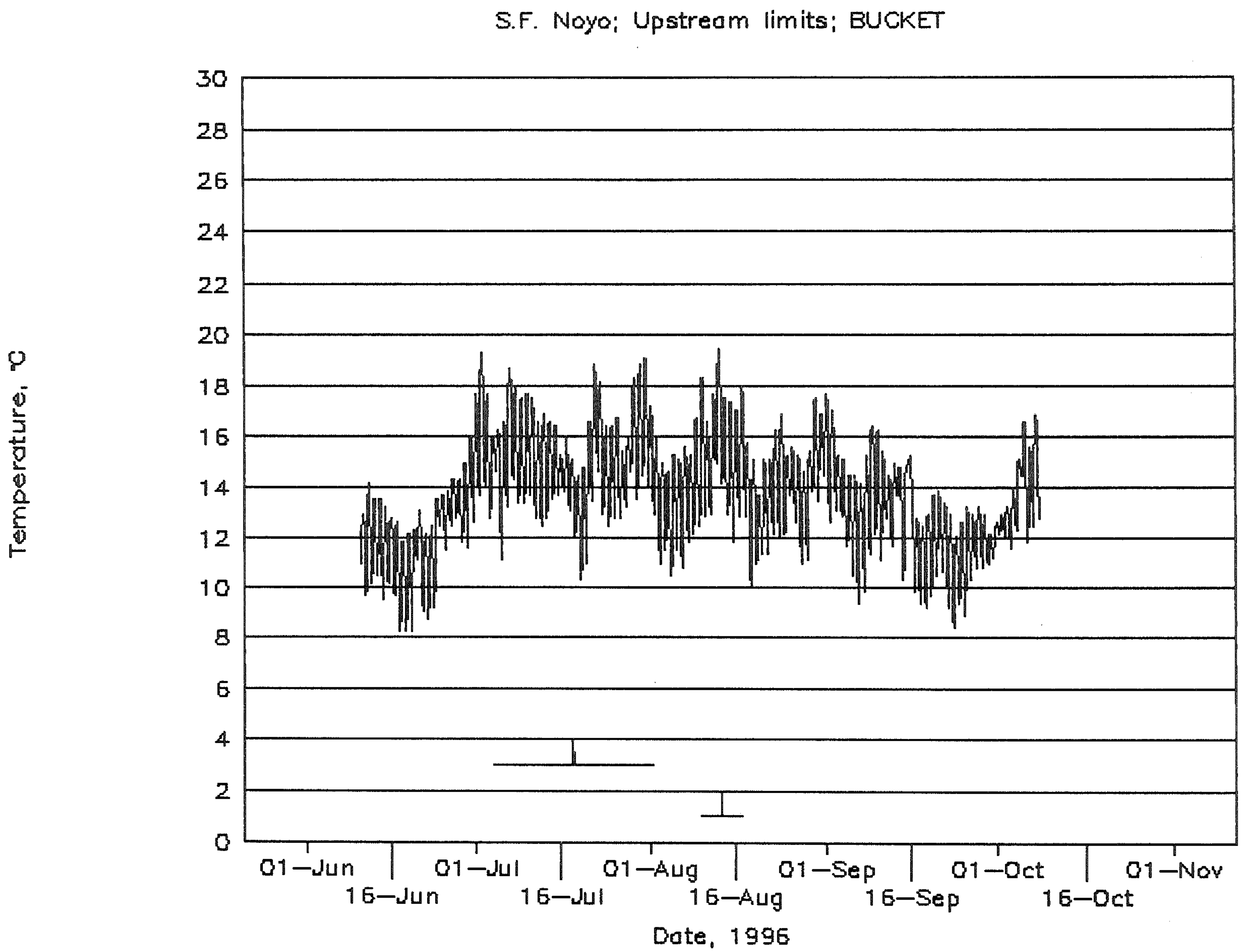
Fig. 1. Cont.

Stream Name & Monitor Placement	Location	Date of maximum 7-day average	Maximum 7-day average temperature (° C)	Date of maximum 4-week average	Maximum 4-week average temperature (° C)	Instantaneous Peak Temperature (° C)
NF Big River Stream	James CK., Lower Limits	July 28	16.76	August 02	16.1	19.76
NF Big River Stream	Chamberlin, Upper culvert	July 12	14.52	August 02	14.16	15.75
NF Big River Stream	Chamberlin, downstream main S drainage	July 28	16.08	August 02	15.52	18.31
NF Big River Stream	Chamberlin, below W & E Forks	No data	No data	No data	No data	No data
NF Big River Stream	Chamberlin above NF	July 28	17.45	August 03	16.82	20.57
NF Big River Stream	WF Chamberlin, below 16 Gulch	July 28	15.21	August 03	14.63	16.86
LNF BigRiver Stream	Wonder Crossing	July 28	13.56	July 18	13.84	14.96
LNF BigRiver Stream	LNF ca. 10 m above Berry Gulch	July 28	15.34	July 18	15.04	16.7

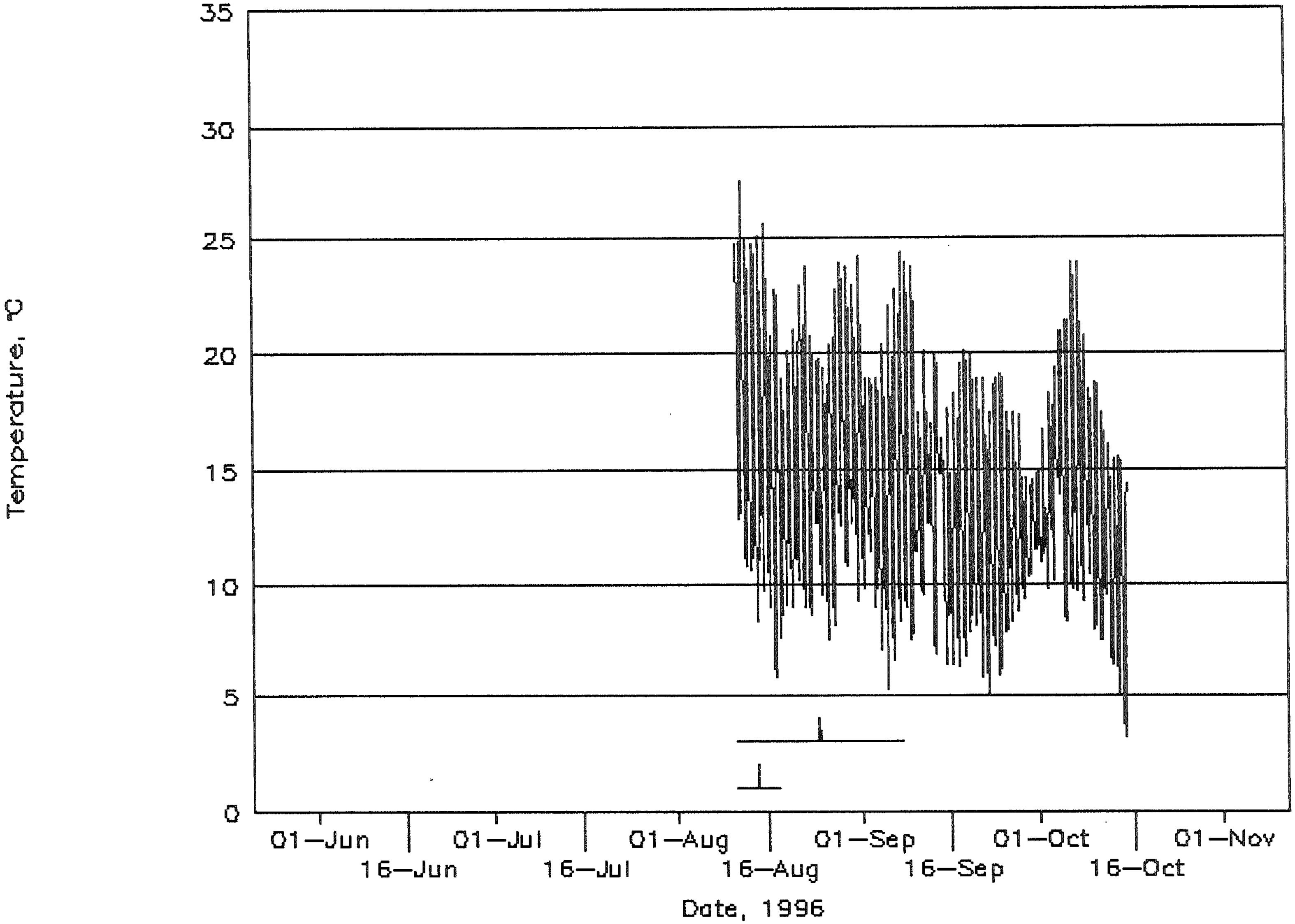
Stream Name & Monitor Placement	Location	Date of maximum 7-day average	Maximum 7-day average temperature (° C)	Date of maximum 4-week average	Maximum 4-week average temperature (° C)	Instantaneous Peak Temperature (° C)
LNF BigRiver Stream	Berry Gulch ca. 5 m above LNF	July 28	14.94	July 18	14.62	16.38
LNF BigRiver Stream	Thompson Gulch about 100m above confluence with LNF	July 28	13.75	August 03	13.44	14.33
LNF BigRiver Stream	Railroad Gulch above marsh	July 28	14.02	July 17	13.71	15.59
Caspar Stream	Caspar up SF	July 07	14.08	July 17	14	15.27
Caspar Stream	Down Bound	August 30	14.96	July 17	13.98	15.59
Caspar Stream	SF Caspar	July 07	13.86	July 17	13.69	15.27
Jughandle Stream	300' downstream of THP	August 31	12.56	720	12.4	12.94

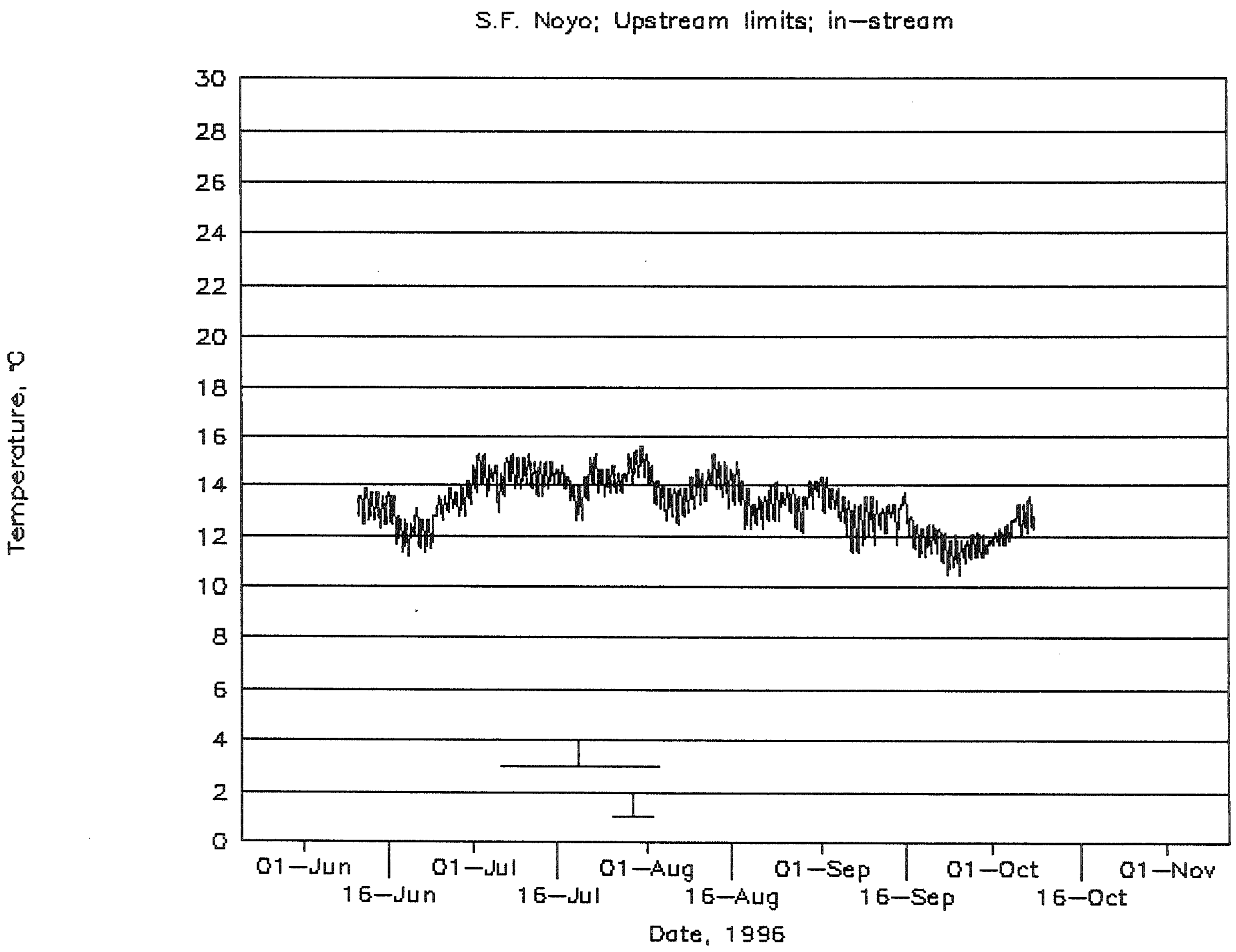
Stream Name & Monitor Placement	Location	Date of maximum 7-day average	Maximum 7-day average temperature (° C)	Date of maximum 4-week average	Maximum 4-week average temperature (° C)	Instantaneous Peak Temperature (° C)
Russian Gulch Stream	(upper	August 29	13.08	July 18	12.75	14.49
Russian Gulch Stream	Lower	August 30	12.56	July 17	12.33	13.4
Big River Stream	Montgomery Creek	July 29	15.47	August 04	15.05	16.86



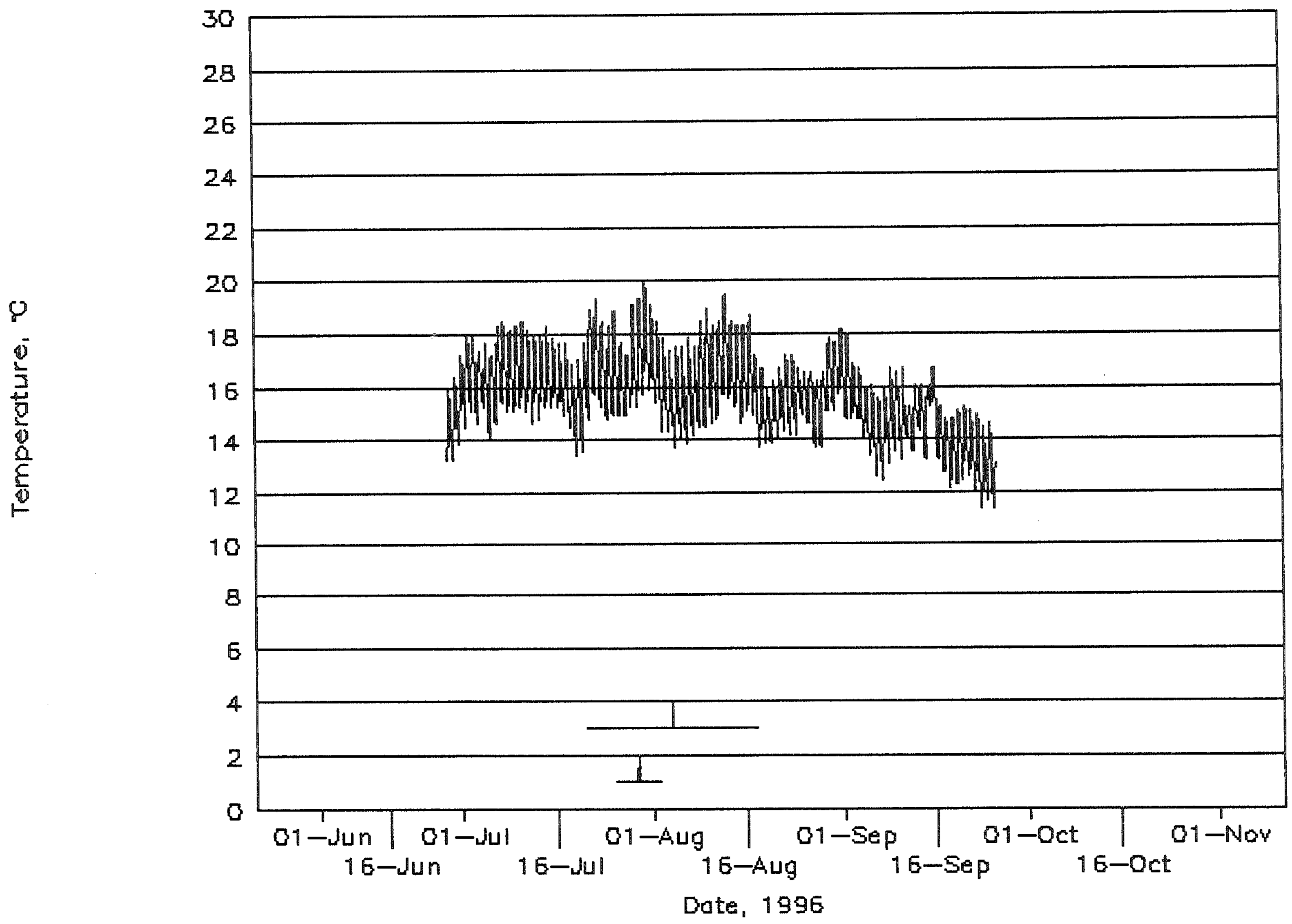
S.F. Noyo; Upstream limits; BUCKET

S.F. Noyo; Upstream limits; AIR

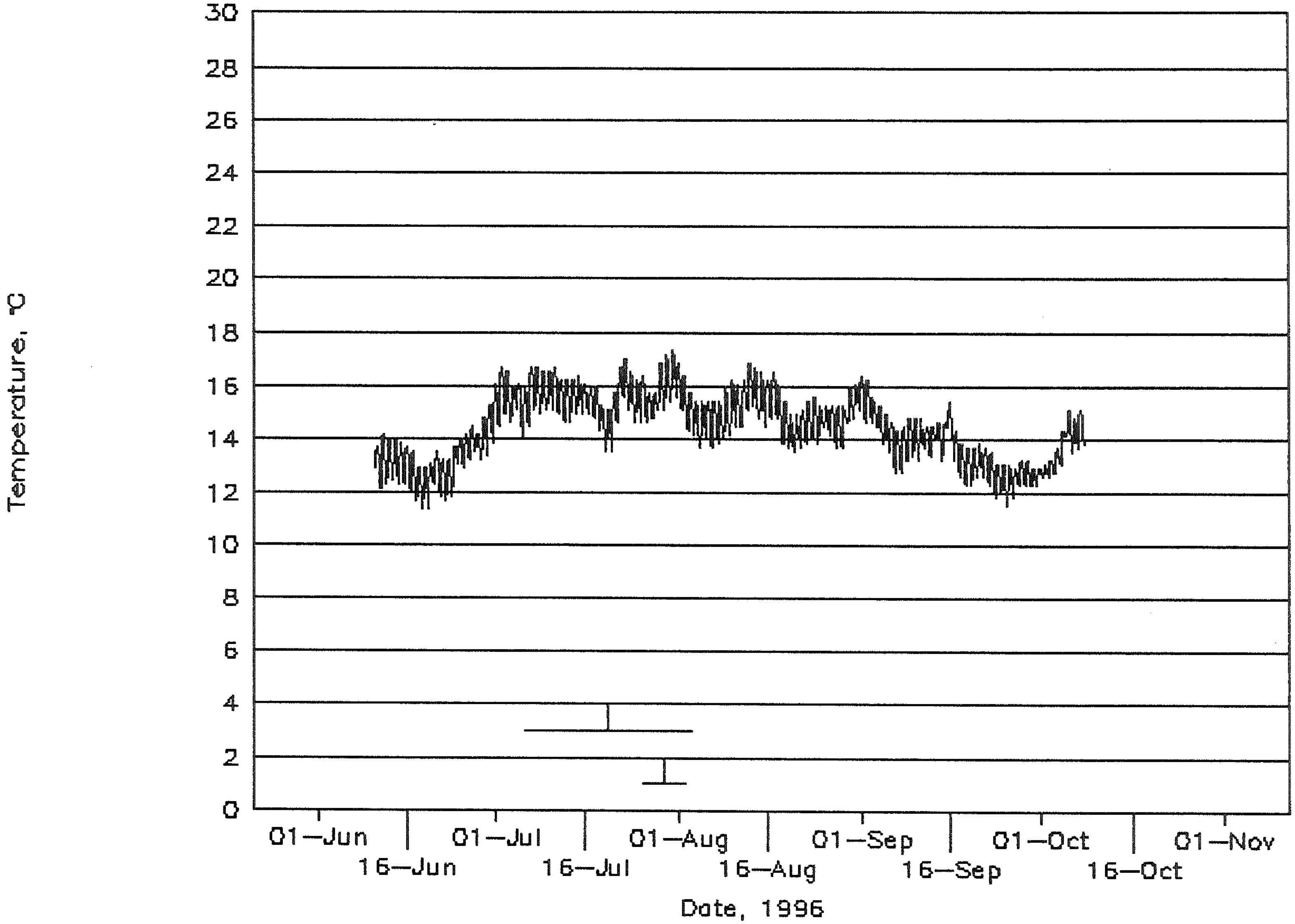



S.F. Noyo; Upstream limits; in—stream

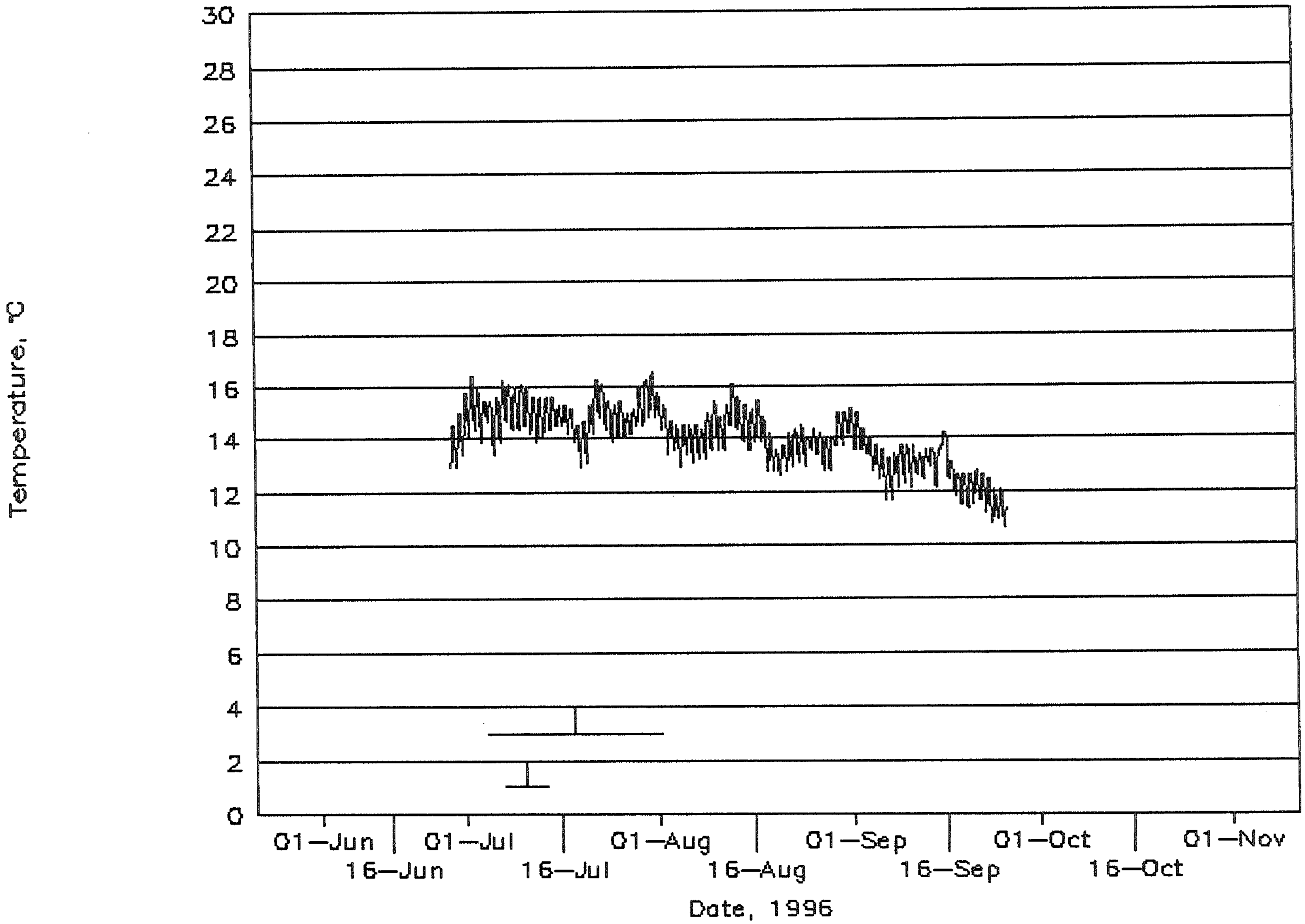
S.F. Noyo above Rd. 320



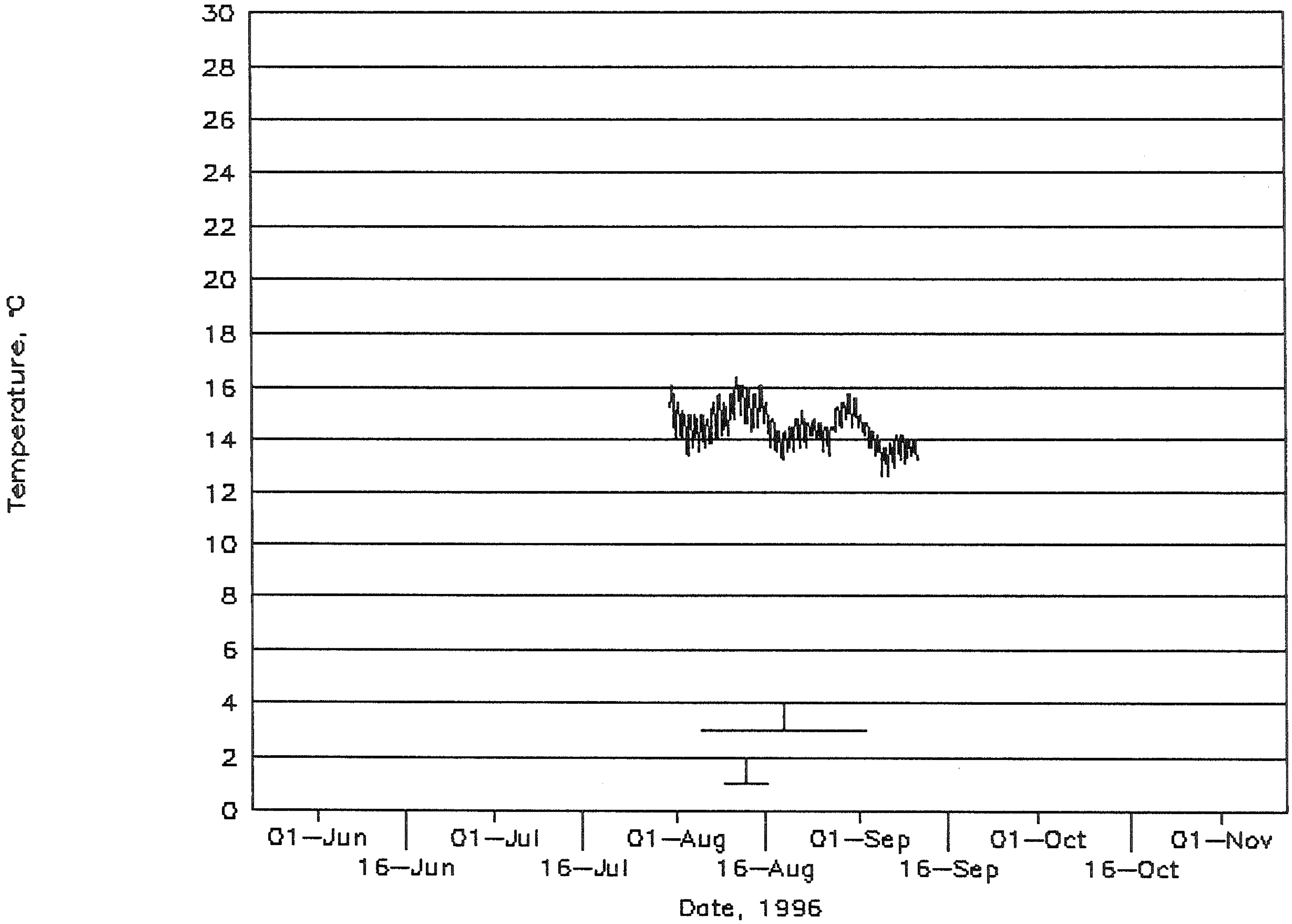
S.F. Noyo, 50m below Parlin Ck.



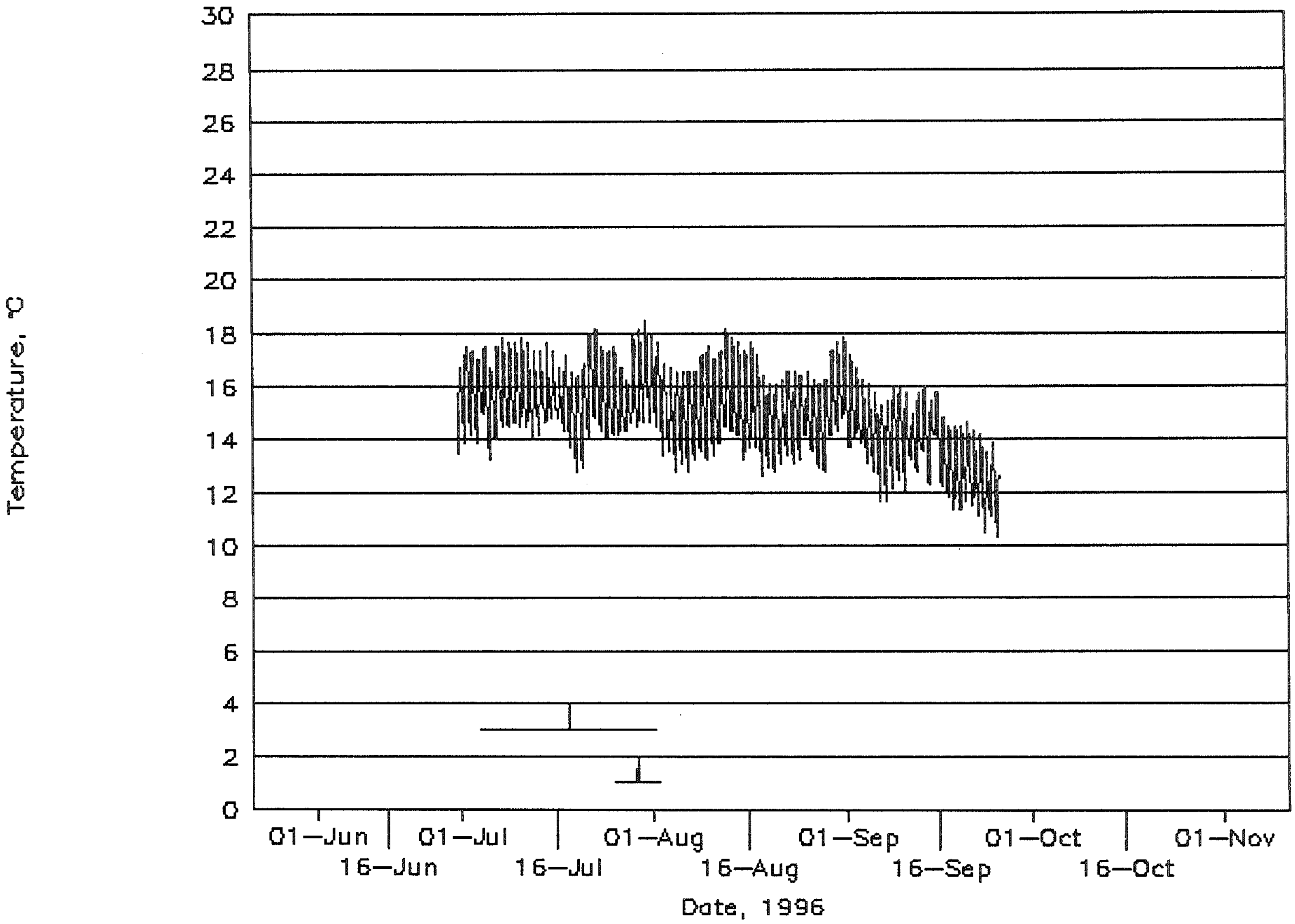
S.F. Noyo between 23 Gulch & Parlin Ck.

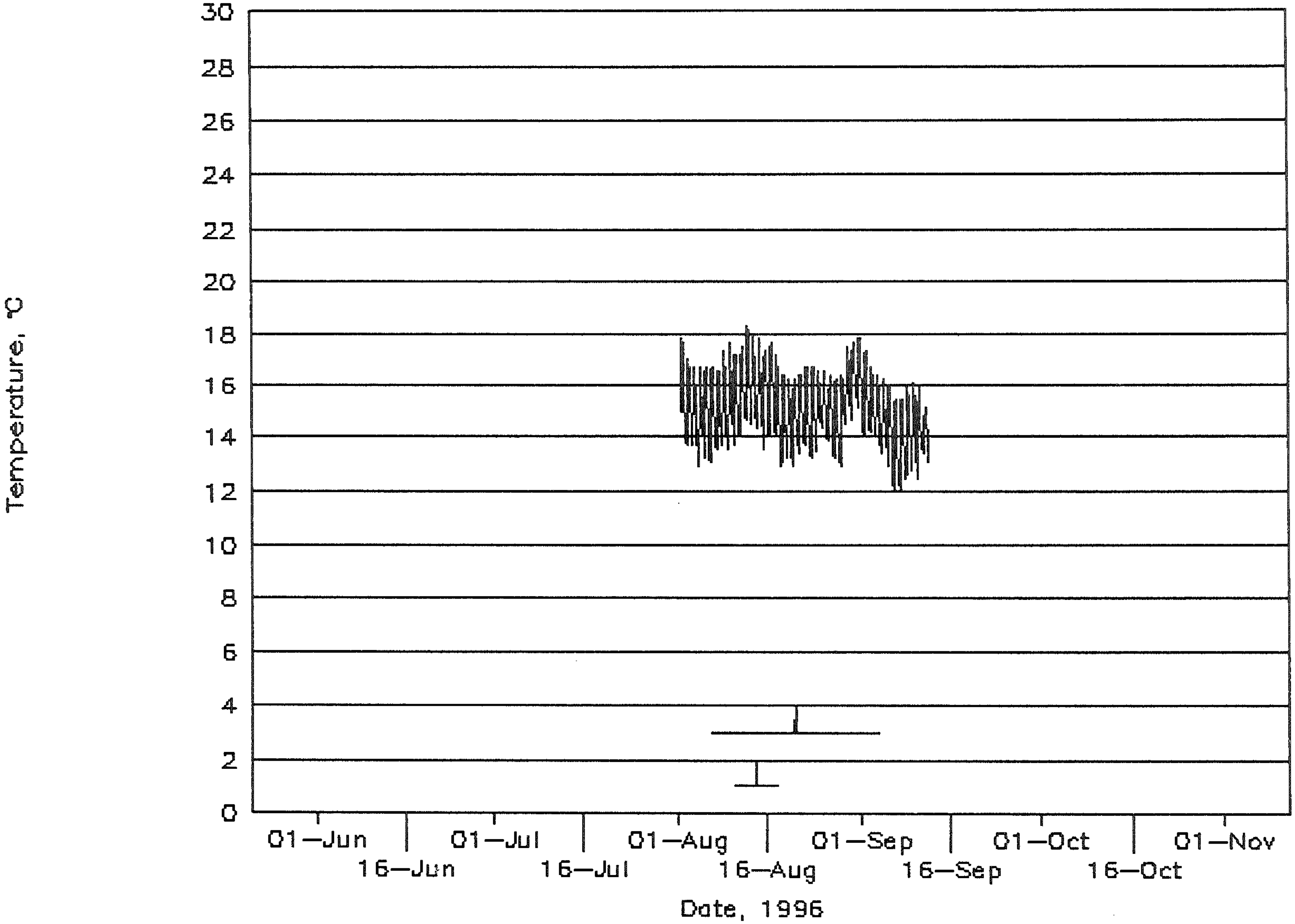


S.F. Noyo, 50 m downstream Parlin Ck.



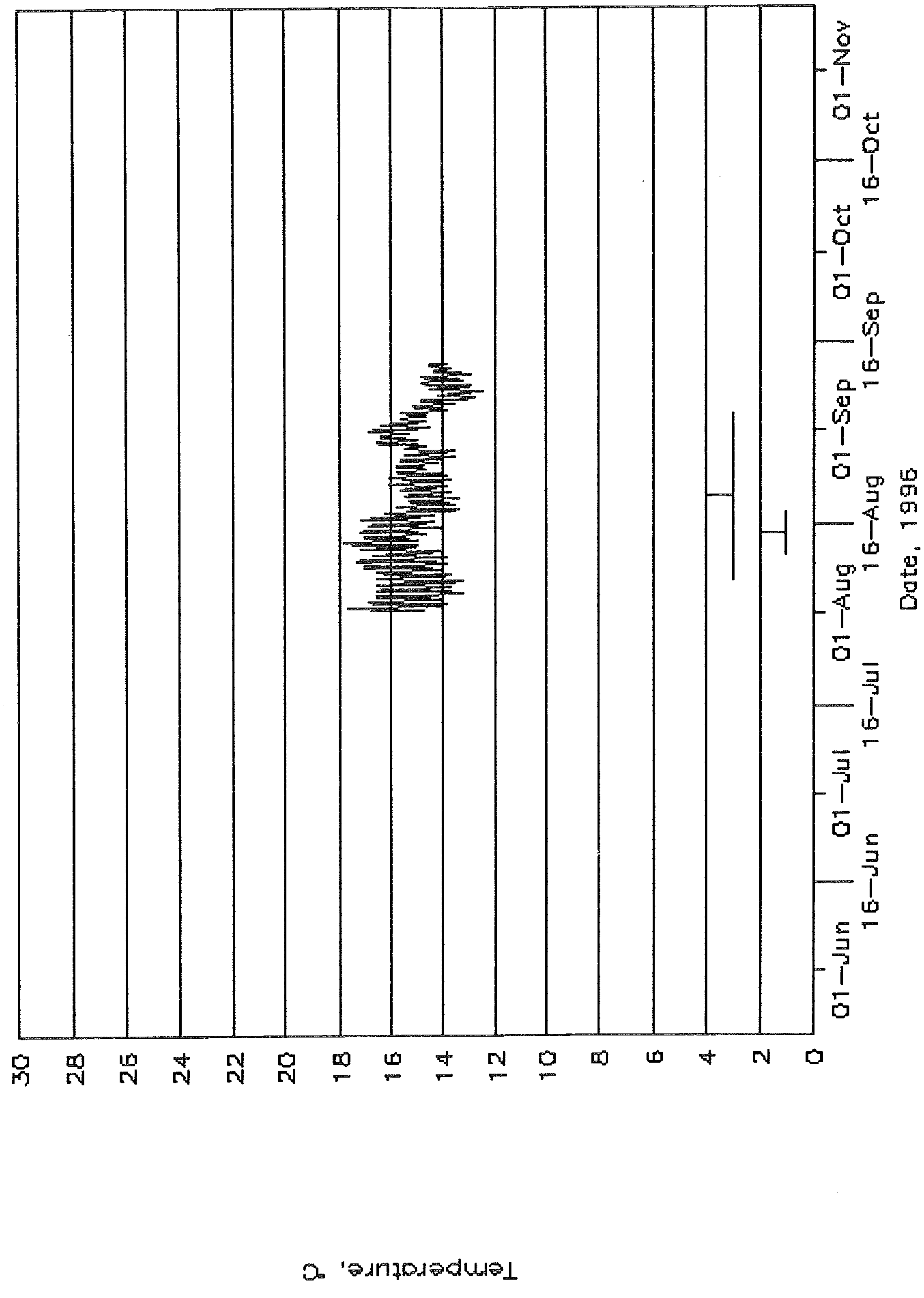
S.F. Noyo; 100m below Bear Gulch

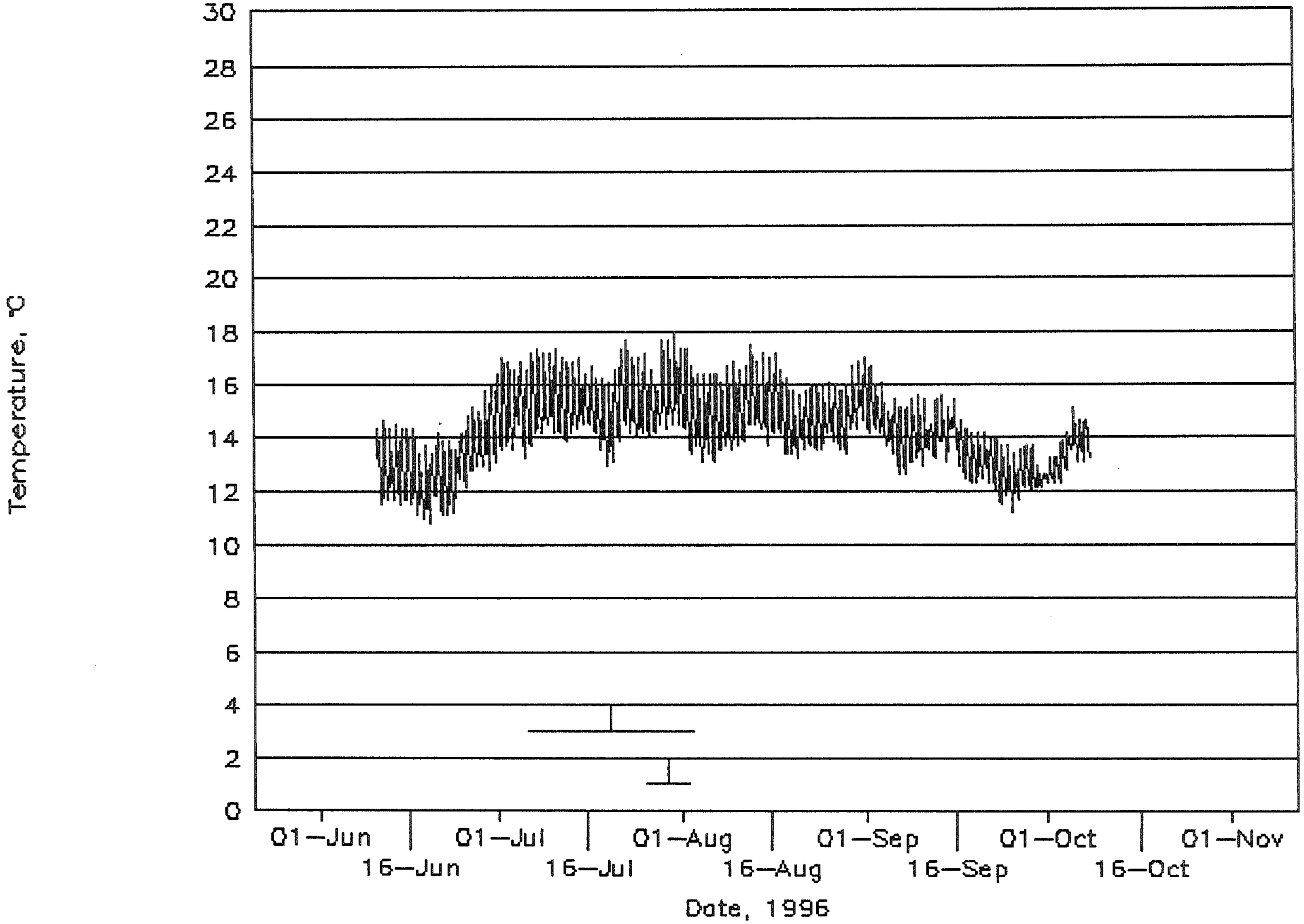




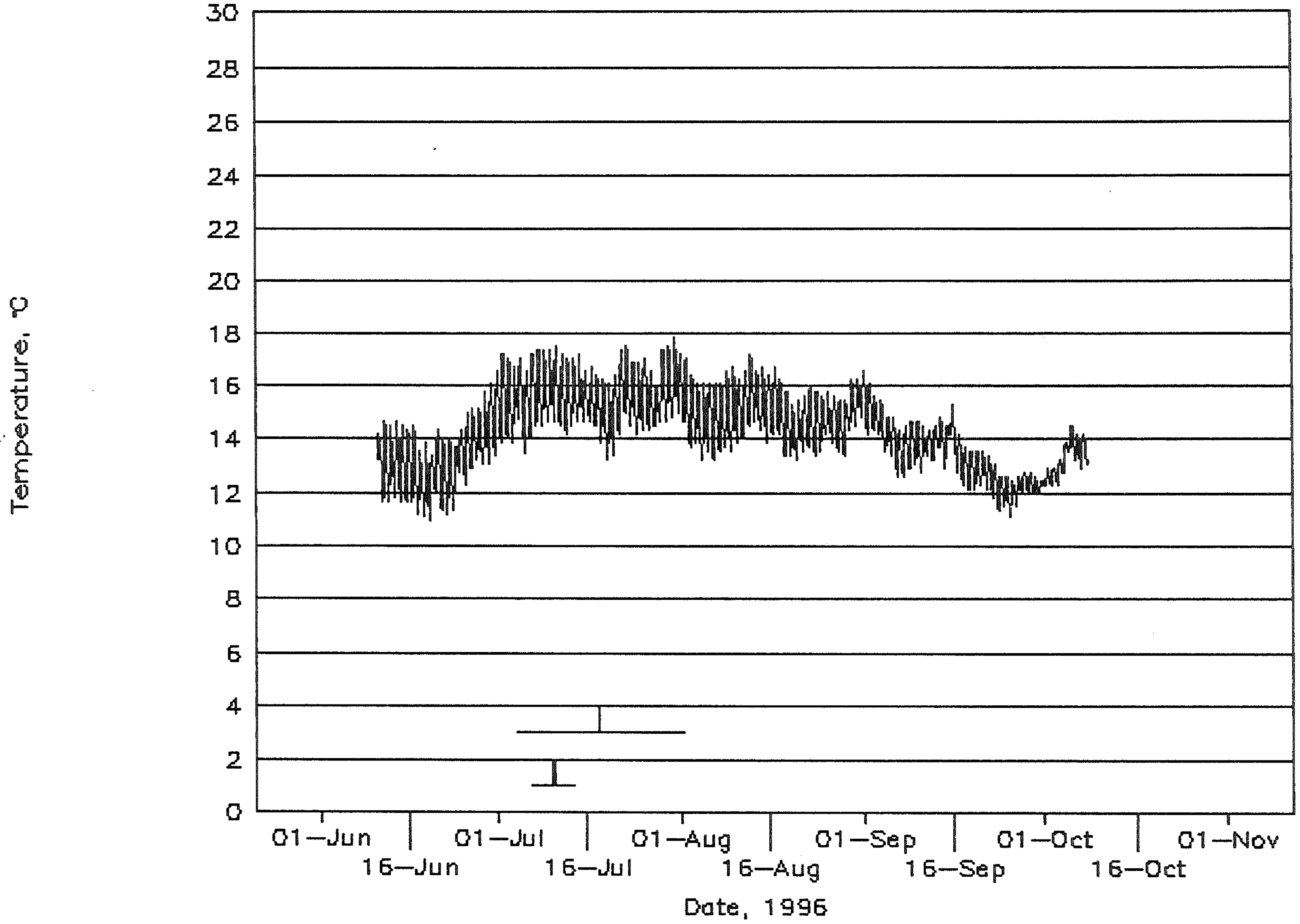
S.F. Noyo, 100 m below Bear Gulch

S.F. Noyo 120 m above Peterson Gulch

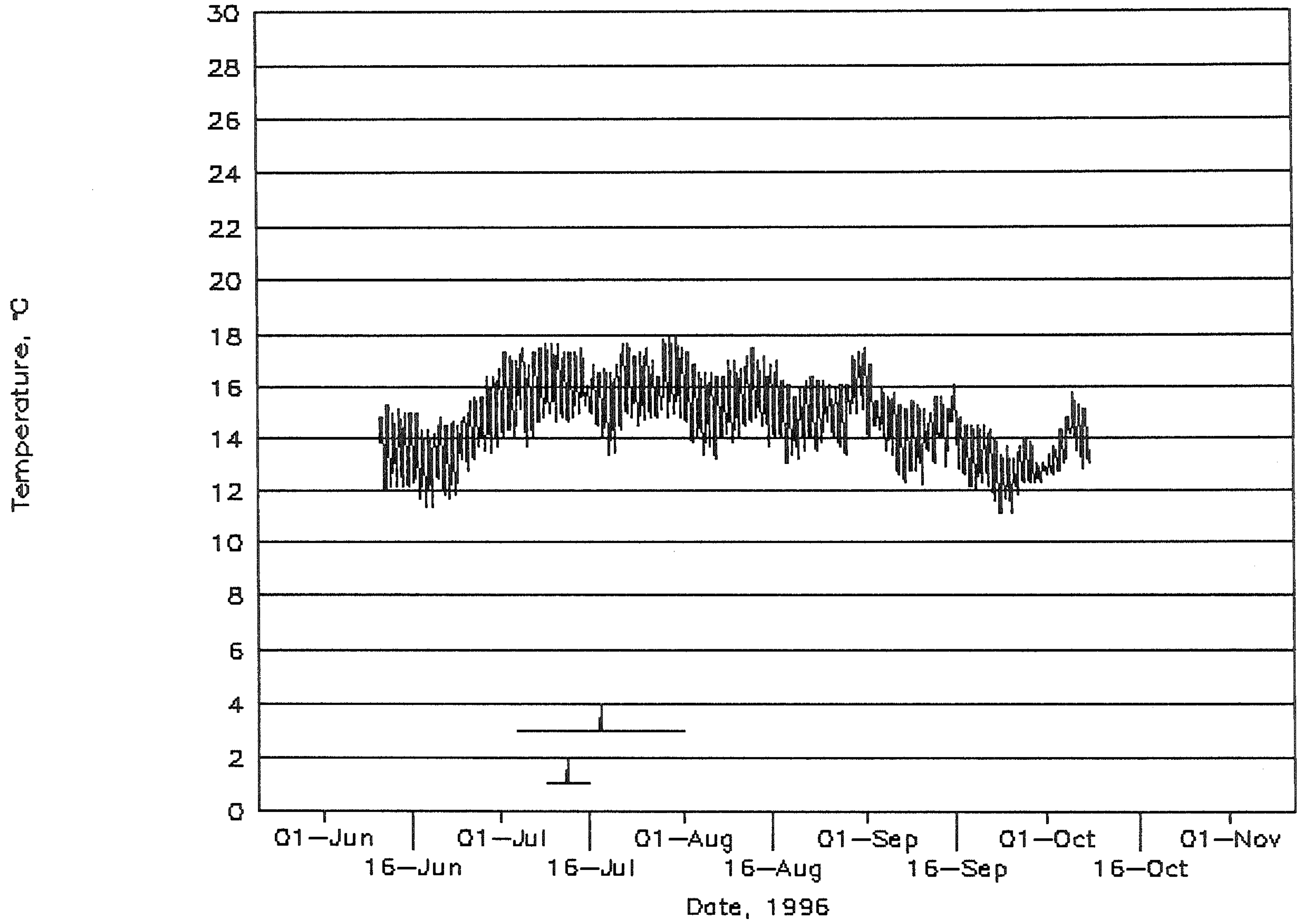



S.F. Noyo above N.F. of S.F.

