive to forest management in riparian areas. Other exchange functions (nutrients, wood, heat and sediment) will offer additional factors affecting management of the riparian buffer. The hydrologic literature reviewed suggest several important considerations with regard to characteristics of the buffer for protecting water exchange functions:

Uncompacted Soils – Soils in riparian zones can be vulnerable to soil compaction due high soil moisture and low soil strength (Dewire et al, 2006). Even dry soils of a riparian zone can loose hydraulic conductivity from heavy equipment operation (Norman, et al, 2008).

Canopy Retention – As described in Section , the effects of riparian canopy removal are probably small. However, since rainfall on the riparian zone generates a rapid hydrograph response, it is reasonable to expect that complete canopy removal from the zone might have an effect on the rising limb of the stormflow hydrograph (Mc Donnell et al, 1998). While some canopy removal may be appropriate for meeting other desired functions, it is not clear from the reviewed literature how much canopy can be removed without substantially degrading hydrologic functions.

Diversity– Diversity in the species, density, age-classes and distribution of riparian vegetation appears to favor the quality of aquatic habitats (Nilsson and Svedmark, 2002; Price et al, 2003; Tabacci et al 2006).

Disturbance Risk – Riparian management (or lack thereof) can significantly affect the conditions and characteristics that influence other disturbance processes including fire and infestation risks (Dwire et al, 2006), vegetative succession (Nilsson and Svedmark, 2002), or landslide risk (Ziemer and Lisle, 1998). For example, fuel management in a riparian zone may decrease the risk of catastrophic wildfire, while opening the canopy and increasing primary productivity in a stream.

In short, the consideration of the water transfer/exchange function does lead to any conclusions about buffer zone delineation, but it does suggest the importance of protecting soils of the riparian zone from mechanical disturbance that compacts soils.

3. Are there regional differences in the effects of forest management activities or disturbances in or near the riparian area/zone for the water transfer riparian function?

Yes, there are regional differences, although the reviewed literature does not highlight them, since most of the studies are restricted to either Casper Creek (coastal Mendocino County) or other regions outside the state.

Flow conditions impose a "signature" that affects ecological and geomorphic functions and processes, and thus regional variation in five key variables are important; runoff timing, frequency, duration, rate of change, and magnitude (Nilsson & Svedmark 2002). While not specifically addressed by the reviewed literature, these 5 key hydrologic variables are most directly influenced by:

Regional Geology –affects the signature of infiltration and hillslope storage and low-flow characteristics. For example, large sedimentary systems (e.g. coastal regions) typically experience much higher rates of hillslope storage than granitic terrains (e.g. Sierras). In the Willamette River Basin, Tague and Grant (2004) showed how summer streamflow volumes, recession characteristics and timing of response to winter recharge are linearly related to the percent of High Cascade (younger volcanic rocks) in the contributing area.

Topography – affects the spatial distribution of stream channels and therefore the travel distance between the hillslope and channel. Elevation influences the form of precipitation (e.g. rain or snow) as well as the intensity and total annual amount of precipitation (e.g. orographic effects).

Dominant Runoff Mechanisms – Rainfall runoff typically results in rapid hydrograph responses with limited canopy interception and variable source-area runoff mechanisms. Snowmelt typically produces higher canopy interception, accumulated seasonal storage and prolonged runoff periods and lower peak flows. Areas prone to rain-on-snow events (e.g. Sierras, Modoc-Shasta plateau) experience both types of runoff signatures, in addition to more frequent, large-magnitude and often highly erosive peak flows events. Areas where substantial snow accumulations are not found (e.g. north coastal California, low-elevation interior California) respond primarily to rainfall-runoff events.

For example, the North Coast region and the Modoc-Shasta plateau region present an interesting contrast in hydrogeology and geomorphology, and their effects on runoff generation. In the former, slopes are steep, drainage density is high, and the rainfall-runoff response is rapid. There is a high degree of connectivity between the riparian zones of first-order streams, and the downstream reaches of larger streams (Ziemer and Lisle, 1998). In the latter, slopes and drainage densities are low, and bedrock fractures and other subsurface openings convey much of the precipitation from soil to rivers. The degree of connectivity between first-order tributaries and larger streams is relatively low, and summer base flow as percent of total annual water yield is high Such contrasts could be drawn for many of the geographic regions of California, though documentation in the literature selected for review is lacking.

INFORMATION GAPS

- There no very few direct studies of the effect of tree removal on hydrologic functions from riparian areas, with the exception of Hewlett and Hibbert (1961). Most studies are conducted at the watershed-scale, and riparian areas typically comprise a small fraction of the entire watershed. To our knowledge such studies are not available, in part because statistically valid measurement of responses from riparian timber harvest alone are very difficult to obtain.

- Effects of riparian water in unchanneled swales affects the stability of the slopes and was not addressed by this review. Extensive studies and literature are available to inform this debate.

- Hyporheic functions and processes are not well-understood, and it's not entirely clear how to manage riparian areas for hyporheic effects.

- The Lewis et al (2001) summary provides important information. We see this phenomenon of channel enlargement (i.e., gully headcutting) as widespread after first cycle logging in coastal zones in particular, and effects are still evident in the streams today (this is documented well in Dewey 2007). However, we don't know how much additional erosion in these channels is occurring and it is an area of active research.