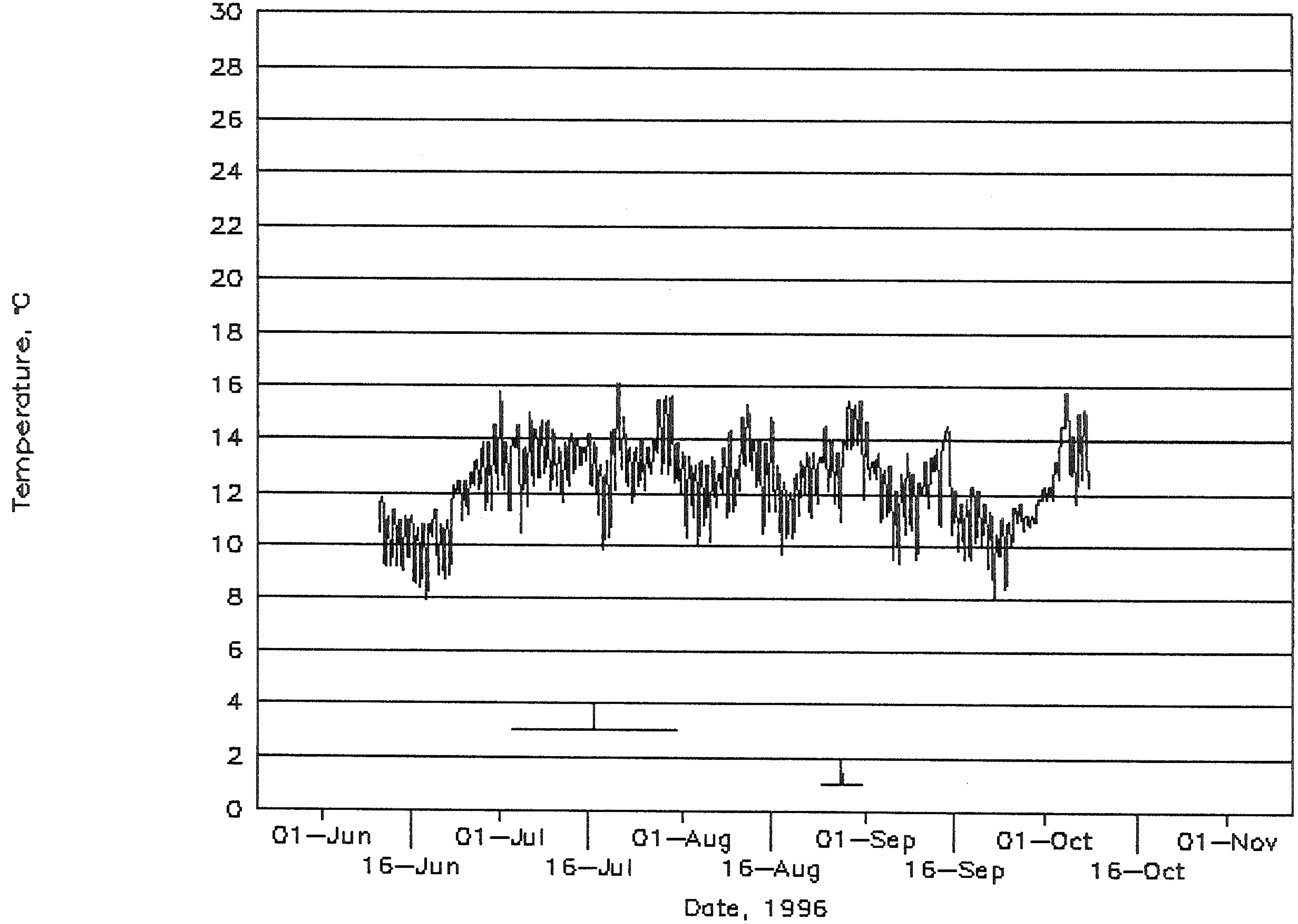
S.F. Noyo downstream of Egg Station



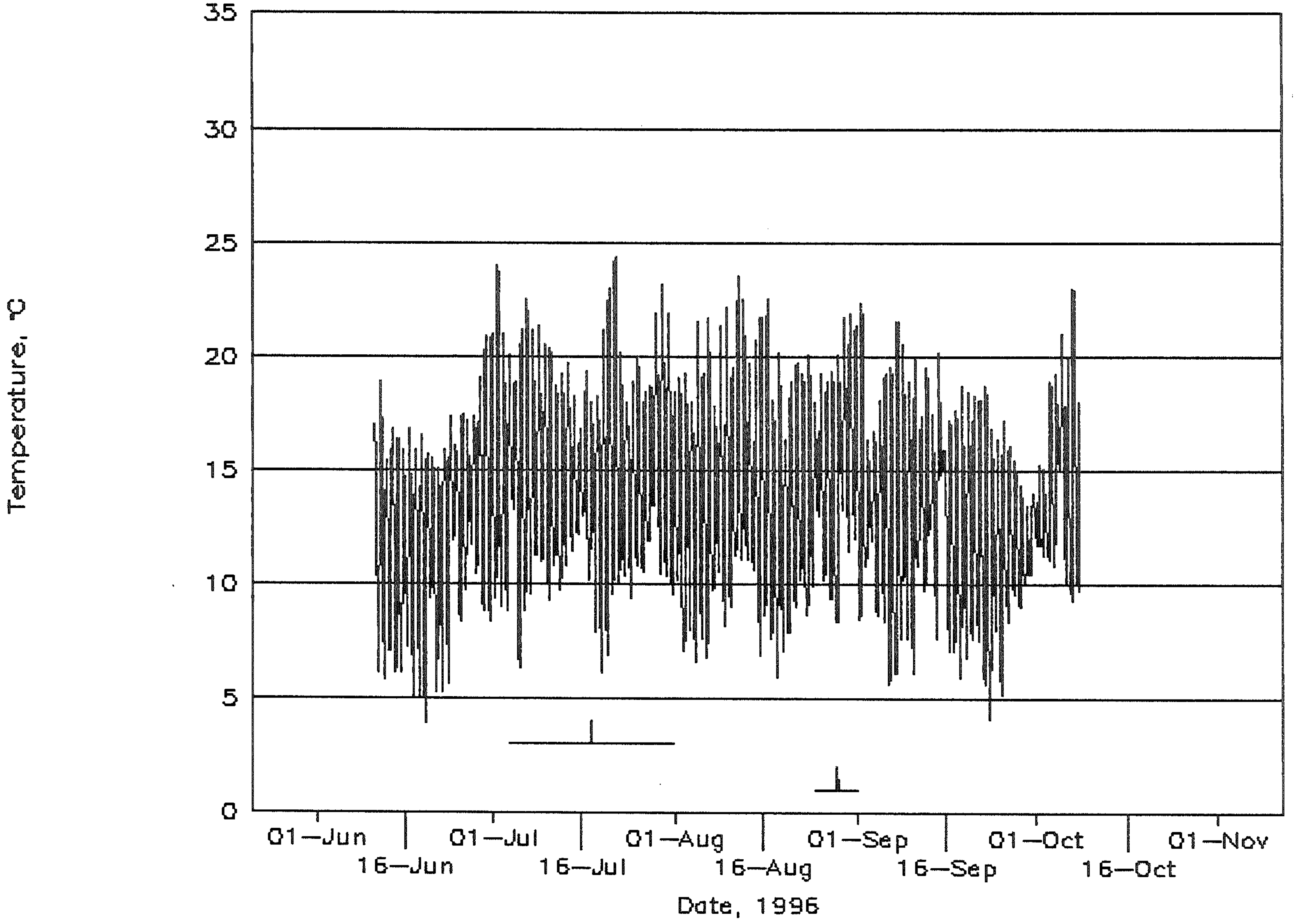
S.F. Noyo; Downstream limits; in—stream



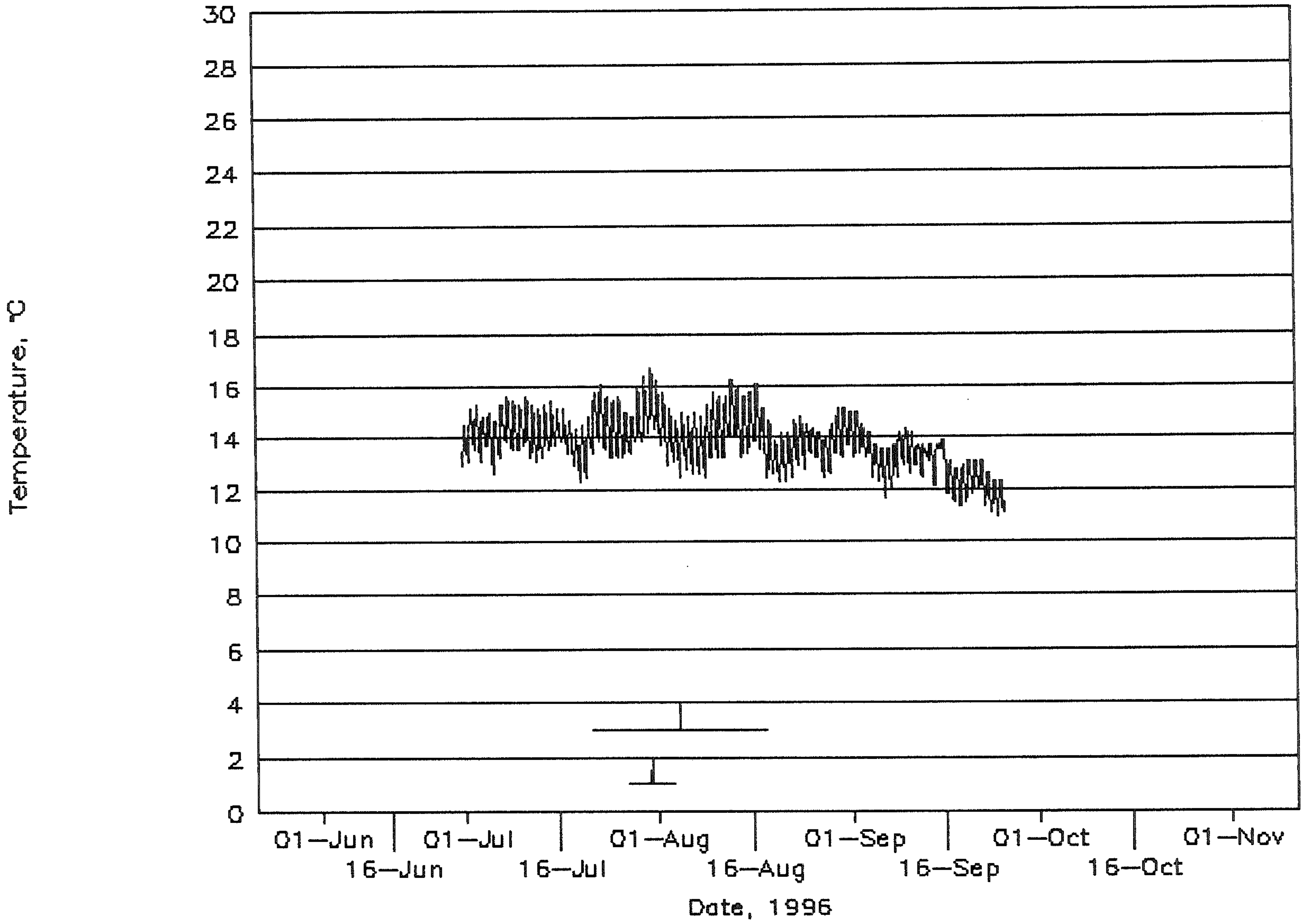
S.F. Noyo; Downstream boundary; BUCKET



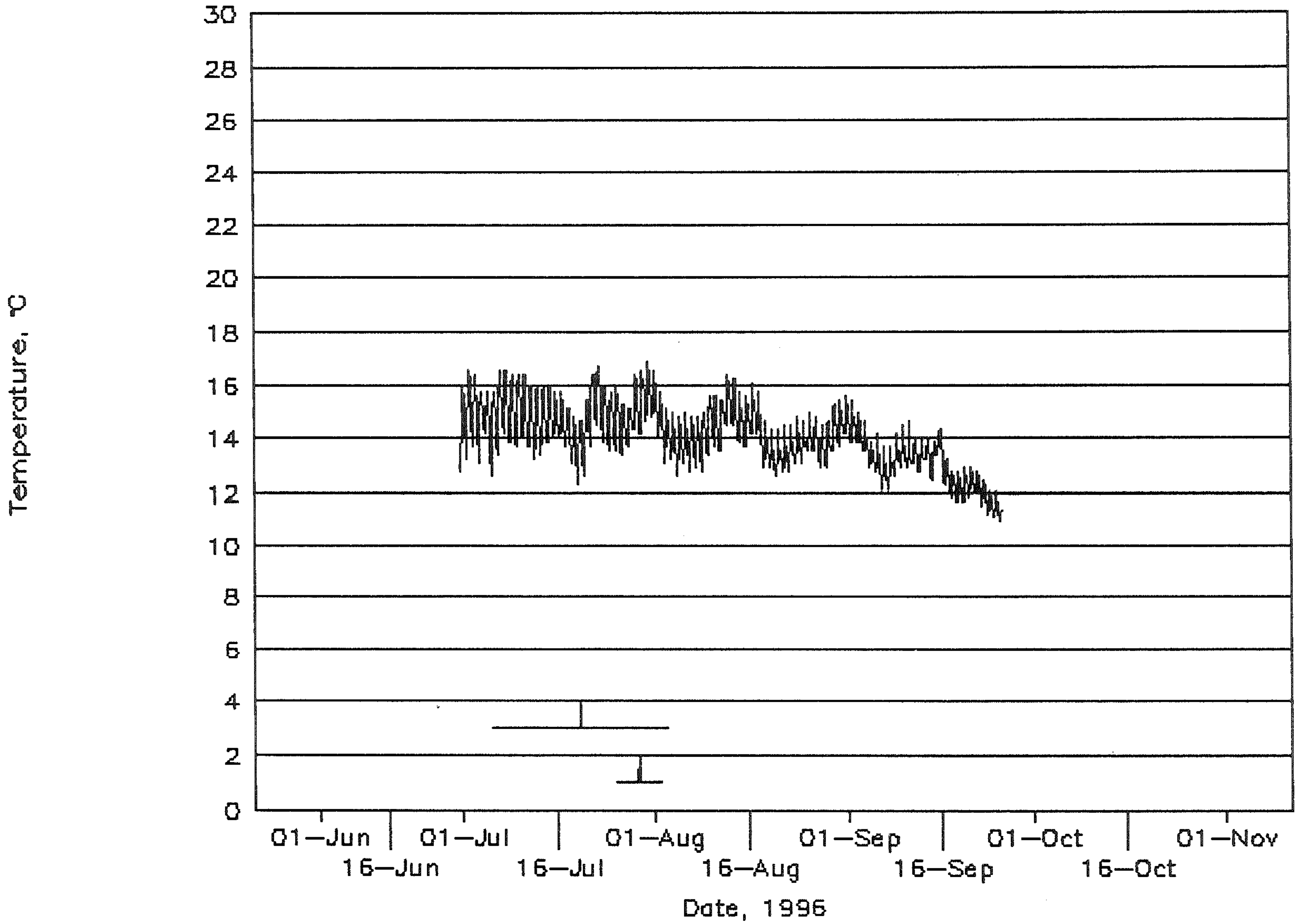
S.F. Noyo; downstream boundary; AIR



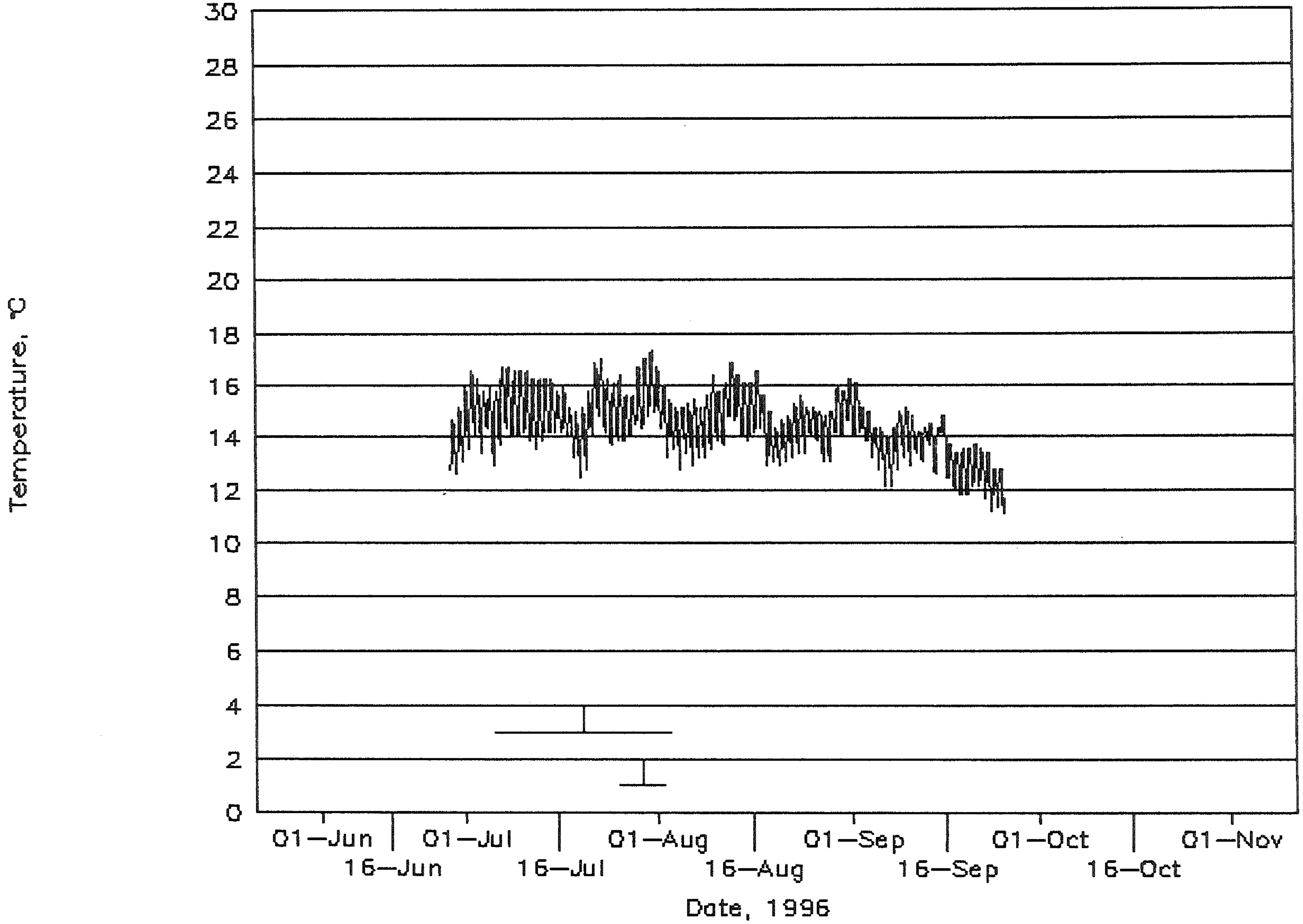
Parlin Ck. above Frolic Sale



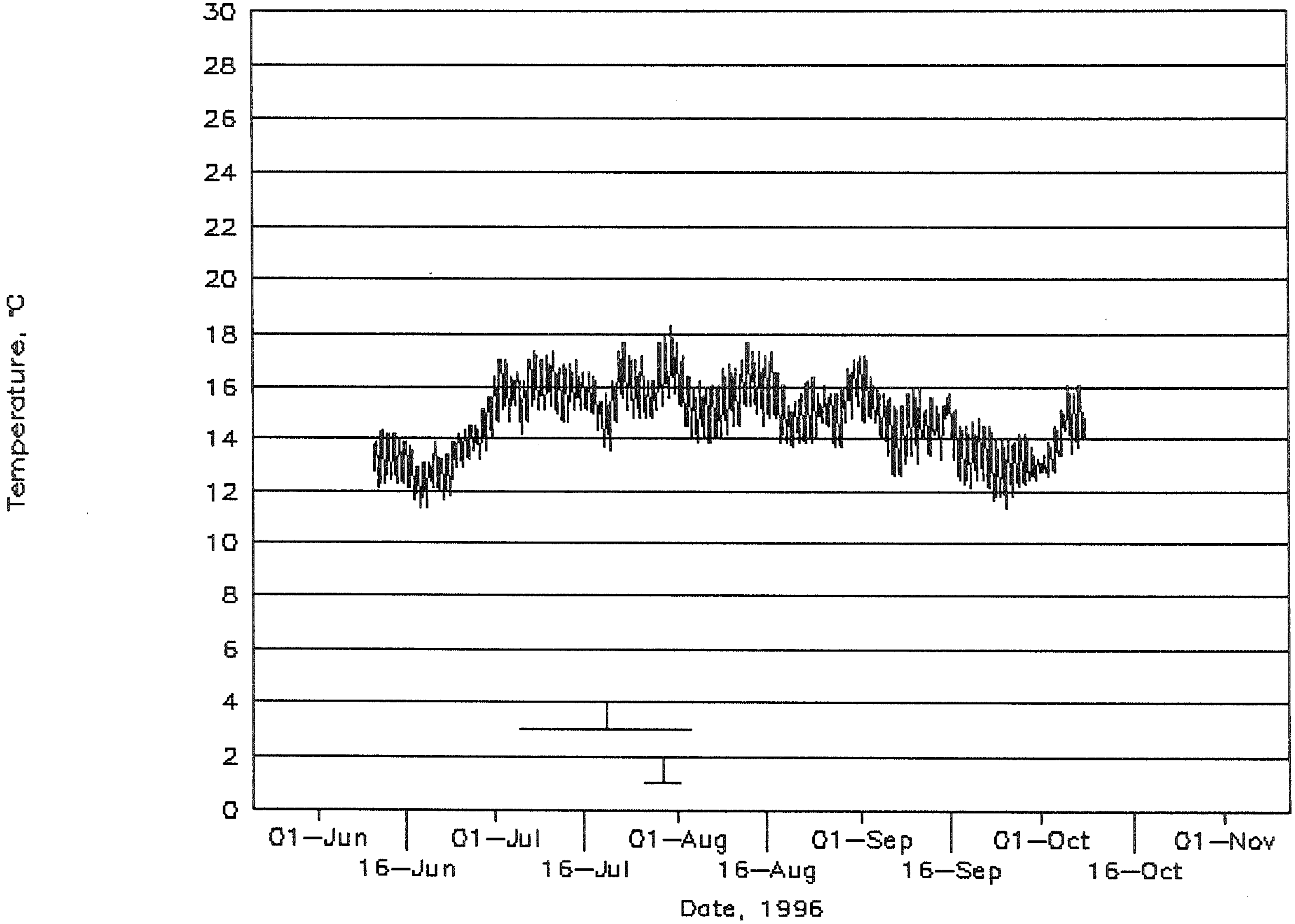
Parlin Ck. above Camp 7



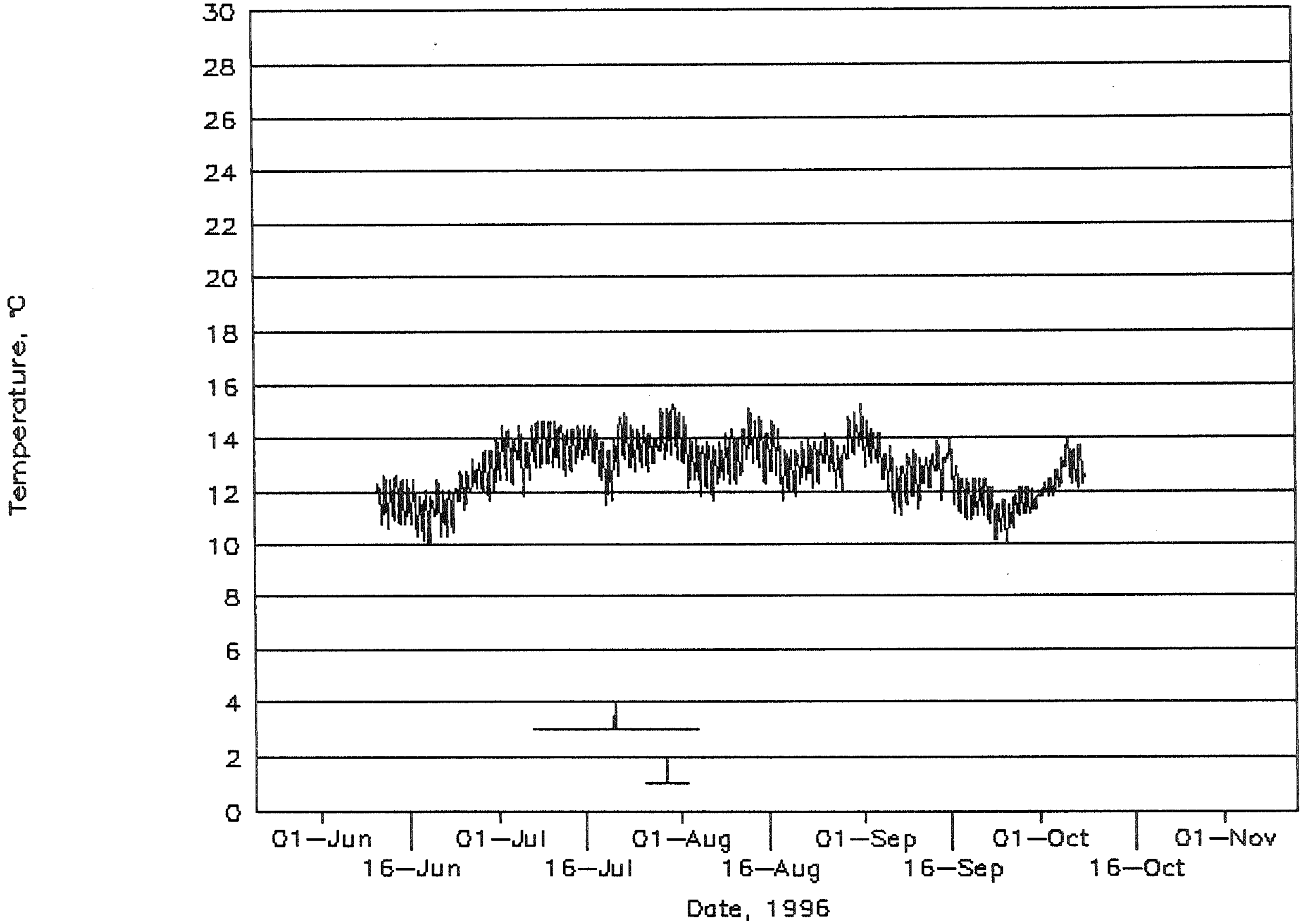
Parlin Ck. below Camp 7



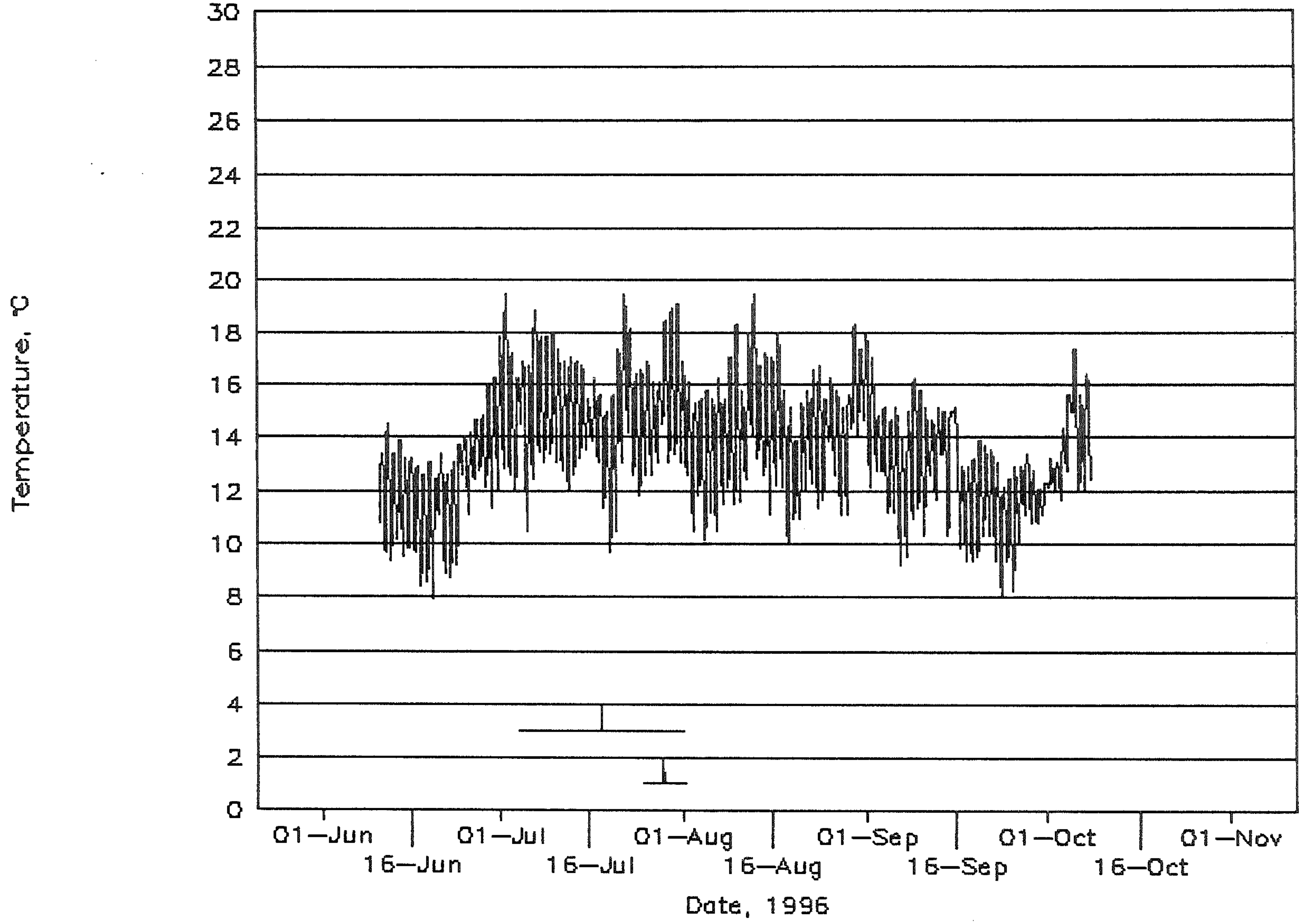
Parlin Ck. above S.F. Noyo

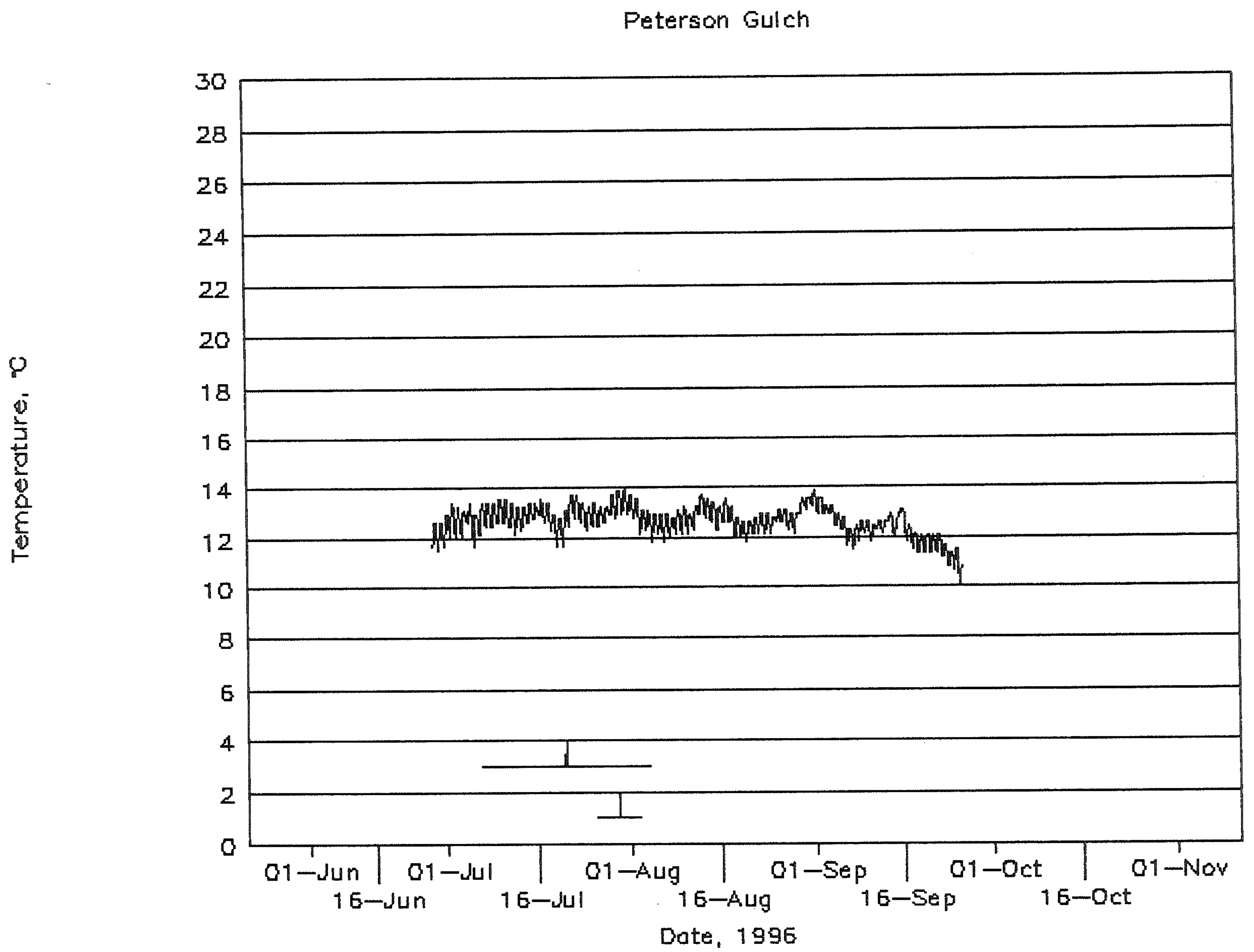


Bear Gulch above S.F. Noyo; in—stream



Bear Gulch; BUCKET




Peterson Gulch
Temperature, °C
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
01—Jun
16—Jun
01—Jul
16—Jul
01—Aug
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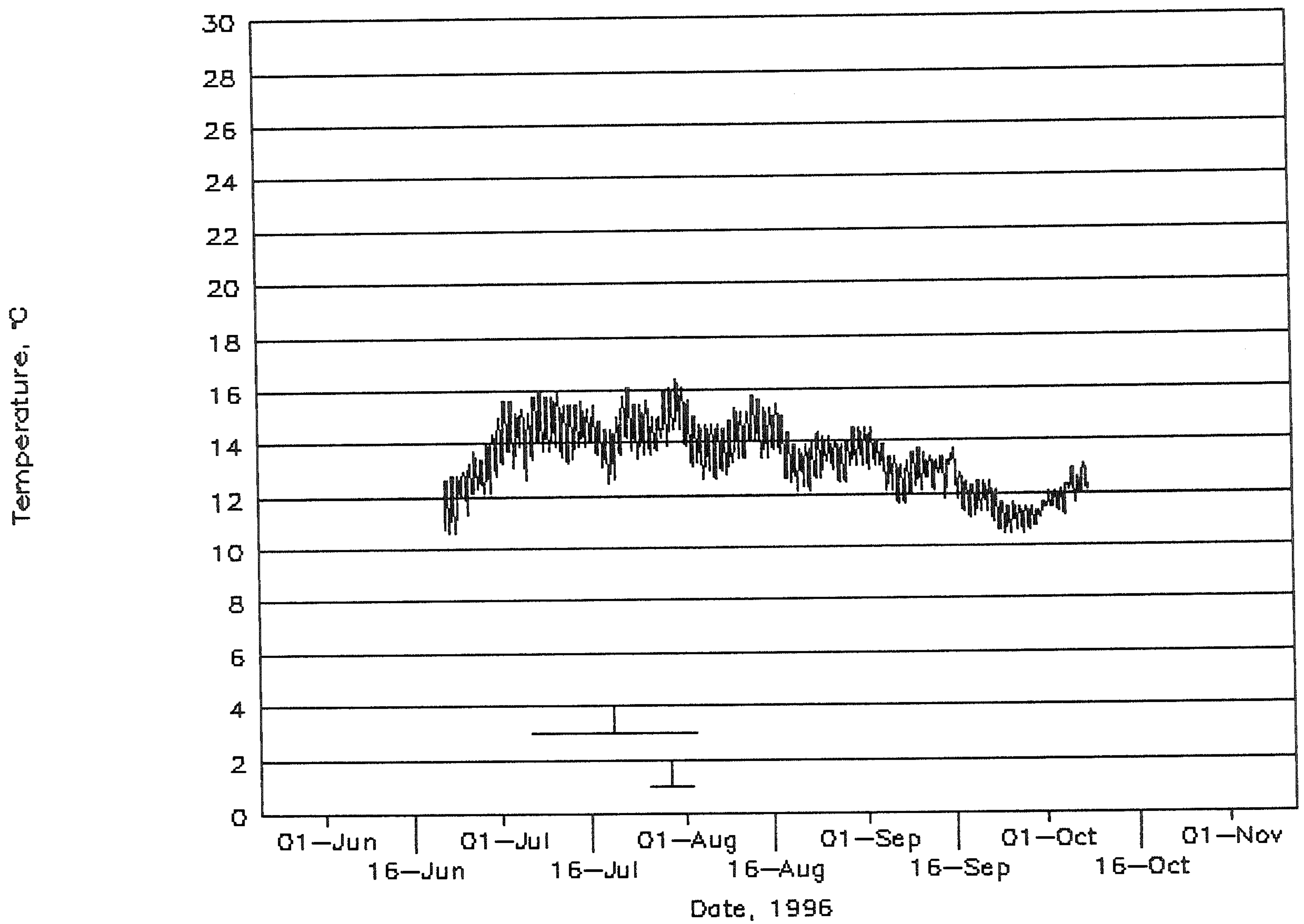
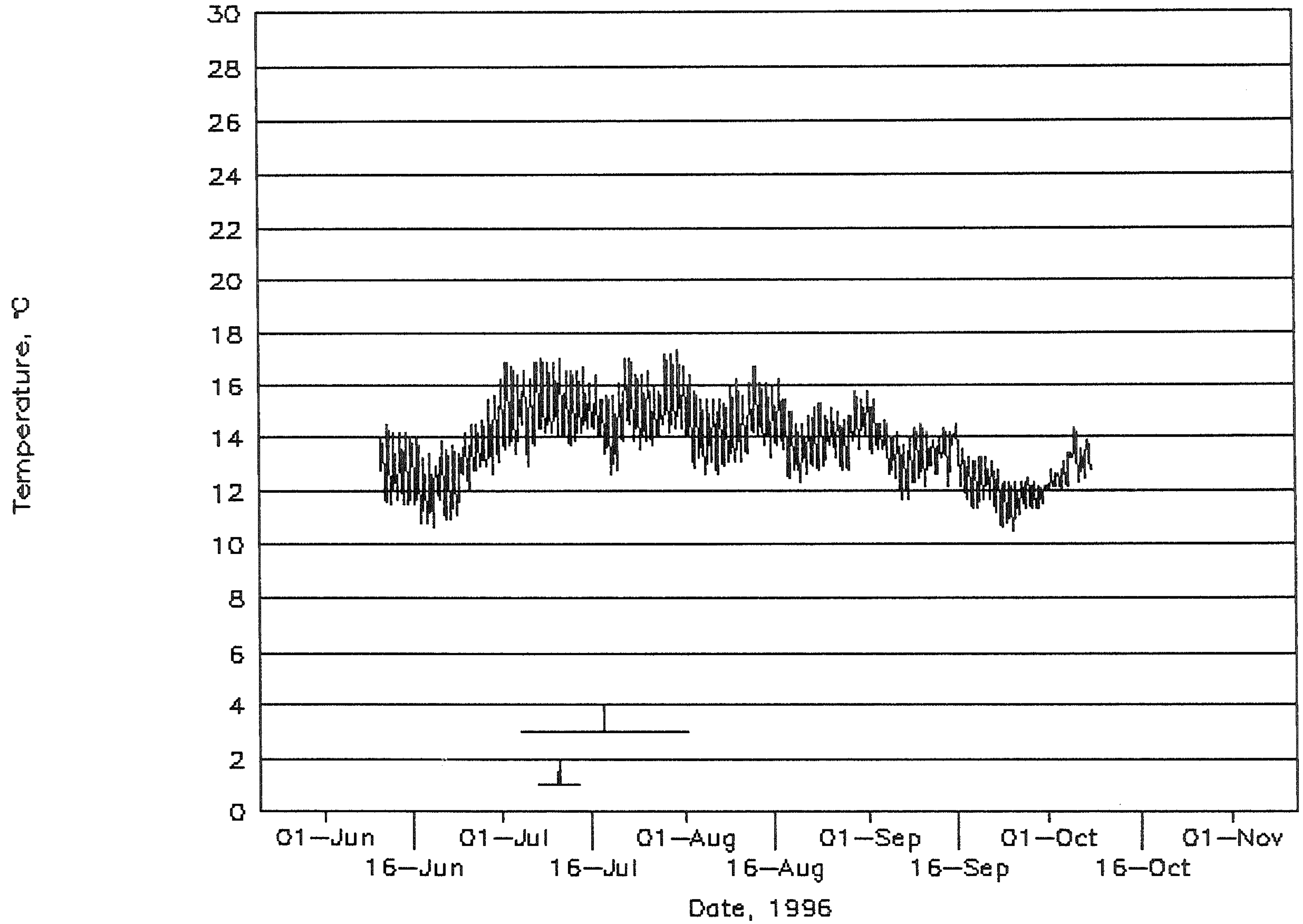
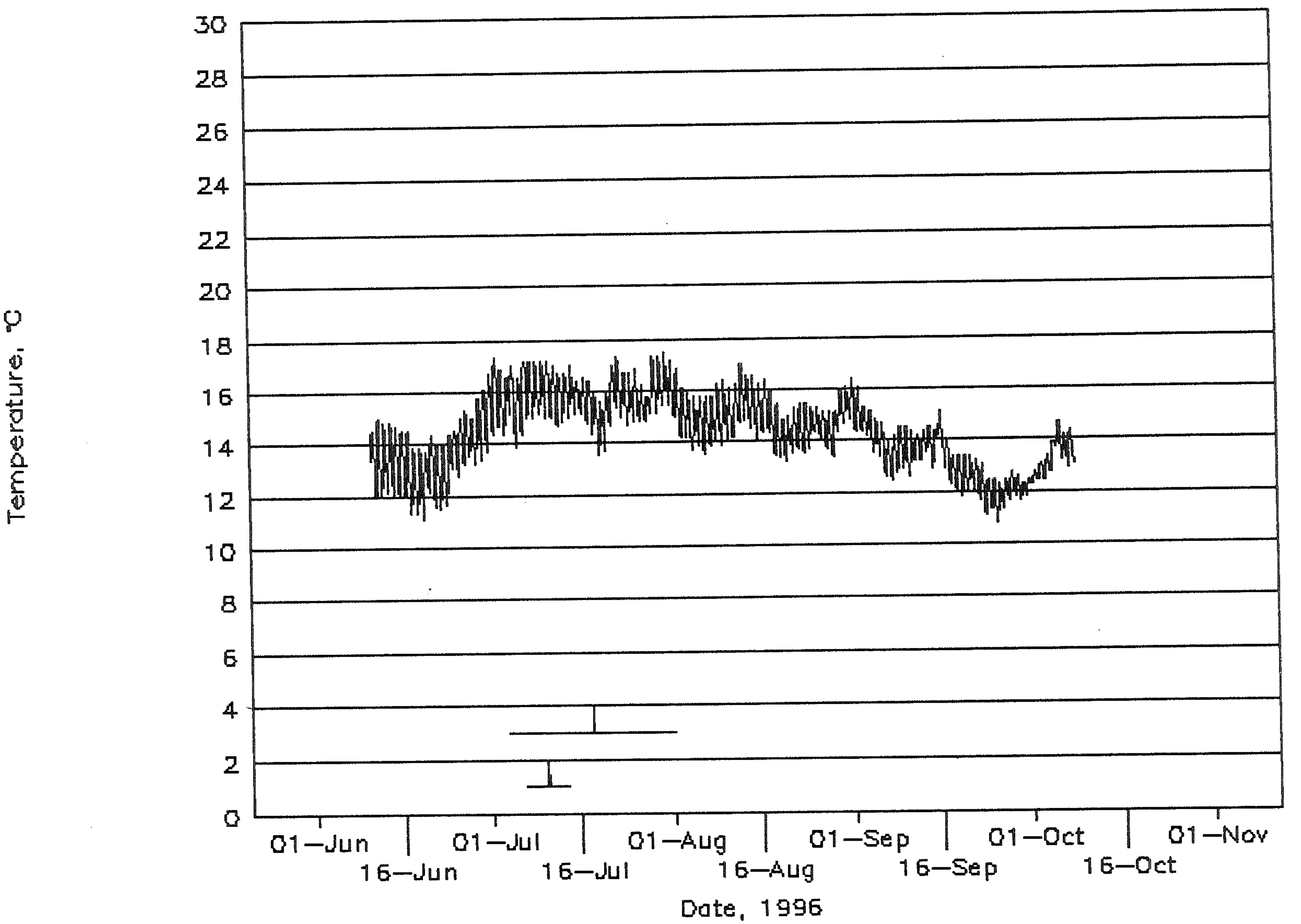
01—Oct
16—Oct
01—Nov
Date, 1996


N.F. of S.F. Noyo at road's end

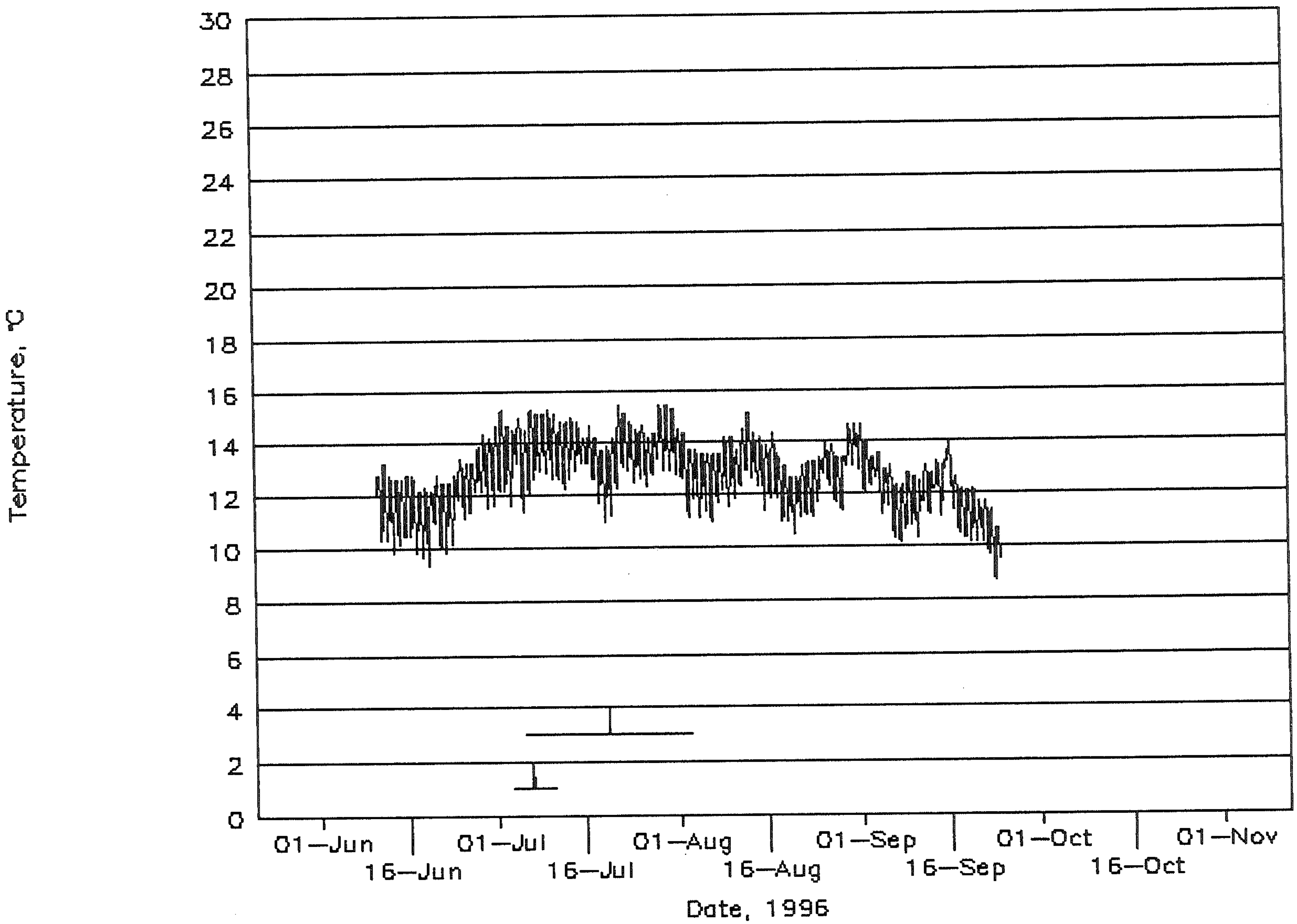
N.F. of S.F. Noyo above Brandon Gulch

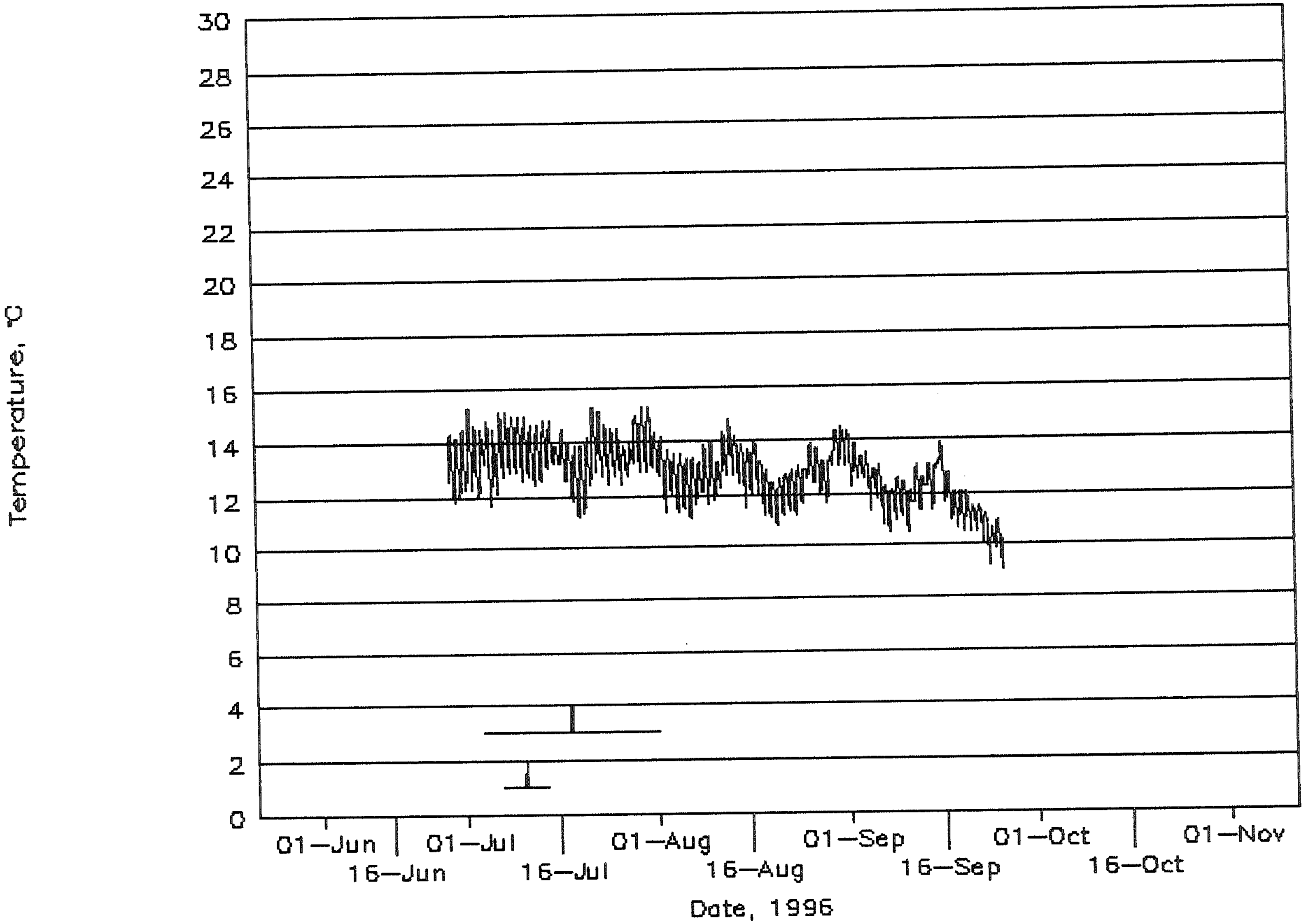


N.F. of S.F. Noyo above confluence

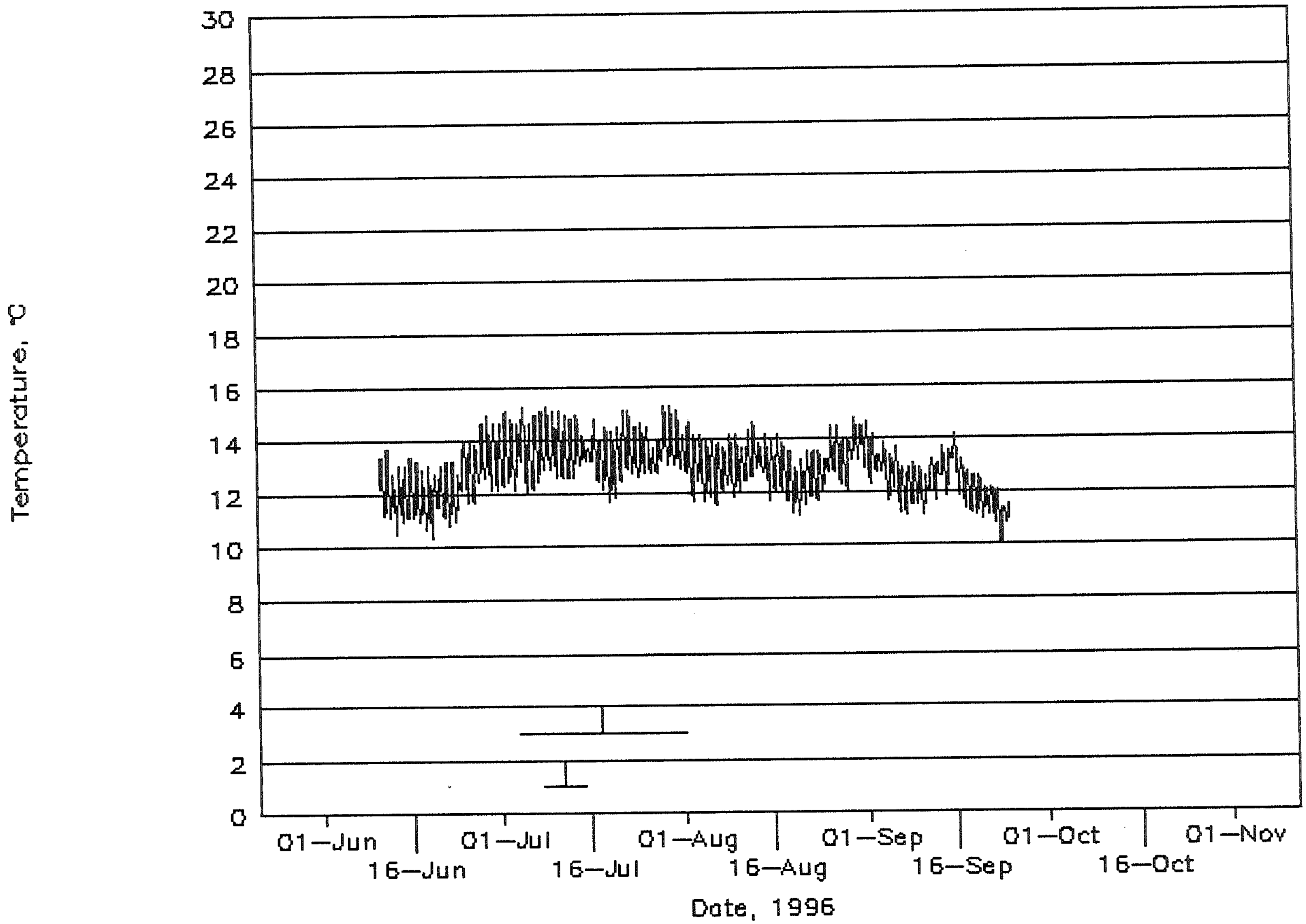


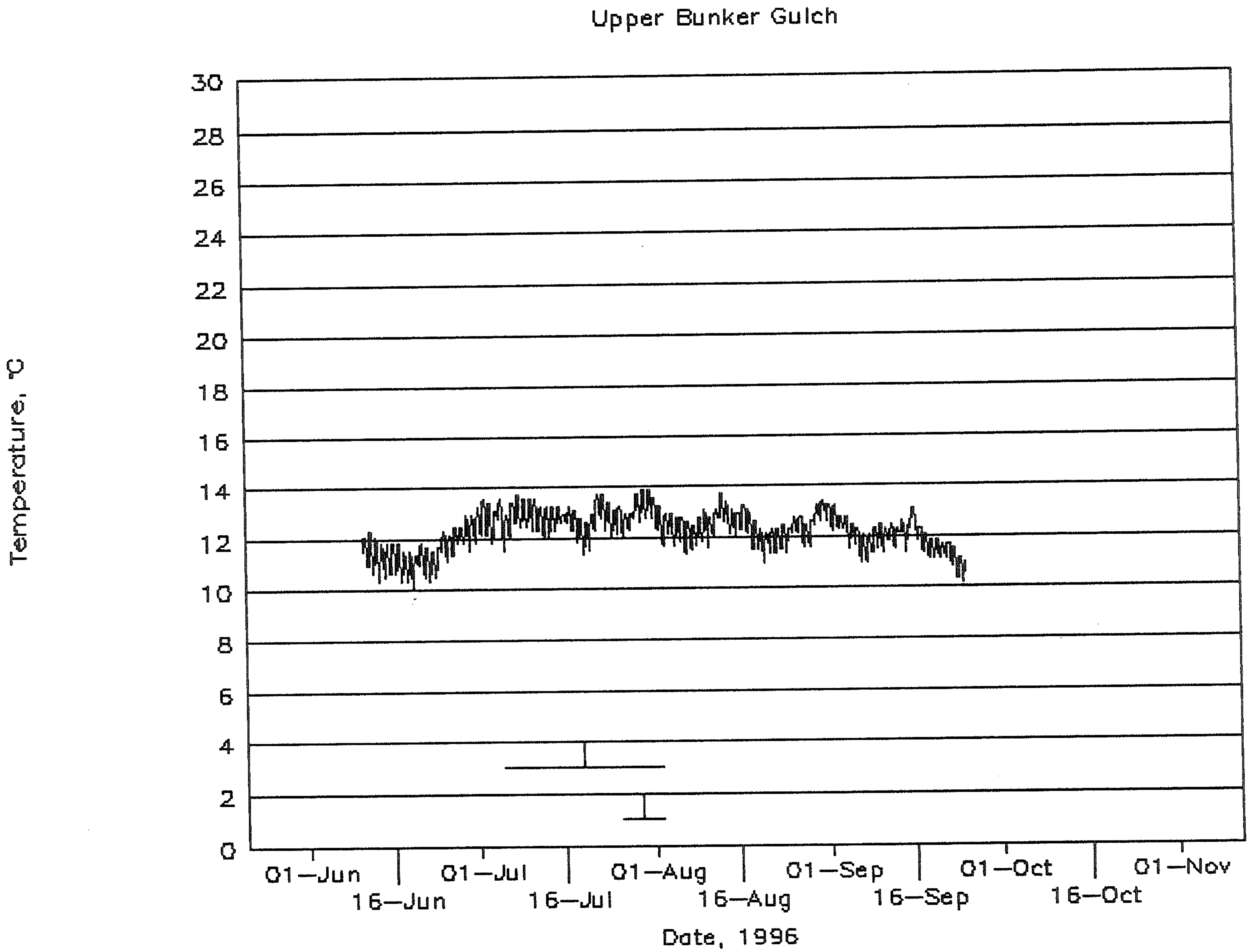
Hare Ck. below Bunker Gulch




Hare Ck. below THP SFHC'97

Hare Ck. near downstream boundary




Upper Bunker Gulch
Temperature, °C
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
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01—Jun
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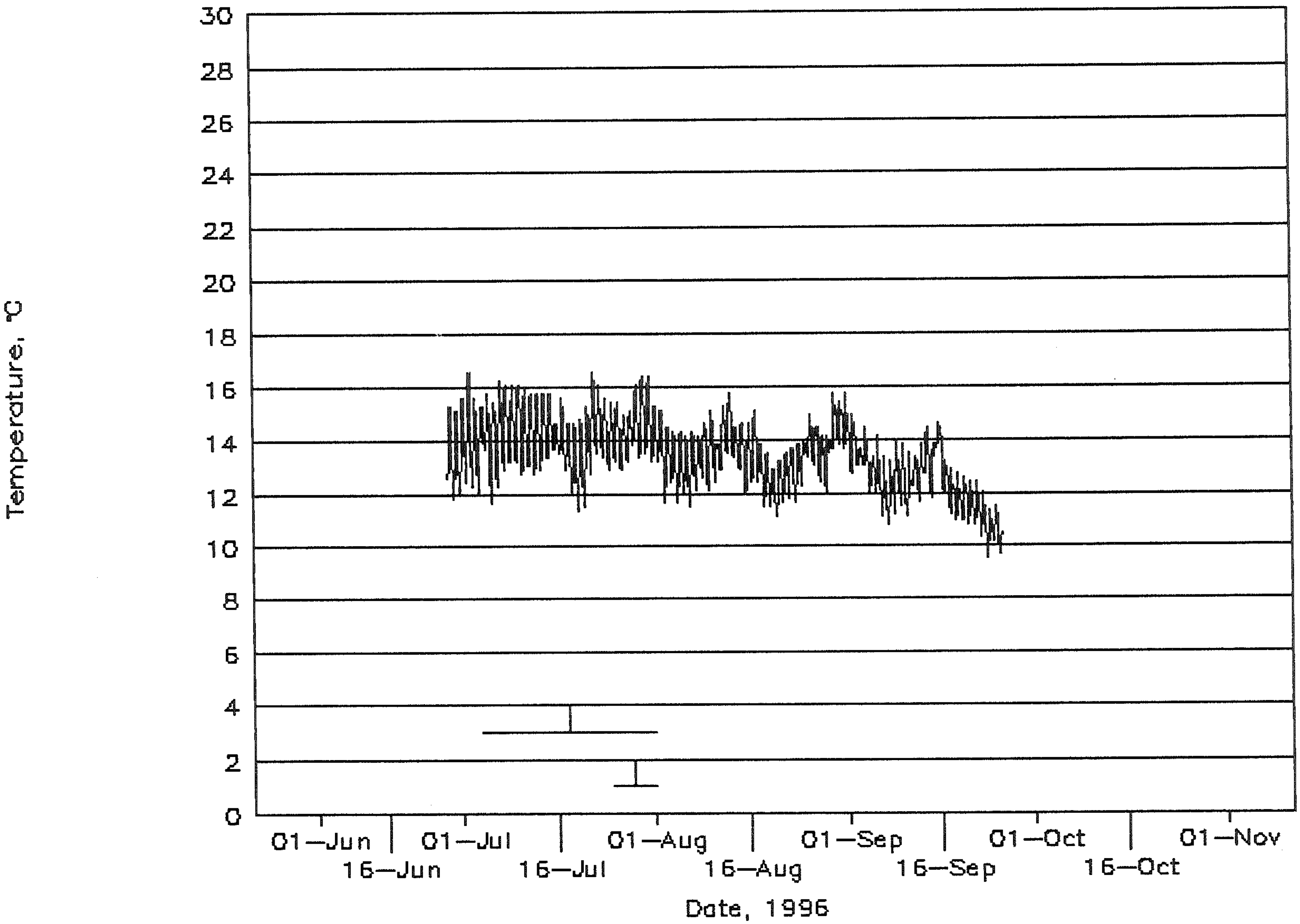
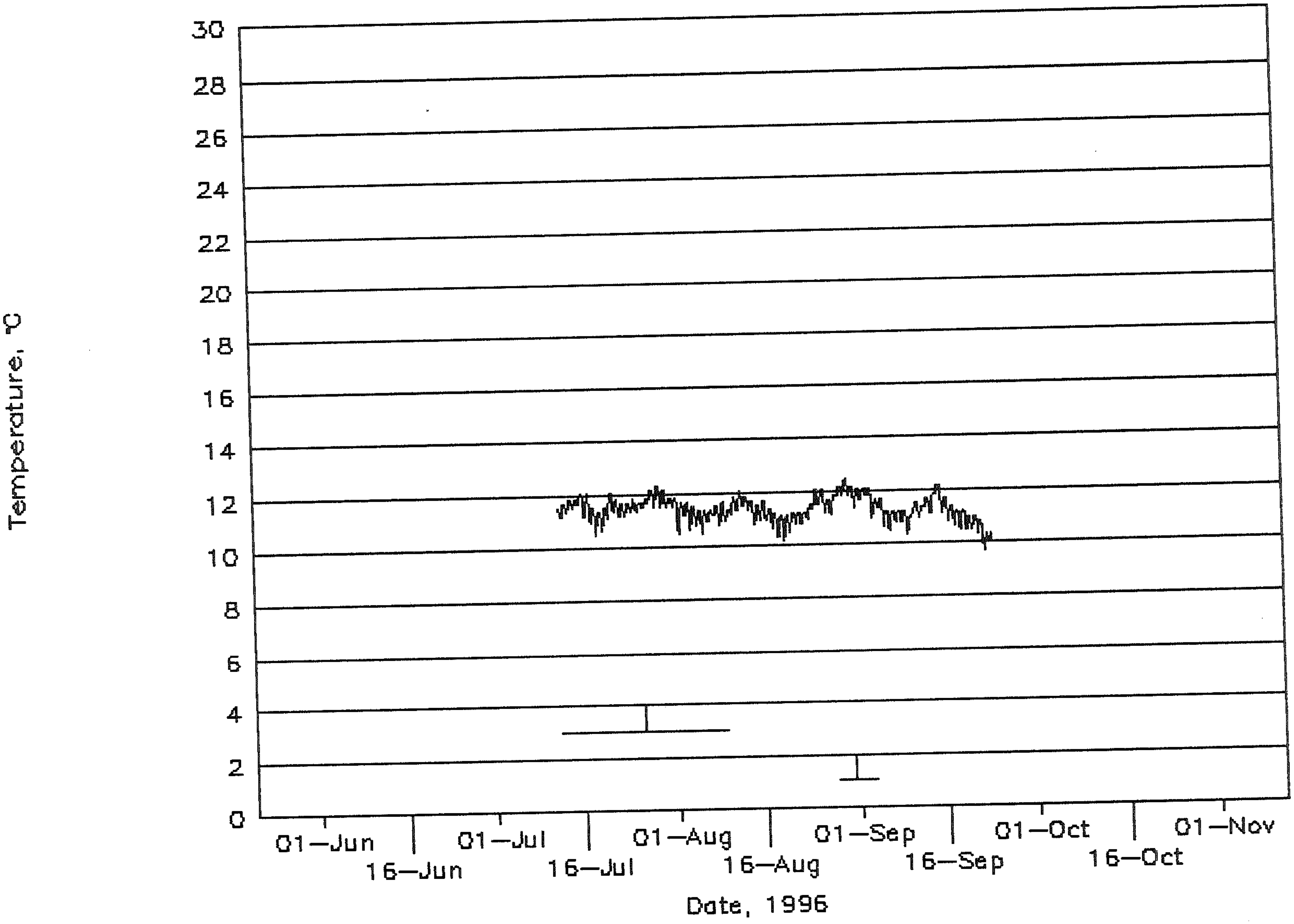
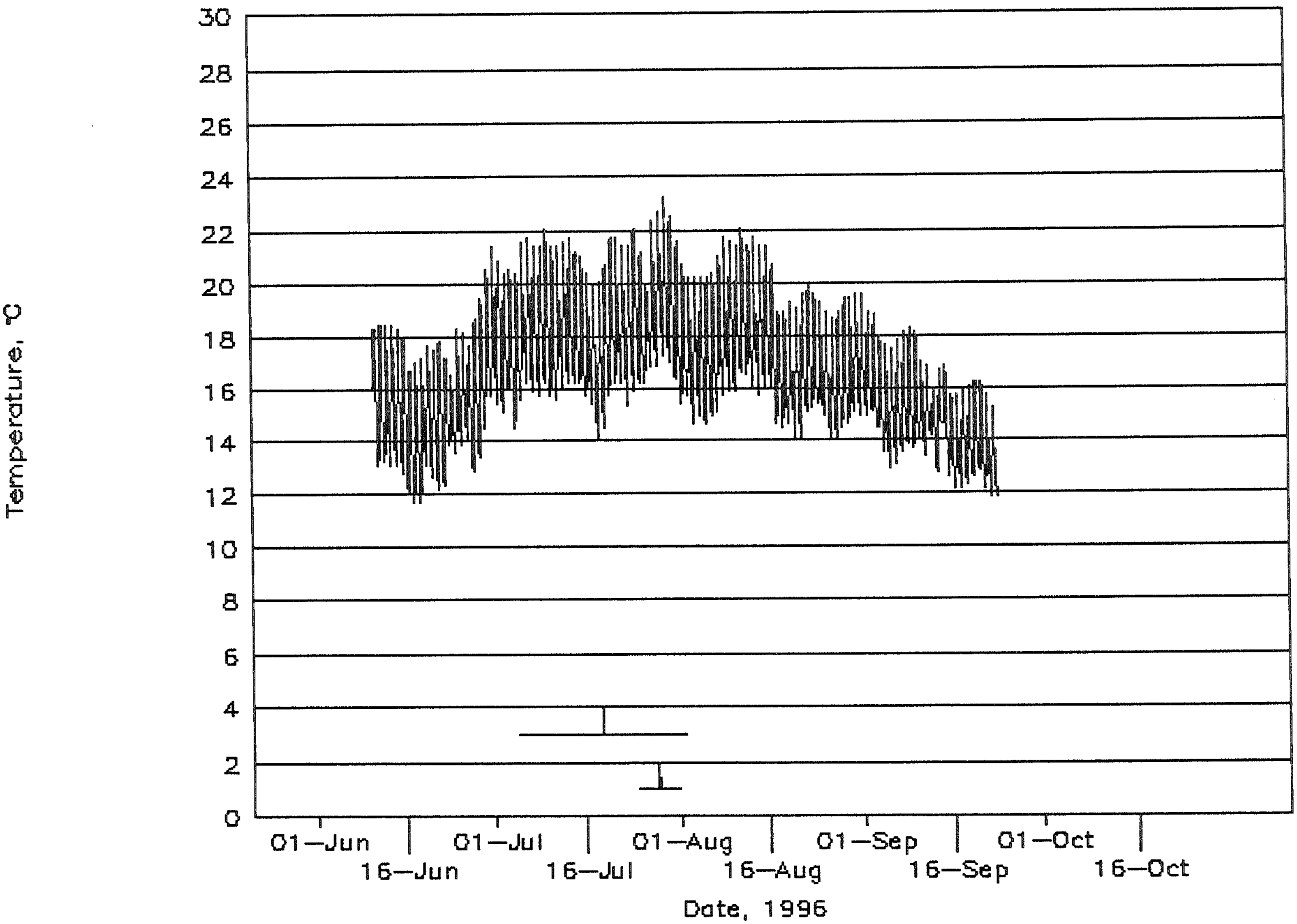
01—Oct
16—Oct
01—Nov
Date, 1996

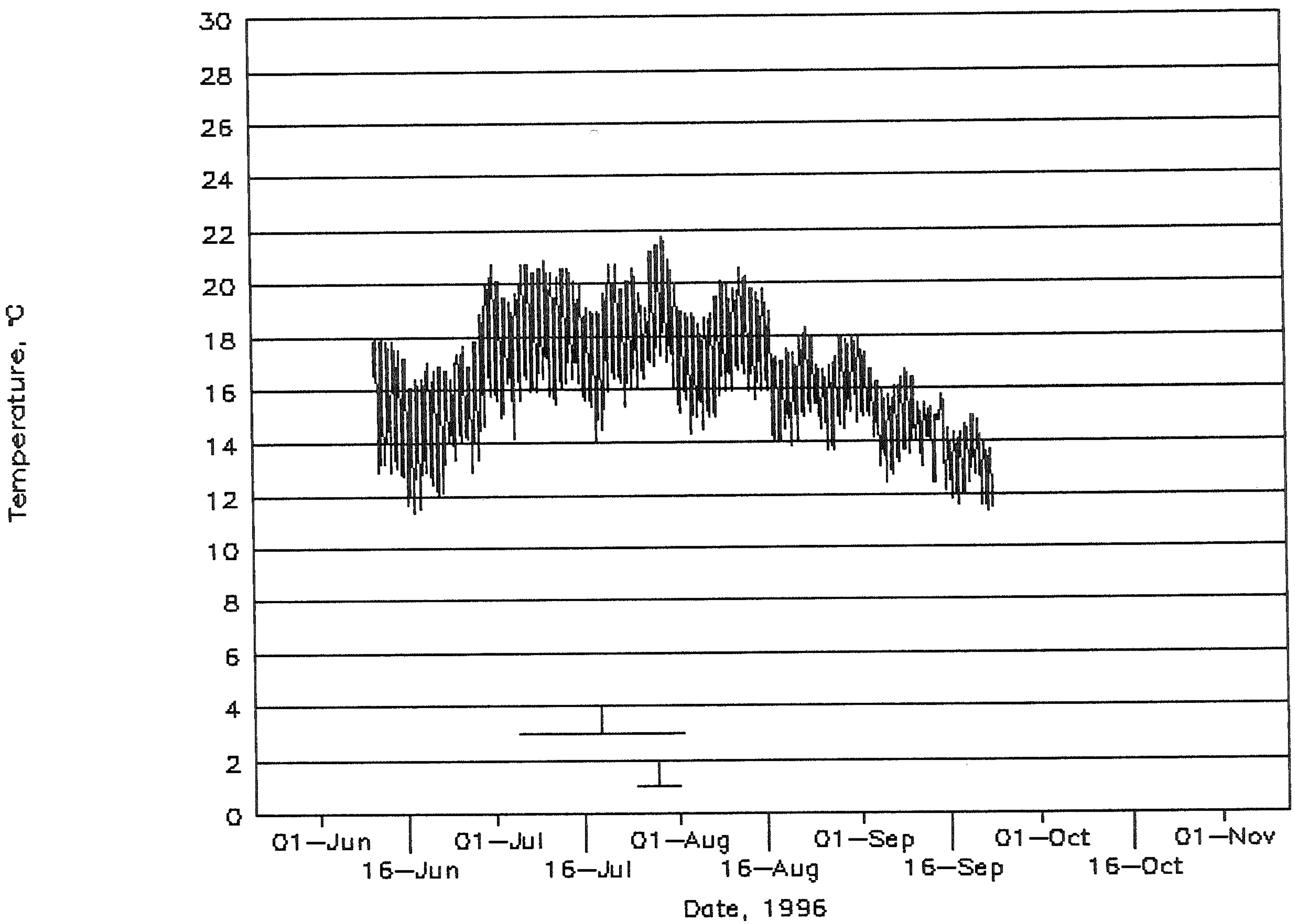

Bunker Gulch above Hare Ck.

Torrent Salamander site on Hare Ck.



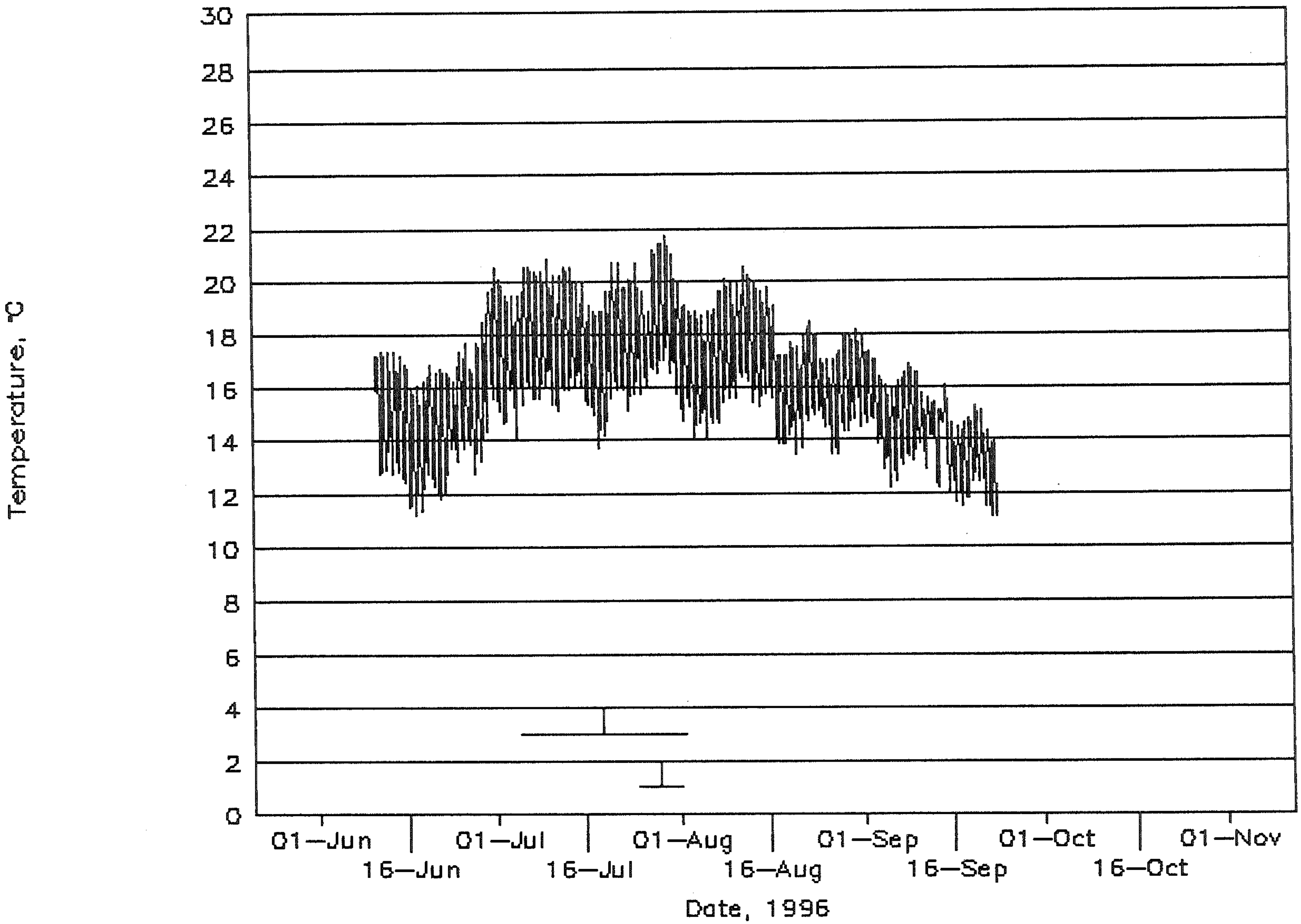
N.F. Big River, End of Rd. 911



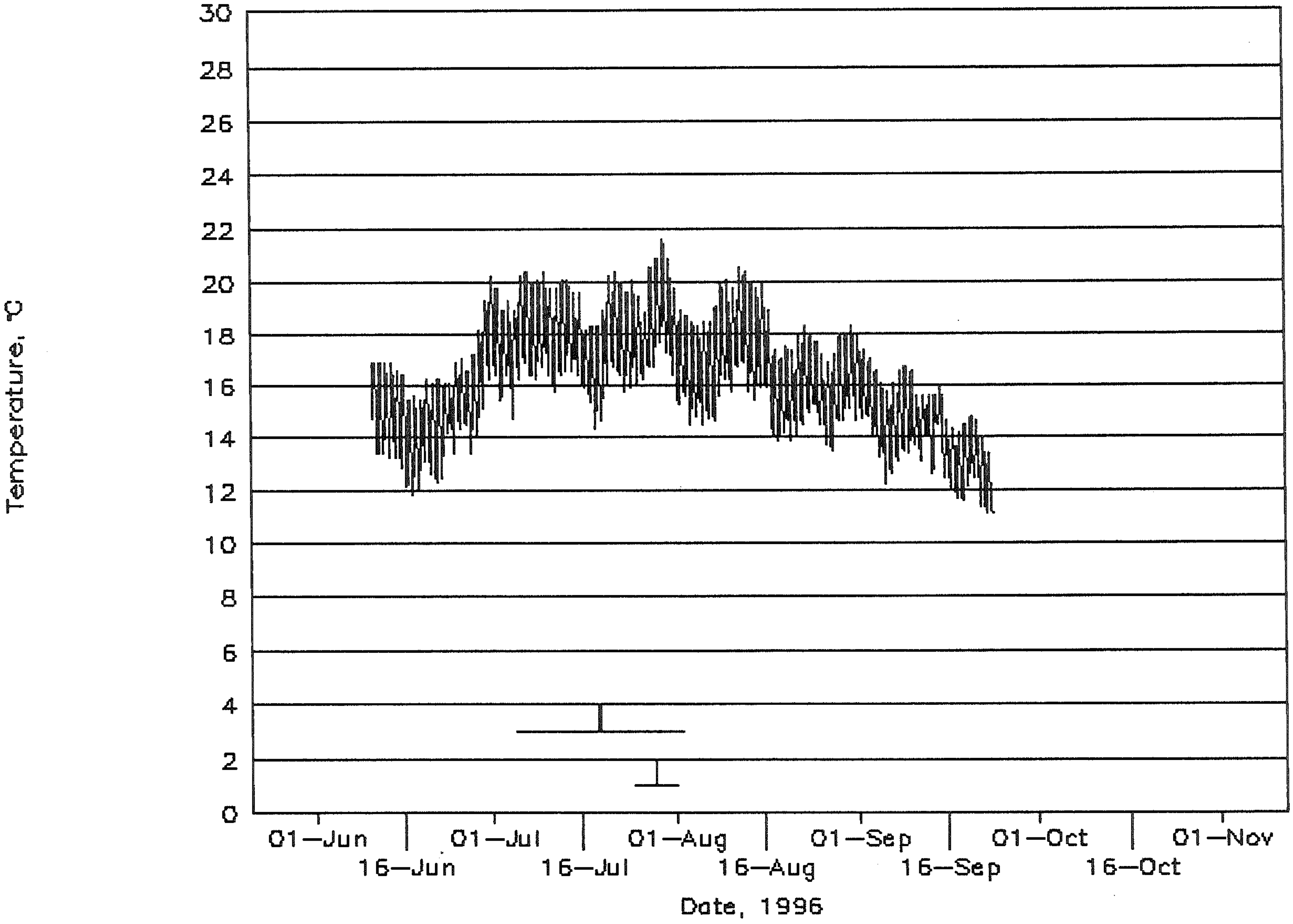


N.F. Big River above James Ck.

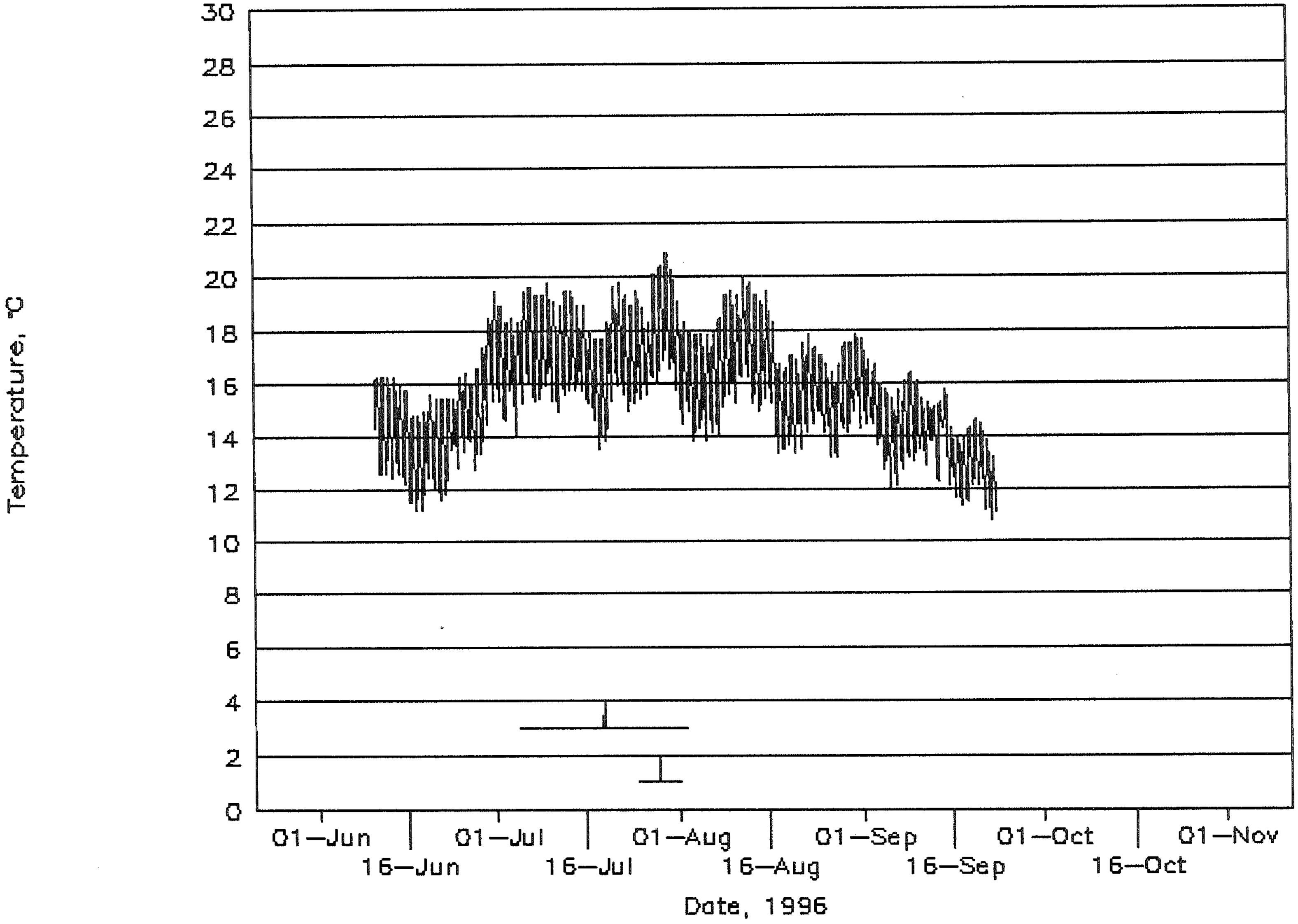
N.F. Big River below James Ck.



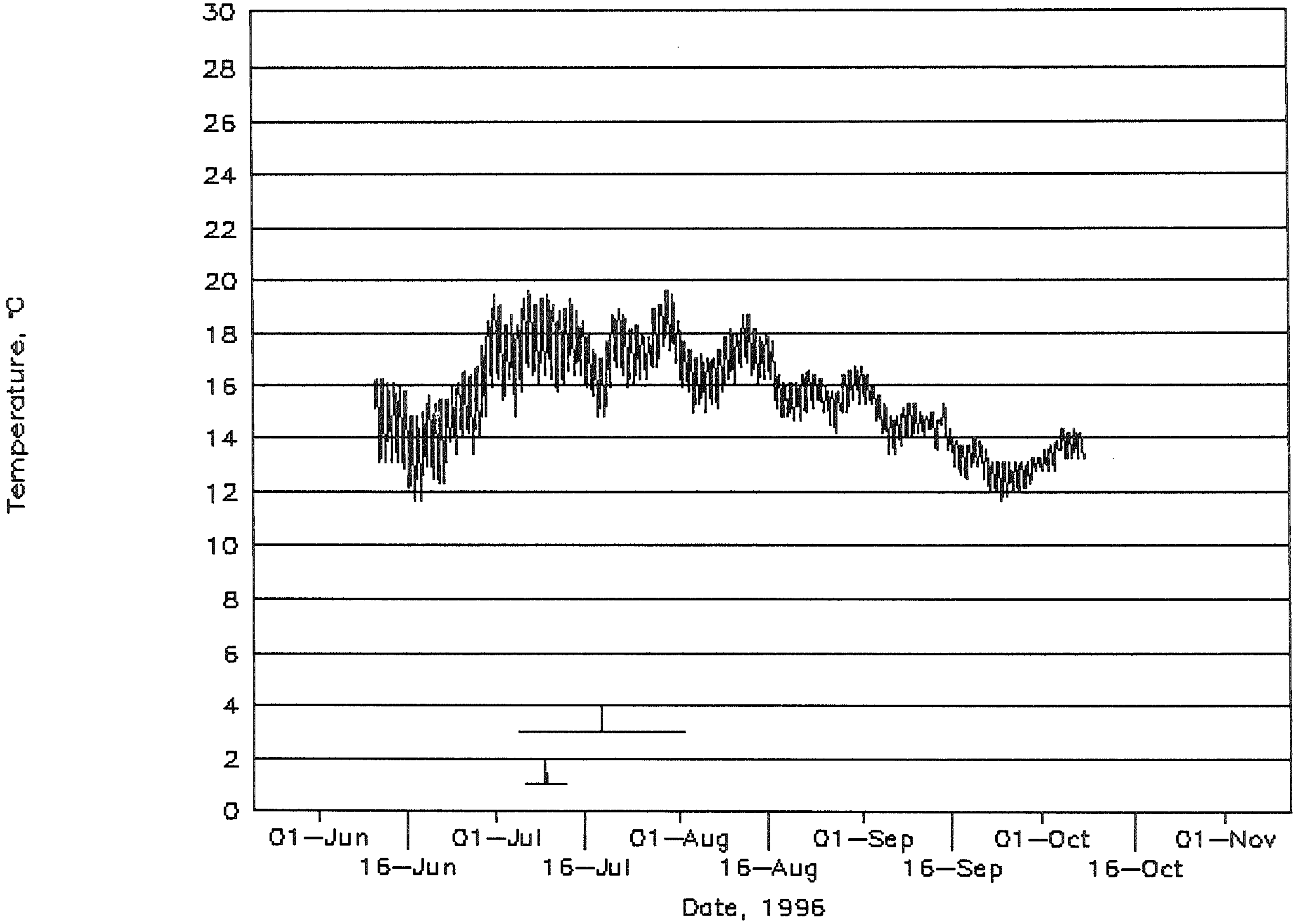
N.F. Big River above Chamberlin Ck.

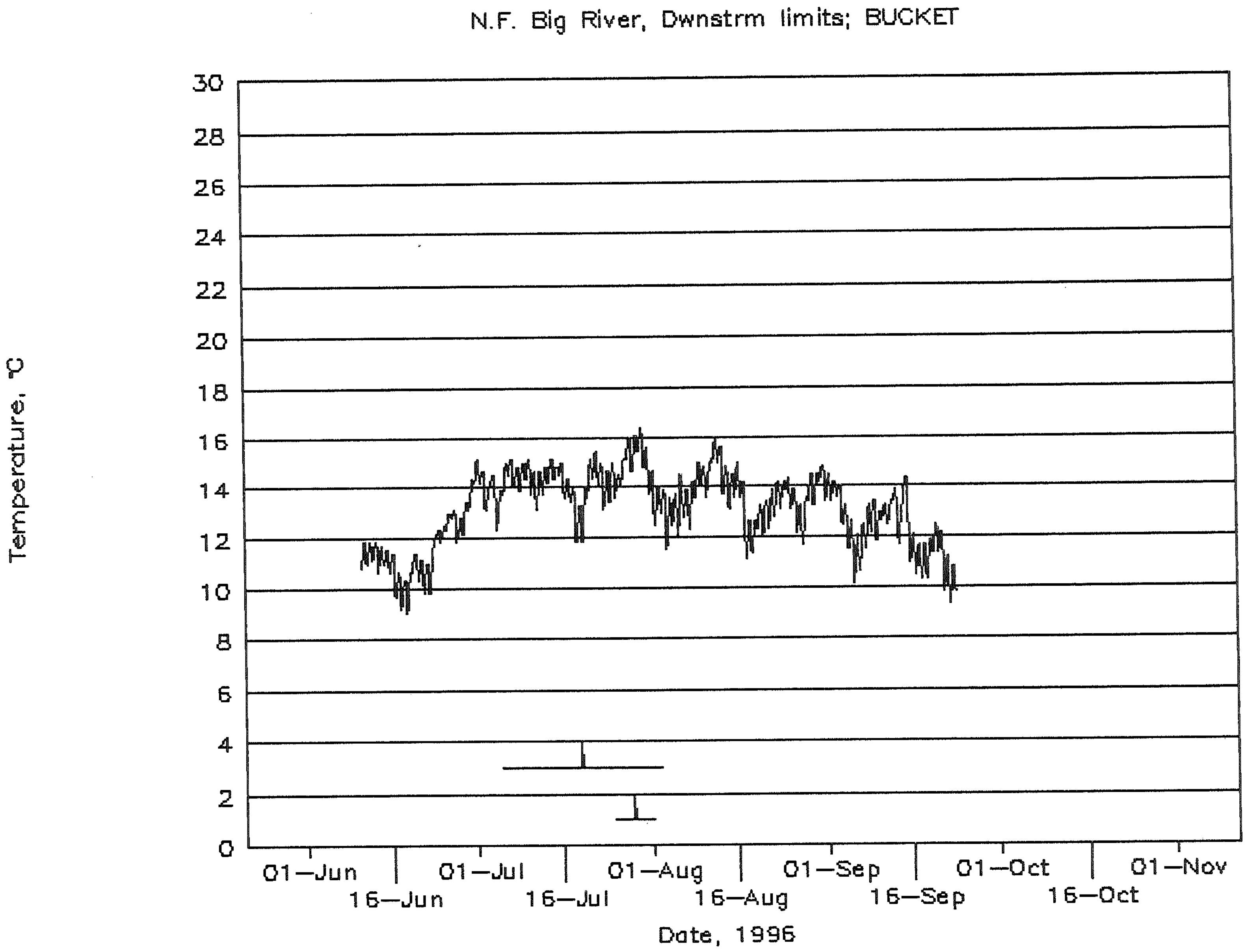


N.F. Big River below Chamberlin Ck.

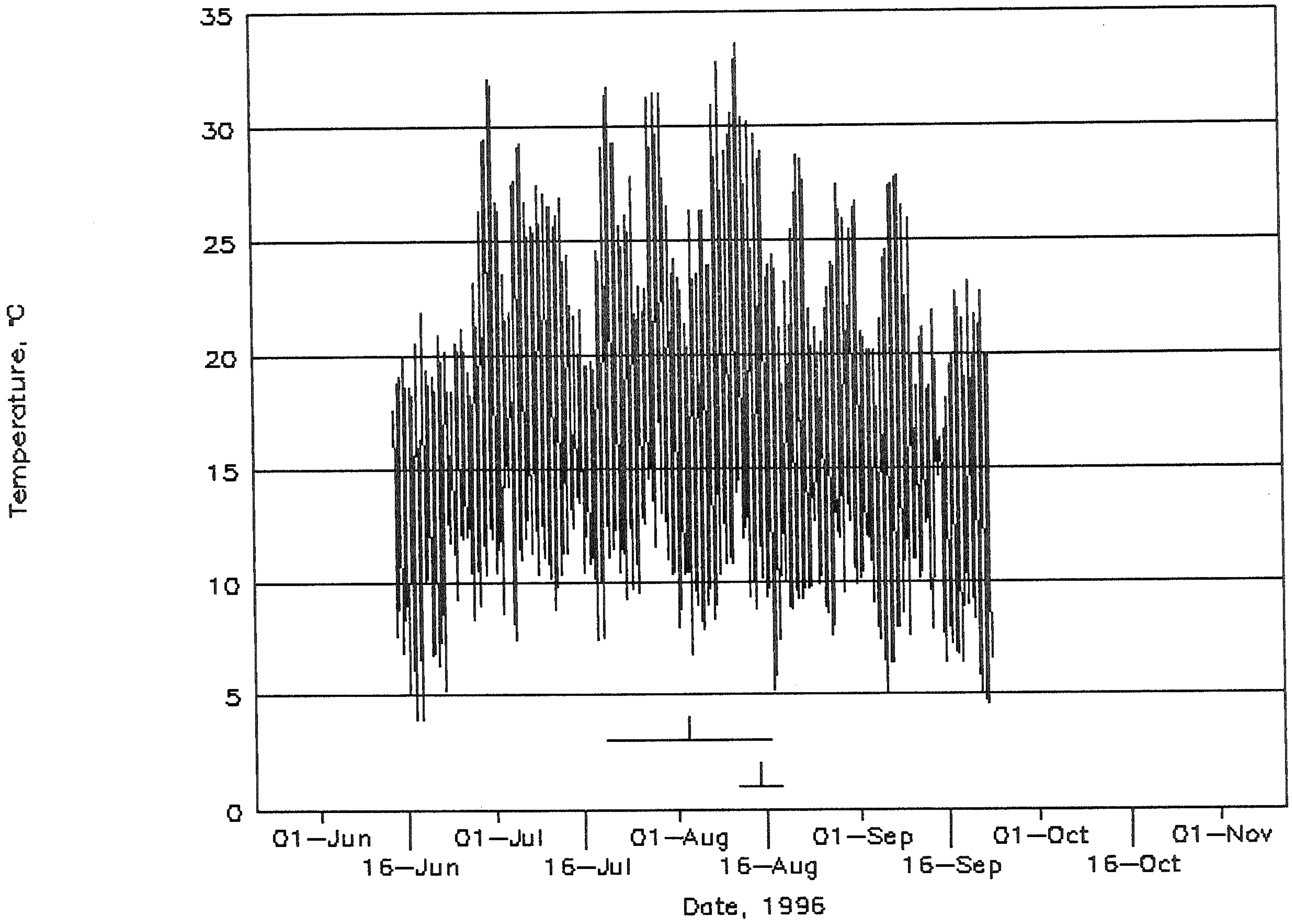


N.F. Big River, Dwnstm lmts; in—stream

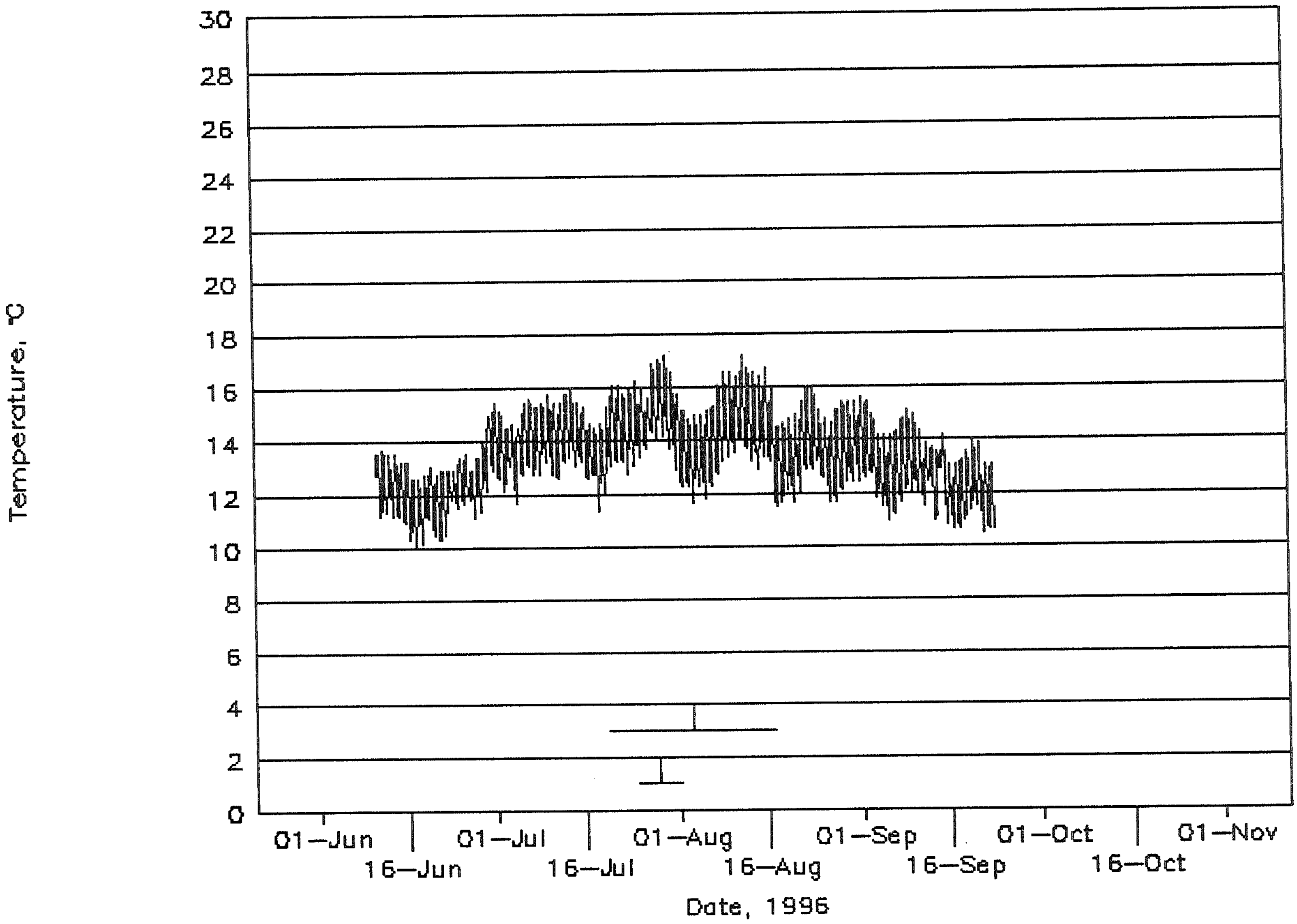



N.F. Big River, Dwnstrm limits; BUCKET
Temperature, °C
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
01—Jun
16—Jun
01—Jul
16—Jul
01—Aug
16—Aug
01—Sep
16—Sep
01—Oct
16—Oct
01—Nov
Date, 1996

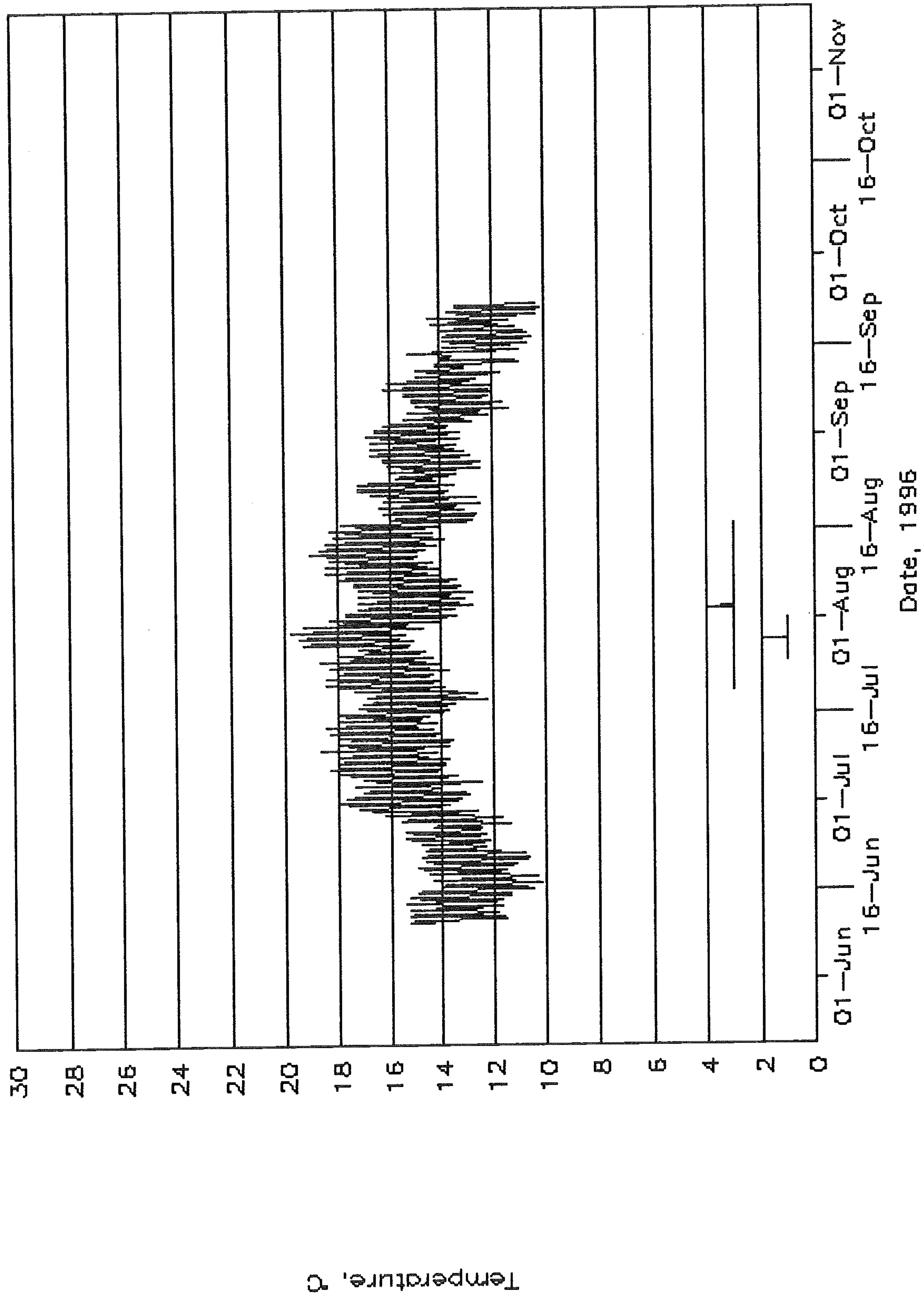
N.F. Big River, Downstream Limits; AIR



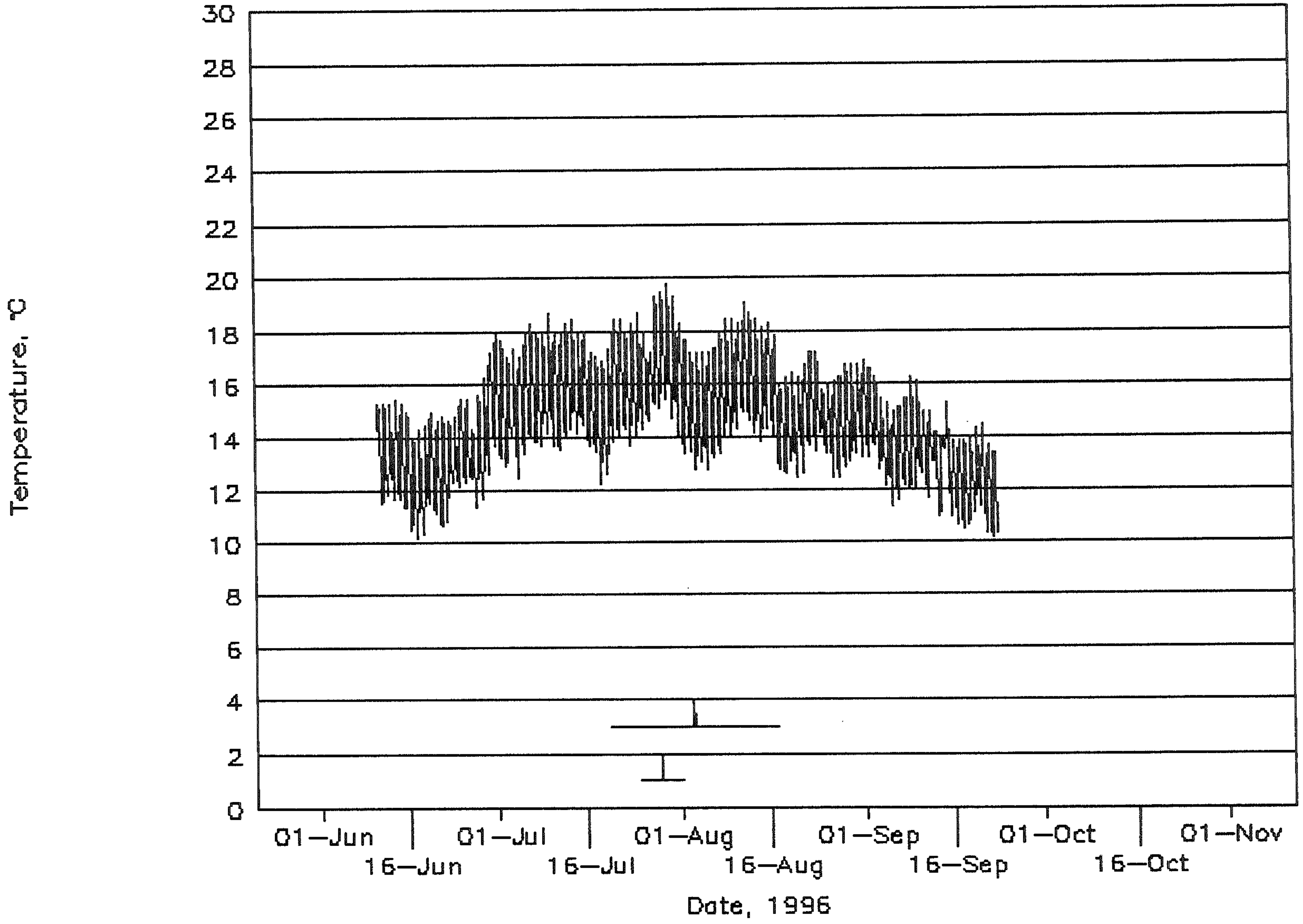
N.F. James Ck @ upper crossing



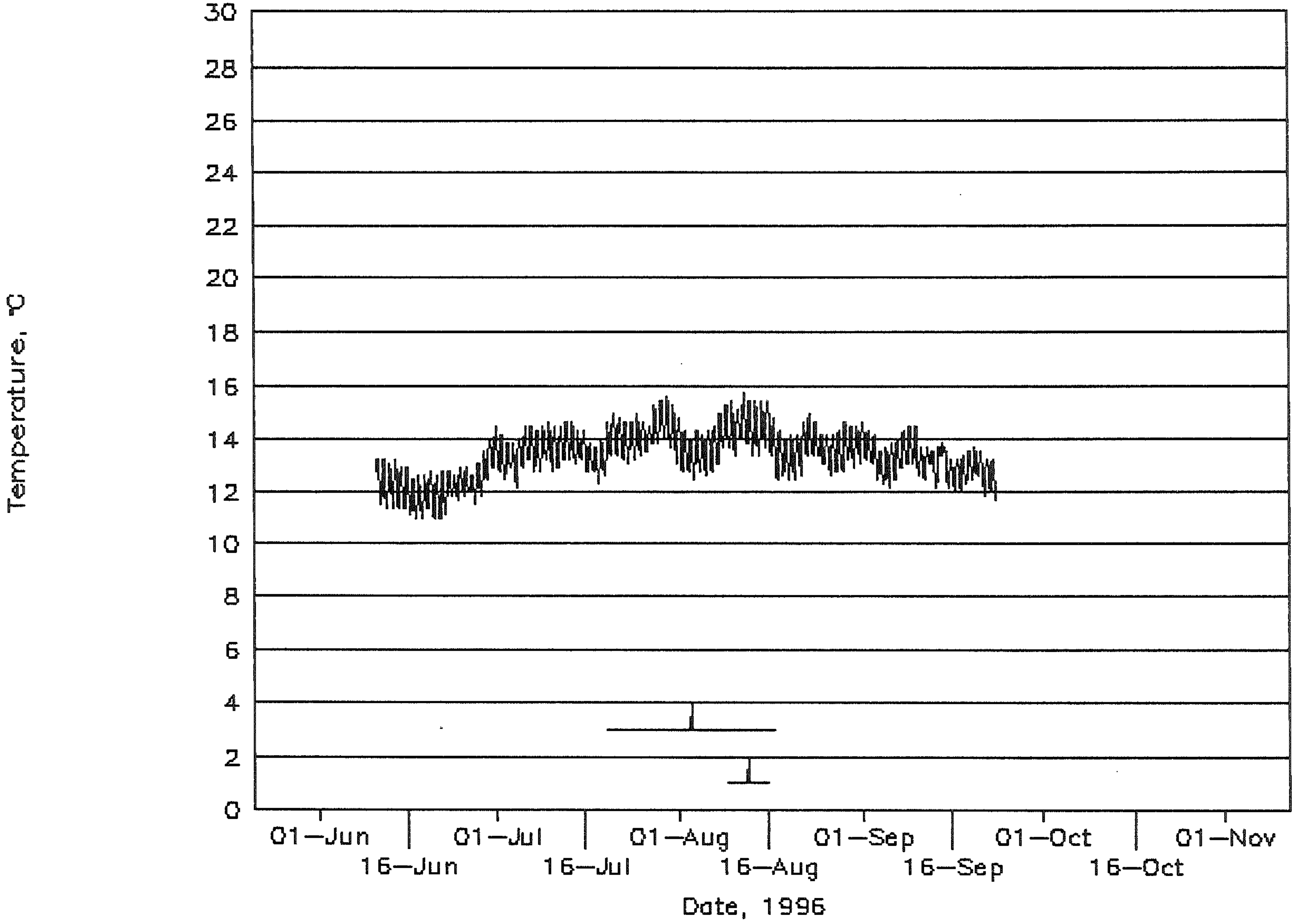
James Ck., 30m below N & Main Forks



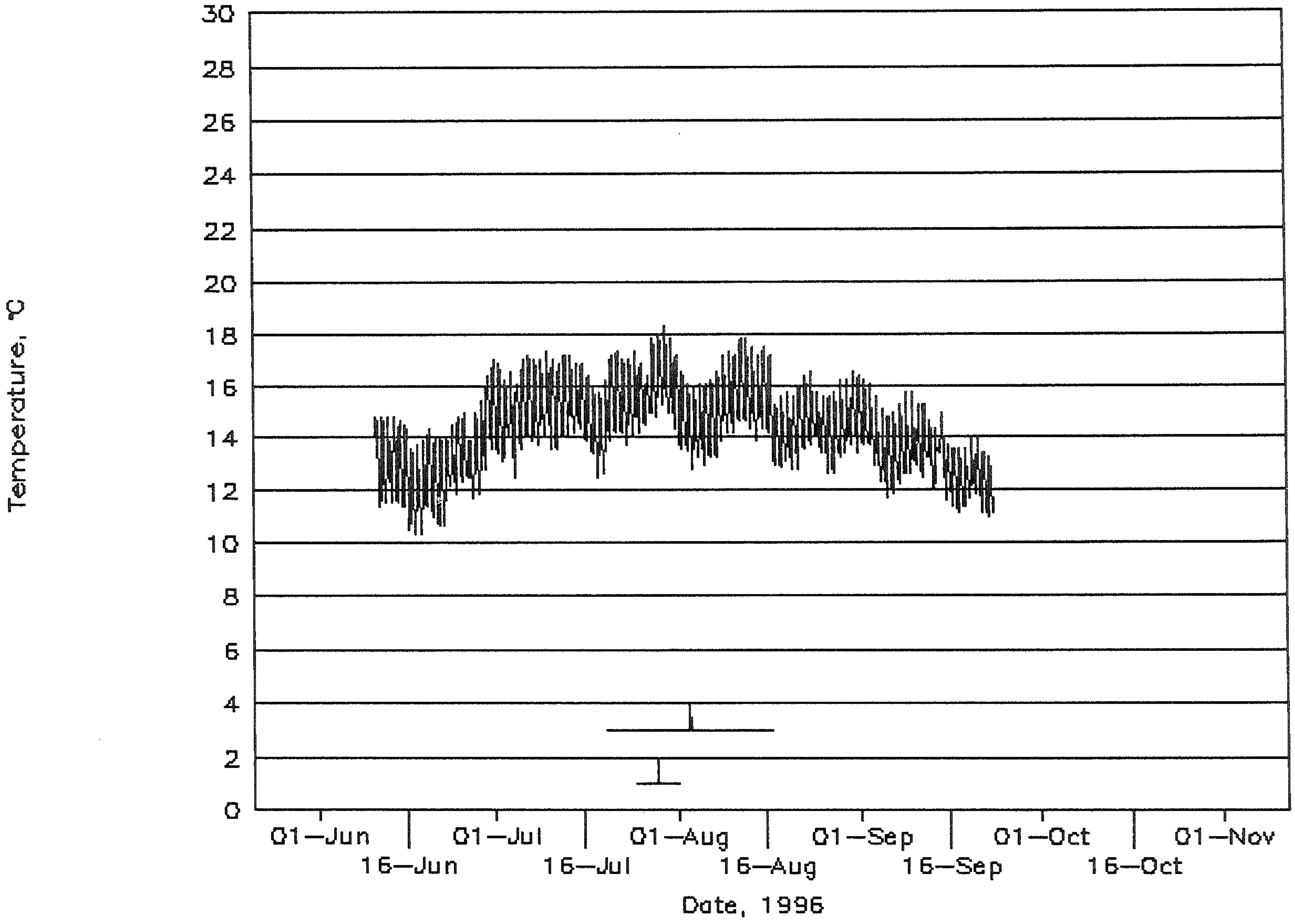
James Ck. above N.F. Big River

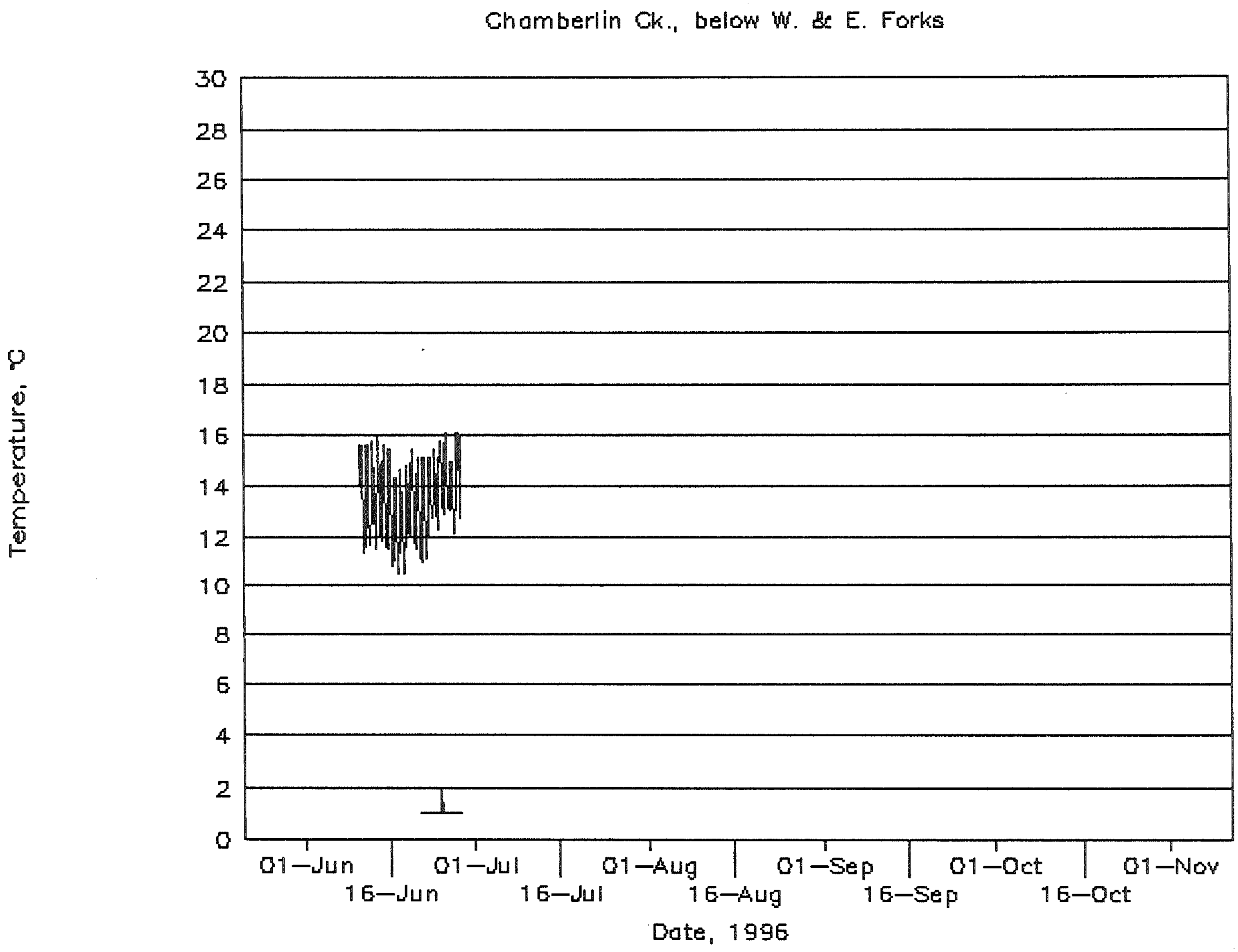


Chamberlin Ck., upper culvert

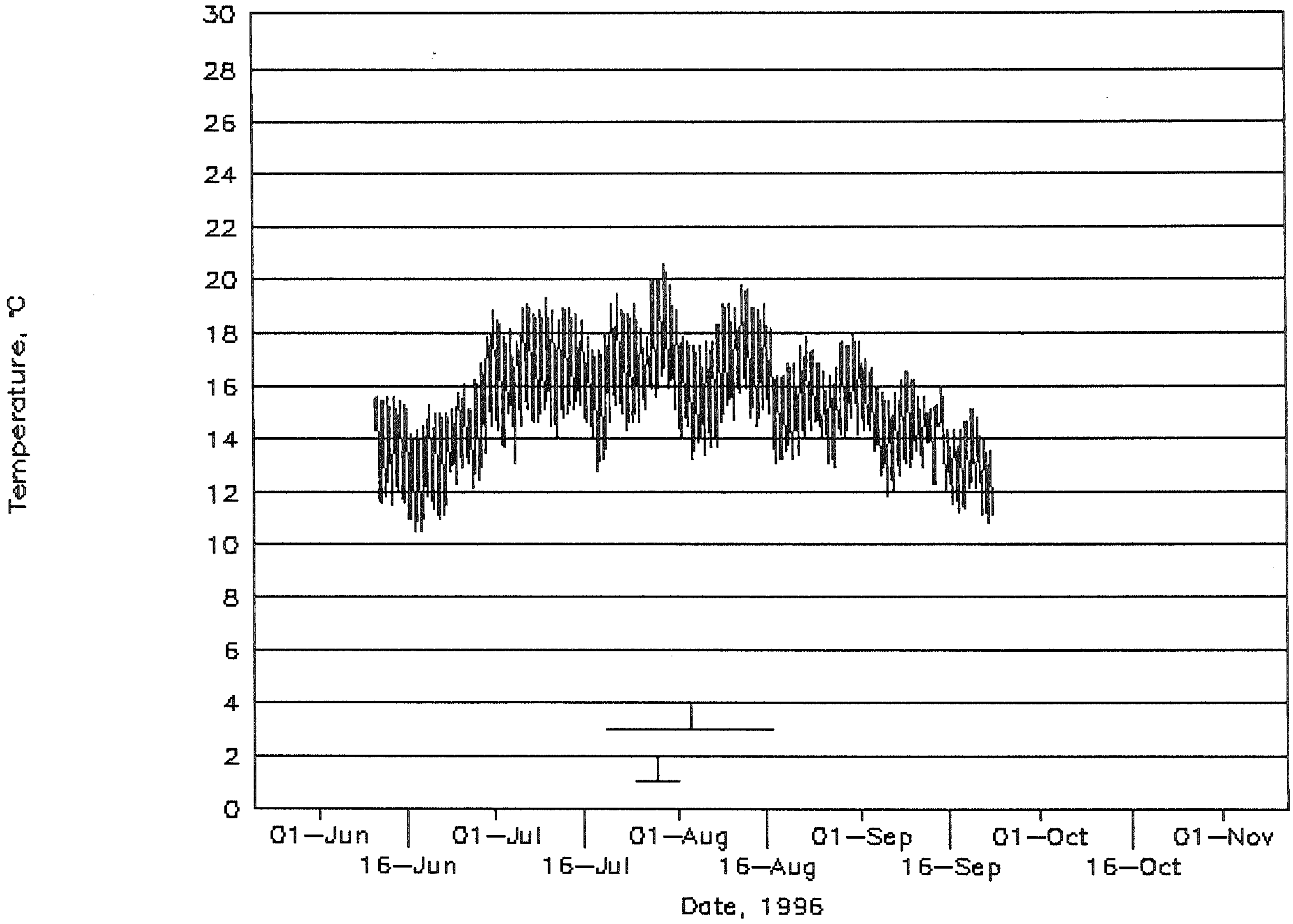


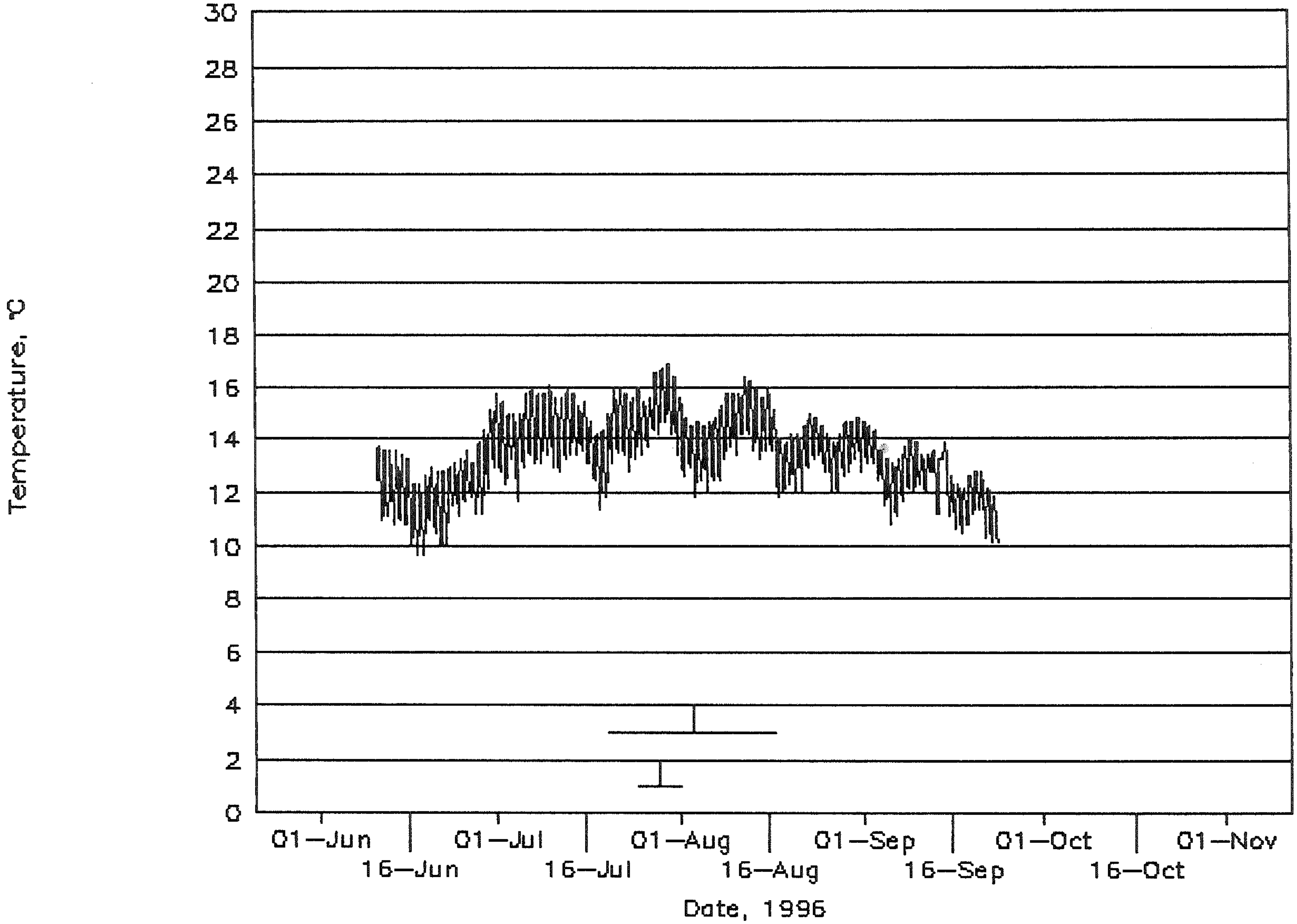
Chamberlin Ck., below main tributary



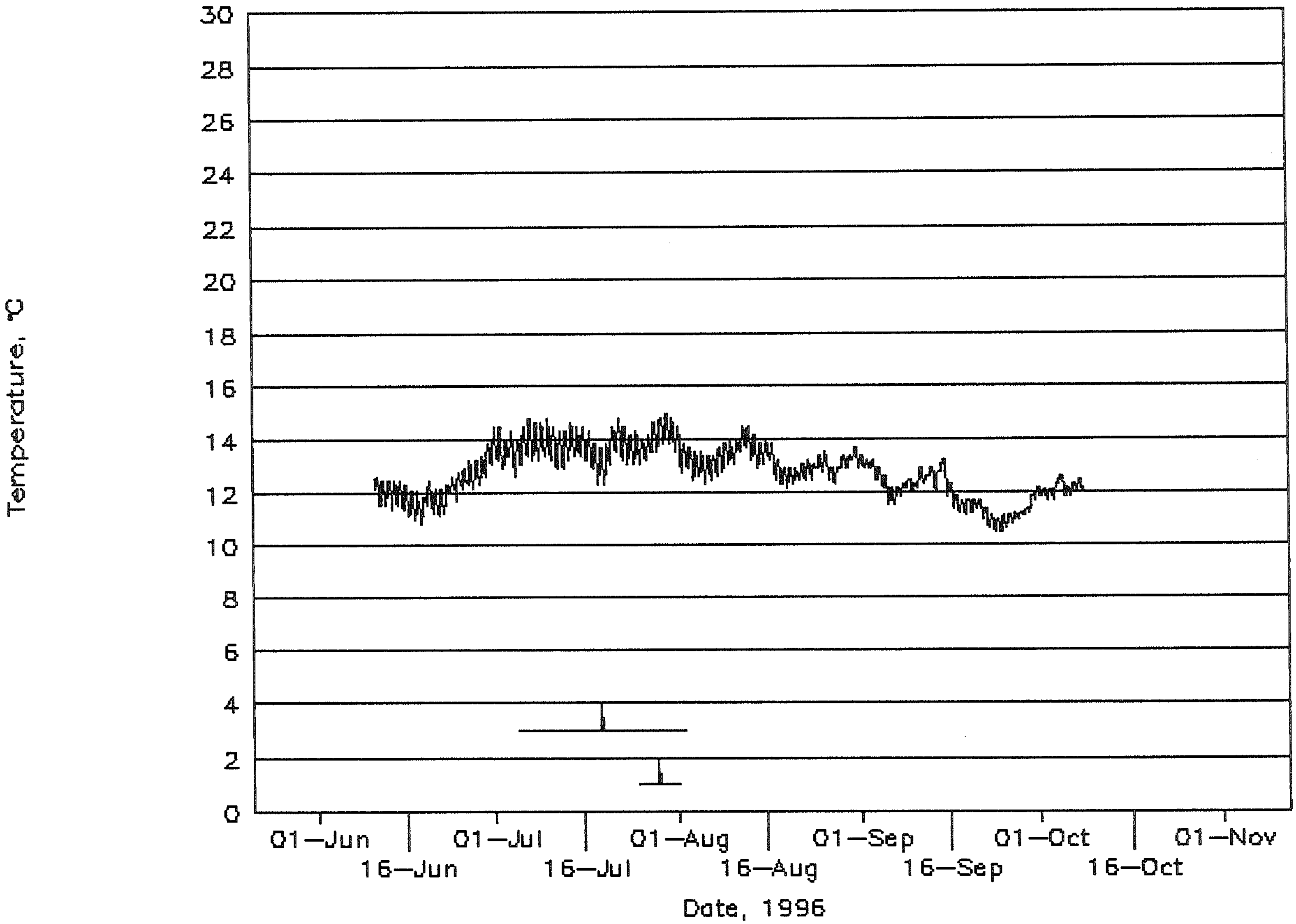

Chamberlin Ck., below W. & E. Forks
Temperature, °C
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
01—Jun
16—Jun
01—Jul
16—Jul
01—Aug
16—Aug
01—Sep
16—Sep
01—Oct
16—Oct
01—Nov
Date, 1996