- This relationship between peak flow increases and sediment production from fluvial processes in headwater streams deserves more research. At least one study that identified peak flow increases from watershed timber harvest also reported increased suspended sediment production, and inferred that sediment was derived from bank erosion (Lewis et al 2001). Steep headwaters are particularly sensitive to increased shear stress during modest flows. However, its not clear if such production comes from stream banks (e.g. channel widening) or the channel bed (incision). It would also be helpful to establish the extent of such processes to determine the effect on salmonids, which at present time can only be inferred. Such studies may also wish to address the extent to which woody debris accumulations mitigate for negative effects.

- There is at lease some evidence of benefits to aquatic habitat in response to increased summer flows from harvested watersheds, which can increase the perennial extent of headwater streams (Keppeler 1998; Liquori 2003). The level of usage by salmonids in these environments, or the benefit in terms of increased biomass availability and trophic support to downstream reaches is not well defined. Thus the extent to which these areas may benefit by riparian management is not well defined, and could benefit by additional research.

INFERENCES FOR FOREST MANAGEMENT

Removal of trees within riparian zones is unlikely to have significant effects on water exchange functions important to salmonids. As noted in CBOF-TAC (2008), Botkin et al. (1994) concluded that there is no evidence that changes in stream flow due to timber harvest would be detrimental to fish. Erman et al. (1988), however, reported that winter rain-on-snow floods in the Sierra Nevada killed young-of-year brook trout, due to increased bedload transport, and suggested that excessively-thinned riparian zones could increase flood peaks during rain-on-snow floods.

The literature on riparian water exchange tells us that most of the hydrologic response to forest management comes from roads and upslope timber harvest (Beschta et al 2000; others). While there are no direct studies, we can infer from existing studies that only a very small amount of additional water can be generated from modest riparian treatments. Additional water is available to runoff from reduced canopy interception and evaporation, and the total amount of additional water is proportional to the total upslope harvested area. Since riparian areas generally represent a small portion of the total area, the net effect is likely to be small.

In higher-order streams with floodplains, the hydrologic response to modest riparian treatments are unlikely to affect salmonids. Upslope contributing areas tend to be much larger than the riparian area, and thus the amount of additional water available for runoff is relatively small to insignificant. The variable source area concept suggests that faster streamside saturation might increase peak flow response slightly, given its proximity to the stream, although any potential effect is likely to be small. With the exception of Hewlett and Hibbert (1961), we are aware of few direct studies that have measured hydrologic response from riparian treatments directly.

In low-order headwater streams, the relative effect of riparian treatments may be higher on a proportional basis, since the riparian area treated will likely be a larger proportion of the total contributing watershed area. While it is easier to detect a change from these areas (Ziemer & Lisle, 1998), the amount of the total volume of water generated from riparian treatments is low in these areas. The studies we reviewed did not specifically identify specific impacts or situations that would pose a risk to salmonids directly.

There may be implications to pore pressures and saturation effects in steep, confined zero-order channels, but we did not review literature on this specific topic. These areas can be significant sources of sediment when increased pore pressures result in slope failures (Dietrich et al, 1987; Torres et al 1998). Review of this topic may be warranted to resolve the issue of appropriate riparian treatments in the most upstream expression of perennial headwater areas, but is beyond the scope of this project.

There also may be increases in the headwater extent of perennial flow that occurs in response to riparian treatments in headwater areas. Such effects may benefit salmonids by increasing available headwater habitat (Keppeler 1998) and can potentially increase food production and nutrient cycling in source areas.

Riparian buffers can prevent compaction to sensitive riparian soils known to have high moisture content and low soil strength, thereby maintaining saturated conductivity and soil water storage capacity, thus maintaining a low risk for surface erosion in riparian areas (Norman et al. 2007). Soils of the riparian zone, even when they are dry, may be vulnerable to compaction and loss of hydraulic conductivity. Because riparian soils are highly variable in their physical properties, exclusion of heavy equipment that may cause compaction should be presumed unless it can be show that soil hydraulic characteristics will not be affected.

The science on hydrologic effects from riparian treatments is quite limited, due to challenges associated with measurement and statistical precision/accuracy. These challenges reflect the traditional approach of empirical studies (e.g. paired watersheds). Future advances in distributed computational, analytical or theoretical modeling capabilities may help to answer more specific questions about when and where hydrologic factors may affect key riparian exchange functions important to salmonids.

GLOSSARY

Baseflows	the amount of runoff in a stream that is primarily sources by subsurface sources
Colluvium	a loose accumulation of rock and soil debris at the foot of a slope that has not been reworked by flowing water
Disturbance	processes that substantially affect the structure, condition and/or evolution of riparian stands. Timber harvest is but one type of disturbance that affects riparian zones. Other disturbance processes include flooding, mass wasting, fire, wind, infestation, disease, animal damage, snowfall, ice breakage, competition mortality, etc.
Heterogeneity	a state consisting of diverse or constituents
Homogeneity	a state consisting of a uniform, often continuous condition
Hyporheic	a subsurface zone immediately below and adjacent to a stream where shallow groundwater and water from the stream mixes
Isotopically	relates to different structure of atoms that can be separately identified using chemical analysis methods. Used in hydrology to help identify specific sources of water
Orographic	relates to clouds that form as air masses move over mountains
Parafluvial	areas adjacent to stream
Peak Flow	the maximum instream flow that occurs directly in response to runoff from rain, snowmelt or both
Solar Pathfinder	a device for mapping the path of the sun and its interception by tree crowns, for a given date at a given point along a stream. The device is commonly used to measure shade or solar radiation.

Water Yield — the volume of water that comes from a watershed over a period of time

Zero-Order Channels — areas where the accumulation of water from adjacent hillslopes and watersheds is concentrated, but not yet sufficient to create a stream channel. These areas are an important source of springflow and can influence mass wasting processes like landslides and debris flows.

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