Chamberlin Ck. above N.F. Big River



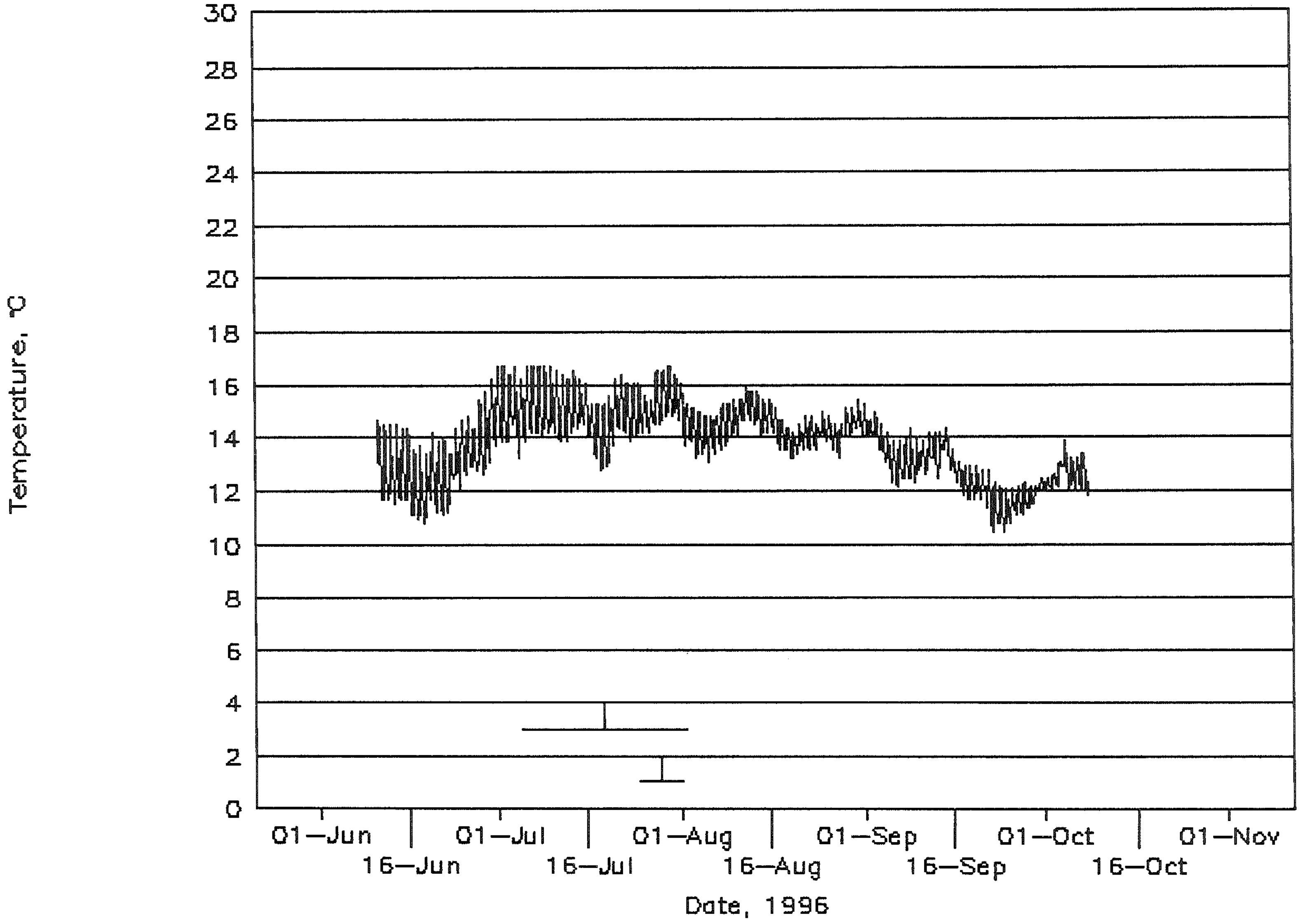


W.F. Chamberlin Ck., below 16 Gulch

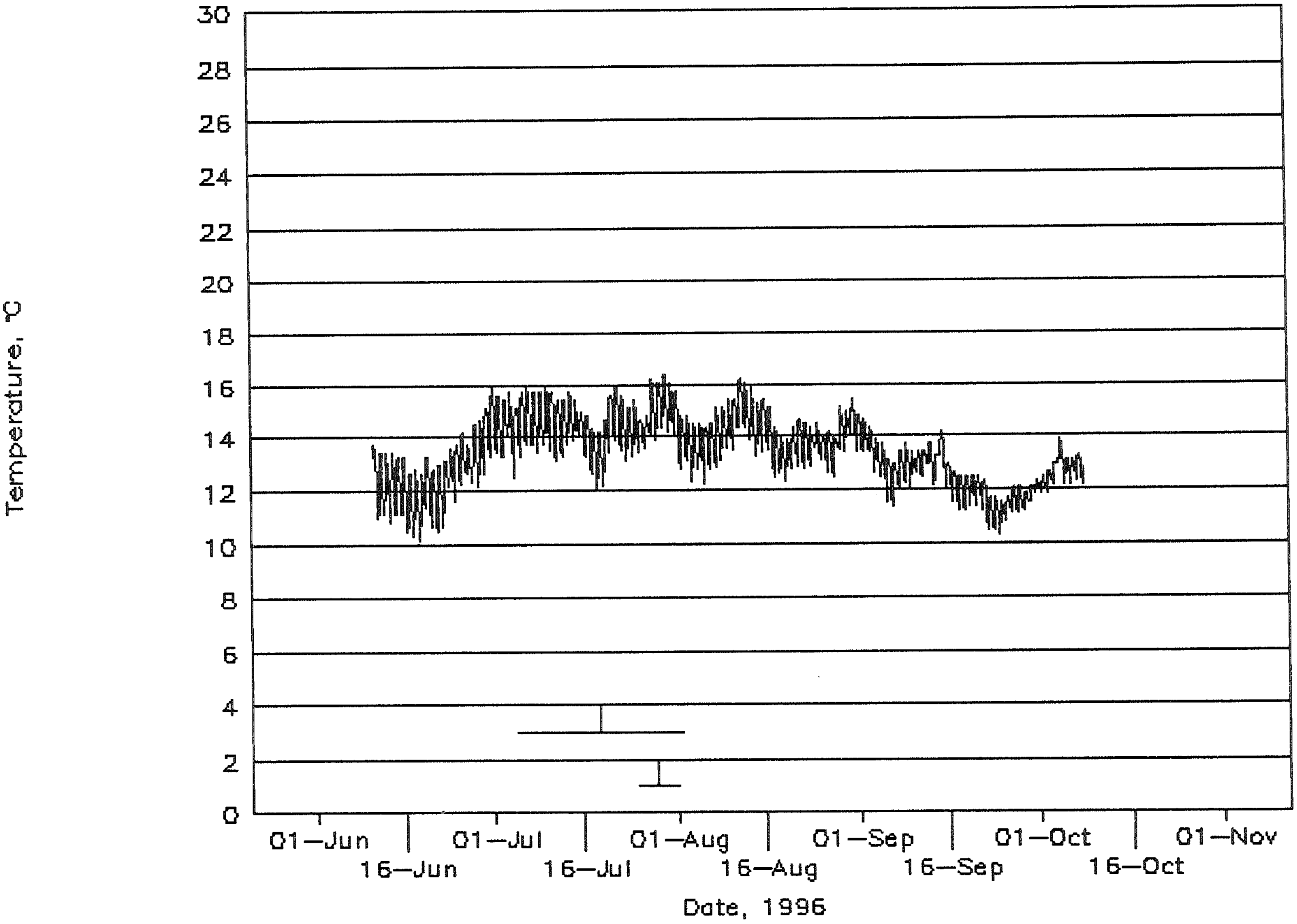


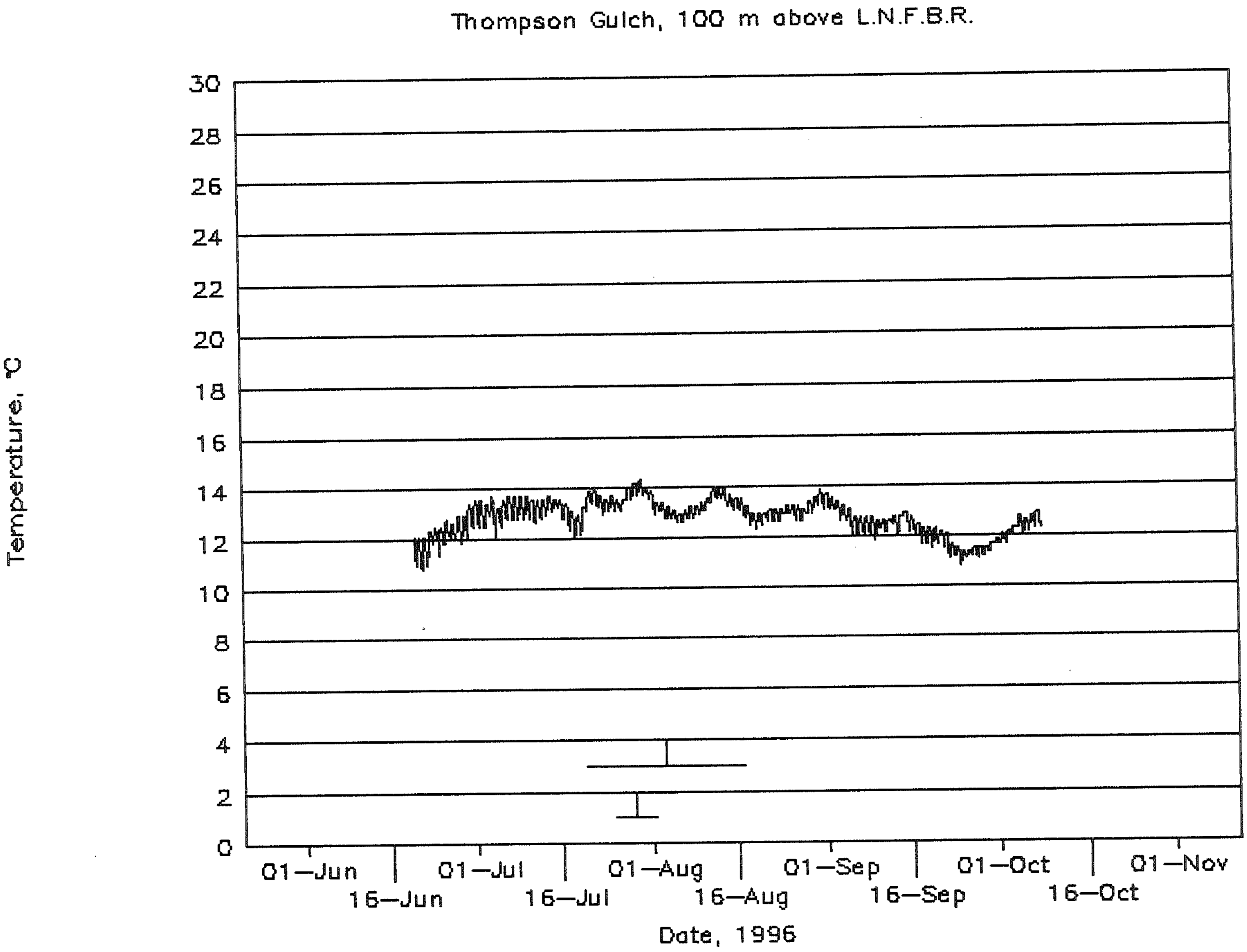
Little N.F. Big River @ Wonder Crossing

Little N.F. Big River above Berry Gulch



Berry Gulch above Little N.F. Big River




Thompson Gulch, 100 m above L.N.F.B.R.
Temperature, °C
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
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16—Jun
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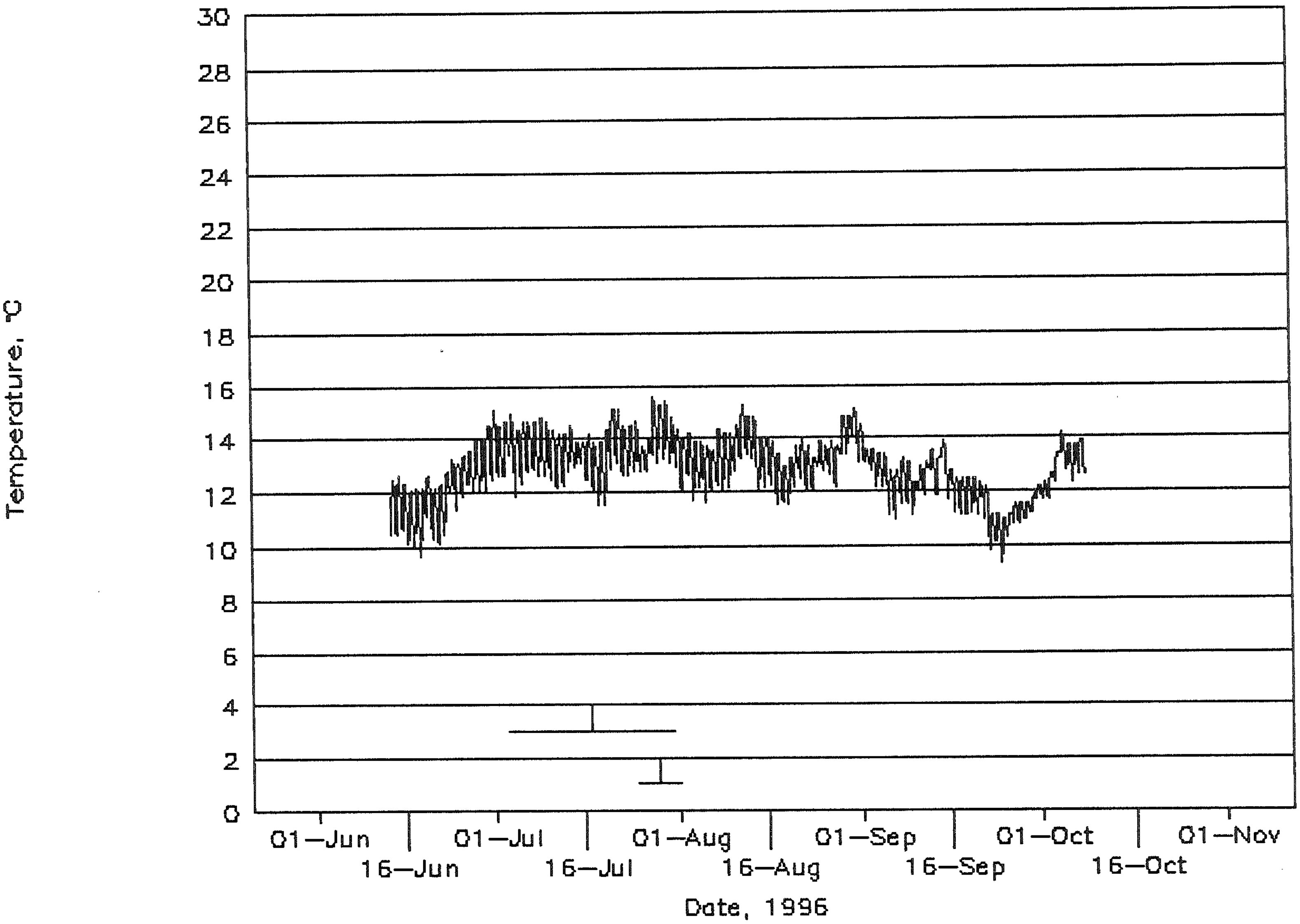
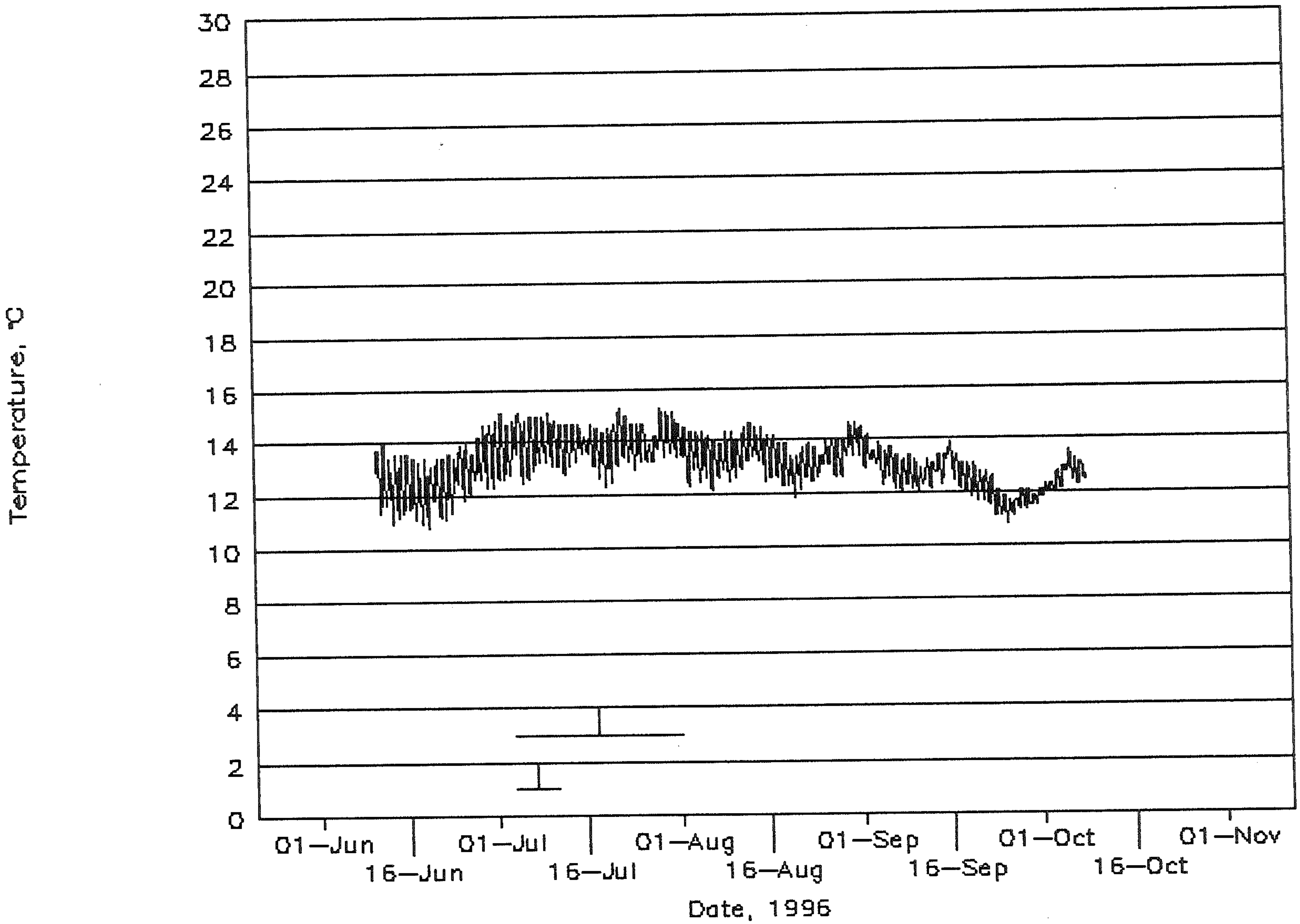
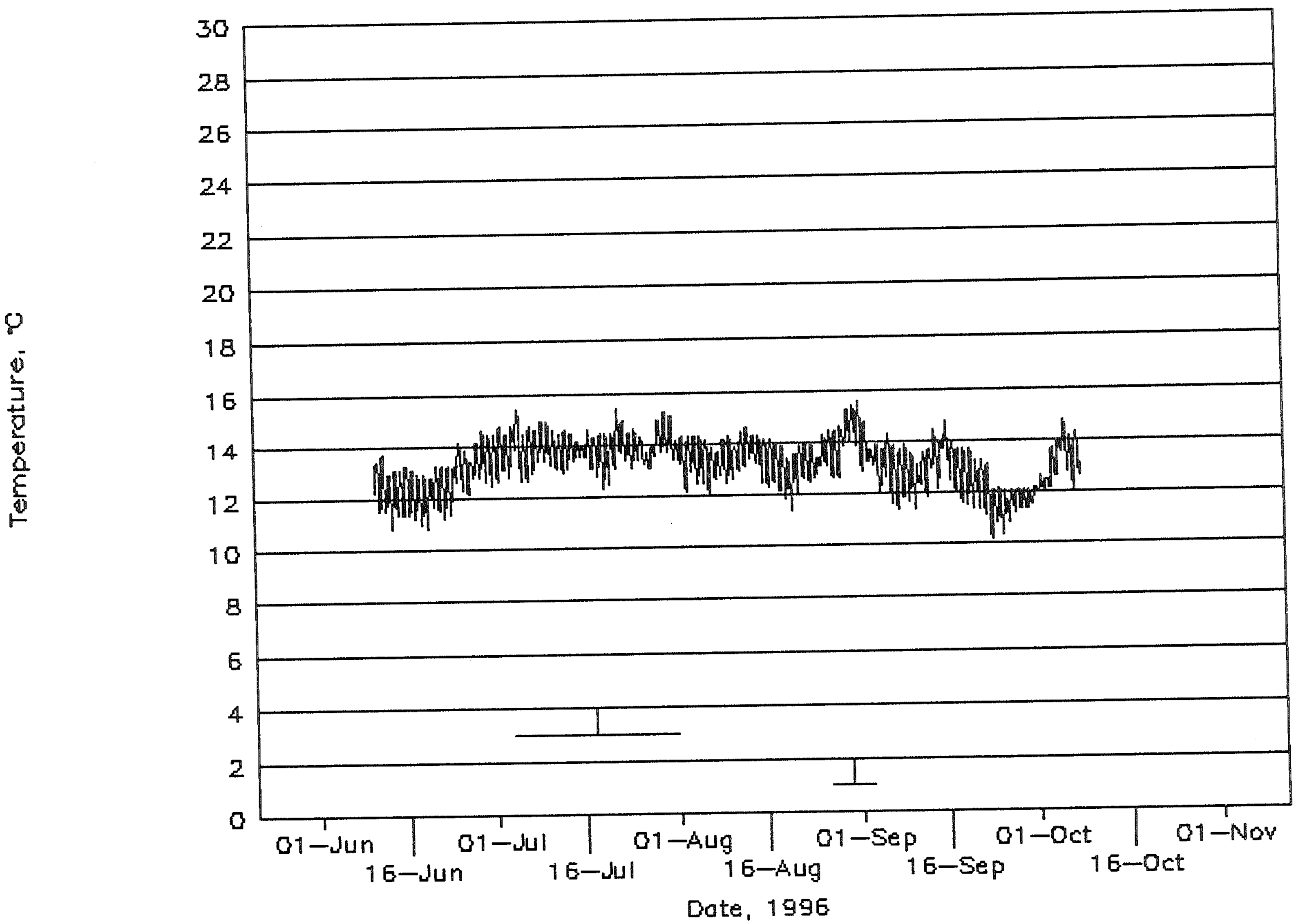
01—Oct
16—Oct
01—Nov
Date, 1996



Railroad Gulch above marsh

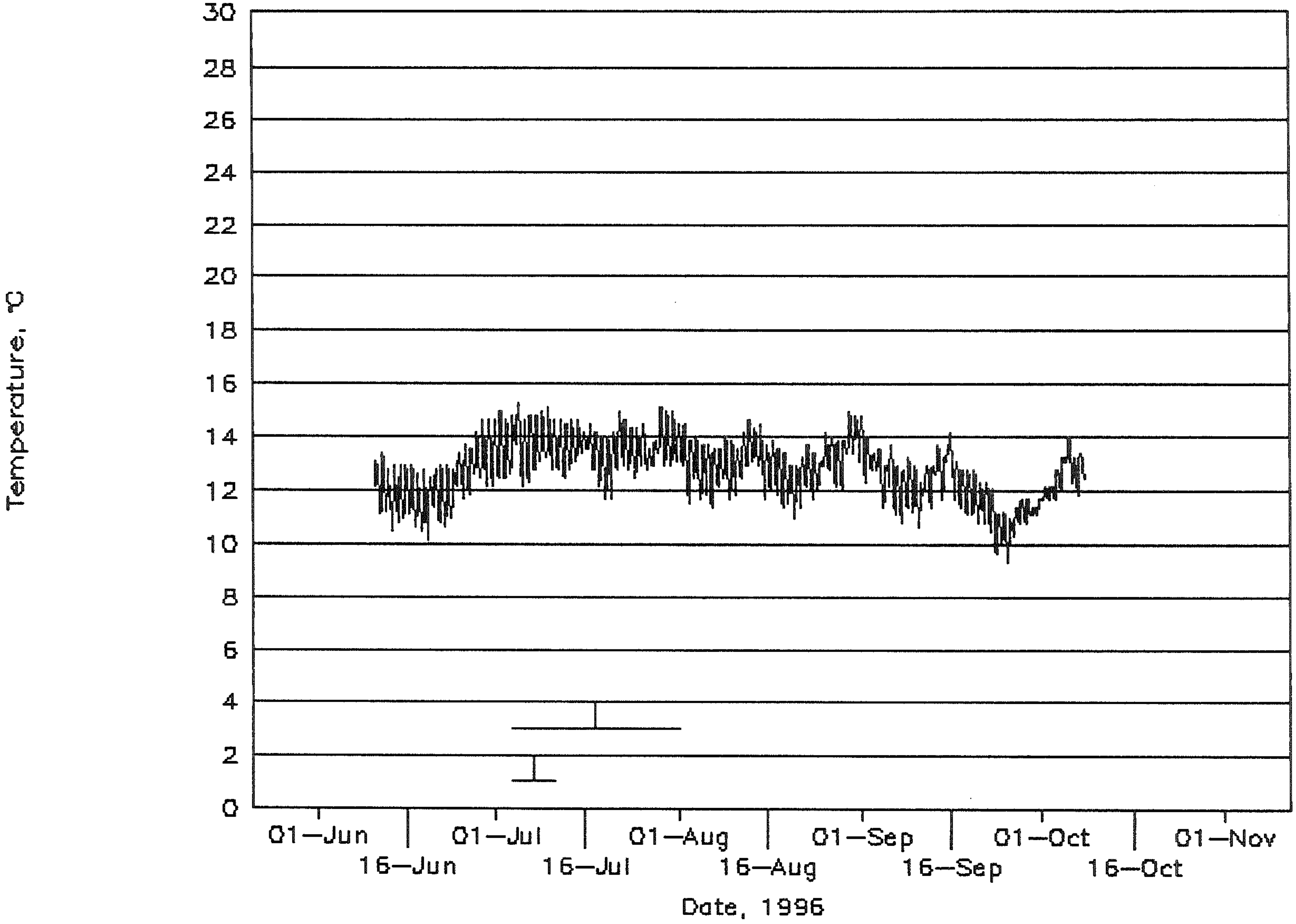
Caspar Ck. above S.F. confluence



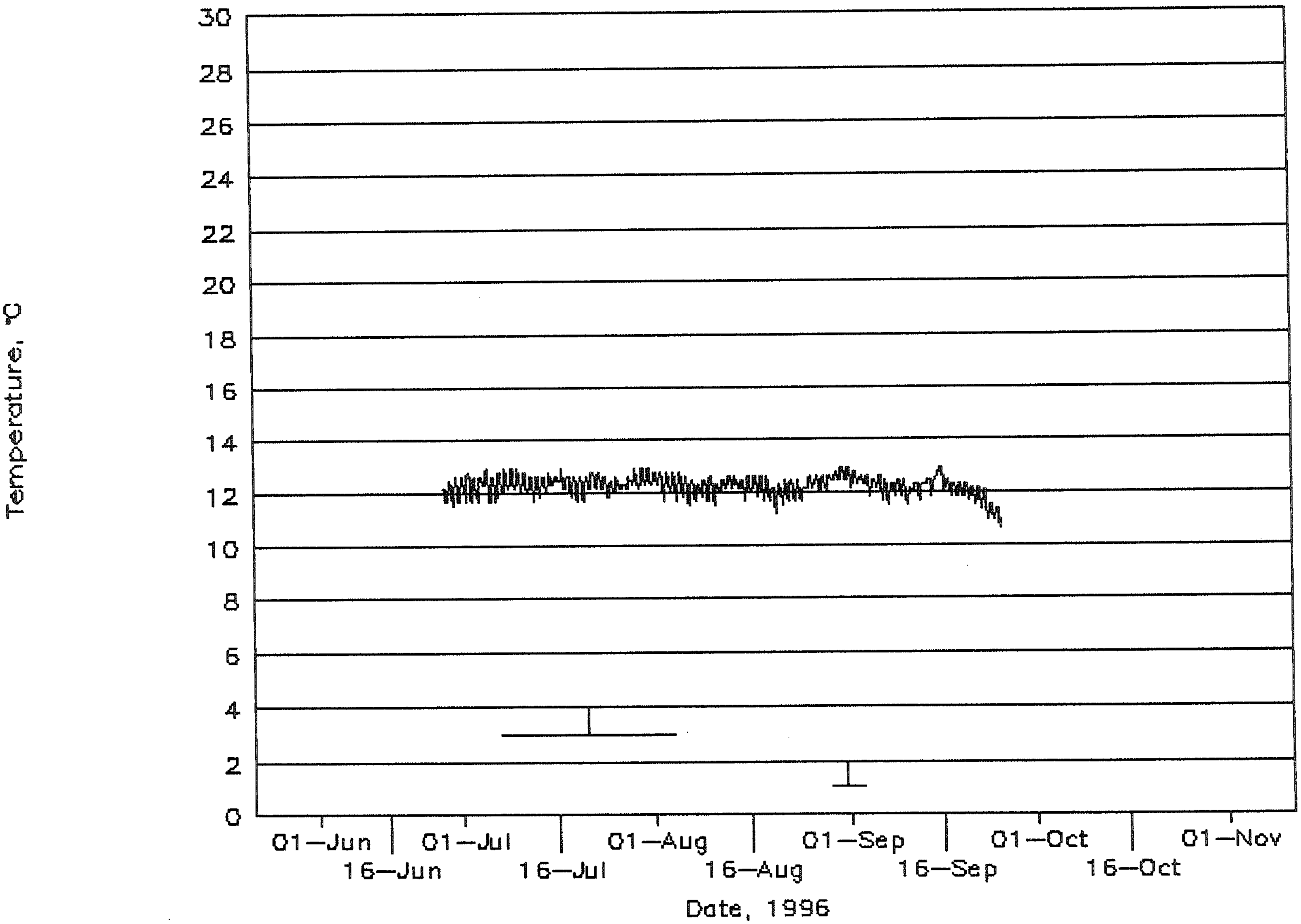


Caspar Creek near downstream boundary

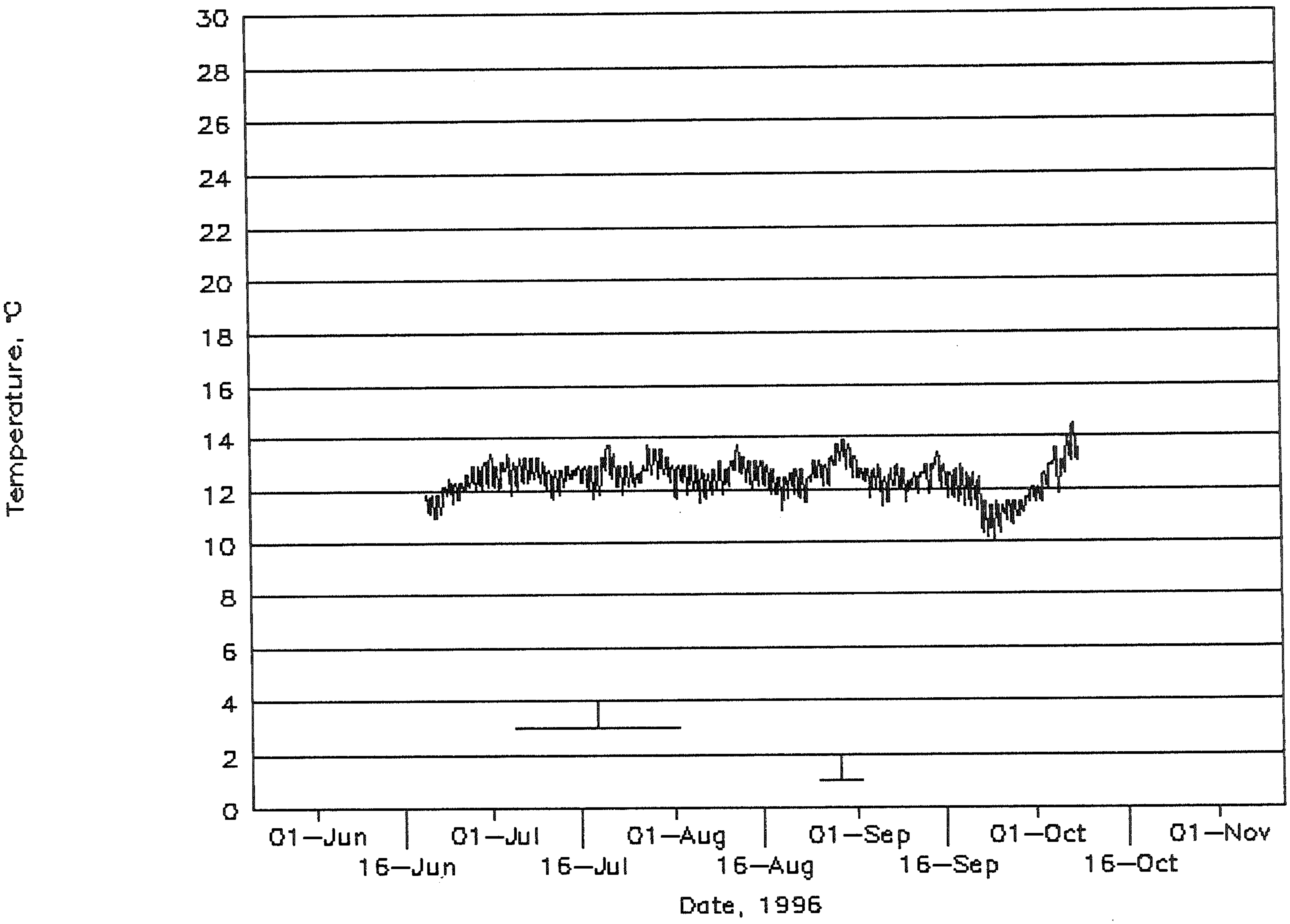
S.F. Caspar above Caspar Ck.



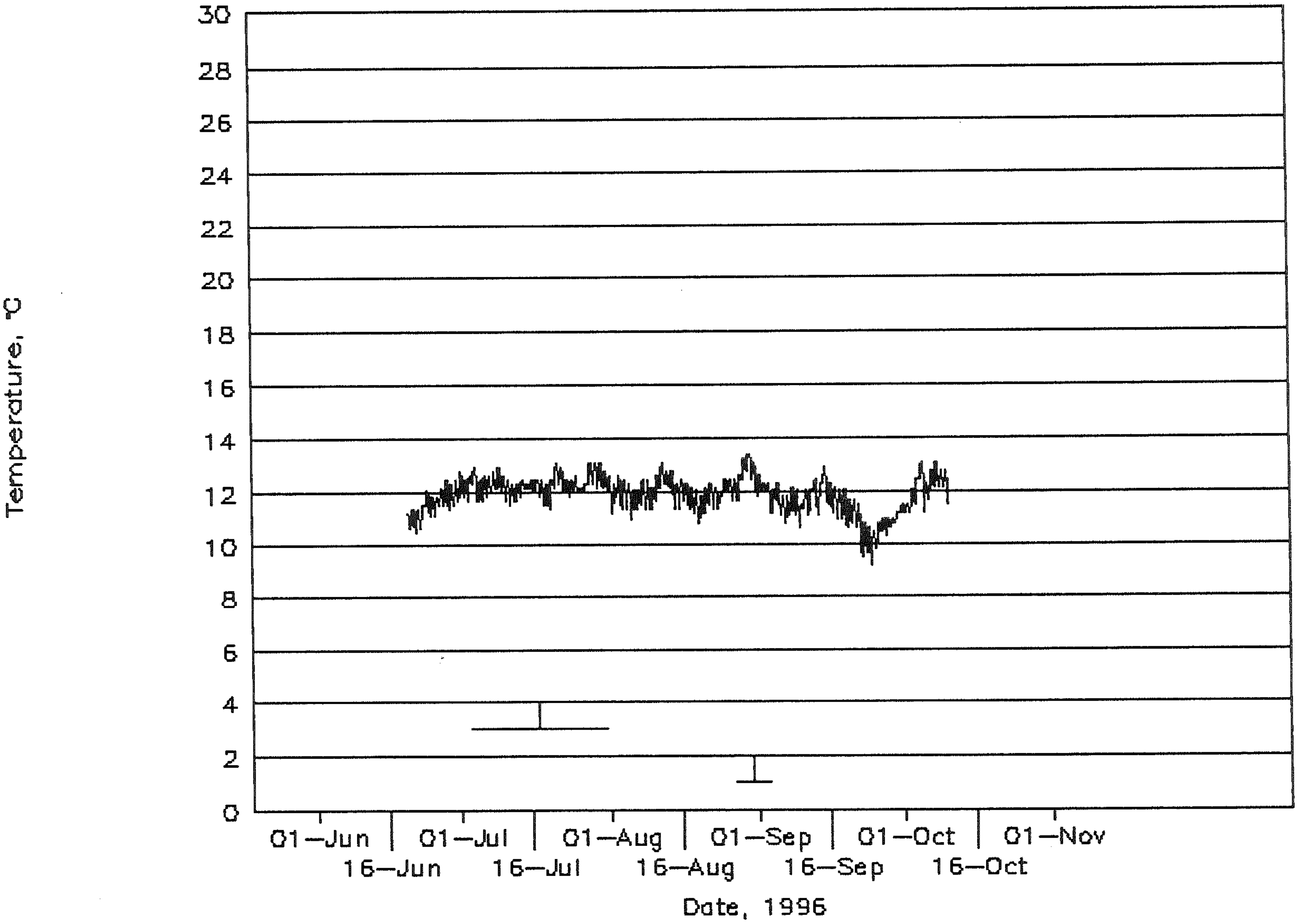
Jughandle Ck., 100 m below THP

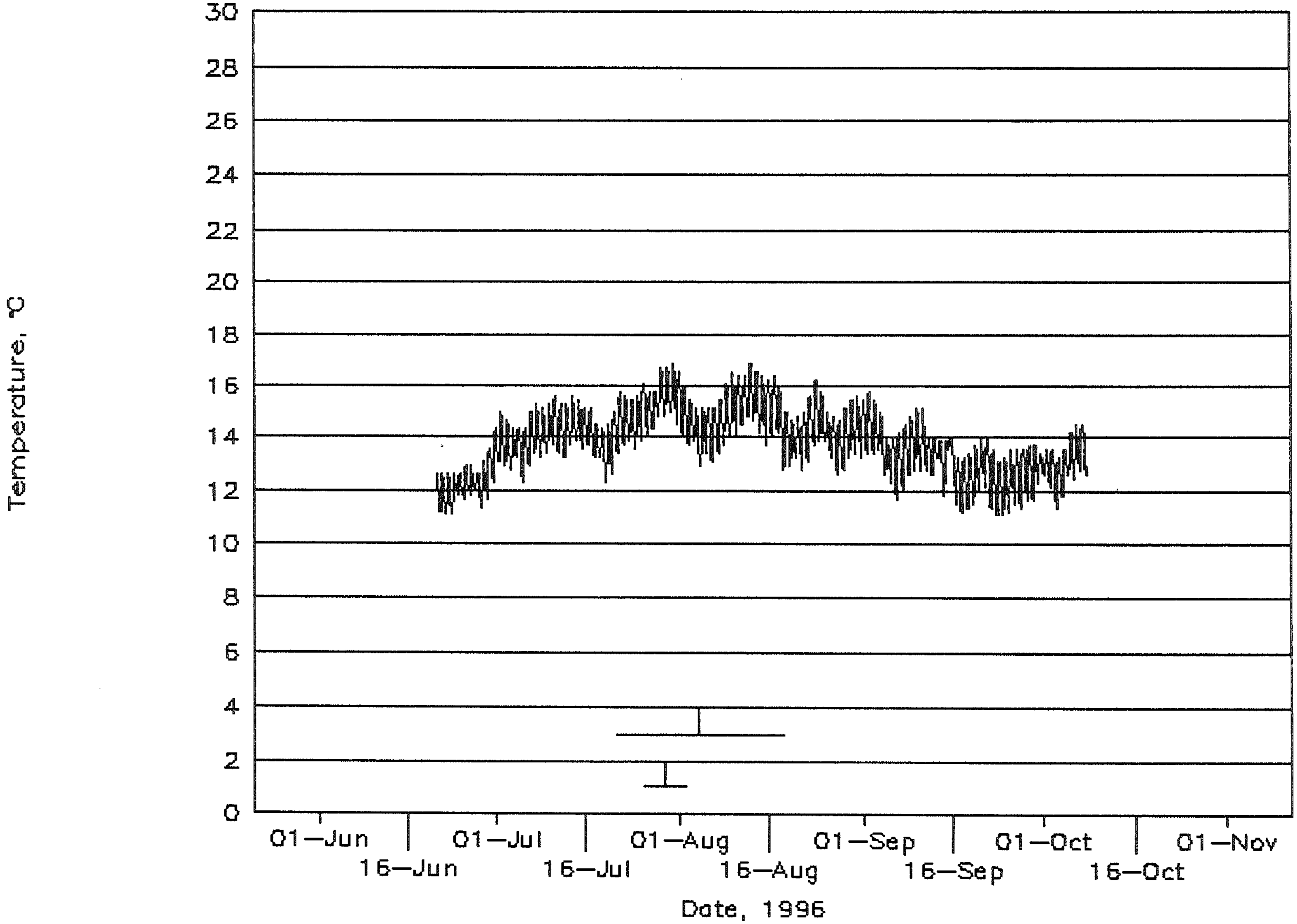


Upper Russian Gulch



Lower Russian Gulch





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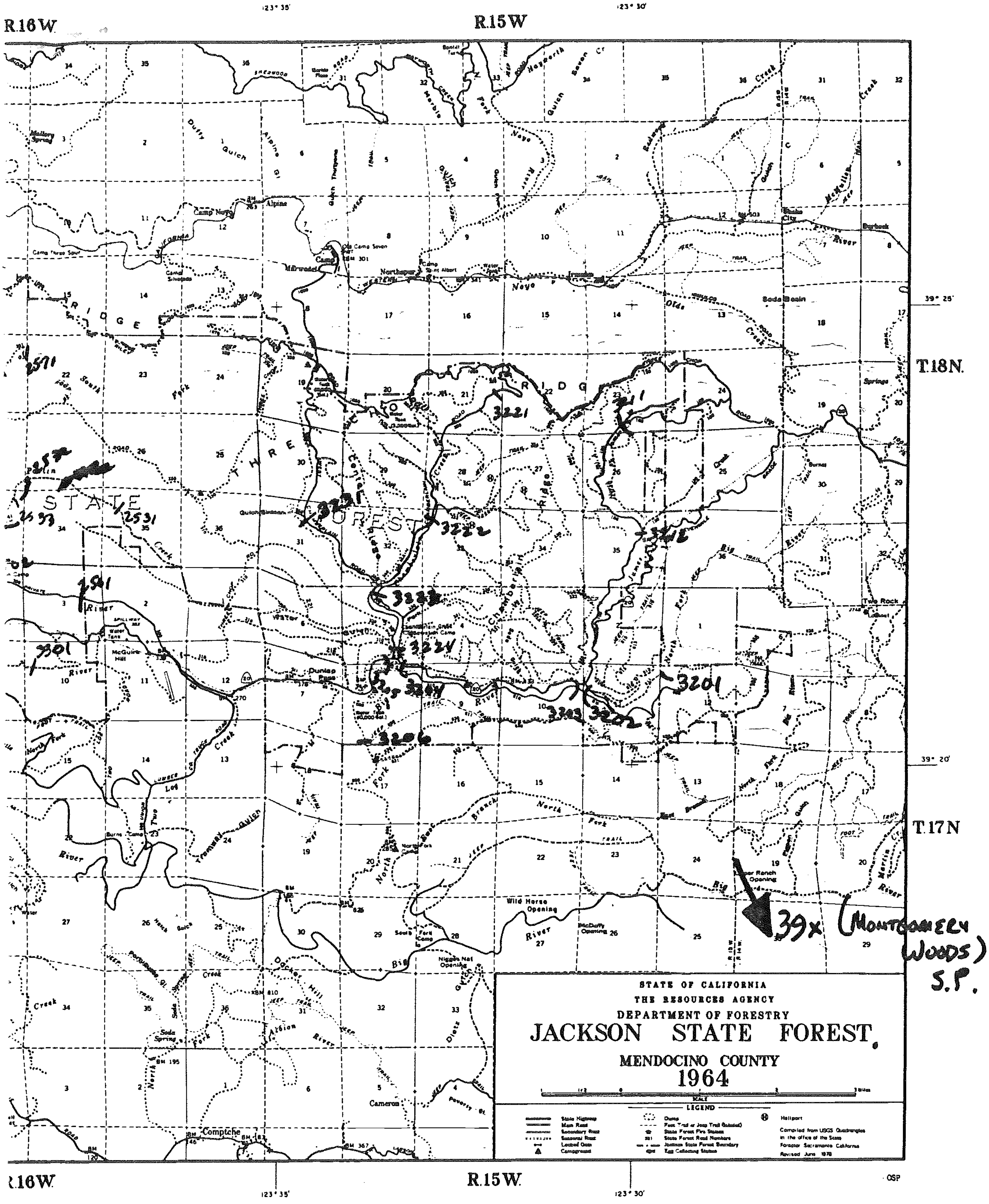


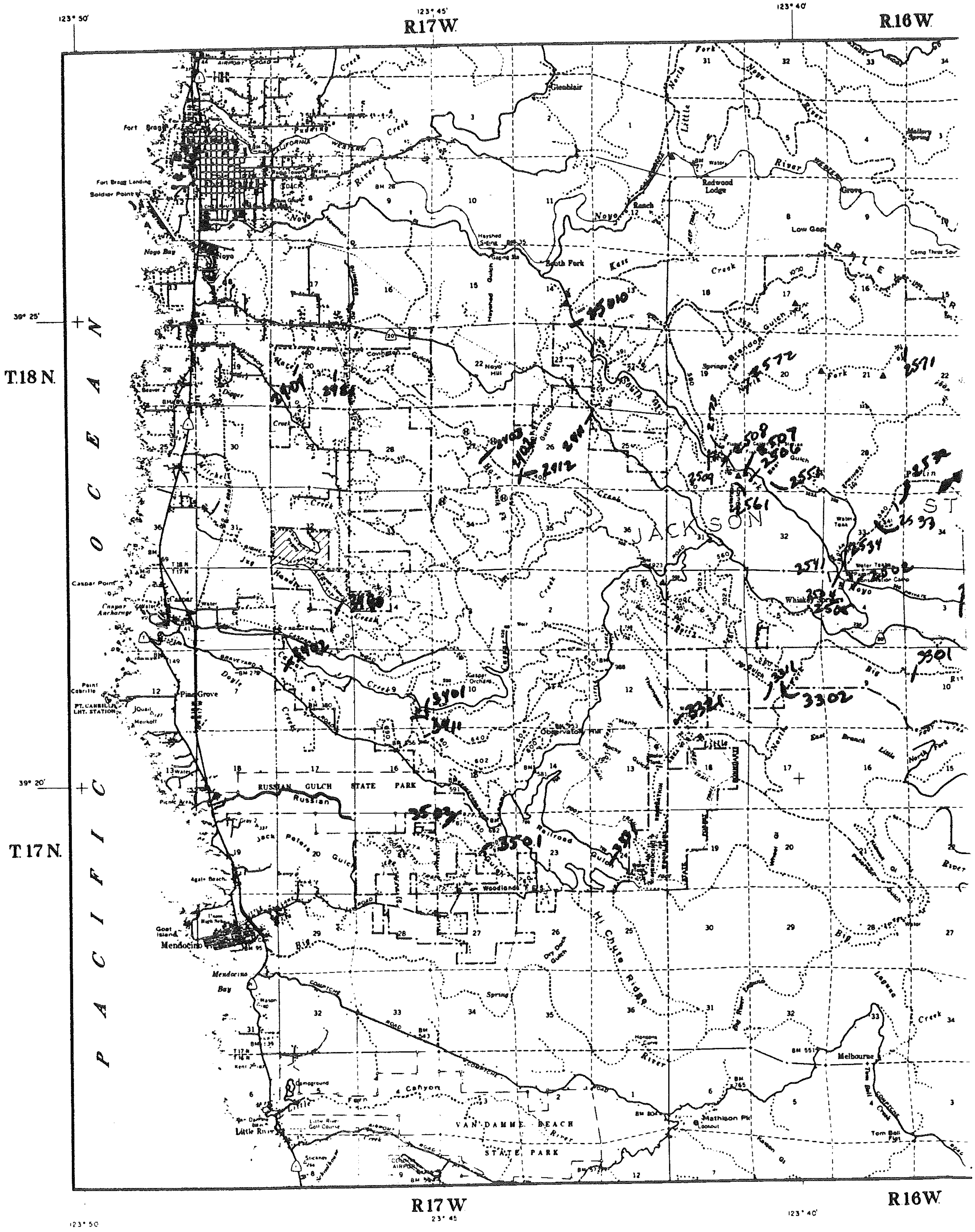
STATE OF CALIFORNIA
THE RESOURCES AGENCY
DEPARTMENT OF FORESTRY

JACKSON STATE FOREST

MENDOCINO COUNTY
1964

Compiled from USGS Quadrangles in the office of the State Forester Sacramento California
Revised June 1978

OSP



123° 50'
123° 45'
123° 40'
R17W
R16W
T.18 N.
T.17 N.
39° 25'
39° 20'
PACIFIC OCEAN
Fort Bragg
Fort Bragg Landing
Soldier Point
Noyo Bay
Noyo
Glenblair
Noyo River
Pudding Creek
Virgin Creek
California Western
Redwood Lodge
Low Gap
Mallory Spring
Grove
Camp Three Sour
Hayshed Siding
South Fork
Hayshed Gulch
North Fork
Little North Fork
East Creek
Brandon Gulch
Noyo Hill
Covington Gulch
Hare Creek
Mitchell Creek
JACKSON STATE
Water Tank
Whiskey Springs
Conservation Camp
Jug Handle Creek
Caspar Point
Caspar
Caspar Anchorage
Caspar Orchard
Doyle Creek
Point Cabrillo
PT. CABRILLO LHT. STATION
Pine Grove
Observatory Hill
Manly Gulch
Rocky Gulch
Little
Big River
East Branch Little North Fork
RUSSIAN GULCH STATE PARK
Russian Gulch
Jack Peters Gulch
Railroad Gulch
Woodlands
Hi Chute Ridge
Dry Dock Gulch
Goat Island
Mendocino
Mendocino Bay
Spring
Laguna Creek
Melbourne
Tom Bell Flat
Mathison Pk
Lookout
Fern Canyon
Little River
Little River Golf Course
Campground
VAN DAMME BEACH STATE PARK
AIRPORT
Stickney
Comptche Road
2501
2401
2404
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2403
2412
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Sound Watershed Consulting
Creating Functional Water Environments

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. Doug Martin
Dr. Lee Benda
Dr. Robert Coats
Dr. David Ganz

September 2008

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Hydrology
Geomorphology
River Ecology
Restoration Design
Sustainable Forestry
Integrated Watershed Management

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

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Prepared for the State Board of Forestry and Fire Protection in fulfillment of California Department of Forestry and Fire Protection Contract # RPF 8CA00010, Agreement Number 8CA07014, executed April 17, 2008.

Contractor: Sound Watershed Consulting

Mike Liquori

Mike Liquori, Principle

Approved by California Department of Forestry and Fire Protection Contract Representative:

Christopher Zimny

Christopher Zimny

Date: September 30, 2008

Sound Watershed Consulting

Creating Functional Water Environments

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

Chapter 1

INTRODUCTION

for

The California State Board of Forestry and Fire Protection

September 2008

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Hydrology
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1) INTRODUCTION

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SWC Ref# 1013

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EXECUTIVE SUMMARY

This report summarizes an independent review and synthesis of relevant scientific literature concerning riparian exchange functions to support the California Board of Forestry's deliberations regarding riparian management rules in support of anadromous salmonids in California's state and private forestlands.

This document represents a comprehensive review of 31 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
- Responds to key questions posed by the Board
- Describes key information gaps not covered within the reviewed literature
- Discusses inferences for forest management from each of the exchange functions

Biotic & Nutrient Exchange Functions

The literature on biotic and nutrient exchange tells us that litter produced in the riparian zone is an important food source for benthic macroinvertebrates , and thus indirectly supports salmonid production. But the quality of litter—its nutrient content and decomposition rate—are as important as the quantity of litter production. Alder produces "fast" (easily decomposed) litter that is rich in nitrogen; maple, willow and cottonwood produce litter of intermediate quality; conifers and oaks produce litter of lower quality and greater resistance to microbial decomposition. The timing of the life cycles of some benthic macroinvertebrates is thought to be synchronized with the production of different litter types.

Alder is not only beneficial to benthic macroinvertebrates, but supports a rich supply of terrestrial insects that fall into a stream from the riparian zone.

Opening the canopy cover over a stream and increasing light intensity has lead in many cases to increased primary (algae growth) and secondary (benthic macroinvertebrate) productivity, which is often beneficial to fish growth and production. In some cases, depending in part on nutrient supply, increased light can shift the dominant algae from diatoms to filamentous green algae, which are less desirable for macroinvertebrates and thus for fish. In opening the canopy over a stream there may be a trade-off between increasing aquatic productivity, which is beneficial to fish, and increasing water temperature, which may be detrimental to fish (see heat chapter)

Small floods increase the supply of food for salmonids by both washing food into the stream, and making flooded areas temporarily accessible for foraging (see water chapter).

A 30 meter wide buffer strip on both sides of a stream (with both equipment exclusion and no tree removal) generally reduces local impacts to a stream that are similar to a “no harvest” level. Completely excluding vegetation management in the buffer strip, however, may forego opportunities to increase fish growth rate and biomass, and to reduce fuel loads.

Topography, geomorphology, regional geography, and associated disturbance regimes strongly influence the vegetative characteristics of riparian zones. The shape and type of these natural landforms may be helpful in guiding buffer configurations including widths and other characteristics (e.g. structure, orientation, density, etc).

The literature suggests that active riparian management could benefit aquatic productivity with silvicultural prescriptions that are designed to enhance temperature regimes, aquatic primary productivity, woody debris recruitment, and reducing fuel loads. These prescriptions could continue to protect streams from known impacts (e.g., erosion from heavy equipment, excessive shade loss), by strategically locating management activities and sizing treated areas to prevent damage yet promote favorable biotic responses. The timing of such riparian management activities could also be scheduled to reduce risk and optimize favorable riparian stand characteristics across a stream network.

Heat Exchange Functions

The literature on riparian heat exchange tells us that shade provided by riparian vegetation is a key factor controlling heat input to streams, even though instream water temperatures are governed by a host of other complex physical factors that control heat transfer between air, water, and the streambed.

There is no single, fixed-width buffer or canopy closure prescription that will provide the desired heat regulation objectives for salmon in all cases. The relative importance of riparian vegetation to influence stream temperature varies by location (geographic province) and by site specific conditions (stream width, depth, flow, groundwater inflow, streambed substrate composition, valley orientation, topographic shading and watershed position). Stream temperature sensitivity to shade is dependent on location and physical conditions.

The science on heat exchange indicates that water temperature protection could be provided by varying the riparian shade requirements in relation to stream temperature sensitivity. This report provides some examples of approaches than can be used, and key variables to consider when designing strategies to manage shade in different settings.

In fish-bearing waters that are directly downstream of headwater streams, the literature indicates that temperature could be positively influenced by providing shaded conditions on headwater stream segments that extend from 500 to 650 ft (150 to 200 m) upstream from the confluence with fish-bearing streams. This distance is based on research findings outside of California, therefore this distance may need to be validated with studies in various California ecoregions.

Our interpretation of the reviewed literature suggests that managing to protect salmonid habitat conditions would require that targets be set for desired stream temperature, and that shade requirements vary in relation to the stream's specific sensitivity to shade as a thermal influence on temperature. The literature indicates that stream temperature is a major factor influencing population performance.

Shade is not static, but varies in response to stand growth dynamics and natural ecosystem processes and disturbances. Suitable thermal conditions could be maintained and hazards to salmonids avoided by altering the timing and spatial position of riparian management activities. Thermal conditions also respond to surrounding conditions as water flows downstream, so downstream stand conditions also influence stream temperature.

Riparian stand effectiveness for shading is a function of the forest canopy density, height, and species composition, which is related to stand type and age. Research shows that effective shading can be provided by buffer widths ranging from 30 to 100 ft (10 m to 30 m) depending on stand type, age, and location.

Timber harvest in or adjacent to riparian areas can influence microclimate, but microclimate changes have not been demonstrated to translate to changes in water temperature.

Timber harvest in or near riparian areas can cause an increase in light penetration, decrease interception of precipitation, and increase wind speed, which can result in higher mid-day air temperatures and lower mid-day humidity near the forest floor and over the stream. These microclimate changes are hypothesized to influence water temperature, however validation is lacking.

Finally, heat exchange is only one riparian function that affects salmonids. Shade conditions can inversely influence biotic and nutrient exchange functions. Similarly, the canopy that provides shade also influences water exchange functions, and can be influenced by wood exchange functions. These dynamics between exchange functions are discussed in greater detail in Chapter 7 (Synthesis).

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.

Wood Exchange Functions

Forested environments strongly influence salmonid habitat in California through the processes of woody debris entering the stream from riparian areas. This report describes the mechanisms for wood recruitment to the stream environment, the influence of forest management, and factors that affect riparian buffer design.

There are three dominant sources of instream wood; bank erosion, streamside landslides, and treefall from within riparian areas. Each of these sources is influenced by the dominant type, frequency and magnitude of disturbance processes (fire, flood, landsliding, infestation, etc), as well as the rates of competition mortality associated with the existing stand structure. Disturbance, mortality and tree growth in riparian stands are dynamically linked.

In California second-growth forests, approximately 40-60% of observed instream wood comes from bank erosion, approximately 30% comes from streamside landslides, and the remaining amount comes from treefall. These rates vary substantially based on the geographic (e.g. region) and geomorphic (e.g. landscape condition) context for the site.

Once in the stream, wood is subject to transport down the channel network either during floods (fluvial) or debris-flows. Wood that is carried by debris flow only occurs in certain terrains (typically steep, confined headwaters). Wood that is carried by floods is typically shorter than the channel width.

It can be important to understand the existing stand conditions and successional trajectory of the riparian stand because the riparian stand structure strongly influences the qualities of recruited wood and the rate of recruitment. The existing stand structure and successional trajectory also influences the types and qualities of disturbances that can occur at any given site, and disturbances are one of the primary recruitment processes for instream wood.

Forest management can manipulate riparian stand structure in ways that a) affect the growth and mortality dynamics for the stand and b) influence the types, qualities and risks of disturbances. Forest management can also reduce tree recruitment potential and shift the functional inputs from various exchange functions. Management has the potential to improve existing conditions that reflect legacy forest practices. Management can also alter short-term and long-term supply and characteristics of wood. Therefore, management within riparian zones must be conducted carefully, and with clear functional objectives.

Riparian silvicultural objectives that would support ecological functions important to salmonids (and other fauna) should balance competition mortality objectives, growth objectives, and disturbance risks in ways that support exchange function objectives based on a diagnosis of site requirements. Diagnoses may be generalized by the spatial context of the site by considering regional variations as well as watershed-scale variations in the dominant processes that affect stand evolution (i.e. disturbance types). Diagnoses should also consider the expected stand growth and mortality processes based on conditions that influence stand dynamics (e.g. tree species, cohorts, density, size, etc). Together, the major factors that are reported to influence wood recruitment conditions include:

- Existing Stand Density, Composition And Structure
- Stream Type, Order and Watershed Context
- Vegetation Type and Soil/ Site Index
- Regional Context
- Disturbance Context

Riparian management strategies require consideration of both science and policy. The reviewed literature offers many opinions, but little hard data to evaluate the scientific effectiveness of any approach. Ultimately, the choice of the best approach must be guided by forest policy. The ranges of policy alternatives includes:

Riparian Reserves: This approach seeks to maintain large buffer widths to minimize management effects within riparian areas, specifically those indirect management effects on natural rates of disturbance. This approach typically calls for uniform and continuous riparian buffers of up to two site-potential tree heights on fish-bearing streams and one site-potential tree height on non-fish streams. The underlying basis for this strategy is that over long periods of time (typically centuries), late-seral conditions will become re-established in riparian areas, and that such conditions best represent the long-term conditions suitable for salmonids.

Selective Management: This approach seeks to actively design the characteristics of riparian forests (e.g. size, height, species) in a way that influences future wood recruitment potential (e.g. timing of mortality, exposure to disturbance risks) and other functions. Its focus is often to maximize the benefit to riparian functions while preserving the capacity to operate on forest lands to achieve other resource objectives. It achieves this focus by encouraging a stand composition that targets wood recruitment characteristics most suitable to the specific stream environment. This approach recognizes that the total wood volume grown onsite is strongly influenced by stand structure (density, species, age-distributions, etc), and that tree volume and diameter can be manipulated to meet management objectives.

Proactive Enhancement: Another approach described by the reviewed literature is the concept of proactive instream restoration and enhancement in the form of wood placement. The ability to properly design and implement restoration or enhancement projects requires knowledge of hydrology, hydraulics, geomorphology, biology and engineering practices. Instream wood placement is a practice that is continuing to evolve in many land-use settings, and the general perception is that such projects are overall a benefit to salmonids.

There are a wide array of tools and methods available that can objectively inform these management strategies using scientific approaches. There are also several existing information gaps that could improve riparian management.

Sediment Exchange Functions

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.

Synthesis

In this chapter, we discuss concepts that will help guide the Board of Forestry toward an integrated approach to riparian management that considers all forms and functions.

We've discovered four key findings throughout our review of the literature that extend across all the exchange functions. These include:

1. Spatial context is important, as it influences functional response patterns.
2. Longitudinal controls (along the channel length) on exchange functions in addition to lateral controls (buffer width) are important in maintaining the watershed-scale ecosystem structure that maintains aquatic habitats.
3. There are dynamic interactions among and between riparian exchange functions that alter the importance of exchange functions for any particular setting.
4. While riparian zones can buffer a stream from direct management impacts, they do not protect streams from disturbances, but in fact alter the disturbance regimes in ways that can affect the functional response expressed by both short-term and long-term evolution of riparian areas.

A shift in thinking from a “protection” mindset (e.g., buffering the stream) to an “ecosystem processes” mindset is consistent with several general themes in the literature in recent years. These papers suggest that it may be a more appropriate management objective to ensure that the ecosystem processes and functions are maintained to provide desired riparian (and instream) conditions in managed settings.

There are three general approaches to achieve this objective that are promoted in the reviewed literature.

Riparian Reserves utilize large buffers so that mature to late-seral stand conditions are eventually achieved.

Resource Optimization seeks to balance appropriate protections against other management objectives.

Advanced Recovery/Enhancement manages growth and disturbance risks to influence ecosystem processes that create conditions favorable to salmonids over the short- and long-term.

The scientific basis for buffer widths is described in terms of source-distance relationships that relate width to the cumulative inputs (or limits) for various functions. The shape of source-distance curves are strongly influenced by the dominant mechanisms or riparian characteristics for contributing (or preventing) the key input associated with each exchange function in that setting. Seven specific limitations in using source distance relationships are described that raise questions regarding the utility and/or effectiveness of using source distance relationships as the sole basis for riparian management.

The scientific basis for longitudinal variation describes regional, watershed, and temporal scales of influence that combine to influence the context for habitat requirements. Managing for longitudinal variation requires an understanding of how different ecosystem processes act to form and maintain habitats throughout the channel network.

The scientific basis for headwater riparian management recognizes that headwaters affect functional responses in downstream reaches. The concept of longitudinal source-distances is offered here as an analog, wherein different characteristic input distances can be measured from the confluence of the headwater tributary junction with fish-bearing reaches. Data to support such source-distance relationships for headwater areas is limited in the reviewed literature.

Riparian forest structure is fundamentally a dynamic expression of growth and disturbance. It is the combination of structural characteristics and disturbance processes that influence functional relationships between riparian areas and salmonid habitats. Management of riparian zones can affect the types of disturbances and vulnerability to disturbances that deliver functional inputs. These disturbances can be beneficial, detrimental, or both.

Our synthesis of the reviewed literature leads us to the conclusion that the importance of maintaining ecosystem functions, including those associated with disturbance, dynamics, growth, and spatial variability, point to the need for an evolutionary step in the design and application of riparian management strategies. A more holistic strategy would integrate landscape-scale concepts into local decision criteria. A wide array of analytical tools for evaluating watershed-scale processes and conditions are available, and the reviewed literature suggests that there is considerable scientific data to inform such tools.

INTRODUCTION

This report summarizes an independent review and synthesis of relevant scientific literature concerning riparian exchange functions to support the California Board of Forestry's deliberations regarding riparian management rules in support of anadromous salmonids in California's state and private forestlands.

The Board has statutory responsibility for a comprehensive set of Forest Practice Rules that govern the planning and conduct of timber operations on private and State-owned timberlands in the State. The Board also has statutory requirements for review of its regulations. Public Resource Code 4553 requires the Board to continuously review and revise regulations to ensure regulatory effectiveness. Specific provisions of the rules are intended to provide protection for anadromous salmonids.

As a consequence of the listing of the Coho salmon as a threatened species under the California Endangered Species Act, the California Department of Fish Game in conjunction with the California Department of Forestry and Fire Protection, landowners and scientific experts, has been directed by the Fish and Game Commission to monitor and review existing timber harvesting regulations for the protection of Coho salmon. This report supports pending deliberations regarding the protection and restoration in watersheds with threatened or impaired values (e.g. 14 CCR §§ 916.9, 936.9, and 956.9).

The Board appointed a 12-member Technical Advisory Committee on Riparian Forests (TAC) to serve as scientific advisors during the literature review and its presentation to the Board. The TAC identified a list of representative scientific literature for review. The TAC compiled 149 articles using several criteria for inclusion in the reviewed literature list. These criteria included a) articles represent recent work (since approximately 1996), b) were conducted with scientific rigor, c) received formal scientific peer review, d) are relevant to processes that are important in California, e) addresses at least one of the exchange functions.

The TAC also developed a set of "Primers" for riparian functions that provided a summary of the accepted concepts associate with 5 key riparian exchange functions associated with water, heat, biotic & nutrients, wood, and sediment. These widely accepted functions are known to affect ecological processes between streams and their adjacent forests. The Primers describe generally accepted concepts as a foundation for the literature review, allowing the review to focus on other important issues.

Project Approach

The Sound Watershed Team provided an independent, objective, non-partisan review of 179 scientific literature articles provided by the Board of Forestry, as well as the 5 “primer” summary articles provided by the TAC. These papers, over 4000 pages of scientific literature, comprise the basis of this review, and are collectively referred to as “reviewed literature”. The Team also incorporated our existing understanding of the literature to support various conclusions, and these papers are cited as additional literature.

In reviewing the provided literature, the Sound Watershed Consulting Team focused on topics that have been less well studied, explore unresolved questions or management relationships, and generally inform variations in these functions specific to California forests, streams, and biota. The TAC outlined these unresolved issues through a series of Key Questions that were provided by the TAC.

For each riparian exchange function, Sound Watershed Consulting identified a team of 2-4 people who shared primary responsibility for reviewing the literature and documenting results. Each sub-team worked closely to compile the results for each exchange function. We believe this approach helped to ensure that our review is objective and independent. We selected the sub-team members based on their experience with each riparian exchange function.

The reviewed literature offered some interesting information relevant to riparian science and management. However, we found that many of the papers had limited value in specifically addressing the key questions. In many cases, there simply may not be studies available that address some of the details implied by the key questions.

In several cases, the SWC Team found it somewhat cumbersome to provide responses for the Key Questions. While the key questions appear to have been posed in a manner that maintained objectivity, we often found that the scope and scale of the questions were often quite broad. We could have described considerably more detail than we did, including various exceptions, variations, requirements, and other complexities associated with these functions. However, in the interest of creating a more readable document, we opted for clarity over detail. We refer those interested in more detail to the original literature.

Our responses to the Key Questions sought to outline the predominant trends reported in the reviewed literature. No doubt that in some cases, our responses might have been more completely informed by additional literature. For example, there was very little information available in the reviewed literature related to hillslope hydrology processes that might inform riparian management in headwater streams. Some of these issues may deserve additional consideration.

One convention used in this study is the citation of "others" in reference to various statements throughout this document. We use this convention to indicate that some concepts are discussed by more papers than those specifically cited. A full citation of every relevant paper on these topics would overwhelm both the reader and the authors.

Throughout this review, we were struck by how much data and information is available from the reviewed literature to address specific management practices and prescriptive strategies for the benefit of salmonids. The broad nature of the key questions limited our ability to hone in on many of these details within the scope of this effort. However, we expect that more specific direction regarding the desired policy strategies for addressing these issues will guide those developing prescriptions, and that the reviewed literature can be viewed as a rich resource.

There is a lot more that could be done with this literature in terms of meta-analyses or more detailed literature reviews to inform specific policy objectives or prescriptions. The information and data available from the reviewed literature is rich, and this summary of the literature required often difficult decisions about what not to include. For example, both lateral and longitudinal source-distance relationships could be refined for various exchange functions based on geographic distributions, disturbance risks, or limiting biological factors.

Similarly, criteria for various localized objectives could be established to help identify variations in riparian management that provide improved conditions for salmonids and other species. For example:

- Where disturbance risks might be relevant
- identifying opportunities for increasing stem growth to expedite the conditions where tree diameters are more appropriate to the local stream conditions
- identifying locations where nutrient objectives might be locally more important than wood recruitment objectives
- etc.

Riparian Functions in Support of Salmonid Habitats

It is widely accepted that salmonid habitat can be impacted by forest management. Forested riparian ecosystems influence physical components of streams, including temperature dynamics, water quality and quantity, sediment supply and deposition, food web resources, and instream habitat heterogeneity (CBOF-TAC 2007). Because of these diverse functions, riparian forests help to maintain high-quality instream habitats that are necessary for salmonids and other aquatic species with specialized habitat requirements (Salo and Cundy 1987; others). Thus, regulations governing the management of riparian buffer widths lie at a nexus between environmental, societal, and land development interests, and can yield especially contentious debates among stakeholders.

Government agencies have struggled with how to define and classify small streams and to specify the kinds of protection they should be afforded. As a consequence, there are marked differences in riparian forestry practices and management among jurisdictions throughout North America, and even within the Pacific Northwest, where one should expect some level of congruence given the commonalities in governing conditions (Young 2000; others). Despite the importance of these processes there remains much debate about how specific management actions can either benefit or impact aquatic conditions for salmonids. This study is intended to support policy deliberations through an objective review of relevant literature regarding riparian exchange functions important to salmonids.

The focus of this study was on the dynamics of riparian exchange functions that are important to salmonids. Much of the focus of this study is on the riparian contributions, including details regarding processes and mechanisms that affect the delivery of these functions to the stream environment. This study assumes that these functions are essential to salmonid ecology, and thus does not spend much time exploring the interaction of these functions to salmonids. Instead the focus is on exploring the dynamic interactions between forest practices, the riparian community, and the stream environment. For more information about the biological and ecological instream functions, we refer the reader to Salo and Cundy (1987); Naiman and Bilby (1998); Gregory et al (2003).

BIOTIC AND NUTRIENTS - riparian biotic and nutrient exchange is important to the growth and survival of juvenile salmonids. Key inputs include a) light and nutrients (including dissolved organics), and b) inputs of particulate organic matter and terrestrial invertebrates. These processes are important management considerations necessary to sustain and/or enhance salmonid populations (Bilby and Bisson 1991).

HEAT- There are several reasons to be concerned about increased stream temperatures in the forest environment. Fishery impacts are generally considered to be the most important. Elevated stream temperatures can reduce salmonid juvenile survival rates and lower the abundance and diversity of food organisms for fish (Beschta et al 1987). High water temperatures increase the metabolic rate of fish, increase the number of pathogens attacking them, and decrease the dissolved oxygen content of the water. These problems are most pronounced in the late summer months, when streamflows are very low and there is a large amount of solar energy available to heat the water. Temperature changes which can occur from logging often result in indirect or sublethal effects on fish populations (Holtby 1988). Examples of these types of impacts include the decrease in the emergence time of fry from gravels, and also earlier, less favorable smolt migration to the sea. Other reasons for concern about high stream temperatures exist as well. They include the increase of algae production, reducing the esthetic qualities of the water (Amaranthus 1984).

WATER- The flows of water through a catchment influence a broad range of processes, including soil erosion, biogeochemical cycling, and in-channel sediment transport. Forestry operations such as harvesting and road construction can have a significant impact on hydrology at the site, hillslope, and catchment scales. There is ongoing, vigorous debate surrounding these influences, and they need to be considered in relation to managing forest harvesting in small catchments. In terms of aquatic habitat, the key concerns relate to changes in summer low flows and in peak flows and their effects on channel stability and sediment transport.

WOOD – woody debris in streams and rivers has been recognized as an important component in aquatic ecology, fishery habitat biology, geomorphology, hydrology, and forestry over the past several decades (Gregory et al 2003). Woody debris in streams regulates and stores dissolved and particulate matter and creates temporary reservoirs of coarse sediment, thereby altering local channel gradients and channel morphology (Salo and Cundy 1987; Sullivan et al 1987).

SEDIMENT- the influence of timber harvest on erosion and sediment supply to streams has been a major research topic over the last 40 years, and has contributed to development of forest practice rules designed to mitigate erosion. In California like elsewhere, sediment is delivered to streams by bank erosion, landsliding, and surface erosion following fires or after other ground disturbances, including forestry activities (Benda et al 2005; Hassan et al 2005; Gomi et al 2005).

These are just a few of the ways that riparian forests support salmonid habitat functions. A complete exploration of salmonid ecology is beyond the scope of this paper. Instead, the focus of this report is on the delivery of key exchange functions to the stream environment, and how riparian management can ensure that these functions are supported.

In the following chapters, we explore several key issues associated with the ways that management can affect these exchange functions.

ABOUT THE SOUND WATERSHED CONSULTING TEAM

Sound Watershed Consulting compiled a team of professional scientists with proven experience in forest watershed science and management. The members of this team each have advanced degrees in watershed sciences and have provided technical support to forest management issues in a wide variety of jurisdictions throughout western North America and Southeast Asia. Our team includes:

Mike Liquori, MS, CEG - PROJECT MANAGER

Principal, Sound Watershed Consulting

Mike Liquori has over 14 years of professional experience as a forest watershed geomorphologist and hydrologist with a strong background in watershed ecology and stream corridor restoration. He has extensive knowledge of the management of forest riparian landscapes, and has had responsibilities for directing watershed management on over 860,000 acres of private forestlands in California, Washington and Oregon. He has chaired or participated on several scientific technical committees in support of forest policy objectives. He has applied his multi-disciplinary expertise to resolve management challenges associated with state-wide forest policy (Washington's Forests & Fish Plan), non-industrial private forests (Washington Rural Technology Initiative), watershed management strategies for several large industrial forestland owners, sustainable forestry audits (SFI), habitat conservation plans and restoration projects.

Mike has helped develop a number of forest regulations and guidance documents addressing riparian management, road maintenance and abandonment, forest slope stability, channel migration zones, fish passage, channel typing, forest wetlands, erosion controls, and various Best Management Practices. He has led numerous management projects in watershed analysis, land-use planning, restoration design and scientific research. He has well-developed field interpretation skills which he uses to diagnose and evaluate hydrologic, geomorphic and ecological processes. Mike has taught courses in Forest & Fisheries Interactions, River Ecology and Wildland Hydrology at the University of Washington.

Mr. Liquori contributed to all chapters in this document. He was a primary author for the water, wood, sediment and synthesis chapters, and provided support to the Heat and Biotic & Nutrient chapters. He also provided senior editorial review for the entire document.

Doug Martin, PhD

Principal, Martin Environmental

Dr. Martin is a fisheries biologist with extensive multi-disciplinary experience in forest management all along the Pacific region. He has been an active co-chair of the Washington State Forest Practice Board's Cooperative Monitoring, Evaluation & Research Committee since 2000, where he has lead state-wide adaptive management programs addressing the impacts of forestry on clean water and salmonid habitats. Dr. Martin was a key scientific advisor to the Washington State Forest & Fish Plan. He has been a principal investigator for several long-term research programs in Alaska and Washington State addressing the use and application of riparian buffers in forestry. Dr. Martin's extensive knowledge of the literature, along with his unique experience across each of the Riparian Exchange Function disciplines makes him a key asset for this project. Dr. Martin's primary contributions were to the Biotic and Nutrient, Heat and Synthesis chapters.

Bob Coats, PhD,

Principal, Hydroikos & Adjunct Research Professor, UC Davis

Dr. Coats has 35 years of experience focusing on the hydrologic and ecological effects of land management on aquatic ecosystems. This work has concentrated in two areas: wetlands and forested watersheds. In both areas, he has drawn on his background in hydrology, ecology, and soil science. His long-term research interests are focused on nitrogen cycling and biogeochemistry at the watershed level.

In the area of forested watersheds, his experience includes research on the effects of land disturbance on water quality; evaluation of the effects of silvicultural activities on both site quality and water quality; review of proposed timber harvest plans and National Forest plans; reclamation and hydrologic aspects of strip mining in arid lands; evaluating the hydrologic and water quality effects of hydropower projects; and developing monitoring programs and habitat conservation strategies for two Habitat Conservation Plans (pursuant to the Endangered Species Act) in north coastal California.

Dr. Coats primary contributions included the Biotic and Nutrient, Water, Heat, and Synthesis chapters.

Lee Benda, PhD

Principal, Lee Benda & Associates

Lee is a world-renowned geomorphologist with extensive knowledge of the forest landscape in California and the Pacific Northwest. In addition to analyzing effects of human land uses on environments, Dr. Benda also endeavors to place human disturbance within the context of natural disturbance, including storms, fires, and floods. This approach has led to a series of contributions in the watershed sciences with implications for resource management, conservation, regulation, and restoration. Benda has been a leader in the development of interdisciplinary analytical tools, like NetMap, that can be used to investigate the naturally dynamic behavior of watersheds and human's interaction within it. Dr. Benda has also pioneered the development of watershed analysis methods and has extensively studied the interaction of wood, sediment and streams. His primary contributions include the Wood and Sediment chapters.

David Ganz, PhD,

David Ganz currently leads the work of the 19-person Global Fire Initiative, for The Nature Conservancy which is focused on abating fire-related threats to biodiversity around the world. David is an expert in fire science, policy and management who also has experience integrating fire with some new and emerging conservation opportunities like sustainable livelihoods, climate change adaptation, ecosystem services, biofuels, avoided deforestation and community forestry.

He has worked for United Nations' FAO at the Regional Community Forestry Center in Bangkok, Thailand, managing a variety of projects focused on Southwestern China and Southeast Asia. More recently, he was a senior scientist in charge of forestry and fire science projects for TSS Consultants and vice president of international operations for the Renewable Energy Institute. Recent projects have included organizing and facilitating both the China E5 Biofuels Assessment and the Pinchot Institute's independent science review of the Quincy Library Group pilot project.

Dr. Ganz's doctoral research in the Sierra Nevada evaluated the forest health and management implications of various prescribed burning and thinning treatments. More recently he has focused on facilitating processes in which local communities have substantial involvement in deciding the objectives and practices involved in preventing, controlling or utilizing fires. He has published more than 30 papers in technical journals with a primary focus in the fields of fire science, forest health, silviculture and community forestry.

Dr. Ganz provided support to the Wood, Sediment and Synthesis chapters.

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Sound Watershed Consulting

Creating Functional Water Environments

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

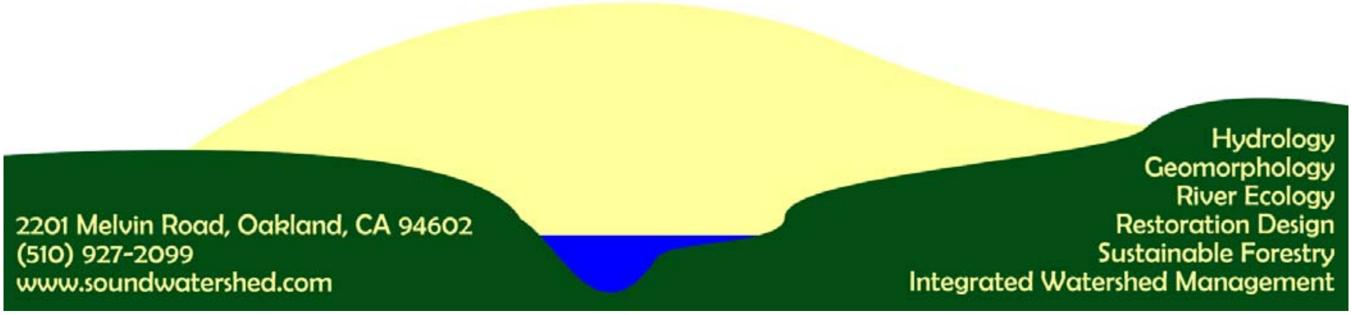
Chapter 2

BIOTIC & NUTRIENTS

for

The California State Board of
Forestry and Fire Protection

September 2008



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2) BIOTIC & NUTRIENT 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

Prepared by:

Dr. Doug Martin

Dr. Robert Coats

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with

Dr. Lee Benda

Dr. David Ganz

September 2008

SWC Ref# 1013

Table of Contents

SUMMARY OF TABLES & FIGURES

EXECUTIVE SUMMARY

This document represents a comprehensive review of 31 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 2007b)
- 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 biotic and nutrient exchange functions

The literature on biotic and nutrient exchange tells us that litter produced in the riparian zone is an important food source for benthic macroinvertebrates , and thus indirectly supports salmonid production. But the quality of litter—its nutrient content and decomposition rate—are as important as the quantity of litter production. Alder produces “fast” (easily decomposed) litter that is rich in nitrogen; maple, willow and cottonwood produce litter of intermediate quality; conifers and oaks produce litter of lower quality and greater resistance to microbial decomposition. The timing of the life cycles of some benthic macroinvertebrates is thought to be synchronized with the production of different litter types.

Alder is not only beneficial to benthic macroinvertebrates, but supports a rich supply of terrestrial insects that fall into a stream from the riparian zone.

Opening the canopy cover over a stream and increasing light intensity has lead in many cases to increased primary (algae growth) and secondary (benthic macroinvertebrate) productivity, which is often beneficial to fish growth and production. In some cases, depending in part on nutrient supply, increased light can shift the dominant algae from diatoms to filamentous green algae, which are less desirable for macroinvertebrates and thus for fish. In opening the canopy over a stream there may be a trade-off between increasing aquatic productivity, which is beneficial to fish, and increasing water temperature, which may be detrimental to fish (see heat chapter)

Small floods increase the supply of food for salmonids by both washing food into the stream, and making flooded areas temporarily accessible for foraging (see water chapter).

A 30 meter wide buffer strip on both sides of a stream (with both equipment exclusion and no tree removal) generally reduces local impacts to a stream that are similar to a “no harvest” level. Completely excluding vegetation management in the buffer strip, however, may forego opportunities to increase fish growth rate and biomass, and to reduce fuel loads.

Topography, geomorphology, regional geography, and associated disturbance regimes strongly influence the vegetative characteristics of riparian zones. The shape and type of these natural landforms may be helpful in guiding buffer configurations including widths and other characteristics (e.g. structure, orientation, density, etc).

The literature suggests that active riparian management could benefit aquatic productivity with silvicultural prescriptions that are designed to enhance temperature regimes, aquatic primary productivity, woody debris recruitment, and reducing fuel loads. These prescriptions could continue to protect streams from known impacts (e.g., erosion from heavy equipment, excessive shade loss), by strategically locating management activities and sizing treated areas to prevent damage yet promote favorable biotic responses. The timing of such riparian management activities could also be scheduled to reduce risk and optimize favorable riparian stand characteristics across a stream network.

RECOGNIZED EXCHANGE FUNCTION ROLES & PROCESSES

The vegetation of riparian zones in forested environments regulates the flow of organic and inorganic nutrients, radiant energy and heat to the aquatic environment. These fluxes of nutrients and energy have major effects on the production of salmonids and other aquatic organisms. Some important principles to consider in understanding the biotic and nutrient exchange function are:

- Primary productivity in streams may be limited by nitrogen, phosphorus or light. In streams of north coastal California and in Oregon, nitrogen is often limiting, though elsewhere phosphorus may be more important (Allan, 1995). Gregory (1979) showed that light was limiting in Oregon streams, even at trace nutrient concentrations of nitrogen and phosphorous.

- Opening the riparian canopy may increase primary productivity, and biomass and diversity of aquatic invertebrates, and biomass of fish (Kiffney and Roni, 2007; Danehy et al, 2007; Bottorff and Knight, 1996).

- Increased light sometimes stimulates growth of filamentous green algae, which may be less palatable to some aquatic invertebrates than diatoms (Shortreed and Stockner, 1983).

The quality of riparian litter determines its susceptibility to decomposition and its availability to aquatic invertebrates. Alder litter is the most available and nutritious, followed by litter of other deciduous species. Conifer litter is generally less available and more difficult to process (Allan, 1995; Cummins 2002).

- In small fish-bearing streams, terrestrial invertebrates account for about half of the diet of salmonids during the summer and early fall (Wipfli, 1997; Allan et al., 2003)

- Biotic productivity in streams with conifer-dominated buffer strips that are wider than about 30 m (100 ft) is similar to that observed in an unlogged forest (Newbold et al. 1980, Castelle and Johnson 2000, Moldenke & Ver Linden 2007). Riparian stands dominated by deciduous vegetation (overstory and understory) within 10 to 20 m (33 to 65 ft) of the stream may increase biomass of consumers, including fish, as a result of nutritious litter inputs and terrestrial invertebrate subsidy (Allan et al. 2003, Richardson et al. 2004, Wipfli & Musselwhite 2004, Hoover et al. 2007).

RESPONSES TO KEY QUESTIONS

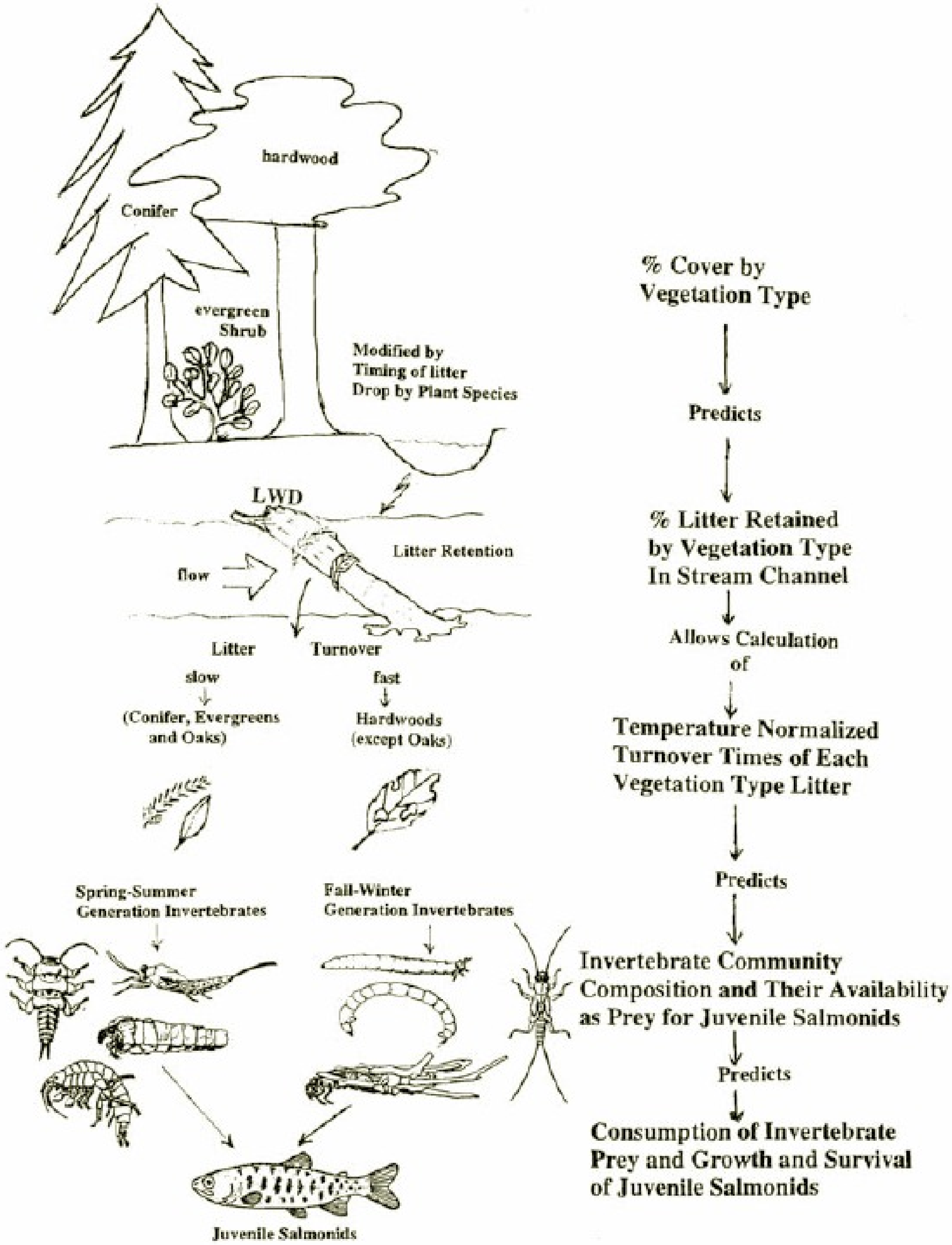
1. How can management (manipulation) of the riparian area lead to the establishment and maintenance of algal stream communities most beneficial to juvenile salmonids?

In a study in Carnation Creek, B.C., Shortreed and Stockner (1983) found that logging without protection of the riparian zone increased patchy accumulations of filamentous green algae, although these accumulations were not reflected in chlorophyll samples from artificial substrates. Nutrient addition experiments in Carnation Creek increased the abundance of filamentous green algae under low light conditions, indicating that phosphorus concentrations were the factor limiting primary productivity. Following logging, the increased light intensity and nitrogen concentrations had little effect on the periphyton community because logging did not increase P concentrations, except sporadically during high flow events. Shortreed and Stockner note that some streams in Oregon have shown an increase in filamentous green algae following logging, although diatoms frequently remain the dominant algal form.

In a study in the Oregon Coast Range, Danehy et al. (2007) found that diatom assemblages dominated sampled streams in clearcuts, thinned and old-growth stands, with substrate the most important variable influencing assemblage characteristics. Clearcut sites had higher invertebrate abundance, more Chironomid taxa, and higher invertebrate biomass than the thinned or uncut sites. There was no shift from diatoms to filamentous green algae.

Periphyton assemblages in streams change seasonally and are influenced by water velocity (Murphy and Meehan 1991). Diatoms dominate in areas of high velocity and peak production generally occurs in spring before riparian leaf-out and in autumn after leaf-off. Filamentous algae occur in low velocity areas and biomass generally peaks in spring and early summer. Filamentous algae may accumulate during the summer low-flow period when velocity declines and is washed downstream with the onset of increased flows in fall. These velocity related distributions for periphyton probably influenced the algal assemblage responses that were observed by the logging related studies. Flow strongly influenced algal biomass in Carnation Creek and the summer low-flow period delineated the algal growing season. Scour from frequent freshets throughout the rest of the year caused uniformly low accumulations of periphyton.

Figure 1. Riparian biotic and nutrient transfers and exchanges process relative to growth and survival of juvenile salmonids (CBOF-TAC 2007)



However, it does not appear that maintaining a closed canopy will maximize the productivity of juvenile salmonids. In streams in the Smith and Klamath River basins, Wilzbach et al. (2005) experimentally removed riparian tree canopy and added salmon carcasses in a factorial experiment to determine the relative effects of increased light and nutrients on density and biomass of rainbow and cutthroat trout. They found that increased exposure of the streams was very effective in increasing fish productivity, whereas carcass addition was not, and that increased primary productivity “appears to be the most important trophic pathway for increasing the availability of aquatic macroinvertebrates preferred by salmonids during spring and summer.”

Modenke and Ver Linden (2007) found that canopy removal increased the biomass and density of certain types of aquatic macroinvertebrates. They (like Nakano and Murakami, 2001) emphasized the importance of the emerging insects not just to fish but also to terrestrial predators. Kiffney and Roni (2007) found that light intensity at the stream surface and its interaction with other physical variables were important factors in explaining the variance in aquatic invertebrates species richness and biomass, and in fish biomass, although they did not measure the inputs of organic matter and terrestrial insects from outside the stream environment.

In a study of the effects of clearcut logging on stream biota at Caspar Creek (Jackson State Demonstration Forest, CA), Bottorff and Knight (1996) found increased chlorophyll-a and algal biomass; doubling of alder leaf decay rate for 2 yrs; increased macroinvertebrate density and diversity, EPT density and diversity, and chironomid density. They suspect that these changes were a result of changes in light conditions and possibly changes in nutrients or temperature. The North Fork Caspar Creek study area was protected by a riparian buffer zone that was 30 to 60 m wide with selective tree harvest in the outer portion of the zone. Post-harvest windthrow also reduce riparian stand density (4-30 % mortality; Reid and Hilton 1998).

A. WHAT RIPARIAN STAND CHARACTERISTICS ARE MOST LIKELY TO PRODUCE LIGHT AND NUTRIENT CONDITIONS THAT FAVOR A PERIPHYTON COVER DOMINATED BY DIATOMS AND SINGLE-CELL OR SMALL COLONY GREEN ALGAE BUT WILL AVOID (THAT IS, REMAIN BELOW THE THRESHOLD FOR) A COMMUNITY SHIFT TO FILAMENTOUS ALGAL FORMS?

Maintaining a vegetated riparian corridor with exchange between surface flow and the hyporheos will help to maintain dissolved nitrogen concentrations below levels that are likely to stimulate filamentous green algae (Poor and McDonnell, 2007). Thus it appears that the best way to avoid a shift from diatoms to filamentous green algae in a stream following timber harvest is to maintain an intact riparian corridor that:

1. maintains moderate to low light intensities on the water surface;
2. maintains a strong exchange of surface flow with the hyporheic zone;
3. limits introduction of phosphorous into the riparian environment;
4. limits deposits of fine sediment that form a medium for vascular plants within the active stream zone.

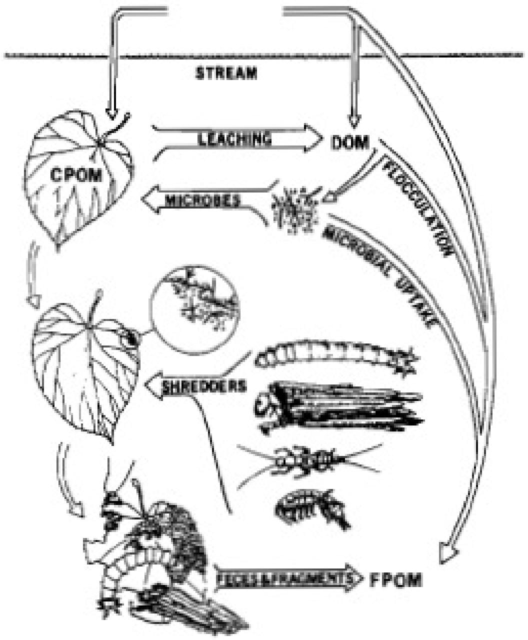
Kiffney and Roni (2007) suggest that supporting biological productivity is essential, and perhaps more important than maintaining physical exchange functions. Several studies suggest selective thinning of the riparian canopy as a way to increase aquatic macroinvertebrate production and thus food availability for salmonids (Wilzbach et al. 2005; Kiffney and Roni 2007; Modenke and Ver Linden 2007) The riparian stand characteristics most likely to achieve these functions would include:

1. a sufficient number of nitrogen-fixing deciduous trees distributed at key locations within the stream network;
2. a sufficient number of riparian canopy gaps that support primary and aquatic macroinvertebrate production while balancing effects on other riparian functions.

2/3. How can management (manipulation) of the riparian area lead to rapid processing (turnover) of riparian litter in the stream and a mix of litter inputs that favors the components of invertebrate prey organisms to yield higher growth rates and densities of juvenile salmonids?

Before litter derived from outside of stream can be processed by aquatic invertebrates, it must undergo the initial stages of breakdown and decomposition. These include leaching loss of dissolved organic and ionic material, and colonization by bacteria and fungi. Litter can be classified as fast, medium and slow, depending on the relative rate of the initial breakdown (CBOF TAC 2007). Alder and basswood produce fast litter, maples and hickory produce medium litter, and most conifers, oaks and ericaceous shrubs produce slow litter (Cummins, 2002). Alder litter is enriched in nitrogen because it has symbiotic root nodules that fix atmospheric nitrogen. As with the decomposition of litter on the forest floor, the nutrient content (especially the carbon:nitrogen ratio) is a key variable. Where the C:N ratio is wide, the initial microbial attack on cellulose is limited by the supply of readily-available nitrogen. Lignin, tannin and hydrophobic substances may also play a role is slowing the decomposition of conifer and ericaceous litter. Fungal species composition and richness in headwater streams are strongly influenced by both species composition of riparian vegetation, and by water chemistry (Meyer et al. 2007).

Figure 2. The sequence of litter fall (represented by a leaf) into a stream through leaching of dissolved organic matter (DOM), microbial colonization (especially by aquatic hyphomycete fungi), and shredder feeding on the conditioned leaf litter (Cummins 2002).

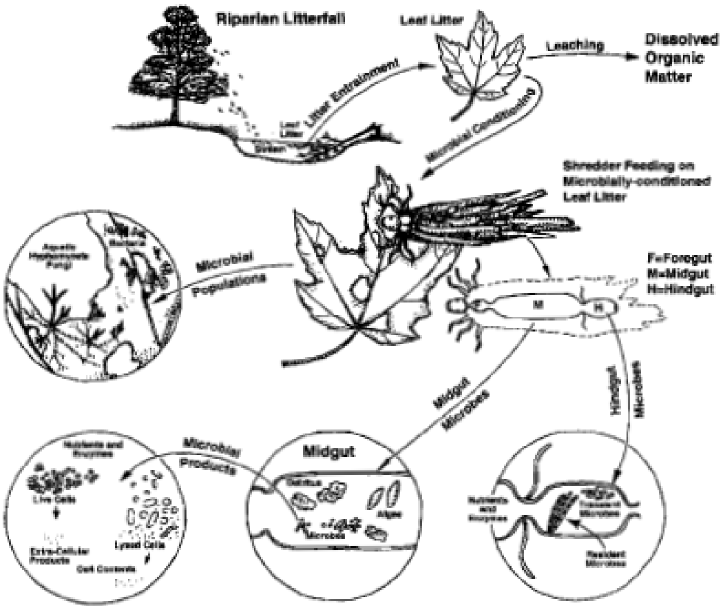


Richardson et al. (2004) measured the rates of breakdown and invertebrate colonization of western red cedar, western hemlock and red alder litter in a small coastal rainforest stream in British Colombia. They found that alder litter, with an N concentration nearly twice that of the conifer litter, lost mass 40-100% faster. During summer, hemlock lost mass faster than cedar, but in autumn the reverse was true. There were no differences between litter types in density of invertebrates per gram of leaf tissue, although alder litter consistently had higher numbers.

A. WHAT RIPARIAN VEGETATION STAND CHARACTERISTICS ARE MOST LIKELY TO PRODUCE NUTRIENT CONDITIONS THAT FAVOR DEVELOPMENT AND RAPID GROWTH OF HYPHOMYCETE FUNGI COLONIZING LEAF/NEEDLE LITTER?

The TAC literature does not provide much additional information concerning the environmental conditions that are conducive for fungal growth other than that presented in the answer to Question 2 above. This limited information is consistent with one other review paper (Murphy and Meehan 1991) in showing that nutrients in stream water and in liter (i.e., nitrate and phosphate) are important for microbes to build proteins as they digest carbon compounds from leaf litter. This would suggest that nutrient inputs, especially nitrogen from alder fixation, may favor fungal growth and boost litter conditioning in streams.

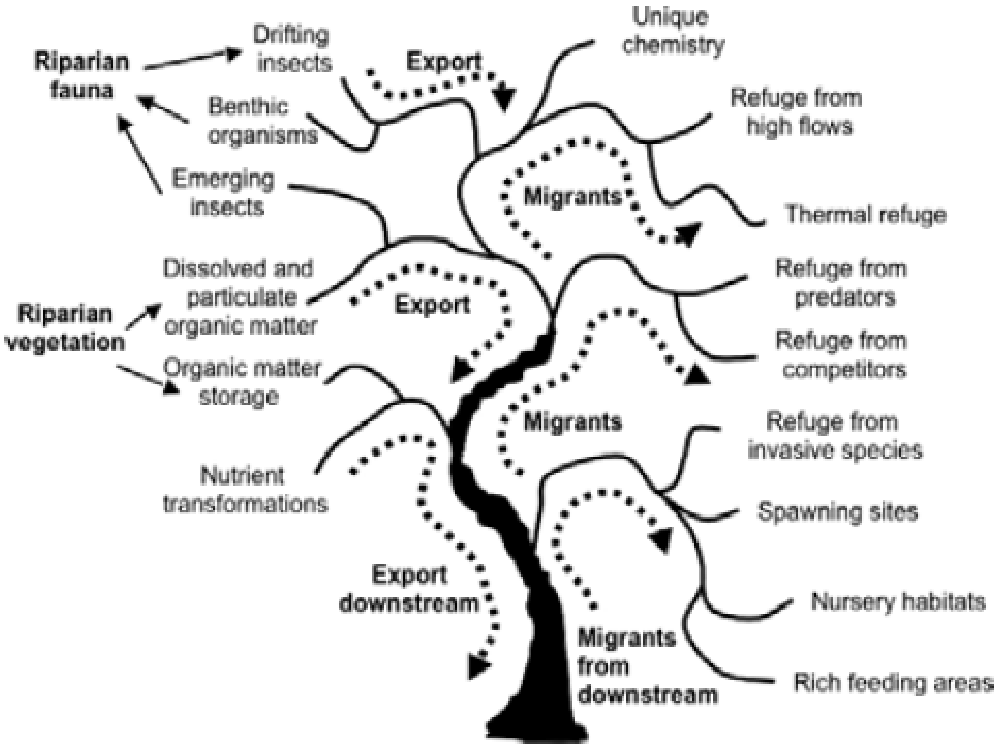
Figure 3. Importance of stream microbes and resident gut flora to shredders in providing assimilable materials including those refluxed forward from the hindgut to the midgut (Cummins 2002).



B. WHAT RIPARIAN VEGETATION STAND CHARACTERISTICS ARE MOST LIKELY TO PRODUCE THE BEST MIX OF FAST (RAPID PROCESSING RATES) AND SLOW (SLOW PROCESSING RATES) OF LITTER TRANSFERRED TO THE STREAMS?

The literature is consistent in showing that aquatic invertebrate assemblages are closely associated with litter composition (deciduous and conifer) and that alder is an important contributor of readily available and nutritious litter. Wipfli and Musslewhite (2004) found (in SE Alaska) that small fishless headwater streams dominated by red alder contributed more detritus and more aquatic invertebrates to downstream fish habitat than did tributaries not dominated by alder Invertebrate export was significantly correlated with the percentage of alder canopy cover. Similarly, Romero et al. (2005) showed that invertebrate drift under deciduous and mixed canopies was about 30% more abundant than under conifer in Oregon coastal streams.

Figure 4. Factors that contribute to the biological importance of headwater streams in river networks. Attributes on the right benefit species unique to headwaters and also make headwaters essential seasonal habitats for migrants from downstream. On the left are biological contributions of headwater ecosystems to riparian and downstream ecosystems.



Since we do not know what the optimum mix of fast and slow litter, it may be unrealistic to expect foresters to manage vegetation in the riparian zone specifically to create the optimum mix. However, an effective management goal for riparian vegetation may be to maintain a diverse mix of species that is spatially and temporally compatible with natural landscape features and timber management plans. For example, floodplains are naturally dominated by a deciduous plant community as a result of frequent disturbance (Rot et al. 2000). Targeted management in these settings may be one place where managing for red alder can support salmonids.

To apply such a strategy, alder patch size (length and width) and distribution could be based on the shape and spatial patterns of floodplain landforms within a drainage network. Similarly, alder patches may be targeted for tributary junctions (natural disturbance areas) of headwater stream segments that feed directly into fish bearing waters. Alder may be promoted in other riparian areas that have low site potential for conifer production, but would support alder because of its nitrogen-fixing ability.

Riparian alder patches may also be strategically located where their replacement of conifer does not have a significant influence on the recruitment of woody debris (e.g., along incised channels where the lack of bank erosion limits wood recruitment), but where biotic inputs are rapidly transported downstream to consumer communities. In California, three species of alder are important: red alder (*Alnus rubra*), white alder (*A. rhombifolia*) and mountain alder (*A. tenuifolia*). Red alder dominates near the coast, especially in the North Coast region. White alder is more common in riparian zones inland and at higher elevations. Mountain alder is found between about 8000 ft (south) and 3000 ft (north). Sitka alder (*A. sinuata*) occurs in Del Norte, Humboldt and Siskiyou counties. All of these species are nitrogen fixers, though the rates of fixation vary with tree biomass and environmental conditions.

4. What mix of riparian vegetation is most likely to produce the best populations of terrestrial invertebrates that are an important seasonal food source for juvenile salmonids?

In their study on the effect of red alder density on invertebrate and detritus subsides to downstream fish habitat, Wipfli and Musslewhite (2004) found that three-quarters of the macroinvertebrates were of aquatic origin, and one-quarter were terrestrial. The downstream flux of aquatic macroinvertebrates was directly related to alder density and basal area, but the flux of terrestrial macroinvertebrates was not.

Wipfli (1997) collected terrestrial macroinvertebrates and leaf fall in traps placed along streams in Southeast Alaska, including old-growth and young-growth stands, and sampled the stomach contents of salmonids. He found that terrestrial macroinvertebrates accounted for about half of the fishes' summer diet, and salmonids from young-growth sites ingested a higher proportion of terrestrial macroinvertebrates than fish from old-growth sites. The variability was too high and sample size too small to detect stand differences in terrestrial macroinvertebrates vs. aquatic macroinvertebrates input.

Allan et al. (2003) also found that terrestrial macroinvertebrates accounted for about half of the diet of coho salmon is Southeast Alaska. Their traps placed beneath red alder, and conifers (western hemlock (*Tsuga heterophylla*) and Sitka spruce (*Picea sitchensis*)) captured higher biomass from the former than from the latter. Sampling of stems of six plant species found much higher biomass of terrestrial macroinvertebrates on deciduous (trees and shubs) than on coniferous trees. These findings are corroborated by studies in coastal Oregon where Romero et al. (2005) found that terrestrial inputs to invertebrate drift in streams with deciduous and mixed canopies was 30% more abundant than in streams with conifer canopies. They also showed that trout diet during summer-fall and prey availability were strongly related to shrub cover and somewhat less strongly linked with deciduous canopy.

The supply of terrestrial macroinvertebrates has been related to the degree of stand openness. In north-central British Columbia, Hoover et al. (2007) found that the drift density of aquatic insects was higher in uncut sections than in sections with 10 m buffers, but drift of terrestrial insects was directly related to stand openness. Terrestrial drift density was greater in clearcut reaches relative to buffered reach, and greater in buffered reaches than uncut reaches. Apparently early-stage successional vegetation produced more terrestrial macroinvertebrates that found its way to the stream when compared to late seral vegetation.

The differential timing of inputs of terrestrial and aquatic production demonstrates the relative importance of terrestrial inputs to salmonids, especially during summer. In Japan Nakano and Murakami (2001) found that salmonid diets were dominated by aquatic insects during winter-spring when terrestrial insect emergence was low and shifted to terrestrial insects during summer-fall, when the terrestrial emergence peaked and aquatic invertebrate biomass was nearly at its lowest. For several salmonid species, they found that the proportion of terrestrial prey in the diets during leafing seasons was much greater than that during defoliation periods. Similarly, Romero et al. (2005) found that terrestrial prey was most common in the diet of cutthroat trout during summer and fall when aquatic prey was relatively less abundant in Oregon coastal streams.

Although terrestrial derived food inputs are clearly important during summer, they can also be an important component for salmonids during winter. For example, in northern California White and Harvey (2007) found that earthworms flushed into streams during winter peak flow events contributed a major portion of the winter energy budget of cutthroat trout. It is not clear how riparian vegetation composition influences oligochaetes, but their occurrence during peak flows indicates an important linkage to the forest floor (e.g., floodplains) and suggests that riparian litter composition (e.g., deciduous litter from hardwoods) may play an important role. Winter flooding may also allow juvenile salmonids access to a wider range of food resources. For example, in Pudding Creek (western Mendocino County) Pert (1993) found that juvenile salmonids had fuller stomachs during winter high flow conditions than at other times.

The literature clearly shows that inputs of terrestrial insects are significantly enhanced by riparian deciduous trees and understory shrubs. Deciduous riparian stands and thinned conifer stands with understory shrubs both promote terrestrial insect fallout that subsidizes the summer-fall diet of juvenile salmonids. Terrestrial inputs of arthropods are less important during winter, but other terrestrial subsidies (e.g., earthworms) could play an important role for salmonids.

As stated above, the best mix of riparian vegetation is not explicitly addressed in the literature. The only conclusion, for now, is that more deciduous vegetation the better for terrestrial derived inputs. However, the trade-offs in terms of shade or reduced wood recruitment will need to be balanced against the gains of terrestrial subsidies. Perhaps the conifer-deciduous mix may be allocated in a longitudinal sequence of alternating patches of vegetation, rather than mixing conifer and deciduous at the same location. The riparian patch sequence may not have a specific dimension, but rather be determined by forest site potential and in disturbed areas, as suggested above. We discuss this in more detail in the Synthesis section (Chapter 7) of this report.

5. What riparian buffer width is required to achieve desired conditions of algal growth (question 1), litter turnover (question 2), and invertebrate prey for juvenile salmonids (questions 3 and 4)?

The studies that evaluated biotic productivity (i.e., periphyton, aquatic invertebrate, terrestrial invertebrate, and litter) responses to different buffer treatments offer some insight to the buffer width question. These studies show that algal biomass and invertebrate prey biomass generally increase with increasing canopy openness and/or increasing densities of deciduous vegetation (Wipfli & Musselwhite 2004, Danehy et al. 2007, Hoover et al. 2007; Table 1). Autotrophic production responds most with an open canopy and heterotrophic production responds most to a full canopy consisting of red alder. Biotic responses to moderate light levels or to deciduous vegetation ingrowth appears to be detectable in buffers that range from 10 m to about 20 m wide, especially in defoliated or thinned buffers (e.g., Danehy et al. 2007, Hoover et al. 2007) or in regenerated riparian stands (12 to 27 years old; Moldenke & Ver Linden 2007). Biotic productivity in streams with conifer-dominated buffer strips that are wider than about 30 m is similar to that observed in an unlogged forest (Newbold et al. 1980, Castelle and Johnson 2000, Moldenke & Ver Linden 2007).

In addition to the buffer width studies, our knowledge of the underlying mechanisms of how riparian conditions influence aquatic productivity can be used to guide buffer width decisions. As described in the Heat Section, light input to streams is controlled by the height and density of the riparian timber stand (primarily within 10 m of the stream; Sridhar et al. 2000) and is poorly associated with buffer width (Beschta et al. 1987). Also, the relative influence of buffers on light level varies with stream width; narrow streams can be heavily shaded and shade potential declines with increasing stream width. Therefore management of riparian stands to improve algal productivity might best be directed at stand density management immediately adjacent to small and moderate size streams. Increasing light input by stand thinning, is one approached that is suggested by the TAC literature (Danehy et al. 2007, Wipfli 2005 Wilzbach et al. 2005) to increasing aquatic productivity.

The literature clearly shows that aquatic macroinvertebrate production and terrestrial macroinvertebrate inputs are strongly influenced by the riparian vegetation complex and that deciduous vegetation, especially alder, is a high quality energy source (Primer, Allan et al. 2003, Richardson et al. 2004, Wipfli & Musselwhite 2004, Hoover et al. 2007). Although the riparian source distances for litter or terrestrial macroinvertebrates are not quantitatively addressed in the literature, it is reasonable to assume that stream adjacent trees and shrubs, especially overhanging vegetation, are probably the most important contributors of litter and terrestrial insect fallout.

Table 1. Summary of case study findings that evaluated flora and fauna responses to riparian buffer strips.

Reference & Location	Treatment	Response
Danehy et al. 2007 Coastal OR	Compared headwater streams with: clearcuts 2-8 years old, thinned 200 trees/ha and no harvest inner 15 m, uncut mature 2nd growth	Clearcut and thinned had higher diatom biomass than uncut sites, and clearcut had higher invertebrate biomass than thinned or uncut sites. Little difference in community assemblage between thinned and uncut
Wipfli & Musselwhite 2004 Southeast AK	Compared headwater streams with range of riparian red alder density (1–82% canopy cover or 0–53% basal area) within regenerated young-growth conifer stands (45-yr-old)	Aquatic and terrestrial invertebrate export (biomass and density) from headwaters is significantly correlated to percentage alder canopy cover
Hoover et al. 2007 North-central BC	Compared headwater streams with: uncut old-growth, 10 m foliated reserve strips, 10 m insect defoliated reserve strips, Clearcuts 4-8 years old	The degree of openness of the riparian reserve strip (clear cut > 10 m defoliated > 10 m foliated) was associated with increased and more variable terrestrial invertebrate drift, and decreased and more variable aquatic invertebrate drift
Moldenke & Ver Linden, 2007 Cascades OR	Compared headwater streams with: clearcuts 12-27 years old, 30-m buffers12-27 years old , no harvest	Canopy removal increased the biomass and density of total EPTs and all feeding guilds except scraper. No change in EPT yield between buffered and mature forest
Newbold et al. 1980 Northern CA	Compared: buffers < 30 m (range 3-25 m) buffers > 30 m (range 30-60 m), unlogged. Buffers in logged areas < 3 yrs old	Aquatic macroinvertebrate diversity was lower, and density was higher (mostly due to increases in Baetis, Nemoura, and Chironomidae) in narrow buffers compared to wide buffers or unlogged sites. Communities in streams with wide buffers not significantly different from unlogged.
Bottorff and Knight 1996 N. Fk. Caspar Creek, Mendocino Co.	Compared pre- and post-logging with 30-60m buffers, inner 15 m no harvest, out portion selective harvest. Post-harvest windthrow mortality ranged 4 to 30% Roads, skid trails and landings kept far from streams; steeper areas cable-yarded	Increased chlorophyll-a and algal biomass; doubling of alder leaf decay rate for 2 yrs; increased macroinvertebrate density and diversity, EPT density and diversity, and chironomid density.

Litter inputs to the stream are assumed to decline rapidly with distance from the stream bank. For example, FEMAT (1993) estimated that most litter input comes within 0.5 tree heights. Streambank erosion and flooding of the adjacent forest floor in flood plain areas is also assumed to be a significant source of litter and invertebrates. Therefore riparian management for high quality litter and terrestrial macroinvertebrate inputs would be most effective by maintaining stream adjacent (e.g., one tree crown width or about 10 m) deciduous overstory and understory vegetation, especially near streams with moderately confined or unconfined channels (i.e., locations susceptible to bank erosion and flooding). Management of riparian vegetation composition to promote aquatic productivity and enhanced fish production is suggested by researchers ranging from California to Southeast Alaska (Allan et al. 2003, Wipfli & Musselwhite 2004, Romero et al, 2005, Frazey & Wilzbach 2007).

Based on the foregoing, we infer that riparian management for a desired riparian condition that provides optimal algal growth, litter turnover, and invertebrate prey load to support juvenile salmonids would need to occur in a zone up to 30 m from the stream edge. Tree thinning to increase light or management for deciduous litter and terrestrial macroinvertebrates would be most effective on the inner-most portion (within 10 to 20 m) of the riparian stand.

6. What valley configuration (e.g. side slopes) and geomorphological characteristics (LWD, sediments, channel structures) set the boundaries for the buffer width required to achieve the objectives in question 5?

As we discuss in greater detail in Chapter 7, buffer width may not be the most effective variable for describing riparian functions. There is some evidence that buffer effectiveness may be better described by the structure, composition, characteristics and orientation of riparian buffers (Castelle & Johnson 2000; Young 2001).

Valley slope and confinement have been used as effective variables for delinating various regulatory domains (WA DNR 1997). These variables, when described within the context of network location and watershed disturbance regimes, strongly influence channel morphology and riparian landforms (Benda et al. 2004). Landforms (e.g., fans, floodplains, terraces) and associated disturbance regimes influence riparian stand composition and their spatial distribution in a riverine network (Naiman et al. 1998). For example, Rot et al. (2000) found that floodplains were dominated by deciduous species, especially red alder, but conifer dominated the overstory of other less disturbed landforms.

The shape and type of landform may be helpful in guiding buffer configurations including widths and other characteristics (e.g.

structure, orientation, density, etc). On landforms that are prone to flooding (e.g., floodplains, alluvial fans, tributary confluences) the width and shape of the flood prone zone delineates the riparian stand area that is functionally linked (i.e., through nutrient and organic cycling) to the aquatic ecosystem. The floodprone zone is the area prone to inundation by large floods, and it can be roughly approximated as twice the bankfull depth (Leopold 1994), although natural variation is substantial, and this metric may not be sufficiently accurate for regulatory purposes.

Debris flow, landslide and avalanche features which occur along steep and confined channels delineate another set of landforms that are often vegetated by invader deciduous stands (e.g., red alder, sitka alder, willow; Naiman et al. 1998). These landforms are linked to aquatic productivity by stochastic disturbances and in some cases (e.g,, hallows) through emergent seeps and springs that flow into adjacent streams. Also, the steep side slopes which are typical with these features may increase the probability that trees far from the channel will contribute litter and terrestrial invertebrates to the stream; a falling leaf will blow farther horizontally if the vertical distance above the creek is greater.

Topographic slope breaks adjacent to streams are known to influence local microclimate (Danehy et al. 2005 , Anderson et al. 2007) and may delineate another natural boundary that could influence nutrient and material transfers to streams. Information on the latter is lacking.

Small stream functions are still poorly understood (Moore and Richarson 2003). While there is a perception that small streams (generally 0 to 2nd order) are steep and confined, several studies suggest that many small streams are shallow and unconfined as well (Liquori 2002; Gomi et al. 2002). Thus the geomorphic variety associated with small headwater streams makes it difficult to describe broad generalities. While, organic matter is as important in small streams as in larger streams (Richardson et al. 2005), its not yet clear how or if the geomorphic expression of small streams is important with regard to nutrient issues.

7. Given a designated riparian buffer width necessary to achieve desired in-stream biological objectives (questions 5 and 6), what timber operations and management practices in riparian areas have been demonstrated to favor or inhibit these objectives? (i.e., How have selective harvesting and operations at differing distances from stream channel bankfull enhanced or inhibited the development of stream invertebrate communities that favor increased growth and density of juvenile salmonids?)

The literature on logging generally shows that removal of the forest canopy stimulates trophic pathways (see Primer and references in Table 1) that favor increased salmonid production in streams from California to Alaska (Murphy and Meehan 1991, Bisson and Bilby 1998). Similarly, increased tropic (food or nutrient) productivity has been observed in streams boarded by dense alder stands that regenerated following clearcut logging (Wipfli & Musselwhite 2004, Romero et al, 2005). However, this favorable response has been nullified for fish populations in streams where instream cover has been removed or habitat (e.g., pools) declined following reductions in LWD (Martin et al. 1986, Murphy et al. 1986, Bisson et al. 1987) or where increased summer temperatures reached lethal levels (Hall and Lantz 1969, Martin et al. 1986). These studies show that riparian management to promote fish-favorable trophic pathways, by itself, is not sufficient to maintain salmonid populations. Rather, riparian management needs to provide an adequate supply of LWD for fish habitat and associated ecological functions (organic processing, sediment storage, channel complexity; see Wood Section), and adequate shade for temperature control (see Heat Section).

The literature reviewed for Question 5 showed that stream invertebrate communities respond to riparian stand manipulations within about 30 m of the stream. Stand management beyond 30 m is not likely to have much influence on either light or litter inputs to streams, except in flood plains as described above.

8. Are there regional differences in the effects of natural disturbance or forest management activities on the biotic or nutrient riparian area functions? Do the same disturbance regimes or management activities have different effects in different regions (e.g. the coastal coast range, interior coast range, Cascade, or Klamath-Sierra Nevada)?

There are few if any studies that relate biotic/nutrient impacts of similar management activities to regional differences. But an understanding of the biotic/nutrient functions of the riparian zone suggests some possible interactions between regional characteristics and biological impacts. In the coastal zone, for example, daily fog can cause a downstream cooling trend as a stream flows toward the coast (Cafferata, 1990). Opening the riparian canopy along these streams may stimulate primary productivity (and invertebrate production) without risking a damaging increase in temperature. Further inland, especially at low elevations, stream temperature may be an important concern. In streams of the coast ranges, assuring an adequate supply of large woody debris (LWD) may be an important factor in determining buffer width, or marking trees to be retained in the riparian zone. In bedrock or boulder-controlled streams of the Sierra Nevada, LWD may be less of a concern.

The regional differences are addressed in more detail in the Synthesis section, since (as with the examples above) they involve the interaction of the biotic/nutrient function with some of the other functions.

INFERENCES FOR FOREST MANAGEMENT

The literature on logging generally shows that removal of the forest canopy stimulates trophic pathways (CBOF-TAC 2007; Table 1) that has led to increased salmonid abundances in streams from California to Alaska (Murphy and Meehan 1991, Bisson and Bilby 1998). Similarly, increased tropic productivity has been observed in streams boarded by dense alder stands that regenerated following clearcut logging (Wipfli & Musselwhite 2004, Romero et al, 2005). However, this favorable response has been nullified for fish populations in streams where instream cover has been removed or habitat (e.g., pools) declined following reductions in LWD (Martin et al. 1986, Murphy et al. 1986, Bisson et al. 1987) or where increased summer temperatures reached lethal levels (Hall and Lantz 1969, Martin et al. 1986). These studies show that riparian management to promote trophic pathways, by itself, is not sufficient to maintain salmonid populations. Rather, riparian management needs to provide an adequate supply of LWD for fish habitat and associated ecological functions (organic processing, sediment storage, channel complexity; see Wood Section), and adequate shade for temperature control (see Heat Section).

The reviewed literature suggests that riparian stand management for biotic and nutrient functions might consider longitudinal variations (e.g. upstream/downstream) along the stream rather than lateral buffer width. Such treatments could be designed to enhance invertebrate communities that favor increased growth and density of juvenile salmonids. For example, management of riparian stands in headwater stream segments that are adjacent to fish bearing waters could elevate headwater productivity and downstream material transport that would benefit the fish community (Wipfli 2005, Danehy et al. 2007). The buffer design could incorporate shade needs depending on temperature sensitivity (see Heat Section) of the fish bearing stream. Similarly, invertebrate and fish productivity could be boosted in fish bearing streams by managing riparian stands along stream segments. Considerations for temperature and LWD could be incorporated into management schemes depending on site specific conditions. For example, segments could be selectively thinned to promote instream nutrient and aquatic macroinvertebrate production and deciduous ingrowth. Some options might include:

- implement thinning treatments to open the canopy in segments with low temperature sensitivity to shade reduction,
- thinning on one side and in areas where LWD recruit potential is low,

- leave key trees with high potential for recruitment (e.g., leaning toward stream),
- alternate patches of deciduous and conifer that are large enough to promote trophic response (e.g., 100-200 m long), but short enough to maintain benefits of conifer zones, and/or
- intentionally place woody debris in managed segments to increase LWD loads and instream habitat on a stand rotation schedule (e.g., Cederholm et al. 1997).

Riparian enhancement activities could be strategically located in or near channel types (e.g., tributary junctions, flood plain segments) where aquatic productivity would benefit most (i.e., biological hotspots; Benda et al. 2004) from riparian resource subsidy. Such landforms create areas of concentrated productivity (e.g., frequent LWD, habitat complexity, detrital storage and processing, widened channel and increased light) and their riparian stands are often dominated by deciduous vegetation.

INFORMATION GAPS

- The zone of influence and utilization of invertebrates that are exported from headwaters to fish bearing streams (e.g., Wipfli, 2005) is unknown. Similarly, the headwaters source area that needs to be managed for biotic and nutrient exports is not well defined.

- The biologically effective length of riparian vegetation patches that are large enough to stimulate trophic energy pathways yet small enough to maintain shade control or wood debris recruitment in adjacent patches needs to be defined. Similarly, options for management that are logistically feasible should be investigated.

- The potential to stimulate trophic pathways through riparian management will vary regionally. More information will be needed for areas (e.g., Sierra and Central Valley) that have limited research.

GLOSSARY

autotrophic	Literally, self-feeding. Refers to organisms that obtain energy from sunlight or inorganic compounds or elements, such as nitrate, sulfide or reduced iron
Chironomid	A small non-biting fly, the larvae of which are sometimes an important food resource for fish
Diatom	any of numerous microscopic, unicellular, marine or freshwater algae of the phylum Chrysophyta, having cell walls containing silica.
functional feeding groups	Groupings of aquatic macroinvertebrates according to their mode of feeding. Includes shredders, scrapers, collectors, filter feeders and predators.
heterotrophic	Literally, other-feeding. Refers to organisms that obtain energy from reduced carbon (dead or living plant or animal tissue)
hydrophobic	Water repellant. Hydrophobicity in soils is sometimes caused by condensation of hydrocarbons (waxes and oils) during a fire.
hyphomycetes	A division of fungi, with naked spores borne on free or only fasciculate threads
hyporheos	Literally, underflow. Refers to water flowing in the bed or banks of a stream and exchanging frequently with surface flow
Oligochaetes	Any of various annelid worms of the class Oligochaeta, including the earthworms and a few small freshwater forms
periphyton	Literally, surface plants. Generally refers to algae growing on the surface of rocks or debris in a lake or stream
phenology	The study of timing of biological events in nature, such as flowering, insect emergence, etc.

trophic pathways	The pathways that energy follows in a food chain, from primary producers, to consumers, to top carnivores.

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Sound Watershed Consulting
Creating Functional Water Environments

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

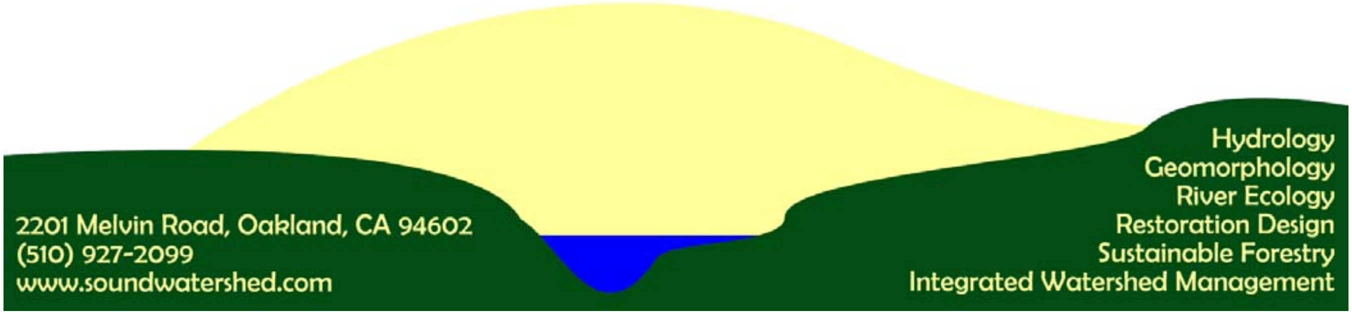
Chapter 3

HEAT EXCHANGE FUNCTIONS

for

The California State Board of
Forestry and Fire Protection

September 2008



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3) HEAT 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

Prepared by:

Dr. Doug Martin

Mike Liquori

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September 2008

SWC Ref# 1013

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SUMMARY OF TABLES & FIGURES

EXECUTIVE SUMMARY

This document represents a comprehensive review of 34 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 2007)
- 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 heat exchange functions

The literature on riparian heat exchange tells us that shade provided by riparian vegetation is a key factor controlling heat input to streams, even though instream water temperatures are governed by a host of other complex physical factors that control heat transfer between air, water, and the streambed.

There is no single, fixed-width buffer or canopy closure prescription that will provide the desired heat regulation objectives for salmon in all cases. The relative importance of riparian vegetation to influence stream temperature varies by location (geographic province) and by site specific conditions (stream width, depth, flow, groundwater inflow, streambed substrate composition, valley orientation, topographic shading and watershed position). Stream temperature sensitivity to shade is dependent on location and physical conditions.

The science on heat exchange indicates that water temperature protection could be provided by varying the riparian shade requirements in relation to stream temperature sensitivity. This report provides some examples of approaches than can be used, and key variables to consider when designing strategies to manage shade in different settings.

In fish-bearing waters that are directly downstream of headwater streams, the literature indicates that temperature could be positively influenced by providing shaded conditions on headwater stream segments that extend from 500 to 650 ft (150 to 200 m)

upstream from the confluence with fish-bearing streams. This distance is based on research findings outside of California, therefore this distance may need to be validated with studies in various California ecoregions.

Our interpretation of the reviewed literature suggests that managing to protect salmonid habitat conditions would require that targets be set for desired stream temperature, and that shade requirements vary in relation to the stream's specific sensitivity to shade as a thermal influence on temperature. The literature indicates that stream temperature is a major factor influencing population performance.

Shade is not static, but varies in response to stand growth dynamics and natural ecosystem processes and disturbances. Suitable thermal conditions could be maintained and hazards to salmonids avoided by altering the timing and spatial position of riparian management activities. Thermal conditions also respond to surrounding conditions as water flows downstream, so downstream stand conditions also influence stream temperature.

Riparian stand effectiveness for shading is a function of the forest canopy density, height, and species composition, which is related to stand type and age. Research shows that effective shading can be provided by buffer widths ranging from 30 to 100 ft (10 m to 30 m) depending on stand type, age, and location.

Timber harvest in or adjacent to riparian areas can influence microclimate, but microclimate changes have not been demonstrated to translate to changes in water temperature. Timber harvest in or near riparian areas can cause an increase in light penetration, decrease interception of precipitation, and increase wind speed, which can result in higher mid-day air temperatures and lower mid-day humidity near the forest floor and over the stream. These microclimate changes are hypothesized to influence water temperature, however validation is lacking.

Finally, heat exchange is only one riparian function that affects salmonids. Shade conditions can inversely influence biotic and nutrient exchange functions. Similarly, the canopy that provides shade also influences water exchange functions, and can be influenced by wood exchange functions. These dynamics between exchange functions are discussed in greater detail in Chapter 7 (Synthesis).

RECOGNIZED EXCHANGE FUNCTION ROLES & PROCESSES

Riparian vegetation in forested environments influences stream water temperature and riparian microclimate (air temperature and relative humidity). The relative importance of riparian forests in regulating water temperature and microclimate is governed by multiple interacting factors (biotic and abiotic) that have been described by CBOF-TAC (2007), and which form the foundation of our review. These principles include:

- Direct solar radiation to the water's surface is the dominant source of heat energy to surface water.

- Shade from vegetation that blocks incoming solar radiation (direct and diffuse) along the sun's path at solar elevation angles greater than 30 degrees is most effective for reducing radiant energy available for stream heating (Moore et al. 2005).

- Vegetation that blocks incoming solar radiation at low solar angles (i.e., at dawn and dusk, and during fall-winter seasons) is less important for reducing stream heating from direct radiation (Moore et al. 2005). The lower the angle, the more solar radiation is reflected.

- Riparian forest cover and understory vegetation influences on solar radiation, interception loss of precipitation, and wind velocity are the primary factors governing microclimate. In addition the stream effect on air temperature and humidity has a strong effect on the adjacent microclimate. Therefore all factors that influence stream temperature (see below) indirectly influence riparian microclimate.

- Stream surface exposure to incident solar radiation is also influenced by channel morphology (exposure decreases with increasing channel incision), channel width (exposure decreases with decreasing width), channel orientation (duration of high angle exposure decreases with east-west orientation, hence streams having a north-south orientation tended to be warmer than those with an east-west orientation.), and topography (exposure decreases with increasing ridge shadow) (Moore et al. 2005).

- Water temperature response to heat input is moderated by inflow from tributaries and groundwater, and the magnitude of response is dependent on the temperature difference between inflow and stream temperatures and on the relative contribution to discharge (Moore et al. 2005).

- Water temperature response to heat input is dampened by hyporheic exchange rate (i.e., streamflow below the streambed is cooled by heat exchange with subsurface water and substrate), which is a function of bed composition (alluvial gravel/cobble bed material enables increased hydraulic retention and increased sub-surface storage than occurs with bedrock; Johnson 2004) and channel morphology.

- Water temperature response to heat input is a function of depth, velocity, and discharge with sensitivity decreasing with increasing depth, velocity, and discharge (Moore et al. 2005).

- In general, riparian influence on water temperature declines with increasing stream size and increasing distance from the watershed divide. Streams that are too wide for canopy to influence temperature are wider than 36 m and located more than 70 km from the watershed divide (Lewis et al. 2000).

- Air temperature varies by location and elevation. Near the coast, air temp is more a function of distance from the coast rather than elevation. In the interior, air temperature follows the expected adiabatic trend; decreasing with increasing elevation (Lewis et al. 2000).

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

RESPONSES 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 are 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 heat exchange function, we found 14 of the 32 papers provided by the Board to be directly applicable to the questions in some manner. The remaining papers were indirectly helpful in addressing these questions, but in most cases did not provide information that directly informed the Key Questions. In general, the questions represent broad topic areas that would require an extensive and detailed treatment to fully address. Our responses focused on building upon the recognized exchange function roles & processes by focusing on new information or important considerations.

1) How do forest management activities or disturbances within the riparian area affect the temperature of forest streams?

Our review of the literature indicates that shade from riparian vegetation is a key factor influencing stream temperatures and that riparian shade prescriptions are an effective tool for protecting salmonid habitat. However, studies show that shade is only one of several interacting factors that govern water temperature. Therefore, simple buffer width and shade curves are not a reliable predictor of water temperature. Stream temperature sensitivity to shade and buffer prescriptions may best be obtained from empirical relationships or physical heat process equations that can incorporate relevant factors for various regional and local conditions.

In general, the influence of riparian vegetation on water temperature declines with increasing stream size and increasing distance from the watershed divide. The downstream temperature response from timber harvest in headwater streams is variable and is highly dependent on the volume of stream flow, substrate type, groundwater inflow, and hyporheic exchange.

It is not clear from the microclimate studies in this review that changes in microclimate can directly translate to changes in water temperature.

A) WHAT CONDITIONS OF CANOPY STRUCTURE, DENSITY, AND WIDTH, INFLUENCE WATER TEMPERATURE? HOW MIGHT THIS VARY WITH CALIFORNIA FOREST TYPES AND STREAM SIZE?

Riparian Condition Influences on Water Temperature

The primary function of riparian vegetation in controlling water temperature is to block incoming solar radiation (direct and diffuse). Direct solar radiation on the water's surface is the dominant source of heat energy that may be absorbed by the water column and streambed. Absorption of solar energy is greatest when the solar angle is greater than 30° (i.e., 90 to 95 % of energy is absorbed as heat) and absorption declines (i.e., reflection of radiation increases) as the solar angle declines. Therefore, riparian vegetation that blocks direct solar radiation along the sun's pathway across the sky is the most effective for reducing radiant energy available for stream heating (Moore et al. 2005).

The literature (Beschta et al., 1987, Sridhar et al. 2004) reports that the attenuation of direct beam radiation by riparian vegetation is a function of:

- Canopy height,
- density of vegetation, and
- Species composition.

Riparian buffer width is important for a given stand type and age, but is not a good predictor of stream shading among different stands because of differences in these key variables. For example, Beschta et al. (1987) showed that shade levels similar to old-growth forests could be obtained within a distance of 60 to 100 ft depending on stand types in Oregon (Figure 1). Similarly, Sridhar et al. (2004) using an energy balance model with empirical data, demonstrated that stream temperature is most sensitive to a stands leaf area index (i.e., an indicator of light attenuation by canopy density) followed by average canopy height (an indicator of direct beam light attenuation), and lastly buffer width. They found the most effective shading for temperature control in eastern and western Washington Cascade conifer stands was predicted for mature (high leaf-area-index) canopies close to the stream (i.e., within 10 m of the stream bank) and overall buffers of about 30 m. Buffer widths beyond 30 m had only minimal effect on stream temperature.

Direct beam solar radiation may also be effectively blocked by a layer of slash that may accumulate in headwater channels following clearcutting in adjacent riparian areas (Jackson et al. 2001). Understory shrub vegetation may provide shade and influence streamside microclimate conditions (Gravelle & Link 2007, Rykken et al 2007). Moore et al (2005) reports that validation of shrub effectiveness for shade is lacking, however Liquori and Jackson (2001) offer some evidence for the idea that shrub cover may yield lower temperatures for similar shade conditions.

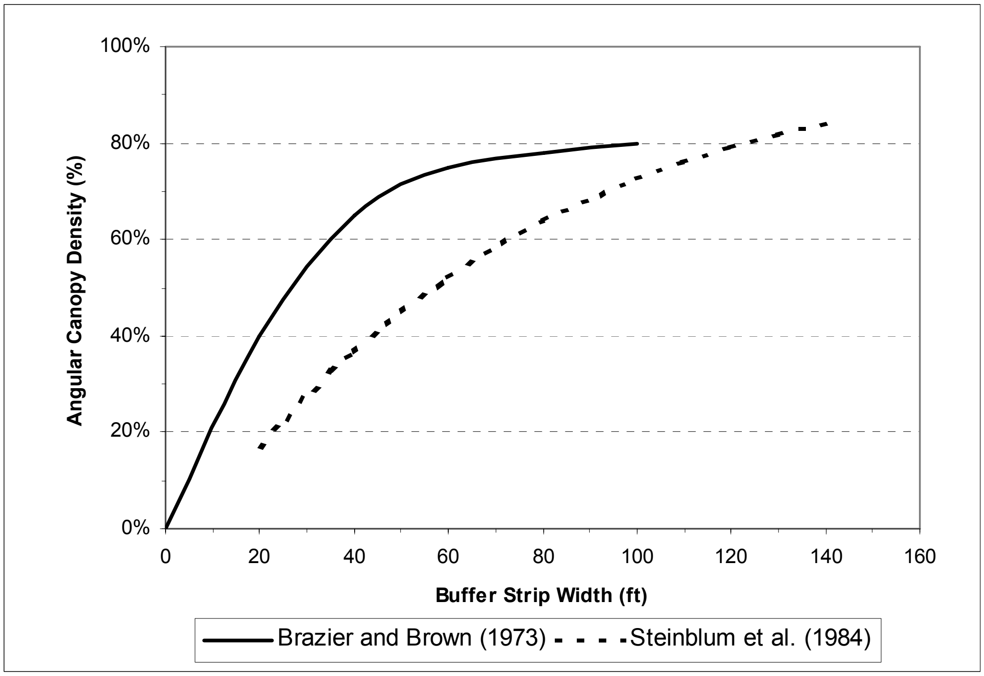

Figure 1 Relationship between angular canopy density (a measure of shade) and buffer strip width for small streams in western Oregon (reproduced from Beschta et al., 1987). The Brazier and Brown study was conducted mostly in the coastal forests and a few sites were located in the southern Cascades (Umpqua National Forest). The Steinblum study was conducted in western Cascade forests at elevations of 2000 to 4000 feet.

The TAC literature does not provide much information on specific riparian vegetation conditions (i.e., canopy structure, density, width) that influence water temperature, aside from the information described above. Only one field study (James 2003), one synthesis (Lewis et al. 2000), and two modeling studies (Sridhar et al. 2004, Allen 2008) provided temperature responses in relation to a canopy cover or shade index. Most of the studies examine temperature responses in relation to a range of buffer prescriptions that are categorized by width and harvest treatment (e.g., no-cut, thinned, partial cut; Table 1).

Table 1. Summary of TAC literature concerning riparian vegetation influences on water temperature.

Reference	Location	Treatment	Relevant Finding For Buffers
Allen 2008	Fish streams, northern CA	Modeled basin wide temperature for: no riparian shade, or full old-growth shade	Model predictions and validation demonstrate the important interactions between relief, vegetation, and hydrology. For example, testing showed that local relief and aspect controls can offer sufficient shading to create intrinsically cool canyons and reaches on the mainstem that cool the flow. Also variation in groundwater inflow rates can reduce or amplify heating effects associated with either vegetation removal or growth to late seral stage.
Anderson et al 2007	Headwater streams, western OR coast and cascade range	Variable width buffers ranging from 9 m to 59 m with upslope thinned stands or patch openings	Buffers that extend to topographic slope breaks appear sufficient to mitigate the impacts of upslope thinning on the microclimate. Aspect should be accounted for when using canopy cover as an index of potential shading of the stream, particularly under conditions where direct and indirect light are not strongly coupled.
Fleuret 2006	Headwater streams, OR coast range	clearcut and partial cut, buffers 6-60 m wide	Mean temperature gradient in treatment reaches was 0.4°C warmer than observed prior to harvesting. Percentage shade is strong predictor of summer temperature.
Gomi et al 2006	Headwater streams, BC coastal	experimental treatments: clearcut to edge, 10 m, and 30 m fixed buffers	Temperature response declined with increasing buffer width. At streams with 30 m buffer the maximum effects for maximum daily temperature was less than 2° C. Thermal recovery within two to four years depending on channel width.
Gravelle & Link 2007	Headwater streams, Northern Idaho	clearcut with 9-m equipment exclusion zone	There was a significant increase in peak temperatures that was negligible a few years after harvest. Understory vegetation response increased overall cover in clearcut reaches toward preharvest levels over the 4 years since harvest.

Reference	Location	Treatment	Relevant Finding For Buffers
Jackson et al 2001	Headwater streams, WA coast	treatments: unharvested 2nd growth, 15-21 m wide buffers, and clearcut to bank	Water temperature at 3 of the 7 clearcut sites were not significantly different, because a layer of slash effectively shaded the streams. At the buffered streams, two became warmer (1.6 - 2.4 °C) and one cooler (-0.3° C).
James 2003	Fish stream, northeastern CA, Sierra's	stand thinned to 50% canopy cover in 175-ft and 100-ft wide buffers	Treatment resulted in minor (+- 1.5°C) changes in the water temperature pattern in study reach. Treatments did not appreciably reduce angular or vertical cover even though 35% of timber volume was removed.
Macdonald et al 2003	Headwater streams, Interior BC	tested three variable retention treatments in 20- to 30-m wide buffers	Five years after the completion of harvesting, temperatures remained 4° to 6° C warmer than in the control streams regardless of treatment. Initially, the high-retention treatment mitigated the effects of the harvesting, but 3 successive years of windthrow was antecedent to reduced canopy density and increased temperature impacts.
Moore et al. 2005	Wide range of streams in Pacific Northwest	Literature review of wide range of riparian treatments	Based on the available studies, a one-tree-height buffer on each side of a stream should be reasonably effective in reducing harvesting impacts on both riparian microclimate and stream temperature. Narrower buffers would provide at least partial protection, but their effectiveness may be compromised by wind throw.
Sridhar et al 2004	Mid-order streams, western and eastern WA Cascades	Modeled effectiveness of buffers with different width and vegetation characteristics	Of the vegetation factors influencing water temperature; leaf area index had the greatest effect (especially for trees within 10 m of the stream bank), average tree height was second, and buffer width third. Buffer widths beyond 30 m had only minimal effect on stream temperature.

None of the field studies identify a riparian stand structure, density, or canopy cover that is sufficient to maintain water temperature; although James (2003) concluded that maintaining 50% canopy cover of the ground after thinning (minimum 80% angular canopy cover) had a minimal impact on water temperature in a Sierra stream. Several studies identified a buffer width among the various prescriptions tested that resulted in minimal impacts on temperature (e.g., 30 m, one-tree-height; Table 1). However, these recommendations are restricted to the stands types and climatic conditions examined and may not be applicable beyond the study locations.

Stand age has not been addressed explicitly, although Moore et al. (2005) cited studies in the Pacific Northwest showing shading recovery after timber harvest ranged from 10 to 20 years depending on stand type. This would suggest that submature stands can provide effective shade.

Interestingly, no recent study has developed a buffer width and shade relationship curve like the ones presented in Beschta et al. (1987; Figure 1), which were based on studies from the 1970's and early 80's. Furthermore, relationships between canopy cover or shade and common forestry metrics (i.e., stand density and basal area) are not well defined for specific sites or stand conditions (Anderson et al. 2007).

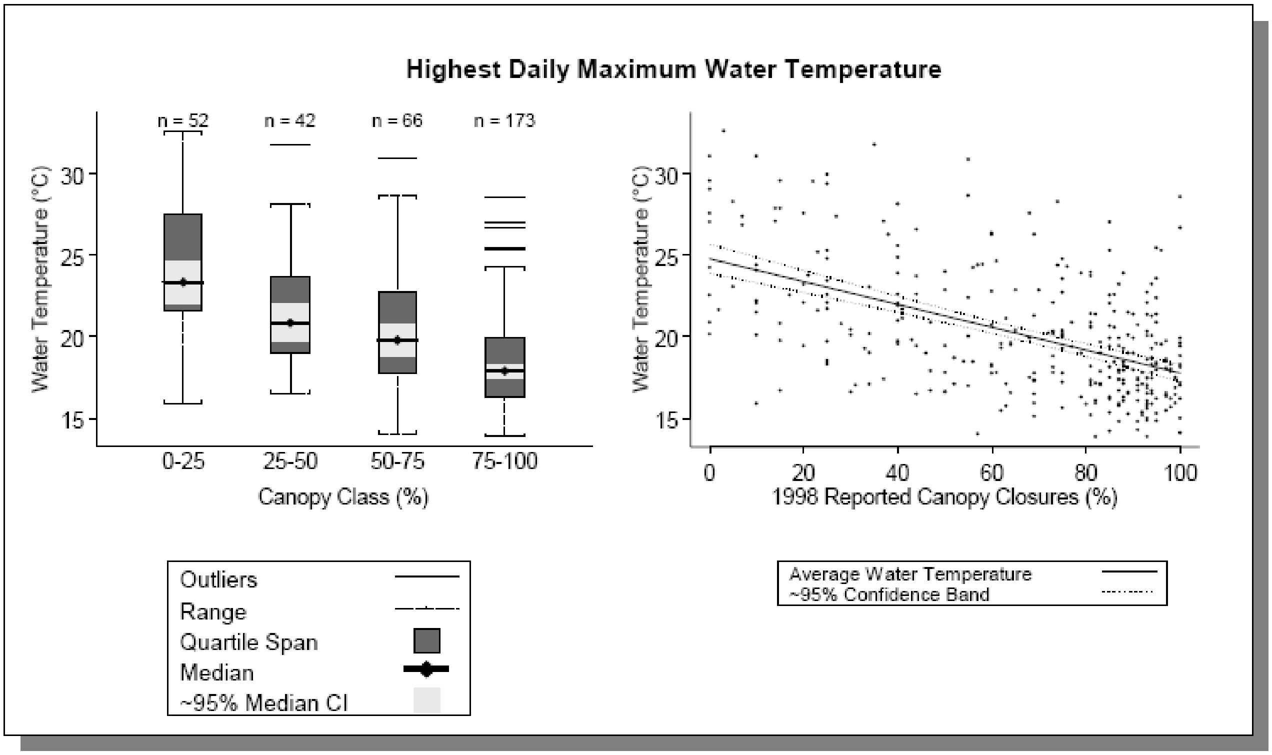

Figure 2 Relationship between stream temperature and canopy closure for streams in California. Regression R2 = 0.286, *p* ≈ 0. (Figure 9.9 from Lewis et al. 2000).

Research shows that water temperature is poorly correlated with shade because shade is only one of the several interacting factors that govern water temperature in streams. For example, Lewis et al. (2000) concluded that the weak, but significant, relationship between canopy closure and water temperature in California streams is due to the myriad of other factors influencing temperature (Figure 2). This finding, however, does not mean that shade is not important. Rather it shows that simple shade or canopy closure relationships are not adequate to predict temperature with high resolution and that other variables (e.g., flow, width, depth, substrate, ground water) need to be taken into account. Lewis et al. (2000) found that watershed position (i.e., surrogate for stream size) and air temperature (i.e., surrogate for location in or out of coastal zone or elevation) along with canopy closure were important factors that account for water temperature differences at the regional scale.

Accurate stream temperature predictions may best be obtained from empirical relationships or physical heat process equations that can incorporate relevant factors for various regional and local conditions (e.g., Cafferata 1990, Sullivan et al. 1990, Lewis et al. 2000, Sridhar et al. 2004, Moore et al. 2005, Allen 2008). Such predictive tools are available and compatible with existing GIS databases and modern timber harvest planning programs. For example, Allen (2008) showed how existing watershed data (DEM, hydrology, lithology) and stand characteristics (DBH, which is a surrogate for tree height) for tributaries of the Eel river can be used to evaluate temperature responses throughout the basin with different scenarios for riparian stands.

California Forest Types and Stream Size Influences on Water Temperature

The stream shading potential of riparian vegetation varies by forest type. For example, the leaf-area-index (i.e., an indicator of light attenuation by canopy density) for a mature stand of Douglas fir is about 15 and for lodge pole pine is about 5 (Sridhar et al. 2004). Beschta et al. (1987) showed that dense coastal stands of Oregon can provide adequate shade in a shorter distance from the stream than can mid-elevation conifer stands in the western Cascades (Figure 1). Similar comparisons among regions are not known for California. However, the coastal stands of redwood and Douglas fir are denser and have a greater potential to shade streams than do low-density lodge pole pine, ponderosa pine, and Jeffrey pine stands of the interior regions.

The effects of forest type on stream temperature are difficult to separate from other factors that influence the distribution of plant communities in California. Research by Lewis et al. (2000) shows that distance from coast and elevation have differential influences on water temperature depending on ecoprovince. In the Coastal Steppe Province (CSP) water temperature generally increases with increasing distance from the coast and in the Sierran Steppe-Mixed Forest-Coniferous Province (SSP) temperature declines with distance from the coast. Lewis et al. (2000) attributed these difference to the presence of fog and clouds in the coastal zone, which filters out solar radiation and moderates air temperatures. They point-out that water temperature is influenced by canopy closure in both regions (Figure 3). However, the relative importance of riparian vegetation in blocking solar radiation may vary between regions. Lewis et al. (2000) also showed that elevation influences water temperature, especially in the SSP where cooler air at higher elevations resulted in lower daily minimum temperatures than was observed in CSP streams.

In general, riparian vegetation influence on water temperature declines with increasing stream size and increasing distance from the watershed divide (Moore et al. 2005). Water temperature generally tends to increase in the downstream direction with stream size as a result of systematic changes in the important environmental variables that control water temperature. Also, as streams get larger, there is a corresponding decline in the effectiveness of riparian vegetation to provide shade. Cooler groundwater inflow also diminishes in proportion to the volume of flow in larger streams. In California, Lewis et al. (2000) found stream temperature increases with increasing channel width and with increasing distance from the watershed divide (Figure 4). They found that this relationship holds for all locations and that water temperatures in the zone of coastal influence are generally 1° to 2°C cooler than for streams sites outside of the zone of coastal influence, at similar divide distances (Figure 4). They estimated that as distance from the watershed divide approaches approximately 70 km, streams become too wide for riparian vegetation to provide adequate shading.

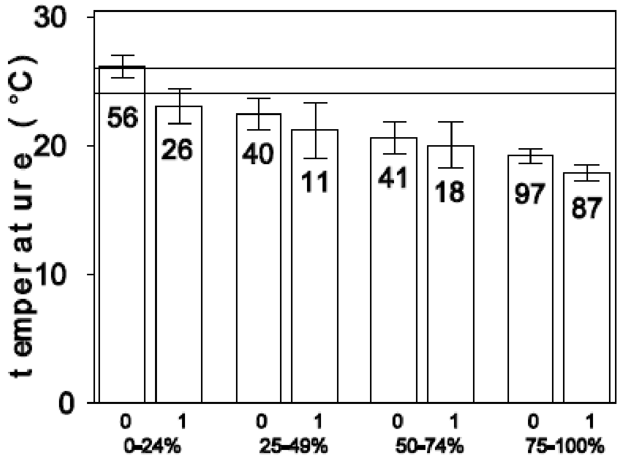

Figure 9.10. Highest 1998 daily maximum stream temperature for sites in four different canopy classes, grouped by whether the site was outside (0) or inside (1) the zone of coastal influence. Horizontal reference lines are drawn at 24°C and 26°C. Number of sites in each group are shown below error bars.

Figure 3 Relationship between maximum stream temperature and canopy closure outside (0) and inside (1) the zone of coastal influence. The influence of canopy cover on temperature is evident for both zones. Horizontal lines at 24° and 26°C correspond to thermal tolerance and lethal temperature thresholds, respectively for salmonids. Only streams in the 0-24% group have temperature maximums that approach lethal levels. (Figure 9.10 from Lewis et al. 2000).

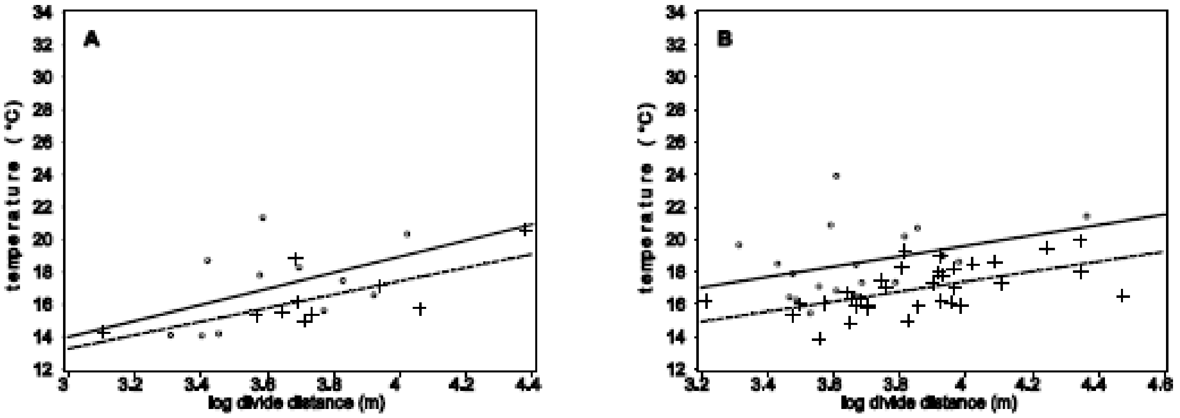

Figure 9.11. Variation in the highest 1999 daily maximum stream temperature with $\log_{10}$ distance from the watershed divide for sites with canopy values greater than or equal to 75%. Sites in the Mad River - Redwood Creek (A) and Big-Navarro-Garcia River (B) hydrologic units are presented. Linear regression lines were fit to sites outside (open circles) and inside (crosses) the zone of coastal influence. Solid lines and dashed lines represent linear regressions for sites outside and inside the ZCI, respectively.

Figure 4 Variation of maximum stream temperature with distance from the watershed divide for sites with canopy cover > 75% inside and outside of the zone of coastal influence. Note, the regression lines show what water temperatures are achievable under fully canopied conditions. (Figure 9.11 from Lewis et al. 2000).

B) ARE RIPARIAN AREA MICROCLIMATES AFFECTED BY FOREST MANAGEMENT WITHIN AND/OR ADJACENT TO FISH-BEARING STREAMS SUFFICIENT TO INFLUENCE WATER TEMPERATURE?

Timber harvest in or adjacent to riparian areas can influence microclimate, but microclimate changes have not been demonstrated to translate to changes in water temperature. Timber harvest in or near riparian areas can cause an increase in light penetration, decrease interception of precipitation, and increase wind speed (Moore et al. 2005), which can result in higher mid-day air temperatures and lower mid-day humidity near the forest floor and over the stream. These microclimate changes are hypothesized to influence water temperature, however validation is lacking.

The TAC literature list included seven documents that addressed the influence of forest management on riparian microclimate. Six of these documents described the riparian microclimate response to specific riparian and upslope treatments and one document (Moore et al. 2005) provided a synthesis of literature concerning water temperature and riparian microclimate responses to forest management in headwater streams (Table 2). The Moore et al. (2005) synthesis did not address the microclimate/water temperature question, but one paper (Brosofske et al. 1997) which was referenced in the synthesis does describe this relationship, so we included it here.

Only Brosofske et al. (1997) and one of the TAC studies (James 2003) examined both water temperature and microclimate responses to a specific riparian treatment. Brosofske et al. found that harvesting influenced microclimate gradients, but water temperature was not responsive to buffer width, except in one case where no riparian trees were retained. Also, water temperature was not correlated to microclimate variables (wind speed, relative humidity, solar radiation). However, a significant correlation between water temperature and soil surface temperature led Brosofske et al. to speculate that upland clearcutting may influence temperature in streams. James (2003) found that riparian thinning (i.e., maintained 50% of canopy closure in the riparian stand) resulted in small changes in average and maximum air temperature within 40 ft of stream (up to 0.5°C) and small changes in water temperature (+/- 1.5°C). Whether the increased water temperature in this study was a result of microclimate changes (i.e., increased air temperature) or of increased heating from direct beam radiation on the stream is unknown.

The other studies, which did not measure water temperature, showed that riparian microclimate may or may not be affected by forest management activities depending on buffer zone width and site specific characteristics (e.g., stream size, aspect, elevation, slope gradient, and upslope stand structure). Several of the studies show that microclimate is unaffected where the buffers extend to a slope break or are at least 30 m (one tree height) wide. In some cases where buffers were narrower or were thinned, air temperatures increased (e.g., 2-4°C) and relative humidity decreased along a gradient that extended away from the stream.

Even though air temperatures over streams may increase in some cases after timber harvest, the influence on water temperature is limited and is strongly affected by site specific conditions (i.e., relative humidity and wind). Moore et al. (2005) found that sensible and latent heat exchanges to be an order of magnitude lower than net radiation on sunny days in recent clear-cuts, thus the potential influence of microclimate on temperature is relatively small compared to direct radiation. They also point-out that heat fluxes, especially over small streams may be limited by the lack of ventilation from bank sheltering, particularly for narrow, incised channels. In California, Lewis et al. (2000) found a moderate correlation between daily mean water temperature and daily mean microair temperatures ($R^2 = 0.61$). However, they point-out that sensible and latent heat exchanges are too small to fully account for this correlation, rather the close correlation is caused largely by solar radiation which affects both water and air temperature.

We found no convincing evidence in the reviewed papers or the primer that forest management effects on microclimate are sufficient to substantially influence water temperature. The results from two studies in this review that actually measured microair and water temperature do not demonstrate a causal relationship. The other microclimate studies either show no effect or very small effects of riparian management on microair temperature. The heat exchange physics indicates the potential effects of microair temperature on water temperature are limited and highly dependent on favorable micro-conditions. Finally, water temperature is not only governed by incoming solar radiation and air temperature, but by factors that are unrelated to microclimate (e.g., incoming water temperature from upstream and tributaries, ground water input, and hyporheic exchange) that have a strong influence on stream temperature. Collectively, the current knowledge does not support the hypothesis that microclimate changes caused by logging influences water temperature

Our finding are consistent with an earlier review by regional experts (Ice et al. 2002) who concluded that research had not been able to measure a microclimate effect on water temperature where there was a buffer 15 m wide or greater. Where buffers are narrower or absent, it becomes impossible to separate the microclimate effect from the more significant solar insolation effect.

Table 2 Summary of TAC literature concerning riparian vegetation influences on microclimate and water temperature.

Reference	Location	Treatment	Microclimate response	Water temperature response
Anderson et al. 2007	headwater streams, OR coast & cascades	9-59 m buffers, upslope thinned	Buffers that extend to topographic slope break mitigate the impacts of thinning	NA
Brosofske et al. 1997	small streams, cascades wa	7-60 m buffers	affected near-stream microclimate gradients, increased temp and decreased rh	Water temp. not responsive to buffer width and not correlated to microclimate (wind speed, relative humidity, solar radiation). Water and soil temp. correlated.
Danehy et al 2005	low-order streams, eastern WA & OR	30-m buffer, upslope partial harvest	Vegetation density and structure did not exert as strong an influence on relative humidity (RH) as steep local topography	NA
Dong & Chen 1998	low-order streams, western WA cascade	16–72 m buffers, upslope clearcut	Air temperature at the stream was raised by 2–4°C after harvesting	NA
Erman & Erman 2000	headwater streams, CA Sierra range	unmanaged buffer, 2 of 8 partial harvest	Openings in canopy cover were directly translated to increases in air temperature and decreases in RH.	NA

Reference	Location	Treatment	Microclimate response	Water temperature response
James 2003	fish streams, northeastern CA	30-55 m buffer, upslope partial harvest	No significant change in daily RH within 40 ft of the stream after treatments	minor (+- 1.5°C) changes in water temp.
Moore et al. 2005	headwater streams in PNW	Literature review	Edge effects on solar radiation and wind speed decline within about one tree height	NA
Rykken et al. 2007	headwater streams, western OR cascades	30-m buffer, upslope clearcut	no significant treatment differences between the 30-m wide riparian buffer and the intact forest	NA

C) HOW AND TO WHAT EXTENT DO TEMPERATURES IN LOW ORDER STREAMS INFLUENCE TEMPERATURES IN DOWNSTREAM FISH-BEARING STREAMS?

Studies of headwater stream temperature influences on downstream fish-bearing waters are limited to the Caldwell et al. (1991) investigation of small streams in western Washington (cited by Lewis et al. 2000) and three studies that are identified on the TAC list (Table 2). Caldwell et al. (1991) found that headwater streams had minimal influence on the downstream water temperature because of the large size difference between headwater tributaries and receiving (typically fish-bearing) waters. Using a stream flow mixing equation and the relationship between distance from divide and discharge, they determined that a headwater stream could not affect the temperature in a typical fish-bearing stream by more than 0.49° C if the confluence of the receiving stream is more than 7 km (4.5 miles) distance from the watershed divide. Caldwell et al. (1991) reported that small streams are very responsive to localized conditions and that the longitudinal effect of any one headwater stream on downstream temperatures is limited to 150 meters or less. This study also evaluated the potential cumulative effects of multiple headwater streams feeding warm water into a fish stream. Based on a map analysis of tributary junctions, they found that spacing between tributaries often exceeded 150 m and concluded that no cumulative effect was likely to occur.

More recent investigations show that the downstream temperature response to timber harvest in headwaters is variable and is highly dependent on stream flow and channel characteristics

(Table 3). Downstream cooling in some stream segments was observed in all three of the studies in our review. This cooling was attributed to groundwater inflow, hyporheic exchange, or both. Research shows that ground water inflow will typically reduce stream heating by increasing the total discharge as well as cooling by conduction (Moore et al. 2005). In stream segments with alluvial substrate, hyporheic exchange promotes conductive cooling as a result of a longer flow path and increased travel time (Johnson 2004). In contrast, streams with bedrock substrate limit hyporheic exchange and may cause warming by reflecting solar energy off the streambed into the surface water (Johnson 2004). Dent et al. (2008) showed that these factors and others (e.g., canopy cover, channel gradient, instream wood jam volume) influence temperature patterns at small reach scales (0.5-2 km in length) and account for the reach-to-reach variability that is common in headwater streams.

None of the TAC listed studies were performed in California, but the explanation for factors governing downstream temperature response are consistent, and suggests that the primary drivers would apply anywhere. Story et al. (2003) recommended that:

> "*efforts to manage the thermal effects of forestry on aquatic habitat should consider the hydrologic characteristics of specific streams and their catchments, since these factors may account for much of the variability in thermal response to forest disturbance and, in particular, may control the potential for downstream cooling in shaded reaches*."

In a related study of large streams in the north coast region of California, Lewis et al. (2000) demonstrated that the temperature of a mainstem stream (5th order or larger) that is receiving flow from a large tributary stream (e.g., 4th to 5th order) is a function of the ratio of flows and that the downstream extent of temperature influence is dependent on the ratio, physical characteristics of receiving water environment, and climatic conditions. They observed that cool tributary inflow (ranged 2.2° to 7.7° C below receiving stream) decreased the receiving water temperature for distances ranging from 3,000 to 35,000 ft (900 m to 10,700 m) downstream of the tributary junction.

These studies lead us to conclude that the downstream temperature response from timber harvest in headwater streams is variable and is highly dependent on a host of factors (i.e., volume of stream flow, canopy cover, substrate type, in-stream wood volume, groundwater inflow, and hyporheic exchange) in both the headwaters and downstream reaches. For example, the potential for downstream temperature impacts would be greater where canopy cover from riparian vegetation and topographic shading is low, tributary or groundwater inflow is low, woody debris jams are sparse, and if substrate is dominated by bedrock. On the other hand, potential temperature impacts would be reduced or eliminated if these characteristics were the reverse.

Table 3) Summary of TAC literature that address downstream water temperature response to timber harvest in headwater streams.

Reference	Location	Treatment	Response downstream	Findings explanation
Gravelle & Link 2007	northern ID	1st and 2nd-order watersheds 50% clearcut or 50% partial cut	No significant increase in temperature maxima, slight cooling in post-treatment peak temperatures	Suspect that temperature increases in clearcut reaches were ameliorated downstream as a result of groundwater inflows and hyporheic exchange
Johnson 2004	western OR	Experimental shading of a 150-m reach, second-order stream	Response depended on substrate type: bedrock reach had higher maximum temperatures, lower minimum temperatures, and wide diurnal fluctuations; alluvial reach had lower maxima, higher minima, and dampened temperatures	Cooling in alluvial reach is attributed to hyporheic exchange and a longer flow path and travel time
Story et al. 2003	interior BC	Variable retention (thinning) in upstream 10 to 30-m wide buffers	Downstream cooling in the daily maximum temperature was observed in two study reaches over a distance of 200 m.	Downstream cooling was strongly influenced by stream flow, groundwater, and hyporheic exchange

2) How and where are the potential temperature effects from forest management likely to impact salmonid species of concern?

The Primer's review of Sullivan et al. (2000) and related research shows that the effects of temperature on salmonids are a function of magnitude and duration of exposure. Generally temperatures above 26° C are lethal depending on duration of exposure and species tolerance (e.g., 50% mortality at 26°C for 96 hours). Temperatures in the 22° C to 26° range are stressful and may result in loss of appetite and failure to gain weight, competitive pressure and displacement by other species better adapted to prevailing temperatures, or disease. Physiologic tolerance improves at lower temperatures and optimal temperatures occur over a range that depends on food availability (Figure 5). Optimal temperatures for growth are in the range of 14 to 17° C, depending on species (Sullivan et al. 2000). This knowledge, which is based on a large body of literature, indicates that the potential effects of forest management depends on the temperature regime at a particular location and on the spatial temperature patterns within a watershed or across regions. For example, Sullivan et al. summarized temperature data from forested, rural, and urban streams throughout the Pacific Northwest and concluded that temperatures high enough to cause direct mortality were rare, and that sublethal effects (i.e., influences behavior or growth) were common. In fact, they found that the majority of temperatures experienced by salmonids are suboptimal.

In California the potential occurrence of temperature impacts in forested areas is probably similar to the Northwest. Temperature data in Lewis et al. (2000) shows that water temperature at 80% of the study sites (N =154) never exceed lethal levels (i.e., 26° C; Sullivan et al. 2000) and of those that do, only a smaller proportion are likely to have continuous lethal temperatures long enough to cause mortality. Note, all of the streams that had temperatures near lethal levels had canopy cover levels (i. e., < 24%; Figure 3) that were well below CA forest practice standards (minimum 50%). Given this context, the majority of forest management activities in CA are likely to influence stream temperatures in the sublethal range and potential temperature related impacts will vary accordingly. The magnitude of salmonid response to temperature changes in the sublethal range are more a function of changes in the temperature regime rather than a change in the annual maximum (see Section 2a for more information on sublethal temperature effects in California). For example, Sullivan et al. found that large differences in maximum temperatures among sites did not translate to big differences in the overall growth potential of salmonids. This is because growth reflects the net cumulative effect of energy intake (feeding) and loss (respiration and waste products) which is regulated by the temperature regime over long periods (weeks to months). Therefore the duration of favorable and unfavorable temperatures, not short-term (hours) maxima, governs the overall growth response. The optimum or favorable temperature for growth varies in relation to food availability; in cases of high food abundance warmer temperatures are more favorable for growth and when food is sparse, cooler temperatures are preferred.

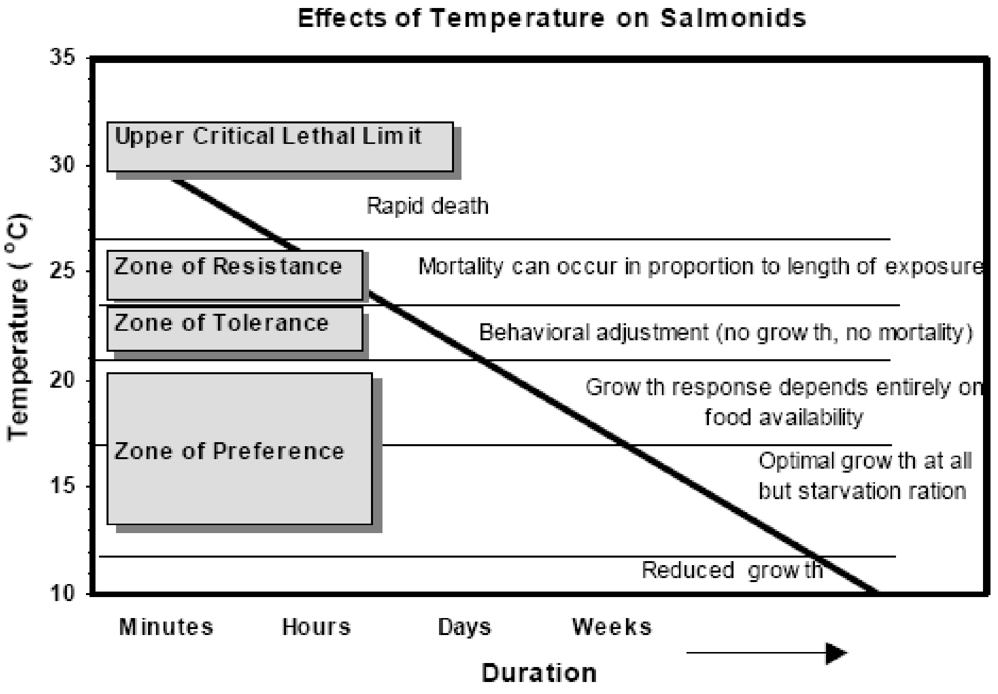

Figure 2.1 General biological effects of temperature on salmonids in relation to duration and magnitude of temperature.

Figure 5. Summary of temperature effects on salmonids. Note, this is a generalized depiction of temperature effects on salmonids. Specific temperatures dividing the zones varies by species. (Figure 2.1 from Sullivan et al. 2000)

The literature on where salmonids may be impacted by forest management influences on temperature in California is limited (see 2a below) and is insufficient to address this question. However the literature about temperature effects and our knowledge of heat exchange mechanisms provides a good clue to the type of streams and locations that would be more or less sensitive to shade loss. In other words, some streams need more shade to maintain a suitable temperate regime than others because of its location and physical characteristics. This does not mean that canopy cover is not important, only that the amount of canopy cover necessary to maintain adequate temperatures will vary. In California, the stream location, inside or outside of the zone of coastal influence, is important because streams located outside of the zone of coastal influence would be more sensitive to temperature effects from forest management than would streams inside of the coastal zone. For example, low-order tributaries to rivers in the central valley and inland rivers along the North Coast outside the zone of coastal influence are particularly vulnerable to shade loss. Within both geographic zones, shade is important, but stream sensitivity to shade loss is a function of reach-scale physical characteristics. For example, streams with high sensitivity may have one or more of the following characteristics: low elevation, no topographic shading, shallow, wide, bedrock substrate. In contrast, streams with lower sensitivity to shade loss would generally occur at higher elevations (especially outside of the zone of coastal influence), where there is topographic shading, where the channel is deep or narrow, and with alluvial substrate. Streams with high sensitivity to shade loss may naturally have temperature regimes that are stressful to salmonids. Therefore small changes in temperature caused by shade loss could have larger impacts on growth, survival, and fish distribution than would an equivalent change of temperature in a stream with a cooler temperature regime. Similarly, streams that are naturally cool may become more favorable for growth as a result of shade reduction and stream warming, Clearly, stream temperature sensitivity to shade loss and the biological consequence of temperature change need to be considered (see below) in determining how and where management could impact salmonid populations.

2A) IS THERE INFORMATION FROM CALIFORNIA ECO-REGIONS INDICATING THE EFFECTS OF OBSERVED TEMPERATURE ON SALMONIDS?

Information in the TAC literature that documents the effects of observed temperature on salmonids in California is limited. Four of the TAC listed studies, plus one additional paper (i.e., Hayes et al. 2008), address temperature effects in the coastal regions (Table 3). The findings from one study are also applicable to the central valley region.

Researchers from two of the studies observed that juvenile coho distribution in north coast watersheds may be restricted by high water temperatures during summer. Welsh et al (2001) concluded that stream reaches with a maximum weekly maximum temperature (MWMT) greater than 18.0°C precluded the presence of juvenile coho in the Mattole River. Similarly, Madej (2006) postulates that coho do not occur further than 20 km upstream in Redwood Creek because high summer water temperature (MWMT ranges 23° to 27°C) in the middle portion of the watershed are unsuitable for juvenile rearing. Water temperature in the lower portion of the watershed is cooler as a result of the coastal fog zone and intact riparian timber stands. The thermal regimes of both the Mattole River and Redwood Creek appear to be recovering from watershed disturbances caused by historic logging and farming activities.

The effects of different temperature regimes on juvenile salmonid growth was measured or estimated by Willey (2004) and Hayes et al (2008). Using empirical temperature data from north coast streams and a bioenergetic model, Willey (2004) calculated that juvenile coho had the best growth potential when daily average water temperatures ranged from 14.7°C to 15.7°C, and that growth potential is less where average temperatures are either cooler (<15°C) or warmer (>17°C). Interestingly, Hayes et al. (2008) found that juvenile steelhead growth was highest in an estuary–lagoon near the mouth of Scott Creek (central coast) where summer temperatures ranged from 15° to 24°C. The differences between studies regarding temperatures that are best for growth is partly explained by different species examined and to food availability. Sullivan et al (2000) demonstrated that the optimum growth temperature for steelhead is greater than for coho. Hayes et al (2008) report that food availability in the coastal lagoon was more productive than in the stream, and probably offset the negative effects from higher temperatures.

The effects of interspecific competition by Sacramento pikeminnow (occurs in central valley and large coastal streams [e.g., Eel River]) on juvenile steelhead growth was examined in a laboratory study by Reese & Harvey 2002. They found that the growth of juvenile steelhead was unaffected by Sacramento pikeminnow in cool water (15–18°C), but interspecific competition increased between species in warmer water (20-23°C) causing a density dependent effect on steelhead growth.

All of the studies in this review deal with sublethal effects of temperature and illustrate that changes in temperature regime can influence population growth potential and alter spatial patterns of habitat use by salmonids, and competing species in California. Some of the studies indicated that population responses to increased water temperature were a consequence of historic logging and removal of riparian timber stands. None of the studies document the effects of modern forest management, although temperature recovery is occurring in some cases (e.g., Madej 2006); presumably as a result of mandated buffers. These studies also suggest that a simple temperature threshold may not be desirable for all eco-regions because the salmonid response varies by species, watershed productivity, and thermal regime.

In addition to the California studies, the TAC literature included two non-California studies that are relevant for assessing temperature risk to salmonids, regardless of location. Sullivan et al. (2000) introduced a bioenergetics approach for assessing temperature risk to salmonids that is based on estimated population growth potential during the juvenile rearing phase. They showed how the annual temperature regime and food availability determines growth potential, and how the growth potential for several salmonid species could be equated to a range of temperature metrics (e.g., summer maximum weekly average temperature [MWAT]). They also showed how the bioenergetics approach could be used to quantitatively evaluate the risk for growth loss as a consequence of temperatures that are not optimal or are altered due to management activities. Further, they suggested that a specified growth loss (e.g., 10% below optimum) could be used as a biological-based threshold for management.

Table 4) Summary of literature that examined the effects of temperature on salmonids in California.

Reference	Region	Fish response to temperature
Hayes et al. 2008	North Central Coast	In Scott Cr, juvenile steelhead grew much faster in the estuary where summer temperature ranged 15–24°C than in upstream reaches where summer temperature were 14–18°C
Madej 2006	North Coast	The apparent juvenile coho distribution in Redwood Cr. may be limited by summer temp patterns (MWMT 23° to 27°C), but relationship is not quantitative.
Reese & Harvey 2002	Coast & Central Valley	Elevated stream temperature may results in a density dependent effect on juvenile steelhead growth caused by interspecific competition with pikeminnow, which prefer waters 20–23°C
Welsh et al 2001	North Coast	Temperature threshold (i.e., MWMT of 18.0°C or less or MWAT of 16.7°C or less) affected juvenile coho distribution within the Mattole River watershed.
Willey 2004	North Coast	Calculated energy allocated to growth of juvenile coho was maximum when daily average water temperatures ranged from 14.7°C to 15.7°C. Calculated growth conversion efficiency declines in either cold (12-15°C) or warm (>17°C) temperature regimes.

The biological threshold concept was examined by Neiltz et al. (2008) for classifying streams in British Columbia. They used the Sullivan et al. bioenergetics model and other empirical models (i.e., to assess growth potential, hatching success, and disease resistance) as tools to assess the temperature effects of streams with different thermal regimes. They also developed empirical temperature models, similar to Lewis et al. (2000), that related the temperature regime of streams in different regions of BC with watershed size, watershed elevation, and air temperature. The empirical and biological models were then used in combination to assess the biological risk of timber harvest in different regions with different thermal sensitivity. Such an approach could be used in California to set regional temperature targets.

2B) ARE THERE CONDITIONS THAT ADEQUATELY AMELIORATE THE OCCURRENCE OF ADVERSE TEMPERATURES?

Yes, several factors, alone or in combination, can reduce stream temperature sensitivity to changes in riparian shading. The occurrence of adverse water temperatures is minimized by:

- climatic influences
- geomorphic/topographic shading, and
- hydrologic dampening

Within the zone of coastal influence (, the fog layer attenuates incoming solar radiation resulting in water temperatures that average 1°C to 2°C cooler than for streams of similar size that are outside the zone of coastal influence (Lewis et al. 2000). The inland extent of the zone of coastal influence ranges from 2.8 to 32 km and varies daily, seasonally, and yearly. Stream network data show that water temperatures decline as a stream flows into the zone of coastal influence (Lewis et al. 2000, Madej 2006). Empirical data shows that riparian canopy cover does influence water temperature in the zone of coastal influence, but the level of adequate shading is not well defined (Lewis et al. 2000).

Outside the zone of coastal influence, water temperature (especially daily minima) tends to decrease with increasing elevation as a result of adiabatic cooling (i.e., air temperature declines with increasing elevation) processes (Lewis et al. 2000).

Adverse temperatures can be minimized by geomorphic and topographic factors that block or reduce incoming solar radiation (Allen 2008). Exposure to incident radiation decreases with increasing channel incision because the water surface may be shaded by the streambank. The area of stream surface exposed decreases with decreasing stream width, which minimizes heat loading. The duration of exposure to high angle incident radiation (i.e., results in greatest heating potential) is least for streams with an east-west valley orientation, and is greatest for streams with a north-south orientation. Exposure decreases with increasing height and decreasing distance of the watershed ridge line on the southside of a basin.

Hydrologic factors that dampen water temperature response to heat input include hyporheic exchange rate (i.e., streamflow below the streambed is cooled by heat exchange with subsurface water and substrate), groundwater inflow, and stream discharge. Streambeds composed of alluvium (sand, gravel and cobble substrate) have greater hydraulic retention and increased sub-surface storage (i.e., greater hyporheic exchange) than do streams with bedrock substrate (Johnson 2004). Also, hydraulic obstructions (e.g., logjams) and meandering channels create complex flow paths that promote hyporheic exchange that can have a reach-scale cooling effect on water temperature (Johnson 2004, Dent 2008). Groundwater inflow, which is associated with lithology (Allen 2008) can cause cooling depending on the ratio of inflow volume to surface flow volume. Similarly, as stream discharge increases the potential effects of shade loss on temperature decreases because the increasing thermal capacity of the stream is less sensitivity to heat inputs.

There are several physical factors that can ameliorate the effects of reduced riparian shading on stream warming. Some of these factors may be generalized at the regional scale, and their location or probability of influence are generally predictable. Other factors are more relevant at the reach-scale and, while important, can be very difficult to evaluate in the field in any quantitatively detailed manner. The effectiveness of some factors (i.e., hyporheic exchange, groundwater inflow) to ameliorate temperature response needs further investigation.

3) What bearing do the findings of this literature review have on riparian zone delineation or characteristics of riparian zones for protecting water temperature?

The findings of this literature review indicate the following about riparian zone delineation:

1. **Shade is substantially more relevant than canopy closure as a variable for managing stream temperature risks.** Buffer design should identify the width of thermal influence based on the shade that block high angles (>30°) of incoming solar radiation along the southern exposure in temperature-sensitive streams. Riparian canopy

shading that blocks direct solar radiation along the sun's path at solar elevation angles greater than 30 degrees is most effective for reducing radiant energy and protecting stream temperature. North-side buffers do not provide shade and evidence for the effectiveness of shade from small trees and understory vegetation is mixed. Note, shade refers to the attenuation of direct beam radiation and should not be confused with riparian canopy cover or canopy closure which is the percentage of area that is covered by the overstory canopy. (California Forest Practices Rules, Title 14, California Code of Regulations, Chapter 4, 916.5(e) "I").

2. **Effective riparian shading is a function of the forest canopy density, tree height, and species composition, which is related to stand type and age.** Because stand type and age may vary by region and disturbance history the buffer width that is adequate for shading will likely vary regionally as well, and therefore regional generalizations may apply. This fact is clearly illustrated by the shade/width curves in Figure 1 and demonstrates that one-size-fits-all (i.e., fixed width) prescription are not applicable to the diverse forest types of California. The shading effectiveness varies in relation to the canopy density and tree height potential of each forest type. Therefore tall-dense coastal stands of redwood and Douglas-fir provide more shade for a given buffer width than would shorter Ponderosa pine mixed-conifer stands in the Sierra's. This difference in shade effectiveness by stand type also indicates that a single canopy cover rule (e.g., 50% cover in CA) will not result in similar shading among different forest types. In fact, 50% cover in a coastal forest will result in more effective shade than will 50% cover in a Sierra forest for buffers of equal width.

   Research, mostly from outside of California, shows that effective shading can be provided by buffer widths ranging from 10 m to 30 m depending on stand type, age, and location. We suspect similar widths may be applicable to California forest, but quantitative relationships between buffer width and shade for typical forest types and stand age classes in California are not reported in the literature. A riparian stand metric (e.g, density, relative density, basal area, quadratic mean diameter) that may function as a reliable surrogate for shade has not been developed.

3. **Stream heating effects in the near-headwater portion of fish-bearing streams could be managed by shade buffers along the upstream headwater stream segments.** The length of buffer necessary to protect

temperature is variable and depends on the stream discharge, substrate type, groundwater inflow, and hyporheic exchange. The findings of research outside of California, suggests that protections/considerations extending from 150 to 200 m upstream may be adequate.

4. **The relative importance of riparian shade for protecting water temperature depends on a suit of physical factors, such as region, elevation, stream size, channel morphology, hydrology, and valley orientation.** Stream temperatures are affected by a wide array of variables, and some streams are more sensitive to shade than others. For example, less shade would be needed to maintain cool water for a stream in the zone of coastal influence than would be needed for a stream of equal size in the interior provinces.

   Identifying shade targets for streams may be best achieved by developing empirical relationships or physical process-based calculations that incorporate local and/or regional factors. Such relationships can accommodate a broader suite of important variables, and may improve the accuracy of predictions over simple canopy closure values. Lewis et al. (2000) and more recently Allen (2008) showed that stream temperatures can be modeled for the zone of coastal influence and interior provinces, although more data are needed to improve their accuracy.

Riparian microclimate factors do not appear to have sufficient influence on water temperature to warrant special rules. Stream temperature is more strongly influenced by other variables, including topography, elevation, flow characteristics, geology, etc. Therefore, buffer design should focus on maintaining trees to block high angle radiation and not be overly concerned about factors influencing microclimate (e.g., decrease interception of precipitation, and increase wind speed).

INFERENCES FOR FOREST MANAGEMENT

The literature on riparian heat exchange tells us that shade from riparian timber stands is a key factor controlling heat input to streams. Therefore, maintaining riparian vegetation to block direct solar radiation (i.e., shade) is the intent of forest practice prescriptions for protecting stream temperature during the summer. However, water temperature is a function of a host of physical factors that control heat transfer between air, water, and the streambed. Consequently, the relative importance of riparian vegetation to influence stream temperature varies by location (geographic province) and by site specific conditions (stream width, depth, flow, groundwater inflow, streambed substrate composition, valley orientation, topographic shading and watershed position). This spatial variability indicates that a simple fixed-width buffer or canopy closure prescription (e.g., minimum 50% canopy cover as required in CA) will probably not achieve management goals in all cases. For example, Lewis et al. (2000) showed that California streams with canopy closure in the 50% to 75% range had maximum water temperatures that ranged from about 14° C to 30° C (see boxplot 50-75% class; Figure 2). Clearly, some of these streams had adequate temperature protection and some did not, even though all of the streams had canopy cover that met the California Forest Practice rules. Some of the streams in the Lewis et al. study were located inside the ZCI where stream temperature is less sensitive to shade reduction because heat input is attenuated by the fog layer and some were located outside of the ZCI where temperature is more sensitive to shade levels. Furthermore, some of the streams may be narrow and at higher elevations where channel incision or topography limits solar exposure and where air temperature is lower, and some streams may be wide and shallow at lower elevations where exposure and air temperature has a greater influence on the stream. The key point is, stream temperature sensitivity to shading is dependent on location and physical conditions.

The science on heat exchange indicates that water temperature protection could be provided by varying the riparian shade needs in relation to stream temperature sensitivity. For example, Washington uses a temperature, elevation, and shade relationship (nomograph) to determine minimum riparian shade needs by stream elevation and region (east and west of Cascade divide; Washington Forest Practice Board Manual). The Washington approach incorporates two key factors (elevation and geographic province) that are applicable and easily adaptable to California. However, since Washington developed the nomograph in the 1990’s, we have greatly improved our understanding of how other physical factors influence temperature sensitivity as shown in this review. Therefore, it is feasible to incorporate other physical factors that influence temperature sensitivity for determining shade requirements of riparian stands. In addition to geographic province (i.e., inside or outside of ZCI) other watershed- and reach-scale (reaches are one to several miles long) drivers, such as elevation, distance to divide, stream size, and channel orientation, could be used for assessing temperature sensitivity and general shade requirements. Geographic Information System (GIS) maps that show temperature sensitivity categories could be developed through the use of models that are appropriately calibrated for California. Specific shade requirements could be determined by combining a reach-scale sensitivity ranking with an assessment of site-specific conditions. Factors such as topographic shading, channel incision (e.g., canyon or flood plain area), streambed substrate, and groundwater influence could be used to further assess temperature sensitivity and to determine a minimum shade requirement that would meet the goals of the BOF. The latter could be accomplished with a model or by an appropriately designed decision tree that assessed risk (i.e., relative importance of shade for temperature protection) based on the presence/absence and characteristics of site-specific factors(e.g., Allen 2008). Finally, the amount of shade that may be removed by timber harvest would depend on the difference between the pre-harvest shade level and the site specific shade requirements.

In fish-bearing waters that are directly downstream of headwater streams, the literature indicates that temperature could be protected by buffering the upstream headwater stream segments. The findings of research outside of California, suggests that buffers extending from 150 to 200 m (500 to 650 ft) upstream may be adequate to protect water temperature in low order streams. Whether this buffer is adequate for California streams and regions would need to be validated. Information on temperature sensitivity, as discussed above, would benefit such validation and could probably be used in a screen for determining the potential need of headwater buffers. A site specific assessment similar to that described above could be used to determine the headwater buffer length.

The shade requirement for streams should not only be based on stream temperature sensitivity to shade, but on the water temperature goals or standards that need to be maintained for the protection of salmonid populations. The literature indicates that stream temperature is a major factor influencing population performance and that population performance can be quantitatively evaluated by a probabilistic risk assessment (e.g., Sullivan et al. 2000). Therefore, the suitability of an existing thermal regime for maintaining salmonid populations could be assessed and temperature goals could be defined in terms of the potential to protect or improve population performance. For example, Willey (2004) showed how coho growth was limited in certain California coastal streams by either cool or warm temperature regimes and was maximum in streams with an intermediate temperature regime. This type of information along with a temperature sensitivity assessment, as discusses above, could be used by resource managers to determine where populations may be vulnerable to shade removal or where shade removal could enhance population performance. Ideally, managers could conduct such an analysis at the watershed scale and use this information to guide riparian harvest or restoration plans that would be the most effective in terms of improving population performance. Suitable thermal conditions could be maintained and hazards avoided by altering the timing and spatial position of riparian management activities.

Finally, riparian stand effectiveness for shading is a function of the forest canopy density, height, and species composition, which is related to stand type and age. Because stand type and age may vary by geographic province and disturbance history the buffer width that is adequate for shading will vary as well. This fact undermines the one-size-fits-all (i.e., fixed width) prescription that is commonly applied in forest management. Research shows that effective shading can be provided by buffer widths ranging from 10 m to 30 m (30 to 100 ft) depending on stand type, age, and location. However, quantitative relationships between buffer width and shade for typical forest types and stand age classes in California are not reported in the literature. Potential quantitative relationships between stand density and shade or basal area and shade are lacking. Consequently a riparian stand metric that may function as a reliable surrogate for shade has not been developed.

KEY INFORMATION GAPS

The findings of research outside of California, suggests that buffers extending from 150 to 200 m upstream may be adequate to protect water temperature in low order streams that drain into fish bearing waters. Additional research is needed in California to validate or refine this relationship. More information about recovery distances would also help establish criteria for patch treatments (i.e., canopy openings) that may be used to meet other riparian goals.

Lewis et al. (2000) and Allen (2008) showed that stream temperatures can be modeled for the zone of coastal influence and interior provinces, although more data are needed to improve their accuracy (e.g., temperatures at low flow, low flow hydraulic geometry) and to identify the key watershed factors (e.g., lithology) controlling temperature. These data could be used to develop GIS maps for classifying stream temperature sensitivity at the reach/watershed scale and to build a hierarchal decision tree for classifying stream temperature sensitivity at the site scale.

A quantitative approach for assessing biological risk of temperature exposure on salmonid population performance should be adopted. The level of population performance or risk of performance loss that is considered acceptable for maintaining populations that are vulnerable to temperature impacts should be defined by Policy. This would facilitate a quantitative and transparent approach for assessing the effectiveness of management strategies and for developing water temperature thresholds.

Additional research into the effect of shade provided by shrub cover and understory vegetation would help to establish the value of other riparian vegetation in meeting stream temperature management objectives.

Additional research into potential factors influencing the relative sensitivity of water temperature to microclimate variables is desirable. Under what conditions or locations, if any, would microclimate variables have a strong influence on water temperature.

GLOSSARY

adiabatic trend	The rate of change of air temperature with elevation; sometimes called the adiabatic lapse rate. The average environmental rate is about 2.0 deg. C per 1000 ft.
angular canopy density	The percentage of time that a given point on a stream will be shaded between 10 AM to 2 PM local solar time
bioenergetic model	A numerical model of an organisms metabolic energy budget. It can be used to calculate the energy available for growth
canopy closure/cover	The percentage of ground covered by a canopy of vegetation directly overhead. This definition does not account for the density of the vegetation within the area, but rather can be considered an outline of a plant's branches and foliage. Overlapping canopies are not counted, therefore the maximum canopy closure value possible is 100 percent.
canopy density	The amount of the sky that is blocked by vegetation. Multiple layers of foliage, deep crowns, and interlocking tree branches can enhance canopy density. Its value can exceed 100 percent.
Coastal Zone	1) The zone of maritime influence; 2) The zone of jurisdiction of the California Coastal Commission, which varies in width from a few hundred feet to about 5 miles. See: http://www.coastal.ca.gov/
Zone of coastal influence	Defined by Lewis et al. (2000) as the maximum inland extend of the coastal cooling effect. The inland extent of the ZCI ranges from 2.8 to 32 km and varies daily, seasonally, and yearly.
densiometer	An optical device for measuring the percentage of canopy coverage at a given point. May use a convex or a concave mirror.
fog zone	The zone of maritime influence with morning fog on most days during summer months. Lewis et al. (2000) found that the zone of coastal

	influence is the best approximation of the fog zone.
hyporehic exchange	The exchange of surface water with subsurface water that is flowing through interstitial spaces within the stream bed or banks. It can have a strong influence on water temperature and nutrient cycling.
leaf area index	The ratio of total upper leaf surface of vegetation divided by the surface area of the land on which the vegetation grows. The LAI is a dimensionless value, typically ranging from 0 for bare ground to 6 for a dense forest.
light attenuation	The rate at which light is absorbed by a tree canopy or column of water; varies with wavelength
microclimate	Climate on a scale of meters or tens of meters. Effects of tree canopy, cold air drainage, wind, proximity to a water body, etc. may be important
regression lines	A line through a set of data points in a X-Y plot such that the sum of squares of the Y distance from each point to the line is a minimum
sighting tube	A device for measuring canopy closure or cover at a point directly above an observer. An estimate of percentage canopy closure can be obtained by taking multiple readings that are evenly spaced along a transect. Also called a "densitometer".
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.

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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

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For

The California State Board of Forestry and Fire Protection

Prepared by

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September 2008

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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.

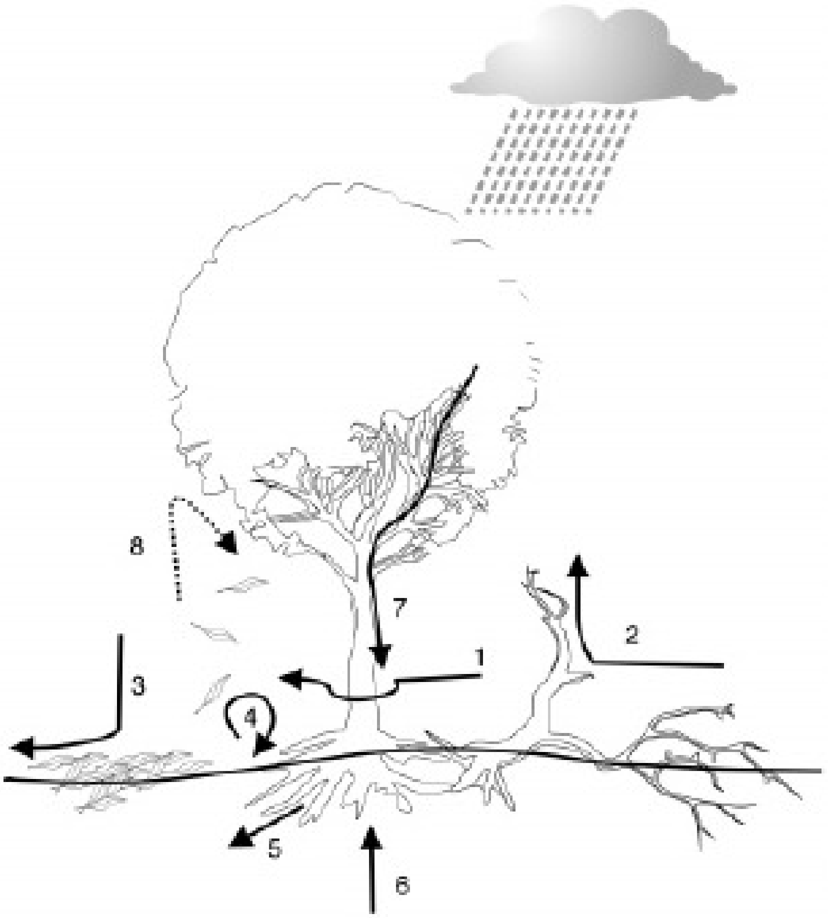

Figure 1) The main physiological impacts of riparian vegetation on water cycling: 1) interaction with over-bank flow by stems, branches and leaves; 2) flow diversion by log jams; 3) change in the infiltration rate of flood waters and rainfall by litter; 4) increase of turbulence as a consequence of root 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

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[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.

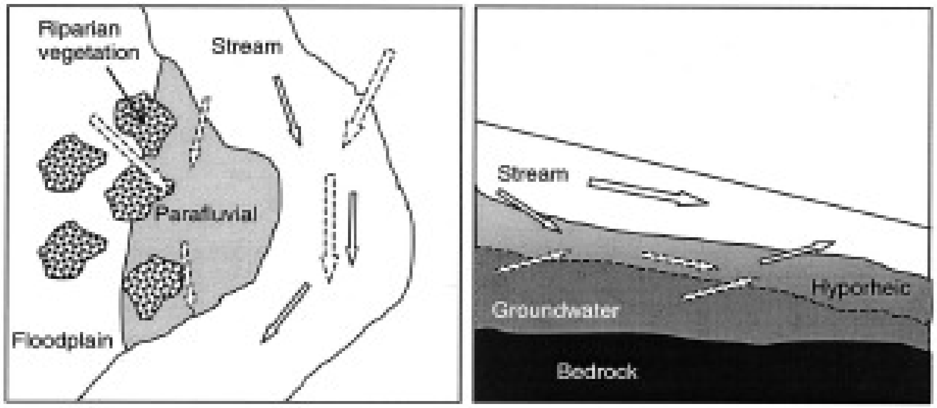

Figure 3) Aerial and side view of the hyporheic and parafluvial zones showing connections with the stream, groundwater, riparian and floodplain systems (Hancock 2002).

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* <u>*zone*</u>” 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* <u>*buffer*</u>” 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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Scientific Literature Review of Forest Management Effects on Riparian Functions for Anadromous Salmonids

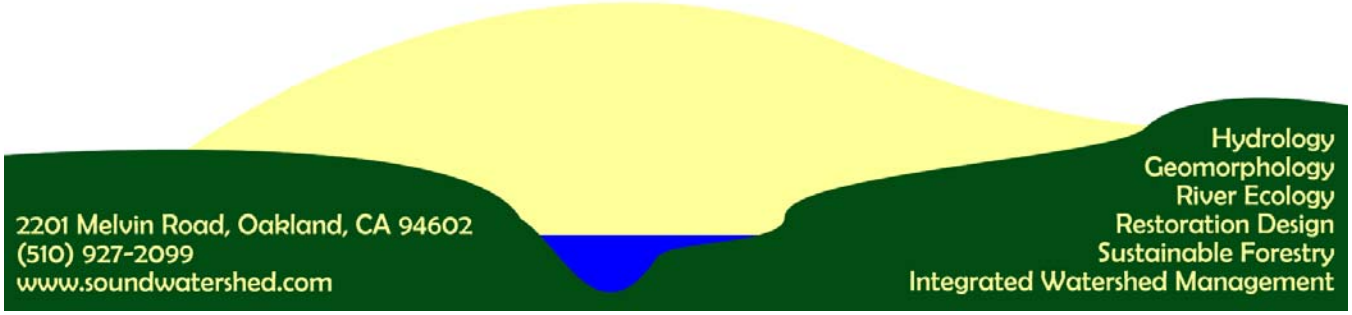
Chapter 5

WOOD EXCHANGE FUNCTIONS

for

The California State Board of
Forestry and Fire Protection

September 2008



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5) WOOD 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

Prepared by

Mike Liquori

Dr. Lee Benda

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with

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September 2008

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Table of Contents

EXECUTIVE SUMMARY

Forested environments strongly influence salmonid habitat in California through the processes of woody debris entering the stream from riparian areas. This report describes the mechanisms for wood recruitment to the stream environment, the influence of forest management, and factors that affect riparian buffer design.

There are three dominant sources of instream wood; bank erosion, streamside landslides, and treefall from within riparian areas. Each of these sources is influenced by the dominant type, frequency and magnitude of disturbance processes (fire, flood, landsliding, infestation, etc), as well as the rates of competition mortality associated with the existing stand structure. Disturbance, mortality and tree growth in riparian stands are dynamically linked.

In California second-growth forests, approximately 40-60% of observed instream wood comes from bank erosion, approximately 30% comes from streamside landslides, and the remaining amount comes from treefall. These rates vary substantially based on the geographic (e.g. region) and geomorphic (e.g. landscape condition) context for the site.

Once in the stream, wood is subject to transport down the channel network either during floods (fluvial) or debris-flows. Wood that is carried by debris flow only occurs in certain terrains (typically steep, confined headwaters). Wood that is carried by floods is typically shorter than the channel width.

It can be important to understand the existing stand conditions and successional trajectory of the riparian stand because the riparian stand structure strongly influences the qualities of recruited wood and the rate of recruitment. The existing stand structure and successional trajectory also influences the types and qualities of disturbances that can occur at any given site, and disturbances are one of the primary recruitment processes for instream wood.

Forest management can manipulate riparian stand structure in ways that a) affect the growth and mortality dynamics for the stand and b) influence the types, qualities and risks of disturbances. Forest management can also reduce tree recruitment potential and shift the functional inputs from various exchange functions. Management has the potential to improve existing conditions that reflect legacy forest practices. Management can also alter short-term and long-term supply and characteristics of wood. Therefore, management within riparian

zones must be conducted carefully, and with clear functional objectives.

Riparian silvicultural objectives that would support ecological functions important to salmonids (and other fauna) should balance competition mortality objectives, growth objectives, and disturbance risks in ways that support exchange function objectives based on a diagnosis of site requirements. Diagnoses may be generalized by the spatial context of the site by considering regional variations as well as watershed-scale variations in the dominant processes that affect stand evolution (i.e. disturbance types). Diagnoses should also consider the expected stand growth and mortality processes based on conditions that influence stand dynamics (e.g. tree species, cohorts, density, size, etc). Together, the major factors that are reported to influence wood recruitment conditions include:

- Existing Stand Density, Composition And Structure
- Stream Type, Order and Watershed Context
- Vegetation Type and Soil/ Site Index
- Regional Context
- Disturbance Context

Riparian management strategies require consideration of both science and policy. The reviewed literature offers many opinions, but little hard data to evaluate the scientific effectiveness of any approach. Ultimately, the choice of the best approach must be guided by forest policy. The ranges of policy alternatives includes:

Riparian Reserves: This approach seeks to maintain large buffer widths to minimize management effects within riparian areas, specifically those indirect management effects on natural rates of disturbance. This approach typically calls for uniform and continuous riparian buffers of up to two site-potential tree heights on fish-bearing streams and one site-potential tree height on non-fish streams. The underlying basis for this strategy is that over long periods of time (typically centuries), late-seral conditions will become re-established in riparian areas, and that such conditions best represent the long-term conditions suitable for salmonids.

Selective Management: This approach seeks to actively design the characteristics of riparian forests (e.g. size, height, species) in a way that influences future wood recruitment potential (e.g. timing of mortality, exposure to disturbance risks) and other functions. Its focus is often to maximize the benefit to riparian functions while preserving the capacity to operate on forest lands to achieve other resource objectives. It achieves this focus by encouraging a stand composition that targets wood recruitment characteristics most suitable to the specific stream environment. This approach recognizes that the total wood volume grown onsite is strongly influenced by stand structure (density, species, age-distributions, etc), and that tree volume and diameter can be manipulated to meet management objectives.

Proactive Enhancement: Another approach described by the reviewed literature is the concept of proactive instream restoration and enhancement in the form of wood placement. The ability to properly design and implement restoration or enhancement projects requires knowledge of hydrology, hydraulics, geomorphology, biology and engineering practices. Instream wood placement is a practice that is continuing to evolve in many land-use settings, and the general perception is that such projects are overall a benefit to salmonids.

There are a wide array of tools and methods available that can objectively inform these management strategies using scientific approaches. There are also several existing information gaps that could improve riparian management.

RECOGNIZED EXCHANGE FUNCTION ROLES & PROCESSES

Forested environments strongly influence salmonid habitat in California through the processes of woody debris entering the stream from riparian areas. The relative importance of riparian forests in regulating wood delivery to the stream environment is governed by multiple interacting factors (biotic and abiotic) that have been described by CBOF-TAC (2007), and which form the foundation of our review. These principles include:

- In-channel wood plays an important role in determining aquatic habitat conditions and riparian ecology by affecting flow hydraulics, regulating sediment transport and storage, influencing channel morphology, and promoting diversity of channel habitat
- Wood is recruited to streams through tree fall, bank erosion, debris flows, and landslides. These processes are strongly influenced by mortality through competition, infestation or disease, as well as disturbance processes like fire, flooding, wind, etc
- In steep channels, wood accumulations often help to trap sediment and promote a stepped morphology.
- Logging activities adjacent to streams that eliminate or severely reduce wood storage in streams can have negative impacts for salmonids
- Wood transport through the channel network is an important source of woody debris for streams that are typically inhabited by salmonids, and transport occurs via both fluvial and debris flow processes
- The legacy of historic forest and stream management practices continues to have significant impacts on the stream environment, and full recovery of natural recruitment characteristics might be over a century or more away
- Forest management practices in riparian zones can have lasting influences (both positive and negative) on the recruitment of woody debris over time

- The dynamics between forest stand growth, wood recruitment and channel response are complex and vary widely across both time and space
- Wood loading and instream wood characteristics vary widely over the landscape, and a clear scientific consensus for how much wood is sufficient to support salmonids needs has been elusive
- The size of functional instream wood generally increases with increasing basin size, although some have argued that large wood in headwater streams might have important functional roles as well

RESPONSES TO KEY QUESTIONS

The Key Questions are grouped into the following sections:

1.2.1 **Mechanisms for Wood Recruitment** – this section includes questions that relate to the processes and functions within riparian areas that support wood recruitment.

1.2.2 **Management Influences on Wood Recruitment** – this section discusses the manner in which management and/or disturbances can affect the natural mechanisms for recruitment

1.2.3 **Factors Affecting Buffer Design** – this section describes those factors that should be considered in developing buffer strategies.

1) Mechanisms for Wood Recruitment

In this section, we describe the key natural wood recruitment processes that occur in forested landscapes of California. Later in this chapter, we address differences in the way that recruitment processes occur in managed forests.

The literature on wood recruitment to streams over the last 30 years has identified the major recruitment mechanisms for wood that is applicable in a general sense to channels of all sizes and in most geographic areas (Keller et al 1995). While most of the wood recruitment studies in California and elsewhere have focused on larger fish-bearing channels, the processes of wood recruitment are generally similar across small headwater (low-order) and larger fish-bearing streams, although there are some specific differences that we describe below. Natural recruitment processes include:

1. Bank erosion and channel migration processes that recruit trees by undercutting the channel margins (Keller et al. 1996; Martin and Benda 2001; Benda et al. 2002; Marcus et al. 2002; Benda et al 2003; Benda et al 2004; Benda et al 2005).

2. Mass wasting processes, including landslides, earthflows, debris avalanches, debris flows, etc (Benda et al 2002; May and Gressweld 2003; Reeves et al. 2003).

3. Treefall generated from toppling of trees in the riparian zone (McDade et al. 1990; Robison and Beschta 1990; Martin and Benda 2001; Benda et al. 2002; Liquori 2006).

Trees can die in response to competition mortality, disease, infestation or disturbances that kill trees and delivers woody debris before mortality would typically occur from competition (Bragg and Kershner 2000; Liquori 2006).

Disturbance typically plays a very important role in wood recruitment in California forests, as it typically sets the context for natural recruitment processes and the evolution of the forest stand. Natural disturbance processes significantly influence the rates of recruitment. Fire, flood, wind, landslide and similar natural disturbances are the primary source of wood recruitment in most unmanaged landscapes. The effect of these disturbances is highly dynamic – disturbances affect the condition of the riparian forest, and the riparian forest condition can affect the probability of disturbance (Benda and Sias 2002; Reeves et al. 2003; Bisson, Rieman et al. 2003; Nakamura and Swanson 2003). For example, wildfire in the riparian zone results in mortality that can recruit wood through treefall, adding a rapid influx of wood to streams that can increase channel migration processes, increasing bank erosion and thus increasing additional wood loading (Benda and Sias 2003).

Bank Erosion

Bank erosion delivers trees and downed wood to the stream by undercutting the banks, typically during large floods. Bank erosion tends to be episodic, and is related to the rate of channel migration or widening. Thus the proportion of instream wood delivered from bank erosion will vary over space and time.

Most trees immediately adjacent to streams will be recruited (McDade et al. 1990; Liquori 2006). In many mature 2nd-growth streams, bank erosion delivers about 40 – 60% of the observed wood loading (Figure 1), similar to the loading rate in old-growth sites (Figure 2), which provided about 30-55% of the observed instream wood (Benda et al. 2002; Benda et al 2003; Benda et al 2004; Benda et al 2005).

Larger, low-gradient channels are more prone to bank erosion through channel widening, meandering, and/or migration, and thus tend to recruit proportionally more wood than steeper, confined channels. However, landslide recruitment of trees adjacent to smaller channels can reverse this trend. Trees recruited through bank erosion typically are rooted within about 1 m of the channel at the time of recruitment

(McDade et al 1990) and recruitment of key pieces[1] is also typically dominated by bank erosion (Benda et al. 2002; Benda et al 2003; Benda et al 2004; Benda et al 2005).

It need not require an extensive amount of erosion to supply trees from bank erosion. Wood budget calculations indicate that as little as 1.5 feet per decade of average bank erosion can supply wood at loads similar to those observed in California. At this rate, it would take 700 years to erode through a standing 100 foot buffer. Of course, actual bank erosion processes are episodic and disperse, and occur in association with large floods, channel migration periods, excessive instream sedimentation or wood accumulation (e.g. from landslides, etc).

Mass Wasting (landslides & debris flows)

Streamside landslides can be significant contributors of large woody debris in steep landscapes prone to hillslope failure.

In the Northern California Redwood region, streamside landsliding was important at selected sites with steep inner gorges, primarily in the old growth forest of Little Lost Man Creek (Benda et al 2002). In old growth sites (Prairie and Little Lost Man Creek) streamside landsliding accounted for 50% of the observed woody debris. In second growth forests, streamside landsliding accounted for 30% of observed woody debris.

May and Gresswell (2003) documented that along headwater first- and second-order streams in the central Oregon Coast Range, streamside landsliding along inner gorges was a dominant recruitment process and thus wood source distances were longer than predicted by mortality alone in those areas. In larger alluvial channels, slope instability was less important but wood transfer from fluvial transport becomes important (Braudrick and Grant 2000).

Treefall

Treefall supplies wood to the stream from the riparian forests, and typically includes trees that die from competition mortality, wind

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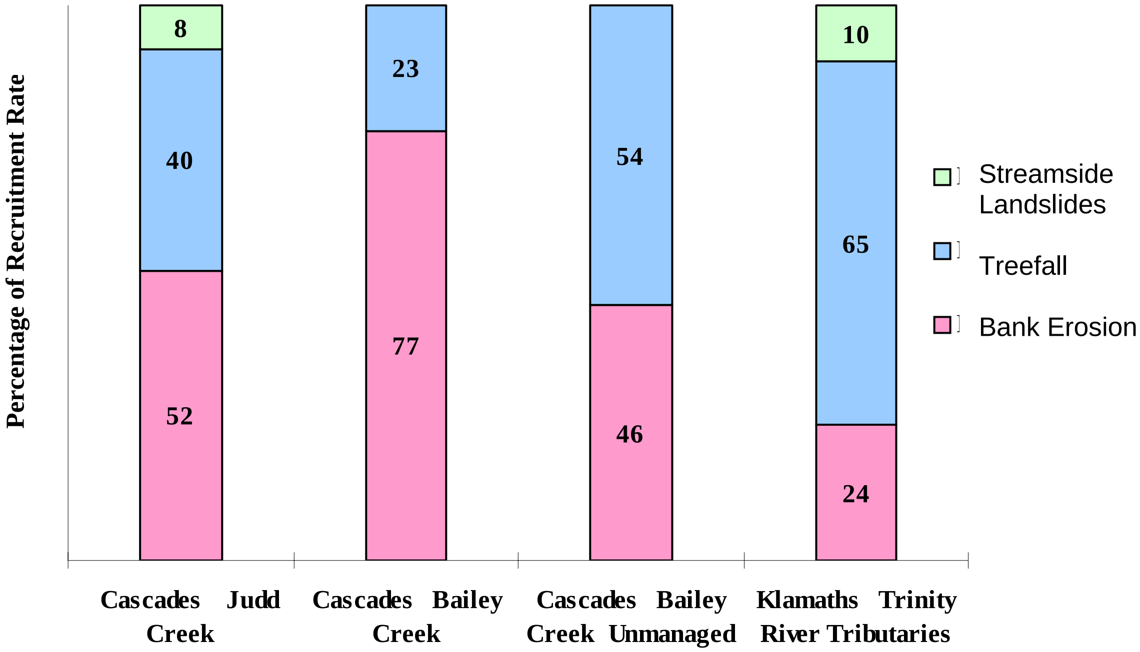
[1] *Key pieces are large diameter trees that are structurally important in supporting woody debris jams in alluvial rivers*

damage, insect damage, root disease, infestation, animal damage, and other processes. Wood budget studies typically cannot differentiate between competition mortality and other forms of treefall (e.g. windthrow, ice or snow weighting, animal damage, etc).

Treefall from riparian stands will typically fall in a random orientation (Robison and Beschta 1990; McDade et al. 1990), with the exception of those processes that have mechanical influence (e.g. wind or ice damage). As the tree dies, roots decay and the loss of root support will cause the tree to topple. Treefall that occurs in response to some disturbances can significantly increased percentage of treefall directed toward the channel (McDade et al. 1990; Liquori 2006).

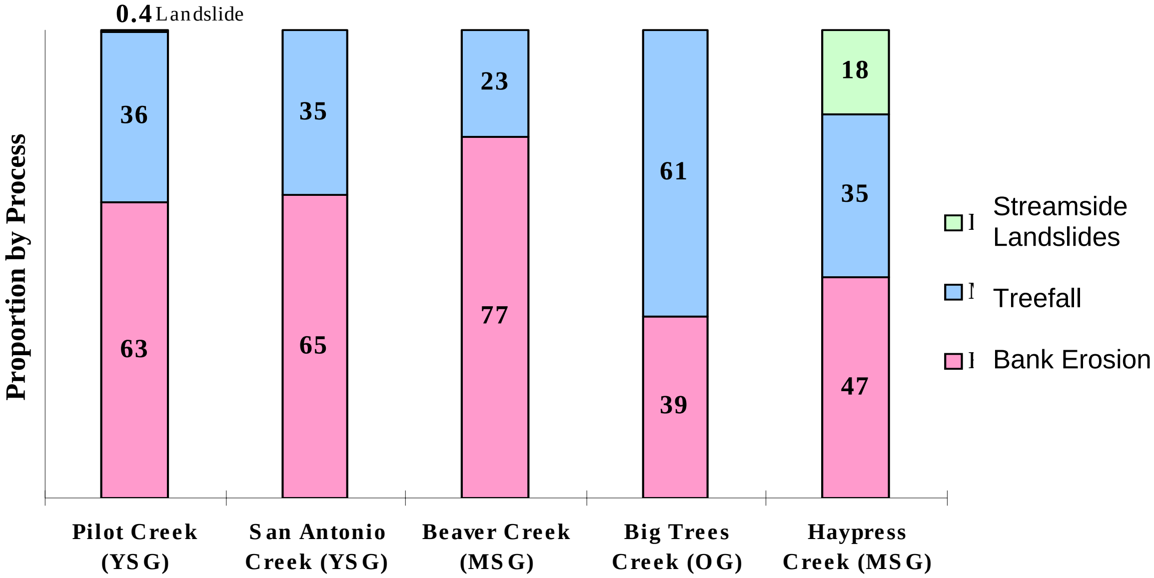
Figure 1. Percentage of wood recruitment by different processes in streams located in the Southern Cascades and Klamath Mountains of Northern California (Benda et al. 2003).



Treefall recruitment is typically limited by the tree height, and the probability of recruitment upon falling declines non-linearly with distance (Robison and Beschta 1990). Trees immediately adjacent to the stream only have a 50% probability of recruiting to the stream, unless influenced by wind (Liquori 2006). Trees that are farther than a tree-height generally cannot recruit to the stream, unless a) the valley is steep enough to allow the tree to slide downslope along small streams or b) on large rivers, floods can redistribute wood both away from and toward the channel.

In the Northern California Redwood region, treefall accounted for 20-45% of wood recruited in old-growth sites and 40% in second-growth sites (Benda et al 2002) (see Figures 1 and 2). In northern California's coastal redwood region, average forest morality rates are higher in second growth forests (0.9%/year) compared to much lower average mortality rates in old growth redwood forests (0.04%/year). This resulted in a higher wood loading in second growth forests from mortality recruitment (4 m^3/km/yr in second growth vs. 2.5 m^3/km/yr in old growth), although the wood supplied was of smaller diameter (Benda et al. 2002).

Figure 2. Percentage of wood recruitment by different processes in streams located in the Sierra Mountains (western slope) in Northern California (Benda et al. 2005). YSG=Young Second Growth; MSG=Mature Second Growth; OG= Old-Growth. Note mortality in this study refers to treefall recruitment.



HOW DOES WOOD RECRUITMENT DIFFER BETWEEN LOW-ORDER AND HIGH-ORDER STREAMS?

Fundamentally, wood recruitment processes in lower-order channels are similar to higher-order streams, in that the same processes of bank erosion (e.g., landsliding and treefall) are relevant, although the relative proportion of wood recruited from each mechanism varies. Recruitment processes and source distances are highly variable and depend on local topography and channel conditions.

The proportion of wood that comes from the 3 primary mechanisms (treefall, bank erosion and landsliding) shifts somewhat between headwater streams and high-order streams. Bank erosion recruitment is proportionally more important in high-order streams (typically responsible for 40 – 60% of observed wood). Similarly, landsliding is often more important in low-order streams, particularly in steep, confined landscapes (Table A).

Table A[2]. Summary of wood recruitment information in high-order (fish- bearing) streams.

Location	Forest Type	Treefall[3]	Bank Erosion	Streamside landsliding	Fire	Debris Flow[4]	Slash[5]	Citations
Redwood N. Coast CA	Second growth	45%	36%	19%	n/a	Observed not quantified	Signif.	Benda et al. 2002
Redwood N Coast CA	Mature	38%	50%	12%	n/a	n/a	Signif.	Benda et al. 2002
So. Cascades N. CA	Second growth	46%	52%	2%	n/a	n/a	n/a	Benda et al 2003)
Klamath Mtns. N. CA	Second growth/ Mature	39%	43%	17%	n/a	Observed not quantified	n/a	Benda et al 2003)
Central CA Coast	Second growth	26%	59%	16%	n/a	Observed not quantified	Signif.	Benda et al 2003)
Sierras Eastern Central valley	Second growth	37%	53%	10%	n/a	n/a	Locally Signif.	Benda et al. 2005
Sierras Eastern Central valley	Mature	61%	---	---	n/a	n/a	n/a	Benda et al. 2005
Oregon Coast Range	Mature	n/a	n/a	n/a	n/a	46%	n/a	Reeves et al. 2003
Oregon Coast Range	Mature	Dominant	?	Less important	n/a	?	n/a	May and Gresswell 2003

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[2] *Because some of the field sites in headwater streams are contained within studies that evaluated mostly larger channels (see above and for example Benda et al. 2002), this section on larger streams includes in the cited statistics data in headwater streams. This is because the cited studies did not differentiate between headwater and larger streams and the exclusion of headwater data would not significantly affect the results reported below.*

[3] *Includes the processes of suppression mortality, disease, insects, and blowdown*

[4] *Refers to debris flows in headwater, first- and second-order streams that deliver WOOD to larger fish-bearing channels at the confluence with low-order tributaries.*

[5] *Refers to old logging debris left in channels prior to modern forest practice rule.*

In addition to the primary recruitment mechanisms, wood loading in low-order streams is also affected by:

- Landslides from steep hillslopes (May and Gresswell 2003;)
- Valley confinement that can prevent falling trees from intersecting the channel, and can increase the rates of breakage

Field studies of wood recruitment processes to headwater channels (specifically first- and second-order channels) that identified specific wood recruitment processes, are limited to Benda et al. (2002) in the Redwood region of northern California, May and Gresswell (2003) in the central Oregon Coast Range, Jackson et al. (2001) in the Olympic Peninsula, western Washington, and Benda et al. (2003) in the southern Cascades of northern California. In the context of these limited data sets, mortality, bank erosion and streamside landsliding are all important wood recruitment processes (Table **B**). Although streamside landsliding can dominate in certain settings, bank erosion and mortality can be dominant sources of wood.

Table B) sources of observed wood recruitment from headwater channels.

Location	Forest Type	Treefall[6]	Bank Erosion	Streamside landsliding	Fire	Slash[7]	Citations
Redwood North Coast CA	Second	22%	39%	39%	n/a	Signif.	Benda et at. 2002
South Cascades CA	Second	78%	22%	n/a	n/a	n/a	Benda et al. 2003
Oregon Coast Range	Mature	?	?	Dominant	n/a	n/a	May and Gresswell 2003

Another study pertaining to headwater channels was that of Bragg et al. (2000) in the central Rocky Mountain region, which concentrated on modeling wood recruitment from stand mortality only, using a forest vegetation simulator (Wykoff et al. 1982) that predicts forest growth and mortality.

Marcus et al. (2002) evaluated wood storage and movement across a range of stream sizes (14 – 242 km^2) and determined that wood storage is highest in the smallest channels, and has increased due to recent floods (assumed increased bank erosion recruitment). Intermediate size channels are approximately in equilibrium in terms of wood storage as input can equal output due to effective fluvial transport.

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[6] *Includes the processes of suppression mortality, disease, insects, and blowdown*
[7] *Refers to old logging debris left in channels prior to modern forest practice rule.*

Less wood can be found in larger rivers due to high wood transport and storage overbank.

In addition to the primary recruitment mechanisms described above, wood loading in higher-order streams is also affected by:

- Import and export of woody debris from fluvial transport (Keller et al. 1996; Benda and Sias 2002; Hyatt and Naiman 2001; others).
- Debris flows that transport wood stored in headwater streams and deposit logs and sediment at confluences with larger fish-bearing channels (Benda et al. 2002; Reeves et al. 2003).

TO WHAT EXTENT DO LOW-ORDER STREAMS DELIVER IN-STREAM WOOD TO HIGHER ORDER, FISH-BEARING STREAMS?

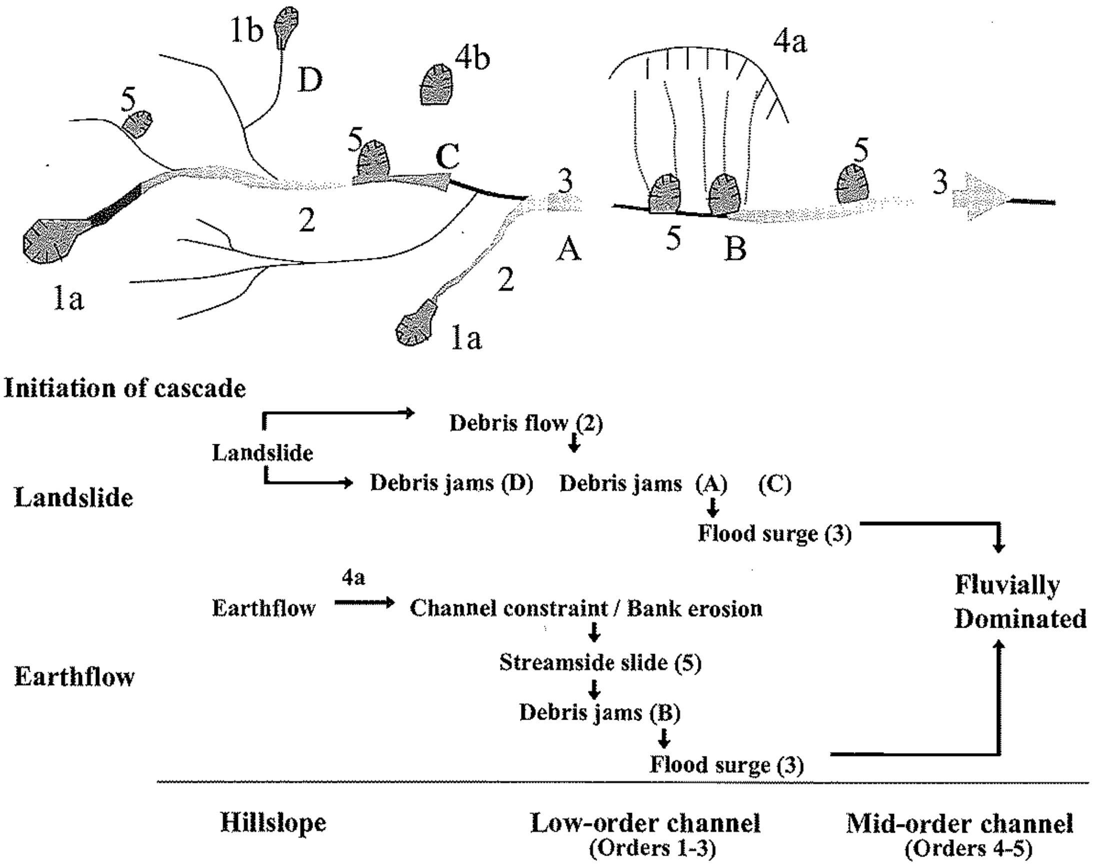
There are two primary mechanisms for delivering woody debris from low-order streams to higher-order streams: fluvial transport and debris flow transport.

Debris-flows

In some landscapes, including parts of coastal California, wood derived from debris flow deposits can play an important ecological role (Reeves et al. 2003; May and Gresswell 2003; Bigelow et al. 2007) although few specific studies have documented interactions between debris-flows and streams in California. Low-order headwater streams can be prone to debris flows in certain physiographic areas in California and can be a source of wood to higher-order fish-bearing streams (Coast Ranges and Klamath Mountains primarily). Wood from debris flows is recruited to the steam via landslides and earthflows that are initiated on hillslopes, and routed to the channel environment (Figure 3).

It was difficult to allocate woody debris from debris-flow sources in the California wood budget studies (Benda et al. 2002; Benda et al 2003; Benda et al 2004; Benda et al 2005) because of the uncertainties of aging debris flow deposits in this terrain. Only one study in the Klamath Mountains documented the importance of debris flows as sources of key pieces, and it identified only 11% of the total wood recruited came from these sources (Benda et al. 2003). In the central Oregon Coast Range, Reeves et al. (2003) concluded that upslope sources of woody debris to fish-bearing streams from unmanaged landscapes can be important in steep, confined landscapes, accounting for 65% of the pieces and 46% of the volume.

Figure 3) schematic of disturbance cascades in headwater environments. Earthflows and landslides deliver hillslope wood to the channel network, where it can be routed downstream by debris flow processes and flood surges. Susceptibility to debris flows can be identified by geomorphic criteria associated with the channel and hillslope environment (*from Nakamura and Swanson 2003*).



Fluvial Transport

Fluvial transport from low-order channels is another potential source of wood to higher-order streams (Keller et al. 1995). The extent of fluvial transport depends on the size of available instream wood and the power to transport that wood, which increases with contributing basin area. When wood is sufficiently large in headwater streams (i.e., piece length > channel width), transport rates tend to be very low (Benda et al. 2002; Benda et al 2003; Benda et al 2004; Benda et al 2005).

In one study in the California Coast Range (Benda et al. 2004), the distance upstream of low- to high-order channel confluences where fluvial wood transport is predicted to supply wood to larger fish-bearing channels ranged from 325 – 650 ft (100 – 200 m).

Similarly, wood transport was predicted using a simple wood transport model (Benda and Sias 2003) and using data on jam size and frequency. The predicted wood transport from low-order, headwater channels to larger fish-bearing streams extended upstream of the junctions 325 – 650 ft (100 – 200 m), with wood piece sizes ranging from 3 – 9 ft (1 – 3 m).

Fluvial transport of wood can lead to accumulations in woody debris jams when trapped by large, stable "key" pieces of wood (Keller et al 1995). Thus downstream reaches can experience higher wood loadings than upstream reaches where riparian conditions are similar. Once a river exceeds the width of the tallest recruited trees, this relationship reverses as wood is exported out to sea (Martin and Benda 2001).

TO WHAT EXTENT AND IN WHAT WAYS DOES PLANT SUCCESSION STAGE OR VEGETATIVE COMMUNITY HAVE AN EFFECT [*ON WOOD RECRUITMENT*]?

Understanding the existing stand conditions and likely successional trends can be helpful toward guiding riparian conditions toward desired states. Successional trajectories can be predicted using relative stand density indices or wood recruitment models (e.g., Bragg et al. 2000; Welty et al 2002).

Successional status affects the potential for wood recruitment in multifaceted ways (Bragg et al 2000; Rot et al 2000). Liquori (2000) described successional implications for riparian management by recognizing that the stage of succession influences the dominant riparian exchange functions. For example, competition mortality is higher during stem exclusion phases (Rot et al 2000), however the quality of woody debris can be limited, depending on factors like stem density and species. During successional periods of vigorous stand growth, competition mortality can decline significantly, causing periods of lower treefall recruitment that can extend for several decades.

Forest successional trajectories can be altered either directly (via management treatments) or indirectly in response to altering disturbance regimes. For example, clearcuts in windprone landscapes can increase the risk of windthrow in ways that transition a stem exclusion stand toward an understory reinitiation stand (Liquori 2006). Similarly, dense riparian buffers in fire-prone landscapes can lead to increased frequency of crown fires, which can rapidly transition a mature stand toward a period of very high treefall recruitment followed by an extended period of minimal treefall recruitment as the stand stage transitions toward stand initiation (Agee 1993).

In unmanaged forests, the lack of disturbance can affect the forest floor, soil temperatures, and some types of microbial activity. Size distributions of trees in unmanaged coniferous forests are strongly related to disturbance history and time since previous disturbances (Oliver and Larson 1996). Typical patterns of size distribution can be identified, although many stands will deviate from idealized patterns. In centuries-old, late successional forests, frequency distributions of trees typically approximate a negative exponential distribution. Intermediate disturbances such as partial fires can remove understory and overstory trees, altering horizontal and spatial pattern of canopy foliage. In some cases, different disturbance histories can produce similar size distributions of trees.

Species assemblages can also influence successional dynamics. For example, in coastal California, mixed Douglas fir (*Psuedotsuga menziesii*) and redwood (*Sequoia sempervirens*) stands have different rates of mortality and different recruitment mechanisms. Douglas fir grows faster during early stand establishment periods, but is more prone to competition and windthrow (Surfleet and Ziemer 1996). Later stand development is dominated by redwood growth and Douglas fir mortality. Young redwood mortality is often low, because of several physiological adaptations in redwood that promote survival under limited growing conditions. Old-growth coast redwood eventually die due to wind throw, toppling, very large floods, and heart rot (Stone and Vasey 1968). So in the absence of disturbance, recruitment rates in pure redwood stands are lower than a mixed species stand where competition mortality can occur.

Overall, recruitment from competition mortality processes can be one of the slowest ways to recruit wood to streams. Mortality rates in forest stands usually range from 0.02% to as much as ~1% per year, and only a fraction of these dead trees are recruited to streams. In general, second growth forests have higher competition mortality rates and higher growth rates when compared to older (old-growth or mature) forests due to increased stem differentiation in response to pressures from limited growing space. In one study, second growth forests had an average treefall recruitment (presumably from competition mortality) rate of 0.9%/yr compared to 0.04%/yr in old growth, a 20-fold difference (Benda et al. 2002). However, competition mortality tends to kill the smallest, weakest trees in the forest, and these trees generally provide lower quality wood to the stream than wood provided through disturbances. Reliance on competition mortality can extend the period of recovery in the absence of other disturbance mechanisms for recruiting wood.

Forest successional pathways establish the context for disturbance risks in many landscapes. For example, fire asserts a significant influence on wood growth and recruitment (Reeves et al. 2003). Models of stand replacing fires with recurrence intervals of 150 and 500 years (representing a gradient from humid temperate to more arid forests) can contribute 50% to 15% of the long term wood to streams from post fire toppling (Benda and Sias 2002). Underburns can promote growth in older cohorts by reducing competition from intermediate and suppressed trees.

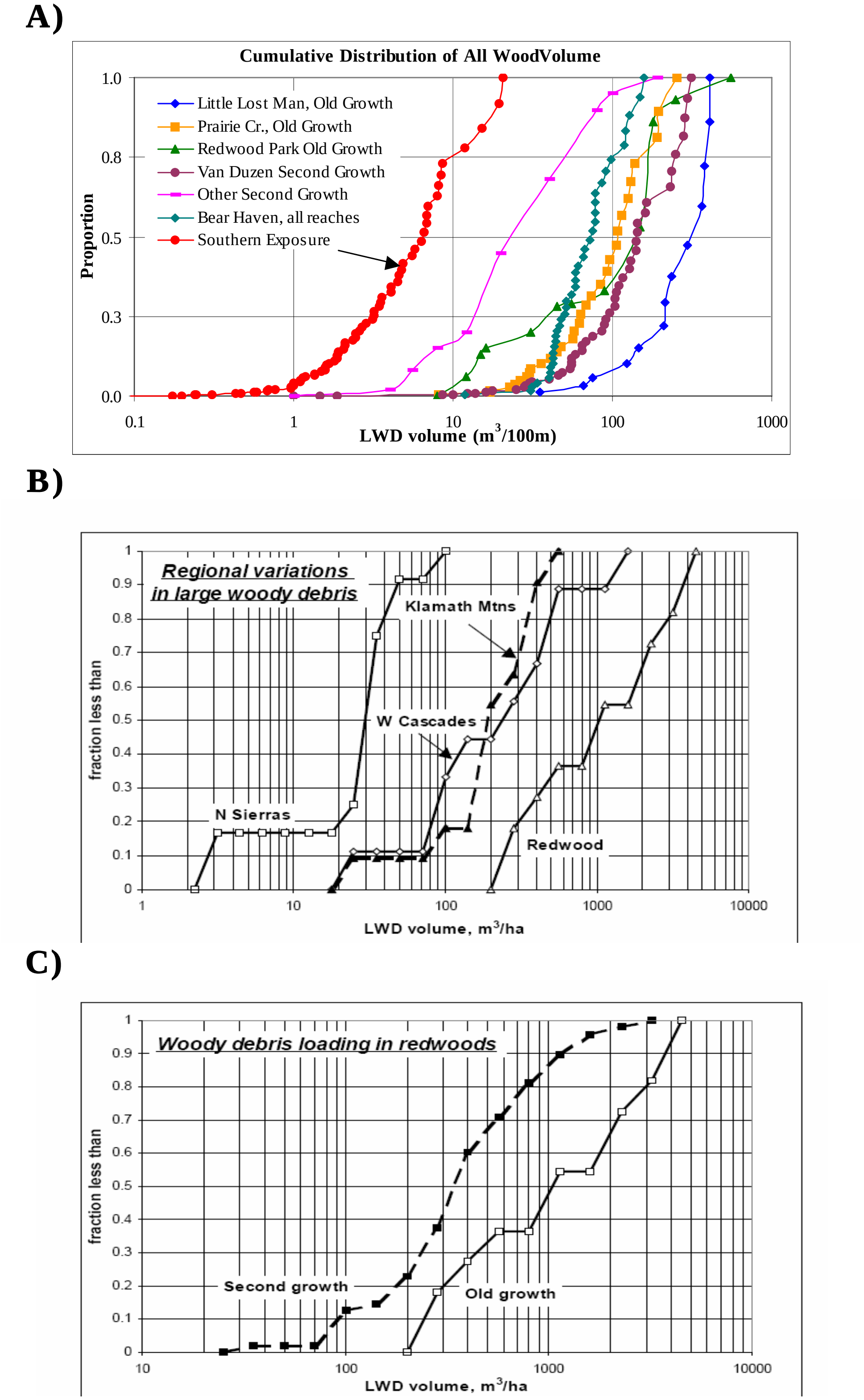
In general, variation in forest types (and associated biomass density) in California strongly influences the amount of wood that is found in channels. Based on wood budget studies in northern California, the largest wood storage occurs in the coastal redwood zone and the least occurs in the Southern Cascades and Sierras (Figures 4A-C).

WHAT IS THE EFFECT OF STAND-LEVEL RIPARIAN FOREST CONDITIONS ON WOOD DELIVERY TO STREAMS TO MAINTAIN SALMONID HABITAT?

There is limited information about the effect of stand conditions on wood recruitment, however, the amount of wood loading under natural conditions is generally related to the qualities and quantities of trees available in adjacent riparian stands (Keller et al 1995). Rot et al. (2000) found that stand age and stand basal area did not influence the in-stream number of wood pieces, wood volume, pool spacing, percent pools, or percent of wood-formed pools. However, stand age did correspond to the diameter of instream wood.

Wood is important for salmonids as it is responsible for forming pools in alluvial environments, helps to sort sediment for spawning, and provides cover (Cederholm et al 1997; Reeves et al 1995; Bisson, Rieman et al. 2003). Many field studies have linked fish habitat (e.g., pools, cover, gravel) with wood across the PNW over the past 20 to 30 years, a conclusion outlined in the wood Primer (CBOF-TAC 2007).

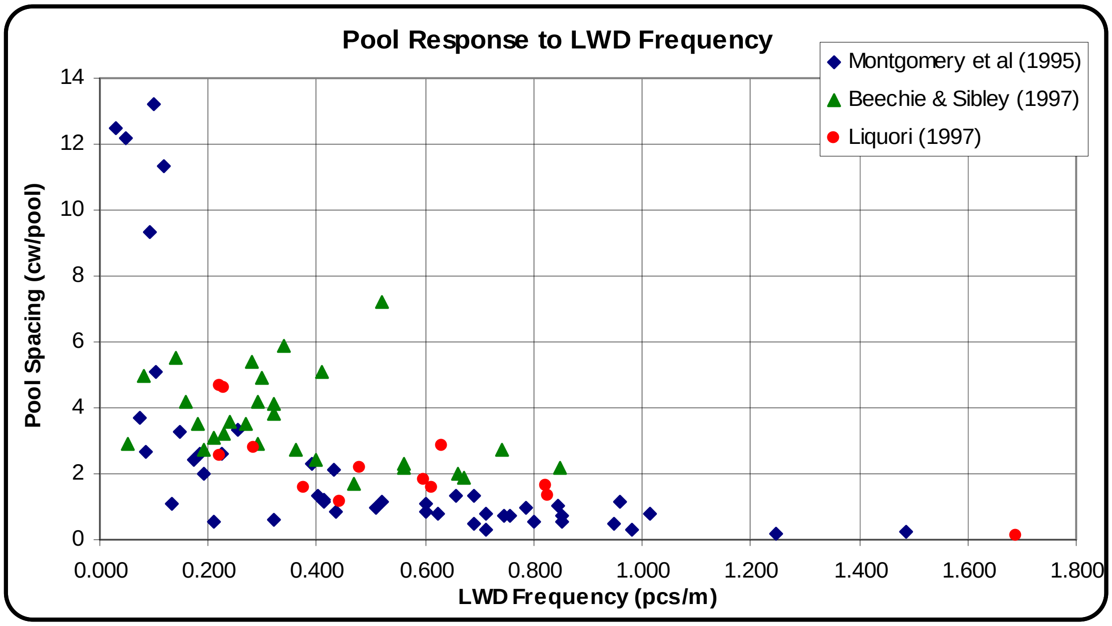
Figure 4. Variation in cumulative wood storage is shown across several northern California's physiographic regions (A) From Benda et al. 2002; Benda et al. 2003; Benda et al 2004; Benda et al. 2005) and Lisle 1999 (B&C).



The reviewed literature (Gregory et al. 2003; Hassan et al. 2005; Lassettre and Harris 2001) also emphasize the positive role of wood on aquatic habitat formation. But none of the reviewed papers supply specific quantitative relationships between riparian forest conditions, wood supply, and abundance and quality and abundance of fish habitats (other than pool frequency).

Several field studies (Montgomery et al. 1995, Beechie and Sibley 1997, Martin 2001) have documented how pool spacing and sediment storage are coupled to in-stream wood storage. In general, more instream wood equals more pools and enhanced sediment storage up until a point of about 650 pieces/mile of stream (~400 pieces/km) (Figure 5), at which point wood loading appears to have declining additional effect on pool density (Montgomery et al.1995; Beechie and Sibley 1997; Liquori 1997).

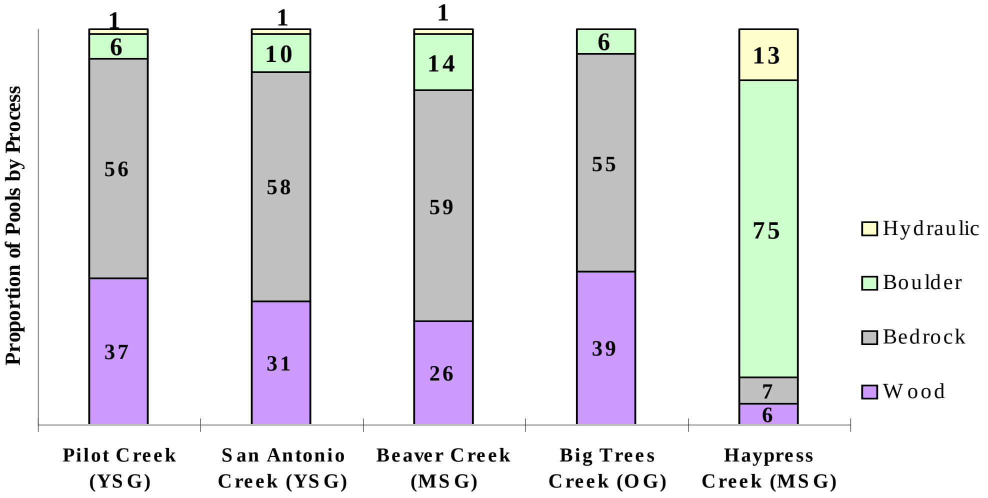
Figure 5) pool density as a function of wood loading in Pacific Northwest streams (developed from data available in Montgomery et al.1995; Beechie and Sibley 1997; Liquori 1997).



Studies in the Pacific Northwest have found that generally, steep and confined streams are significantly less responsive to woody debris inputs than shallow unconfined streams (Rot et al.2000; Montgomery and Buffington 1997). However, other studies of wood in California streams have documented the significant role of wood on pool formation (Benda et al.2003; Benda et al.2004; Benda et al.2005). In the Sierra's, Ruediger and Ward (1996) found no variation in wood loading between stream types, and relatively little geomorphic pool-forming response to wood loading.

In the Sierras also, wood was a relatively minor contributor to pool formation (Figure 6). Reduction of large wood along headwater streams could reduce sediment storage in those channels (May and Gresswell 2003; Jackson et al. 2001).

Figure 6. The proportion of pools formed by different processes is shown for a range of streams in the Sierras in northern California (Benda et al. 2005). Pools are formed by concentrated flow of water acting on the bed. Different instream features are typically attributed to the concentrated flow. In the case of "hydraulic" pools, the concentrated flow is self-formed (i.e. without the benefit of scouring features)



Another factor relating wood recruitment to fish habitat concerns the concept of "Key Pieces". Key pieces of wood are those that form stable structures (such as log jams) in streams and thus create long term pools and areas of sediment storage (Bilby and Ward 1991). In general in northern California, the recruitment of key pieces is driven by bank erosion (Figures 7 and 8).

A problem lies in quantifying an absolute relationship between wood loads and aquatic habitat. A common question posed by managers is "how much wood is enough?". Lisle (2002) considers this problem unsolvable due to the complexities of watersheds and fluvial systems, the variable and stochastic nature of natural systems, and the multifaceted nature of fish habitats (pools, cover, complexity etc). A strictly habitat approach to wood loading shifts the emphasis onto wood loading dynamics of riparian zones and effects of logging on wood supplies to streams, a question that can be informed through wood budgeting (Lisle 2002; MacDonald and Coe 2007). Wood budgets investigate the controls on wood abundance in streams and the effects of forest management on wood input dynamics, an approach that has been carried out along 100-km of streams in California over the past 5 years, and which is summarized in this report

(Benda et al. 2002; Benda et al.2003; Benda et al.2004; Benda et al.2005).

Figure 7. The proportion of key piece recruitment by different processes across the southern Cascades and Klamath Mountains in northern California (Benda et al. 2003).

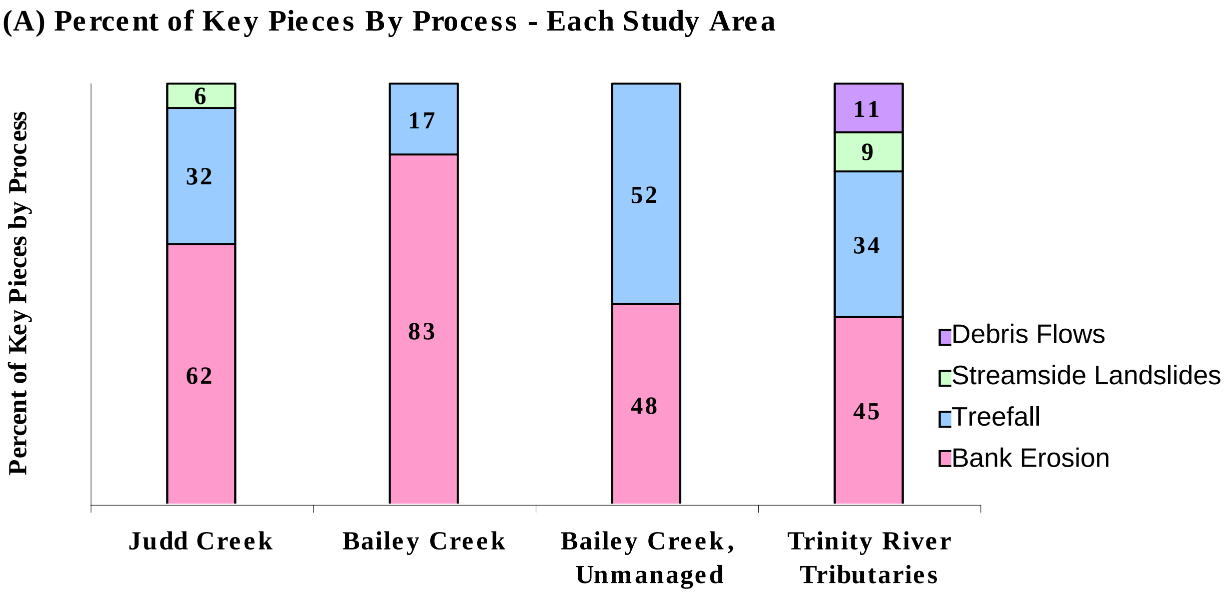
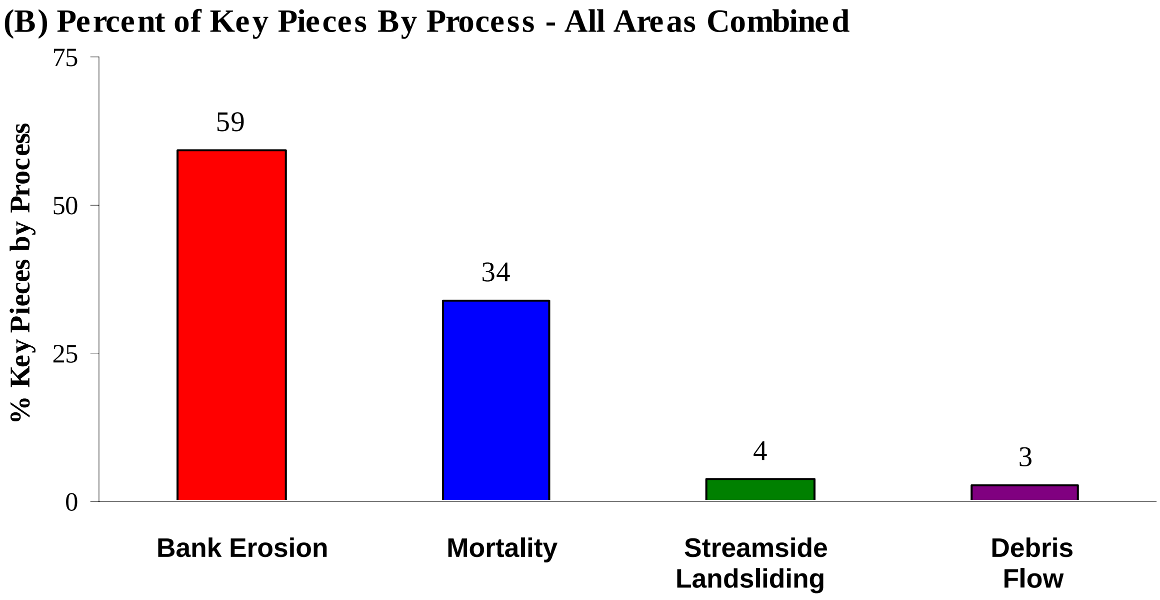


Figure 8. The proportion of key piece recruitment by different processes across the southern Cascades and Klamath Mountains in northern California, all areas combined. Bank erosion is the dominant recruitment agent of large, key pieces of wood (Benda et al. 2003).



WHAT IS THE EFFECT OF NATURAL DISTURBANCE ON THE POTENTIAL RECRUITMENT OF WOOD TO A STREAM?

In the context of the scientific literature, natural disturbances include floods, fires, infestation, disease, windthrow, and landsliding, among others. Many of the reviewed literature papers emphasize the role of natural disturbance as a major wood recruitment agent in streams (Gregory et al. 2003; Hassan et al. 2005; Lassettre and Harris 2001). The emerging science argues that disturbance is a natural and important mechanism for the development and long-term maintenance of diverse and productive riparian and instream habitats (Young 2001; Bisson, Rieman et al. 2003; Nakamura and Swanson 2003; Rieman et al. 2003; others).

Using a wood recruitment model that simulated the role of natural disturbances in the form of landslides, debris flows, and wildfires, Benda and Sias (2003) and Benda et al. (2003) showed that wood loading in streams strongly influenced by the frequency, magnitude and type of disturbance. Landslides and debris flows can be an important source of wood to channels and its specific importance depends on the temporal frequency of failures and spatial density of landslide sites (Nakamura and Swanson 2003). The role of wildfires depends on the frequency and intensity of fires; higher frequency of stand replacing fires in semi arid areas can lead to higher proportion of fire-related wood in a wood budget (up to 50%) (Benda and Sias 2003). Similarly, some studies have found that buffers alter wind patterns that strongly influence the rates of delivery for large woody debris (Surfleet and Ziemer 1996; Bragg and Kershner 2004; Liquori 2006).

A common theme in the reviewed literature is a shift in recognizing that forested watersheds are dynamic systems dependent on conditions in riparian zones that support natural rates and types of disturbance (Bisson, Rieman et al. 2003; Bragg and Kershner 2004; Kobziar and McBride 2006; Ellis 2001; Nakamura and Swanson 2003; Rieman et al. 2003; others). Specific studies and data are limited on this topic, and opinions vary widely. One widely held concept in the reviewed literature is that a sufficiently wide riparian zone that allows riparian areas to grow without management interference can provide conditions where natural disturbance regimes support normal seral development (Lisle 2002; Reid and Hilton 1998; Spence et al. 1996). However, there is a growing sense that human activities (including fire suppression, various land-use practices and forest management) inevitably affect the rates of natural disturbance, and that consideration and mitigation of these affects might be appropriate to promote riparian functions (Dwire and Kauffman 2003; Reeves et al. 2003; Nakamura and Swanson 2003; Kobziar and McBride 2006; others).

Fire

Fire plays a significant role toward direct and indirect contributions of wood to streams (Benda and Sias 1998; Nakamura and Swanson 2003; Rieman et al. 2003). Direct contributions typically come from fire-driven mortality in streamside areas. However, fire also plays an important role in shaping the characteristic disturbances that affect stand growth and dynamics.

Dendrochronological evidence indicates significant and consistent historical fire influence on riparian vegetation structure and composition (Olson 2000; Russell and McBride 2000; Skinner 2001; Everett et al., 2oo3). Yet, modern forest management practices have not yet found an effective approach in managing fire risk in riparian areas. (Debano and Neary 1996; Dwire and Kaufman 2003; others). Fire suppression practices and upslope timber harvest practices have altered rates and characteristics of fire behavior in such a way that natural fire disturbance patterns appear to be substantially altered (Figure 9).

Figure 9. An example in California's Sierras of a wildfire that preferential burned through a riparian area. In this event, fuel loads were higher in the riparian zone compared to the upland forests (courtesy of Dr. Jim Agee).

For example, fire suppression has increased fuel loading in riparian areas in a way that substantially increases the risk of catastrophic crown fires, often in landscapes that naturally experienced frequent low intensity underburns (Hemstrom and Franklin 1982; Barrett 1988; Morrison and Swanson 1990; Camp et al, 1997). While we did not review any specific studies of the effects of riparian crown fire, we suspect that the effects would not benefit salmonids, as crown fires remove canopy coverage, dramatically affect both short-term and long-term wood loading, increases sedimentation in streams, etc.

Some studies are beginning to recognize that fire was historically a predominant mechanism for wood recruitment and riparian stand development, and that the role of fire has changed substantially in recent decades. Although no field studies in the identified literature documented the role of wildfire in wood recruitment, widespread tree death and post fire toppling of trees should lead to increased short-term wood loading in streams.

Flooding

Floods that trigger bank erosion and recruit trees to streams can be a important disturbance agent across all areas and leads to pulsed wood recruitment (see Keller et al. 1995; Swanson et al. 1998; Benda et al. 2002; Benda et al. 2003; Benda et al. 2004; Benda et al. 2005; Hyatt and Naiman 2001; Marcus et al. 2002). Floods can also expand the zone of potential recruitment in large, braided, or avulsing rivers.

Wind

While wind risk is generally perceived to be low in California, wind can affect riparian buffers along clearcut boundaries, primarily along coastal regions (Surfleet and Ziemer 1996; Lisle and Napolitano 1998; Ried and Hilton 1998; Martin 2001; Liquori 2006). Riparian stands grow in conditions that are not exposed to significant wind stress. When exposed suddenly, the root systems often cannot absorb the additional wind stresses following clearcutting, sometimes resulting in a large proportion of buffers experiencing wind-driven treefall. Such windthrow can offer short-term benefits in some systems (Lisle and Napolitano 1998) and minimal benefits to others (Liquori 2006). However, in some cases, such benefits might come at the cost of reduction in recruitment potential over the next 30-50 years (or until the next cohort of trees achieves a functional size relative to the stream).

Increased blowdown mortality and a preferential fall direction to the stream within streamside buffers indicate that wood loading could be higher in managed forests with buffer strips (Martin 2001). Windthrow has also been reported to knock over adjacent trees in a domino-like fashion (Reid and Hilton 1998). Liquori (2006) documented a 72-fold increase in recruitment from windthrow as compared to chronic (competition) mortality estimates in buffer strips along low- to mid-order fish-bearing channels in western Washington. Additionally, the observed wood loading increased to streams within most buffers since fall directions were preferentially directed to streams. Risk of blowdown in this study was strongly correlated to tree species.

Landslides

Streamside landslides, and to a lesser extent debris flows in headwater streams in several of California's physiographic regions (e.g., Coast Ranges, Klamath Mountains) can deliver wood to streams and comprise up to 50% of the total wood load to streams (more commonly 10 – 30%) (Benda et al. 2002; Benda et al. 2003; Benda et al. 2004; Benda et al. 2005). Other studies outside California support this general principle (Reeves et al. 2003, Benda and Dunne 1997).

2) Management Influences on Wood Recruitment

The reviewed literature suggests a broad agreement that there are distinct differences between managed and unmanaged forests in the recruitment and wood production into riparian systems. Most studies show that timber harvesting in upslope and adjacent forests can directly affect wood input (Swanson and Leinkaemper 1978; Bilby and Bisson 1998, Rieman 1998). Several studies have documented that downed wood derived from managed forests are smaller in diameter and have less volume than in unmanaged forests, contributing to lower instream loading in logged streams (Bilby and Ward 1991; Ralph et al. 1994). However, virtually all the studies compare relatively young managed forests to substantially older unmanaged forests. Studies generally have not compared managed forests against unmanaged forest of similar ages, so it is difficult to determine the extent that management alters wood production and recruitment processes.

The following discussion seeks to outline ways in which managed forests alter that natural riparian stand dynamics and wood recruitment processes necessary to support instream wood loading conditions.

In many ways, management of forests and fishes are both dependent upon the restoration of natural processes that create diverse and productive ecosystems (Nakamura and Swanson 2003; Rieman et al. 2003). Recovery will generally require better integration of a common ecologically-based conceptual foundation, as well as improved attention to the landscape and ecological context.

This section addresses the ways that management affects wood growth (Section 1.4.2.1) and wood recruitment (Section 1.4.2.2) in riparian areas.

HOW DOES FOREST MANAGEMENT AFFECT WOOD PRODUCTION (I.E. TREE GROWTH) IN RIPARIAN AREAS?

There was limited information in the reviewed literature about the production (i.e. growth) of wood that can be recruited to the stream. However, it is widely accepted that mature and late-seral stands experience slower growth than younger stands, and that stand structure strongly influences the rate of growth within the stand (Oliver and Larsen 1990; Franklin et al. 2002).

The abundance and distribution of dead wood and in-stream wood production in a forest is strongly controlled by disturbance history and stand growth dynamics. Old forests typically accumulate relatively large amounts of dead wood because the debris accumulates over many decades, and decays slowly. By contrast, higher amounts of woody debris are usually generated from young forests following disturbances that kill overstory trees (Spies et al. 1988). However, wood recruitment from small diameter trees does not persist in the stream as smaller trees decay faster (Bilby et al. 1999). Consequently, the greatest difference in the structure of managed vs. older natural forests is that the young riparian stands associated with managed landscapes have greater stems per acre consisting of much smaller diameter wood.

Forest management adjacent to or within the riparian zone can lead to a decrease of in-stream wood recruitment by changing the competitive advantage through above and below ground competition. Acker et al. (2003) studied tree composition, stand complexity, and temporal patterns of tree mortality and found that the variability in tree diameters, tree life-form diversity, and tree species diversity to be important variables affecting stem mortality rates. Wood production and recruitment was much higher from stands where forest management activities changed the dynamics of intra-tree competition and stand dynamics. Therefore, the type of forest management appears to influence the role of tree growth, tree life-form diversity, and tree species diversity on wood recruitment and production.

Riparian wood production is closely linked to riparian structure (e.g. foliage distribution, crown attributes) or the potential to produce other features (e.g. dead wood of different sizes). Disturbances and forest management activities like thinning can lead to a reduction in canopy leaf area, resulting in an increase in the penetration of radiation and precipitation to the forest floor, often leading to the establishment of an understory cohort of new trees (Oliver and Larson 1996). This ingrowth potential is something that most studies of future wood loading ignore because: a) science currently lacks the ability to predict stocking of ingrowth, and b) many scientists studying wood recruitment processes (e.g. hydrologists and geomorphologists) are often not familiar with the principles of stand dynamics. Yet, it is a natural mechanism by which riparian stands evolve.

During the period after thinning events (either thru management or disturbance), nutrient and water uptake will increase per unit of leaf area. Additional light penetration generally increases photosynthetic rates in the lower canopy and additional access to water and essential minerals means plants allocate proportionally less carbohydrate to roots. For these reasons, the rate of wood production per unit of leaf area typically increases (Mattson and Addy 1975). Under careful forest management, the residual stand structures are typically more vigorous, expressed through significantly increased diameter and height growth as well as potentially increased ingrowth (depending on the level of thinning). However, these benefits come at the cost of reduced competition mortality (and thus short-term treefall recruitment) as the existing stand expands into the newly available growing spaces. Such reductions in stem mortality can last a few years to a few decades. During this time of reduced competition mortality, tree recruitment from disturbance processes (e.g. bank erosion, landslides, floods, wind, ice/snow damage, etc) will continue to provide woody debris recruitment.

Riparian forest conditions substantially influence wood loading in streams (Bragg et al. 2000; Liquori 2000). While tree removal from riparian areas can reduce the number of trees that can be recruited, forest silviculture practices can improve the quality and size of riparian trees by improving tree growth, selecting for preferred species, affecting rates and timing of competition mortality, and disturbance regimes (e.g. fuel loading, insect infestations, disease). Riparian species typically have a large array of survival strategies that support growth and recovery from disturbances (Dwire and Kauffman 2003).

Wood recruitment models (Benda & Sias 1998; Bragg & Kerschner 1997; Bragg & Kerschner 2000; Gregory et al. 2003; Bragg & Kerschner 2004; Welty et al. 2002) have been used to evaluate the future potential of wood production in riparian zones. Some studies suggest that models are useful because they provide objective, scientific tools that can be used to evaluate various responses to management treatment. However, many of the wood recruitment models use forest growth simulators that were developed for very different management purposes that might not be entirely suited for predicting riparian response (Bragg et al. 2000; Welty et al. 2002). Forest growth simulators are calibrated from upland stands that are specifically selected to minimize natural variability while riparian stands are typically quite diverse (Welty et al. 2002). Additionally, model results often imply that any tree removal will reduce wood loading over time. However, existing models do not account for ingrowth (new trees that germinate in response to opening the canopy), which can increase total wood production over a given period, and can affect future wood loading in thinned forests. They also poorly account for depletion (decay) or breakage, and thus are not yet fully predictive (Gregory et al. 2003). Models also have limited capacity to account for disturbance processes in terms of how disturbance can affect mortality and growth.

Ecologically-driven objectives for manipulating riparian stand structure can include: improving riparian tree growth, affecting the timing of competition mortality periods, mitigating for significant disturbance risks, redirecting successional trajectories, species conversion, and targeting other desired riparian stand conditions (Welty et al. 2002; Ligon et al. 1999). Such treatments could have significant benefits to aquatic ecosystems in certain settings, although such treatments might require compromises between short-term and long-term wood loading potential. Silvicultural methods and tools are available that can help guide such objectives.

It is important to note that responses to riparian forest management are sensitive to the varied site conditions. Each riparian ecosystem will respond differently to treatments, depending on the forest properties, site productivity, stream conditions, and the effectiveness of management (Bragg and Kershner 1997).

HOW DOES FOREST MANAGEMENT AFFECT IN-STREAM WOOD DELIVERY TO CHANNELS?

There is almost universal consensus that unrestricted clearcutting to the waters edge in fish-bearing streams is clearly detrimental to aquatic environments. In the absence of clearcutting, forest management in or near riparian zones can be beneficial, detrimental, or both, sometimes at the same site.

Management can affect the frequency and magnitude of natural recruitment processes associated with disturbance (Dwire and Kauffman 2003), and can influence the successional pathways, species composition, and structure of the stand in ways that affect growth and competition mortality (see above). Management in headwater areas can also affect the natural landslide regime in ways that affect wood delivered from landslides and debris flows by affecting hillslope pore pressures, root reinforcement, hydrologic impacts, sediment loading, and wood loading on the hillslopes (Ziemer 1981; Dietrich et al. 1986; Torres et al. 1998; others). Landslide rates have historically increased in response to forest management (Bishop 1964; Robison et al. 1999; Gomi et al. 2001; Miller et al. 2003; Cafferata and Munn 2002; Gomi et al. 2005; Hassan et al. 2005; others). It is possible that there might be implications for future wood recruitment as: a) forest management practices reduce the rate of landsliding, and b) fewer available source areas are prone to sliding (since the pressures have been reduced over the last 50+ years). The extent that this is an issue could not be explored, as the literature to support such an analysis was not the focus of this review.

Both theoretical (model based) and field based studies demonstrate that younger stands have smaller trees (in both height and diameter) and therefore have lower in-stream wood potential relative to larger, older stands (Benda and Sias 2003, Benda et al. 2002; Benda et al. 2003; Benda et al. 2004; Benda et al. 2005, Bragg et al. 2000). Stands with identical recruitment rates and processes will experience different wood recruitment volumes based on the available height, diameter and density of riparian trees. Legacy forest practices continue to affect instream wood loading conditions. Instream wood loading conditions are low along many (probably most) 2nd-growth forests along the Coast Range (Wooster and Hilton 2004). It is difficult to determine the extent that wood delivery rates are different between old-growth and 2nd-growth, since many studies report wood volume (not pieces), which is substantially higher in older stands due to the difference in tree sizes. Some studies report higher wood delivery rates from managed stands, but lower total wood volume. Older, taller trees can also deliver wood from farther distances, increasing the area that can deliver woody debris. In addition, taller trees can increase the proportion of wood that is derived from treefall compared to bank erosion (Benda et al. 2005) because of the larger potential source area for treefall.

There are several common themes associated with forest management effects on wood recruitment. These include:

- Legacy effects
- Altered short-term supply
- Altered long-term supply
- Altered susceptibility to disturbance
- Altered timing of competition mortality

Legacy Effects

Historic logging practices have had lasting impacts on aquatic systems. Such "legacy" practices can affect existing conditions in ways that range from severe to subtle. Legacy effects are not equally significant in all regions of California. The coastal legacy included stream cleaning and instream yarding. Inland legacies might also exist, but can be more subtle. Some inland areas were "hi-graded" which resulted in poor stocking quality during subsequent forest regeneration. To a certain degree, fire suppression activities in recent decades can also have resulted in legacy effects. Fire frequencies have decreased in many California forests, increasing fuel loading and risk for high intensity crown fires. Riparian areas have not been immune to such activities.

Early practices in the 19th and early 20th Centuries along the coast included not only logging in riparian areas, but yarding logs through the stream corridor (often within the stream itself). Early "splash dams" held logs in ponded areas for sudden release in the form of a manufactured flood. Such floods dramatically scoured the stream and riparian areas, leaving substantial geomorphic effects than can still be observed today.

Early logging practices also included large clearcuts over entire watersheds. Large floods following such disturbances had impacts on stream channels, often causing incision, channel migration and widespread channel erosion. Early clearcut logging practices on steep slopes also increased rates of landsliding and other mass wasting processes in ways that: a) increased sediment load to aquatic environments; and b) altered the natural frequency and magnitude of landsliding, affecting future landslide risks (and potentially the distribution of wood loading from landslides) (Benda and Dunne 1997).

Even as recent as the 1980s, active instream restoration practices along the coast promoted and funded by State agencies involved wholesale removal of instream woody debris, a practice referred to as "stream cleaning" (Berbach 2001; Wooster and Hilton 2004). The mistaken perception was that instream wood loading created passage impediments for fish.

Buffers in California were first mandated with the passage of the modern Forest Practice Act in 1973 (and enforced on the ground in 1975). Early rules were focused on temperature functions, often to the exclusion of wood functions. On the coast, riparian timber harvest under the Forest Practices Act practices was common, often removing all conifer trees next to streams. Inland areas were more prone to temperature risks, so practices requiring canopy closure can have given preference to conifers in riparian zones, resulting in long-term depletion of riparian hardwood stands. These practices ended when the current T&I Rule Package was implemented in 1999, and a broader set of functional controls were required.

As a result of these and other legacy practices, riparian areas that are found in lands that have been managed for more than 20 years or so will typically have some legacy effects that have altered the riparian environment. In some cases, the alterations can be easily detected. For example, many coastal riparian stands are stocked with relatively young riparian trees (as compared to old reference stands). Other legacy effects can be more subtle, like increased fuel loads and altered fire regimes, or altered landslide regimes.

Altered Short-Term Supply

Timber harvest that removes all or some of the trees within a zone one tree height of the channel will reduce the number of trees that can potentially recruit to streams (Bragg and Kershner 1997; Welty et al. 2002). The width of the zone is dependent on tree age to the extent that height is related to age (McDade et al. 1990). However, because the probability of tree recruitment increases non-linearly towards the stream and bank erosion is a major wood recruitment agent, the reduction is much smaller if areas closest to the stream are not harvested. In many California streams, 80 to 90% of wood recruitment comes within a zone 30 to 100 feet (10 to 30 m) of the channel edge (Benda et al. 2002; Benda et al. 2003; Benda et al. 2004; Benda et al. 2005).

Wood loads in buffered streams adjacent to clearcuts increase relative to unharvested streams (Surfleet and Ziemer 1996; Liquori 2006), primarily in response to increased susceptibility of windthrow and other disturbances. Yarding slash has also been shown to increase wood loading in the short-term. Certain types of historical logging increased wood storage in streams if wood debris (slash) was left in channels (Jackson et al. 2001; Benda et al. 2002; Benda et al. 2004).

Altered Long-Term Supply

Silvicultural treatments in riparian areas can increase the diameter growth in riparian areas, which can increase the rate of recovery for streams requiring large diameter wood (Welty et al. 2002). Clearcutting riparian zones areas can lead to greatly reduced wood loading for 50 to 100 years following harvest (Bragg et al. 2000;

Benda and Sias 2003; Hassan et al. 2005). Many models also predict that long-term recruitment is diminished by any tree removal from riparian zones, although most models have at least one or more challenges with accurate long-term predictions (Gregory et al. 2003).

Models are the only available tool for projecting future wood recruitment potential. Wood recruitment models have been used to investigate the implications of various riparian management regimes on the recruitment of wood to streams (Rainville et al. 1986, Van Sickle and Gregory 1990, Beechie et al. 2000, Bragg et al. 2000; others). Models use upslope growth and yield relationships because such relationships are not available in riparian zones. Models also cannot accurately predict ingrowth (new stems that germinate or suppressed stems that experience rapid growth). In-channel processes such as tree entry breakage and log breakage, movement, depletion and decomposition are poorly understood, yet many models are very sensitive to these variables. Models that have incorporated these variables have used simplified assumptions (Murphy and Koski 1989; Beechie et al. 2000; Bragg et al. 2000). Transport of wood from upstream sources has either been ignored or has been assumed to equal output of the reach for a given time interval (Murphy and Koski 1989; Van Sickle and Gregory 1990).

Altered Timing of Competition Mortality

Stand conditions affect the growth and mortality dynamics in riparian stands in a manner that affects wood recruitment (Liquori 2000). Some forest management activities (e.g., thinning) can reduce short-term rates of competition mortality while increasing stand growth. Other activities (e.g., prescribed fire) could increase short-term mortality and reduce long-term competition mortality. For example, in the redwood forest zone, timber harvest that initiated a new stand of trees can lead to increased forest mortality rates compared to the reduced rates in old growth redwood forests (Benda et al. 2002).

Altered Susceptibility to Natural Recruitment Processes

Forest management alters the very patterns of growth and disturbance that influence riparian conditions and functional responses. Forest management activities affect fire regimes, wind patterns, landslide patterns, and stand growth dynamics in ways that also affect riparian structure and function. Riparian, aquatic and upland ecosystems are linked and dynamic, and our understanding of these interactions is still developing (Bisson, Rieman et al. 2003). In many cases, the over-generalized nature by which management establishes practices can compromise ecosystem resilience (Rieman et al. 2003).

Where debris flows in low-order headwater streams are a wood recruitment process (mostly in California's Coast Ranges and Klamath Mountains), harvest of trees along headwater channels and hollows could reduce that source of wood to larger fish-bearing streams (Reeves et al. 2003, May and Gresswell 2003; Benda and Dunne 1997). However, typically only a portion of trees delivered from these sources are effective as woody debris. Where timber harvest or road construction change the likelihood of landsliding and debris flows in headwater channels, then wood loading supplied by these processes will also be changed. Legacy forest management practices dramatically increased rates of landslides and debris flows (May and Gresswell 2003). Modern practices seek to minimize these processes, and that will certainly affect the recruitment dynamics in some landscapes.

Riparian buffers can also affect the preferred direction of treefall, potentially resulting in a significant and substantial increase in trees falling toward the channel (Liquori 2006) than would be predicted by a purely random treefall assumption (Robison and Beschta 1990b). Many of the wood recruitment models are quite sensitive to treefall direction (Bragg and Kershner 2004), yet in the absence of fall direction data, most models apply the random treefall model, and thus can underpredict the delivery of wood. Treefall bias toward the channel can deliver up to 3 times more wood from the riparian stand when compared to random fall directions (Van Sickle and Gregory 1990; Bragg and Kershner 2004; Liquori 2006).

Creating buffer strips along streams could lead to accelerated mortality in the buffers due to increased blowdown (Lisle and Napolitano 1998), most likely along the north coast area, where winter storms can yield strong winds. This could lead to a tree mortality rate orders of magnitude higher compared to suppression mortality alone in natural forests (Liquori 2006).

Under some circumstances, such as dry pre-fire climatic conditions and the accumulation of dry fuel, riparian areas become corridors for fire movement (Pettit and Naiman 2007). Riparian areas tend to have higher growth and biomass accumulation as compared to upland stands (Agee 1999). Riparian zone fuel loadings are influenced by fire suppression and exclusion. Ladder fuels in the form of shrubs and understory plants bridge these riparian surface fuel loadings to highly flammable overstory fuels. In contrast to upland forests, the geomorphology and hydrologic features of riparian corridors typically result in a greater dominance of shrubs and deciduous trees. Depending on the regional microclimate, these understory and deciduous trees can either contribute to crown-fire behavior or retard the spread of fire through moister and cooler microclimates with higher levels of both live and downed fuel moisture contents (Dwire and Kaufman 2003). Fire suppression that reduces fire occurrence in riparian zones might reduce wood loading to streams over the long term since in semi-arid Mediterranean areas wood recruitment by fire can be substantial (Young 1984; Benda and Sias 2003). Stand-replacing riparian fires can occur preferentially within riparian zones that have not been burned or thinned to reduce fuel loads (Murphy et al 2007). Although there are several recent papers reviewing different aspects of wildfire in riparian areas (Bisson, Rieman et al. 2003; Dwire and Kauffman 2003; Raiman et al 2003; Reeves et al. 2006; Pettit and Naiman 2007), there is general agreement that there is much to be learned concerning fire in these environments.

In parts of California where the lack of disturbance has contributed to heavier than normal surface and ladder fuels, riparian zones can lead to altered fire behavior in riparian systems. In several recent examples (e.g., Angora, Trabing, Antelope fires), wildfires entering the riparian zones have exhibited higher intensities than upland zones, creating fire "wicks" where behavior crowns and "runs" around or through fuel treatments by moving upslope through the riparian zone (Murphy et al. 2007). Based upon these observational reports and studies, it is difficult to ascertain the exact nature of how riparian management (or lack thereof) can change the susceptibility to disturbances like high-intensity, stand-replacement wildfire events.

3) Factors Affecting Buffer Design

There are two broad strategies for maintaining riparian functions in forested landscapes. The specific factors that are important depend on the strategic policy direction that guides management.

One strategy is to buffer streams with large riparian reserves to minimize the disturbance in the riparian zone so that riparian stand conditions can evolve naturally. Support for this approach is described in several papers (FEMAT 1993; Spence et al. 1996; Reid and Hilton 1998; others).

Another strategy is to directly manage aquatic functions, often at landscape scales (e.g. watersheds) to promote ecological processes and functions that can be affected by forest management practices. This approach typically calls for integrated management strategies that respond to the dynamic and varied ecological context that exists over the landscape. Support for this approach is also provided in several papers (Kobziar and McBride 2006; Naiman et al. 2000;

Nakamura et al. 2000; Dwire and Kaufman 2003; Everett et al. 2003; Rieman et al 2003; Thompson 2006; others). Often, this latter approach focuses on minimizing major disturbances in favor of the types of smaller (often more frequent) disturbances that support ecosystem processes.

This section addresses some of the thoughts expressed in the literature about how to design riparian buffers.

WHAT CHARACTERISTICS OF RIPARIAN BUFFER ZONES AFFECT THE PRODUCTION OF POTENTIAL IN-STREAM WOOD AND HOW SHOULD FOREST MANAGEMENT GOALS DIFFER BY STREAM ORDER, VEGETATION TYPE, AND REGION TO DELIVER WOOD TO THE STREAM OF THE APPROPRIATE DIAMETER SIZE, SPECIES AND OTHER CHARACTERISTICS TO MAINTAIN SALMONID HABITAT OVER SPACE AND TIME?

Salmonids clearly benefit by higher levels of wood loading. Wood loading creates pools, regulates sediment transport processes, helps to sort gravels into spawning sites, provides cover, and provides a substrate for macroinvertebrate production (Cederholm et al. 1997; Montgomery et al. 1995; Beechie and Sibley 1997; others).

Many streams in California are depleted in wood loading as a result of legacy forest and stream management practices (Wooster and Hilton 2004). Recovery of this depleted condition will require both more wood recruitment and increased tree diameter growth. Natural recovery of wood loading conditions could take a century or more (Bragg and Kershner 1997; Hassan et al. 2005). Management activities in some riparian stands can potentially reduce this recovery time while promoting ecological diversity and quality salmonid habitat conditions by:

- Using silvicultural strategies to affect growth and mortality dynamics (Welty et al 2003; Bragg and Kershner 1997)
- Managing the risks of disturbance to encourage relatively frequent, low-intensity disturbances over larger, high magnitude disturbances (Kobziar and McBride 2006; Naiman et al. 2000; Nakamura et al. 2000; Dwire and Kaufman 2003; Everett et al. 2003; Rieman et al 2003; others).
- Balancing the trade-offs between various exchange functions as driven by limited biological factors. For example, identifying sites where other functional objectives might be locally more

important biologically than wood recruitment objectives (see Chapters 2 and 7).

We suggest that riparian silvicultural objectives that would support ecological functions important to salmonids (and other fauna) would seek to balance competition mortality objectives with growth objectives or other exchange function objectives based on a diagnosis of site requirements. For example, a site with low wood loading might seek to shift the balance toward promoting mortality of desired species. Similarly, a site with riparian tree diameters that are too small to support ecological functions might encourage stem growth in a manner that can reduce the time required to achieve a functional diameter, perhaps by several decades (Bilby and Ward 1989; Welty et al. 2002). Silvicultural science has developed a number of tools for manipulating forest stands to meet specific management objectives, and such tools are not necessarily restricted to maximizing timber yield.

Several key factors affect riparian community composition and structure. These include several that cannot be manipulated easily, like climate, landform, and soil types (Naiman et al. 1998; Rot et al. 2000; others). Other major factors to consider in the design of riparian buffers for in-stream wood production are:

- Existing Stand Density, Composition and Structure (Bragg et al. 2000; Franklin et al. 2001; Welty et al. 2002; others)
- Stream Type, Order and Watershed Context (Bilby and Likens 1980; Bilby 1984; Lassettre and Harris 2001; Young 2001; Wing and Skaugset 2002; Rieman et al. 2003; others)
- Vegetation Type and Soil/ Site Index (Oliver and Larson 1996; Franklin et al 2001; Welty et al. 2002; others)
- Regional Context (Ruediger and Ward 1996; others)
- Disturbance Context (Nakamura and Swanson 2003; Rieman et al 2003; others)

As we've described in Section 0, woody debris in streams comes from several major sources, including channel movements, streamside disturbances, tree mortality, streamside landslides, and debris flows in headwater areas. Thus the management of stream channel structure and watersheds might consider all sources of potential wood recruitment when designing site treatments. The buffer design should accommodate the physical and biological stream requirements, long term stand resilience, and disturbance risks. For example, if surface and ladder fuels in the buffer are predisposing the riparian stand to crown/stand replacement fire when the disturbance history does not show any evidence of growth trajectories from this type of stand development, then the buffer design might include some amount of small and/or moderate managed disturbances to break up the fuel continuity, prevent the likelihood of a catastrophic event, and ensure that functional impacts are minimized. Alternatively, if the stream environment requires large trees to function, and riparian conditions consist of densely stocked, small diameter trees, then thinning alternatives designed to promote growth could expedite recovery by a factor of decades (Welty et al. 2002).

The following sections describe some details associated with these factors.

Stand Density, Composition and Structure

In upland stands, there is a direct relationship between stand density, composition and structure, and the growth and mortality dynamics in the stand. We assume that such trends persist in riparian areas, although direct studies are not available to our knowledge. Generally, growth and mortality in forested stands are cyclical, dynamic, and vary depending on the stand composition. Single cohort, single species stands respond differently than multi-cohort, multi-species stands (Oliver and Larson 1996; Noss 2000). When competition mortality rates are high, recruitment tends to increase, but tree growth can vary from very slow in early stem exclusion phases to more rapid growth in advanced stem exclusion phases. Often, growth rates correspond to the amount of available growing space opened up by mortality, regardless of whether the mortality is from competition or disturbances. Such openings in available growing space can take decades under competition mortality, or can be nearly instantaneous in the form of site disturbance processes.

The stand density, composition, and structure will determine the potential for wood production and recruitment. At the stand level, overstory canopy characteristics such as stem density and gap size have been linked to composition and dynamics of tree regeneration (Gray and Spies 1996; Spies 1997). These attributes also change with time, as the stand grows and responds dynamically.

Stand manipulation in support of wood (or other) functions should consider the benefits in shaping the stand density, structure, and composition against the impacts on stem mortality and recruitment.

Two general trends exist for stand development that have relevance to in-stream wood production:

1. A growth trend that follows large disturbances or management activities where tree growth and biomass increase slowly at first, then increase rapidly until trees reach the carrying capacity of the site (based on stem density) and sites reach maximum capacity to support vegetative growth. In this case, growth slows and mortality increases resulting in a pulse of recruitment that can persist for a period of years to decades.

2. The other growth trajectory that typically follows modest disturbances or management activities leads to more rapid growth of residual trees (those that survive disturbance) followed by a period of declining growth as the carrying capacity is reached. In this case, the period of rapid growth is much shorter than the stand-replacing growth period.

The period with the greatest stem losses can occur in even-aged stands between ages of about 50 and 110 years, when stand densities decline from more than 200 trees per acre to about 100 trees per acre or less. At this age, stems are typically large enough to function as instream wood. By contrast, older stands can have stem densities of 15-50 trees per acre. Thus earlier cycles of competition mortality can yield significantly more stems to the stream, although these stems are often of smaller diameter than in older stands (Oliver and Larson 1996).

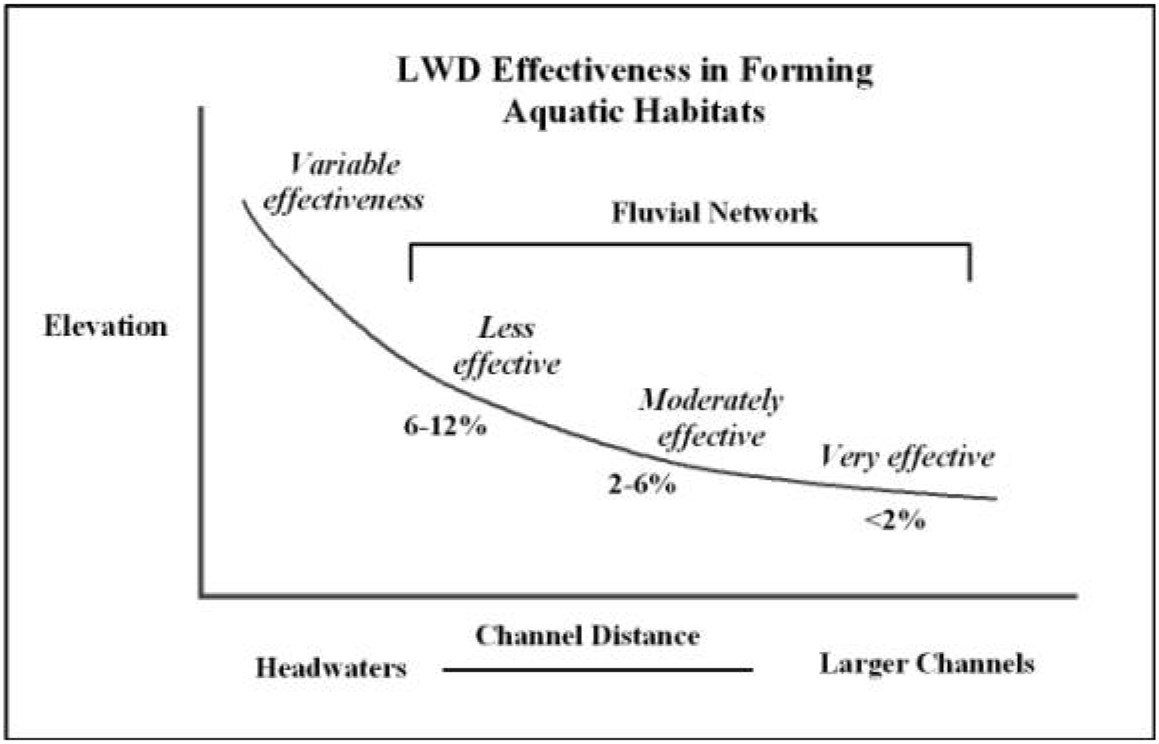
Although individual stands develop in a wide variety of ways, general tendencies allow one to predict the characteristics of one type of forest structure from knowledge of another (e.g. foliage height distributions from tree diameter variation) (Spies and Franklin 1991) and to predict future states of population stands from knowledge of their current forest structure (e.g., knowledge of current size/age distributions and species of live trees can be used to estimate future characteristics of dead trees).

Stream Type, Stream Order and Watershed Context

Wood functions tend to vary by stream type, and thus the qualities and characteristics needed to support those functions varies. Generally, larger streams require large diameter wood (Bilby and Ward 1989), and habitat functions in lower gradient streams are more responsive to wood loading (Beechie and Sibley 1997; Montgomery & Buffington 1997).

The reviewed literature indicates that the relationship between wood and in-stream habitat varies across different stream types in California (Figure 10) (Ruediger and Ward 1996; Berg et al. 1998; Rot et al. 2000; Lassettre and Harris 2001; Benda et al. 2005). Stream order is one type of classification that is helpful in describing the relative scale of stream functions and processes, however, it does not describe other important factors like stream type, confinement, and gradient that has been shown to significantly affect stream processes and functions (Montgomery & Buffington 1997).

Figure 10) Wood effectiveness in providing instream functions for salmonids. In steeper streams, wood is primarily a source of gradient control that acts to trap and store sediment. In lower reaches, wood acts to modify the channel bed and morphology in support of specific life-cycle requirements for salmonids (e.g. spawning, rearing, etc.)



For example, Rot et al. (2000) found significant variation in wood loading and effectiveness in Pacific Northwest plane-bed and pool-riffle channels, and relatively little effect in cascade and bedrock channels. Similarly, Wing & Skaugset (2002) found that channel morphology was more important than land-use in predicting wood function. Ruediger & Ward (1996) found limited geomorphic response in Sierra channels and little variation between channel types. These variations imply that stream type might be more important than stream order in defining the role of wood, although there is a general relationship between stream order and stream types.

Larger-order, lower gradient streams experience channel migration processes that increase recruitment from bank erosion processes (Benda and Sais 1998). Such channels also are prone to wood transport, and wood tends to accumulate in jams that can persist for only a fraction of the lifespan of the wood (Hyatt and Naiman 2001). Recruited conifer wood can exist for several decades to centuries if not transported downstream (Keller et al 1995; Hyatt and Naiman 2001). Typically these systems are more dependent on larger “key pieces” of woody debris that act as structural anchors for jams. Wood volume is a good indicator of effectiveness in these reaches.

Mid-order, mid-gradient streams typically accumulate the largest amount of woody debris, and are typically most responsive to wood loading (Keller et al 1995; Nakamura and Swanson 2003). Effective wood loading in these streams tends to be driven by the number of pieces of wood.

Low-order, steeper channels accumulate wood from logging slash (Jackson et al 2001), competition mortality, and streamside landslides (Benda and Sias 1998). Smaller wood tends to function in these systems (Hassan et al. 2006). Steep, confined channels utilize wood less for habitat, and more for sediment regulation and channel stabilization functions.

These generalizations assume that gradient and order are related, which is not always the case. Small, low-order, low-gradient streams can express behaviors similar to mid- or large-order streams. Similarly, large-order confined channels can express functions more similar to low- to mid-order conditions.

Vegetation Type and Soil/Site Index

Vegetation types strongly affect the quality and quantity of wood recruitment (Hassan et al. 2006). Conifer species are typically preferred for wood loading functions, since hardwoods break down quickly in stream environments, typically within a few years (CBOF-TAC 2007). The vegetation type and soil/site index also affects the site-potential tree height, and thus the scale of the source distance curves (see below and Chapter 7).

Typically, vegetation types that support more wood volume in the riparian stand also tend to support more volume in the stream (Keller et al. 1995). Thus coastal redwood stands have a potential for more wood loading that Sierran Ponderosa Pine.

Regional Context

Regional variation strongly influences the predominant disturbances that are likely to drive wood recruitment processes (Nakamura and Swanson 2003). For example, landslide and debris flow processes are more common in the coast and Klamath landscapes. Similarly, variation in forest types influences wood recruitment rates and processes. For example, redwoods deliver more wood loading and storage than mixed Sierra conifers (Benda et al. 2002; Benda et al. 2003; Benda et al. 2004; Benda et al. 2005).

The reviewed literature also suggests that the relationship between wood and in-stream habitat varies across different regions in California. Wood is a major pool former in many coastal and inland areas (Benda et al. 2003; Benda et al. 2004; Benda et al. 2005) but becomes less important in the boulder and bedrock dominated Sierras (Ruediger and Ward 1996; Berg et al. 1998; Benda et al. 2005).

Other than these somewhat obvious relationships, specific regional variation in wood recruitment that would guide streamside protection strategies is not apparent from the literature. While regional variation is important to understand, the literature for California is limited, and thus specific recommendations can only be inferred.

Disturbance Context

As described previously, management practices can directly and indirectly affect the frequency, intensity and magnitude of the disturbance processes that are responsible for recruiting wood to salmonid streams (Nakamura and Swanson 2003; Bisson; Rieman et al. 2003; others). Understanding this context is essential to properly restoring functional riparian conditions in managed landscapes (Rieman et al. 2003). We describe this in more detail in Chapter 7 of this report.

WHAT MINIMUM BUFFER WIDTHS HAVE BEEN SHOWN TO BE EFFECTIVE?

There has been little agreement in the scientific community in defining the *minimum* buffer width necessary to provide sufficient wood recruitment to sustain salmonid habitat (Young 2001; Lisle 2002). One of the reasons that these issues remains unresolved is that there is no recognized ecological endpoint for which individual streams should be managed (Young 2001), and no consensus about how much wood is “enough” to support ecological functions (Lisle 2002). For example, the reviewed literature reports that the maximum width needed to contribute almost all of the woody debris recruitment *from treefall* is 1 tree-height (McDade 1990; Robison and Beschta 1990; others). However, within 1 tree height, there remains a wide variation in responses, due in part to variations in the dominant recruitment mechanisms (Castelle & Johnson 2000; Benda et al. 2002; Benda et a.l 2003; Benda et al. 2005; Liquori 2006). Approaches to address this question have followed several lines of logic.

Some of the reviewed literature have argued for wider buffers to protect the riparian community from direct and indirect disturbances associated with timber harvest (Reid and Hilton 1998; FEMAT 1993; Spence et al. 1996). Others have promoted the use of instream wood loading observation in reference streams to establish targets. Such targets would establish the required width, following the line that higher instream loading targets would require wider buffers (Fox and Bolton 2007; others). Yet others have modeled riparian recruitment processes to identify riparian stand conditions necessary to achieve functional objectives (Van Sickle and Gregory 1990; Bragg 2000; Welty et al. 2002; Gregory 2003; others), and yet others have used empirical data from adjacent riparian stands as a reference (McDade et al. 1990).

A number of investigators have used cumulative source distance relationships to establish buffer widths (McDade et al. 1990; Van Sickle & Gregory 1990; Robison and Beschta 1990; FEMAT 1993; Welty 2002; Liquori 2006). These curves (Figure 11 thru 15) depict the cumulative sources of wood as a function of the distance away from the stream (primarily using mortality as the only recruitment agent), and offer the most robust evidence for effective buffer widths. These papers usually describe distances in the form of a site-potential tree height to account for variation by species and site potential. However, we’ve translated this variable into a distance for the purposes of this discussion. Note that the shape of these curves depends on the wood metric (volume v. trees) as well as the dominant recruitment mechanism.

Figure 11) Source distance relationship originally described in FEMAT.

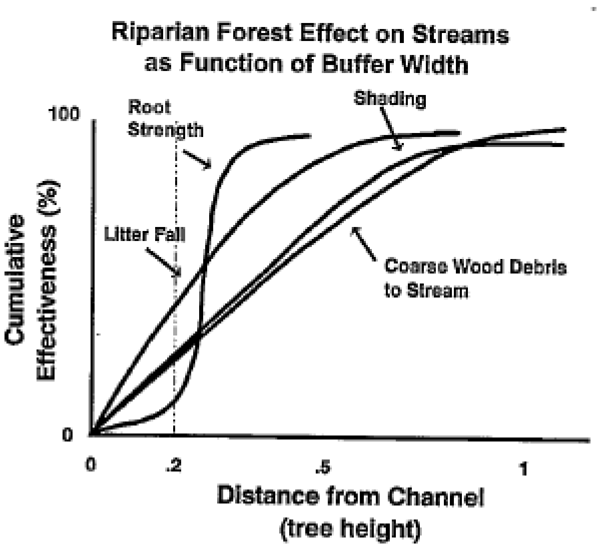
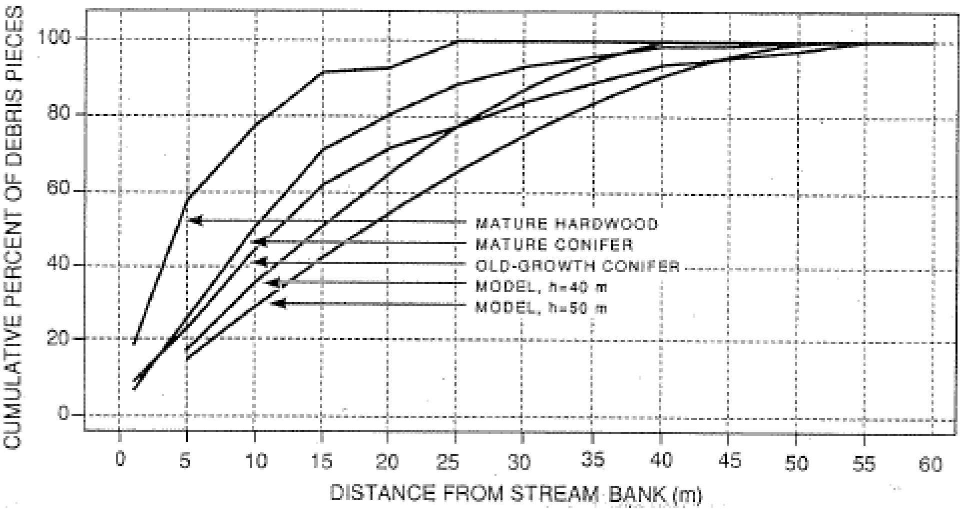


Figure 12) Source distance curves described by McDade et al 1990.



The source distance studies generally report that most (ranging from ~50-95+%) of the potential wood recruitment *from riparian areas* occurs within ~30-100 feet (10-30 m) of the channel. In California streams, 70 to 90% of wood generally originates from with ~30 to 100 feet (10 to 30 m) of the channel (Figures 13-14). Riparian area width beyond 100 ft (30m) had a relatively small effect on wood recruitment functions in most cases (McDade et al. 1990; Van Sickle and Gregory 1990; Robison and Beschta 1990; FEMAT 1993; Welty 2002;

Liquori 2006). Extensive data are available for these relationships; a comprehensive meta-analysis of data from all regions is beyond the scope of this report.

Figure 13) Source distance relationship from Benda 2005. See Chapter 7 for a more detailed discussion of source distances.

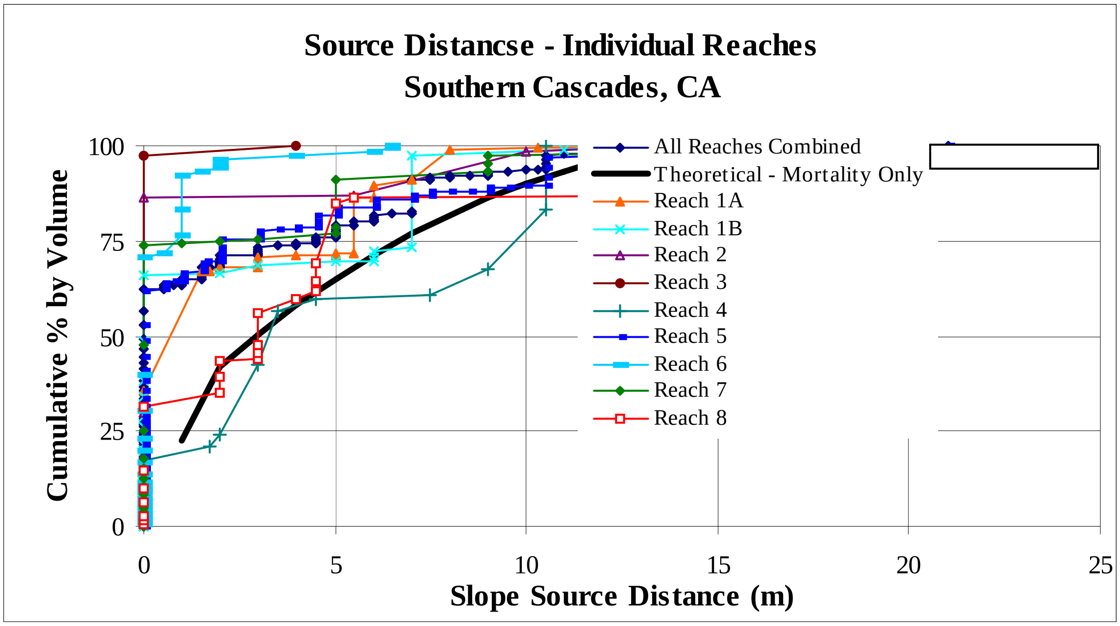


Figure 14) Variations in source distance curves based on dominant recruitment process are plotted for streams in the Sierras in northern California (Benda et al. 2005). Mortality in this figure refers to treefall.

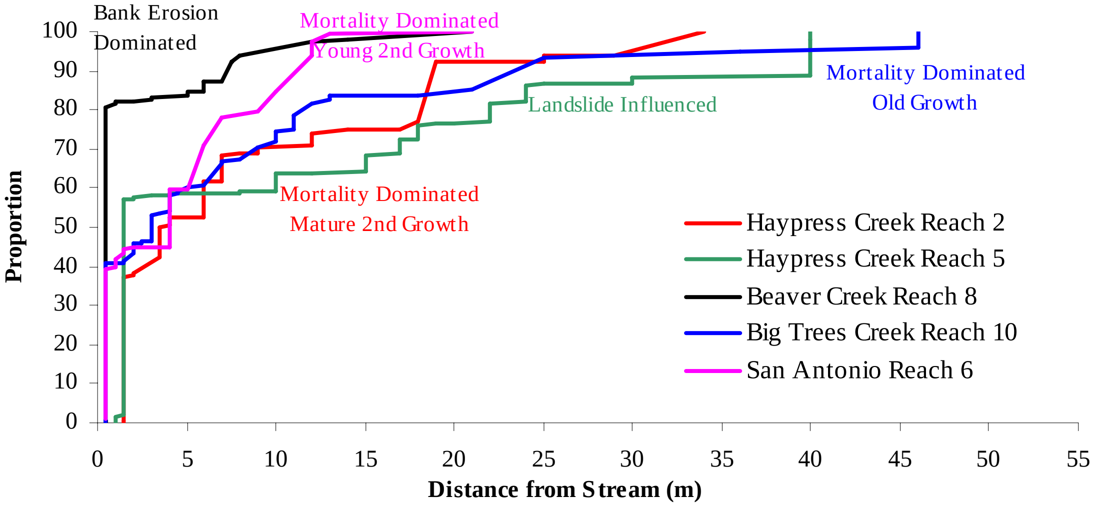
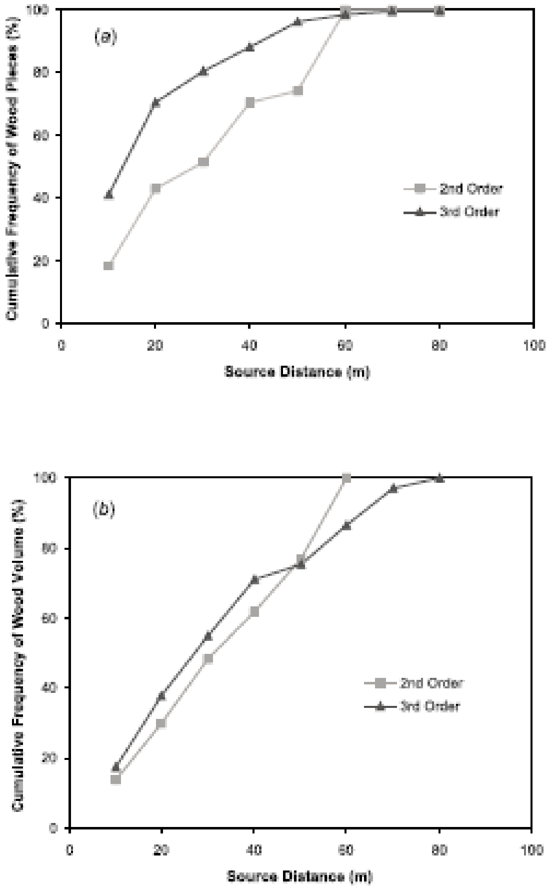
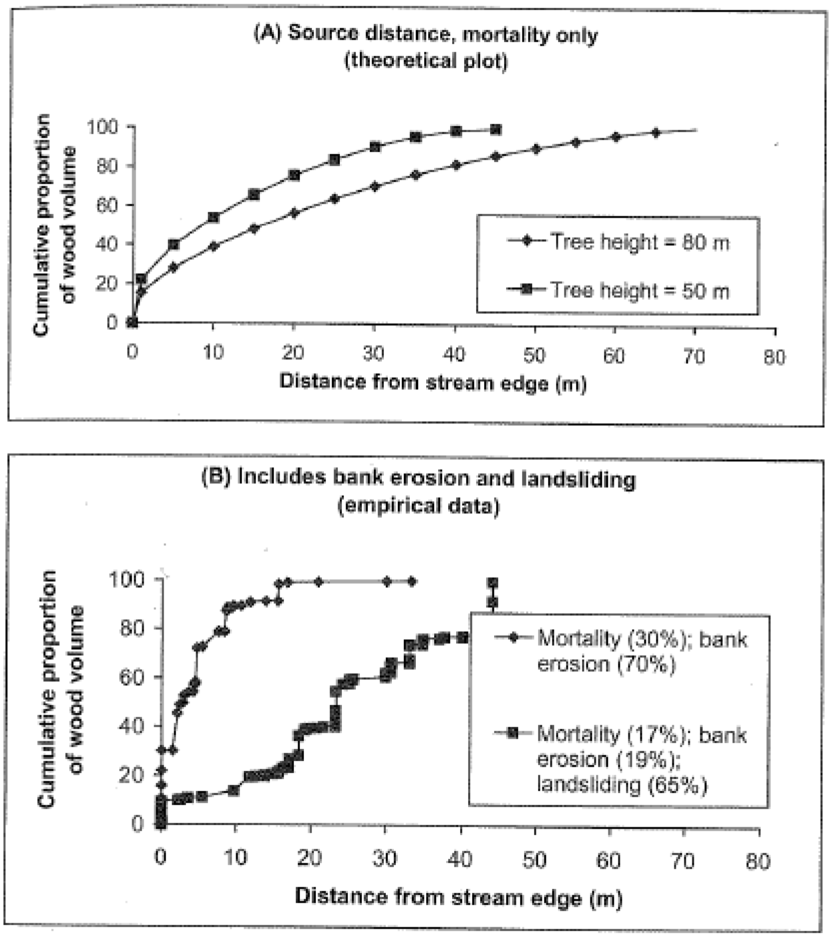


Figure 15) The source distance of large wood a) pieces and b) volume for second-order colluvial tributaries and the third-order mainstem channel in the North Fork Cherry Creek basin (May and Gresswell 2003). Mortality in this figure refers to treefall.



Much debate about these source distance curves has occurred in the literature. Over the last 20 years, a growing recognition developing is that there is not a single "right" curve for riparian recruitment, but that there are families of curves that depend on the relative proportion of wood contributed from various sources. These process variations can often be inferred from the site context (e.g. topography, confinement, stream type/order, etc), as described in more detail in Section 0.

Figure 16) Theoretical predictions of source distance for two different tree heights based on random tree fall (A). Field data demonstrating difference source distance relationships due to recruitment by bank erosion and streamside landsliding (B). NOTE: mortality in figure refers to treefall. (*From Benda et al 2003*).



- For areas that are dominated by mortality-driven treefall, about 80% of potential short-term wood recruitment typically occurs within the first 20 m (65 feet) from a channel with the remaining 20% of wood coming from the next 20 m (65 feet) of the riparian zone (Figure 17 and Table C) (Benda et al. 2002; Benda et al. 2003; Benda et al 2004; Benda et al. 2005).

- Areas prone to windthrow can dramatically shift this zone of maximum efficiency away the channel by increasing the proportion of wood that falls toward the stream (Liquori 2006). This study also found that windthrow dramatically increased the total amount of wood delivered to the stream (i.e., more trees fell toward the stream than would occur in the absence of windthrow).

- Areas prone to *streamside* landsliding shift this relationship away from the channel (Benda et al. 2002; Benda et al 2003; Benda et al. 2004; Benda et al. 2005; Martin and Benda 2001). In steep areas prone to debris flows, certain landscapes (coast and Klamath Mountains), might benefit by some retention of large trees along certain headwater streams (May and Gresswell 2003).
- Areas where bank erosion is a dominant source of wood, most wood is generated from a much narrower zone. However, where bank erosion is so pervasive as to result in significant channel migration, a much wider zone might be appropriate to accommodate the encroachment of the channel into riparian areas over time. The width of such channel migration zones depend on the specific site conditions and potential for the channel to move over time which is constrained by several processes and conditions beyond the scope of this study to describe.

We note that this approach to establishing buffer widths describes only the amount of wood that has been observed to be recruited from adjacent riparian stands. It assumes that the stocking of the riparian zone is appropriate (it may not be) and that forest management within or near this zone will not affect long-term production and recruitment processes (it can).

Figure 17) Typical zones of wood recruitment. The Streamside Bank Erosion Zone in California can typically provide 30-60% of the total observed instream wood. Up to 90% of the total observed instream wood load is usually recruited from the combined Streamside Bank Erosion Zone and the Inner Core Mortality Zone. The width associated with the Inner Core/Cuter Core transition is described in Table C. (*source: Lee Benda*).

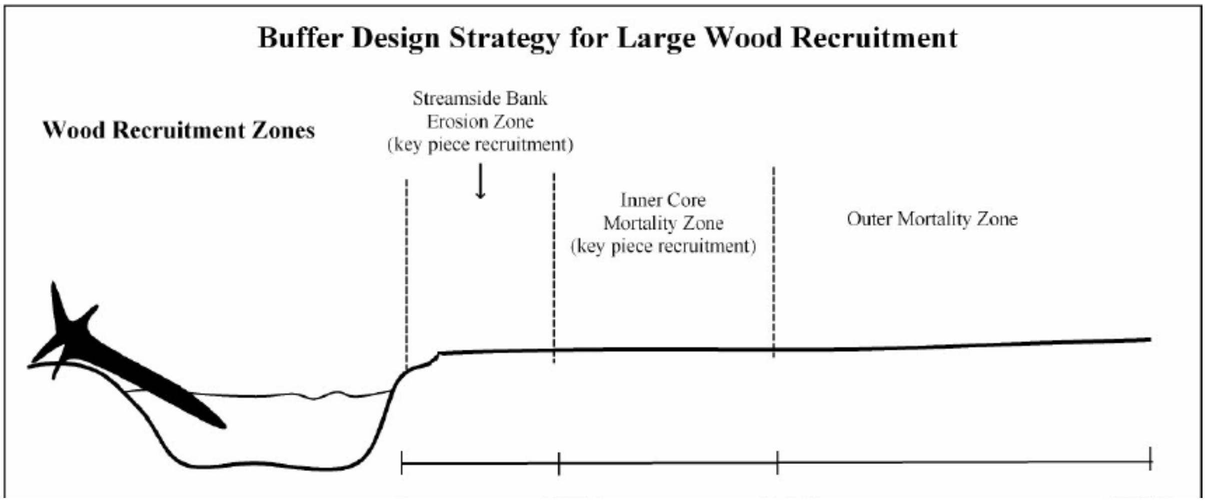


TABLE C) Typical effective source distances for California regions (based on Benda et 2003; Benda et al 2005; Reid and Hilton 1998); also see Figures 11):

Site	Observed Efficiency	Distance	Dominant Source	Notes
Mendocino County	90%	26-46 ft (8-14 m)	Bank Erosion	Includes streams affected by stream cleaning
Mendocino County	90%	115 ft (35 m)	Wind	
Redwood Region	90%	98 ft (30 m)		
Redwood Region	90%	164 ft (50 m)	Streamside Landsliding	
Southern Cascades	80%	16 ft (5 m)	Bank Erosion	
Western Sierras	70%	33 ft (10 m)		
Western Sierras	92%	66 ft (20 m)		
Klamath	80%	66 ft (20 m)		

HOW CAN FOREST MANAGEMENT PRACTICES ENCOURAGE STAND CONDITIONS THAT PRODUCE AND MAINTAIN THE POTENTIAL FOR FUTURE IN-STREAM WOOD OVER TIME?

Based on the reviewed literature, and as discussed in previous sections, wood recruitment to streams is strongly dependent on the varying importance of the different wood recruitment processes, including bank erosion, mortality, landslides, and disturbances (e.g., wildfire, infestation, disease, etc). The predominant wood recruitment processes depend upon geomorphic and ecological factors that vary spatially within individual watersheds and across physiographic regions in California. Wood loading is also dependent on the forest type (larger older redwoods supply more wood compared to smaller trees in the Sierras), structure, and the successional state of the forest (e.g., young vs. old).

The literature addresses several approaches to setting forest management goals for wood recruitment. We outline them here as it affects the response to wood loading issues.

Understanding the existing site-specific controls on wood abundance in streams can focus forest management by directing the most appropriate treatments in support of these functional processes (Liquori 2000; Lassettre and Harris 2001; Lisle 2002; Bisson; Rieman et al. 2003; Benda et al. 2003; Benda et al. 2005; Liquori 2006). As such; targets are set for each site based on their short-term and long-term potential. Process domains can be mapped with a fair degree of accuracy using existing GIS tools, aerial photos, geospatial models, and/or field criteria.

These tools could be used to establish maps or to evaluate generalized prescriptions that guide forest management. These tools might also be appropriately used in an adaptive management context to validate assumptions about forest treatments over time and space and to test site effectiveness.

Forest Management Approaches

Riparian management strategies require consideration of both science and policy. The reviewed literature offers many opinions, but little hard data to evaluate the scientific effectiveness of any approach. Ultimately, the choice of the best approach must be guided by forest policy.

Riparian Reserves

This approach seeks to maintain large buffer widths in order to minimize management effects within riparian areas, specifically those indirect management effects on natural rates of disturbance (FEMAT 1993; Spence et al. 1996; Reid and Hilton 1998). This approach typically calls for uniform and continuous riparian buffers of up to two site-potential tree heights on fish-bearing streams and one site-potential tree height on non-fish streams. The underlying basis for this strategy is that over long periods of time (typically centuries), late-seral conditions will become re-established in riparian areas, and that such conditions best represent the long-term conditions suitable for salmonids. It also ensures that natural processes dominate in controlling the structure and functions provided by riparian areas.

Some underlying assumptions inherent in this approach is that a large untreated buffers will evolve toward mature stand conditions despite any indirect effects of management on the landscape and that the best riparian stand condition suitable to salmonids are mature to late seral conditions.

Selective Management

This approach seeks to actively design the characteristics of riparian forests (e.g., size, height, species) in a way that influences future wood recruitment potential (e.g., timing of mortality, exposure to disturbance risks) and other functions. Its focus is often to maximize the benefit to riparian functions while preserving the capacity to operate on forest lands to achieve other resource objectives, including timber harvest.

The focus is on encouraging a stand composition that targets wood recruitment characteristics most suitable to the specific stream environment. This approach recognizes that the total wood volume grown onsite is strongly influenced by stand structure (e.g., density, species, age-distributions, etc), and that tree volume and diameter can be manipulated to meet management objectives. It also recognizes that wood functions vary geographically and by stream type (Bilby and Ward 1989).

This approach also acknowledges the effects on wood growth from silvicultural treatments or other forest management activities. Often, this approach integrates information from stand dynamics to encourage growth and affect rates of mortality, typically through thinning practices (Liquori 2000 Bragg et al 2000; Welty et al. 2002; others).

This approach is limited by difficulties in estimating future disturbance rates sufficient to accurately predict wood recruitment potential over time.

Proactive Enhancement:

Another approach described by the reviewed literature is the concept of proactive instream restoration and enhancement in the form of wood placement (Bragg and Kershner 1997; Bisson, Wondzell et al. 2003; others). The ability to properly design and implement restoration or enhancement projects requires knowledge of hydrology, hydraulics, geomorphology, biology and engineering practices. Instream wood placement is a practice that is continuing to evolve in many land-use settings, and the general perception is that such projects are overall a benefit to salmonids.

One challenge in evaluating the benefits of proactive enhancement is that biologically systems are inherently complex, and determining the specific benefit from wood placement or enhancement is difficult. Other biological factors associated with ocean survival, predation, inter-annual variability, and population dynamics make conclusive determinations of success difficult. In most cases, the monitoring and research elements required to answer these questions are not sufficiently developed or implemented to provide the data necessary to evaluate success (Bisson, Wondzell et al. 2003).

Environmental Goals & Targets

It is helpful for both of the above management approaches to establish environmental goals and targets that can be used to evaluate the effectiveness of riparian management practices. Science can be helpful in establishing objective target based on empirical studies of wood loading and functional instream responses to wood.

Reference Loading Targets

Reference wood loading targets are often based on comparison to “pristine” reference reaches that have been minimally impacted by management (Martin 2001; Lisle 2002; Fox and Bolton 2007; others). While such reference sites can offer some insight to pre-management conditions, it can be difficult to extrapolate these conditions to managed landscapes. As shown in Table D, empirical studies show very wide differences in wood loading conditions both across regions and within regions (Martin 2001; Lisle 2002; Fox and Bolton

2007), and thus selecting management criteria becomes an arbitrary decision that might not reflect the physical capacity of the stream to achieve such targets (Lisle 2002). Another challenge with this approach is that natural disturbance regimes have been greatly affected by a wide array of human activities (e.g., global warming, fire suppression, stream diversions, etc) that distort the perspective that historically derived reference conditions can have toward understanding future loading potential.

TABLE D) Wood volumes (m^3/ha) from pristine reference sites in California (from Lisle 2002).

		Range		
Region	**# of sites**	**Low**	**High**	**Median**
Sierras	12	2.2	100	30
Cascades	11	36	1100	300
Klamaths	9	18	1600	250
Redwood	11	200	4600	1000

Functional Loading Targets

Functional targets seek to establish wood loading levels based on the amount needed to achieve desired ecological functions. Studies using this approach focus on the wood loading required to maximize pool density or fish habitat characteristics (Montgomery and Buffington 1995; Beechie & Sibley 1997; Berg et al. 1998; Martin 2001). The scientific debate here typically revolves around identifying “how much is enough”. Biologically, there has yet to be consensus established by the literature about how much is enough (Lisle 2002; Young 2001), however there are observed geomorphic trends that suggest that there are diminishing returns on wood loading beyond about 650 pieces of large woody debris per mile (~400 pcs/km) in pool-riffle channels (see Figure 5). Loading targets for other channel types depend on the geomorphic context, and are subject to some debate.

Tools for Wood Management

In addition to setting targets, there are other tools that can be used to help support wood management in forested settings.

Wood Budgets

Wood budgets support the development of testable hypotheses for riparian management. Wood budgets can provide key data that can be useful in predicting future wood recruitment potential by using an understanding of wood recruitment processes and observed rates (Benda and Sias 1998; Benda et al. 2003). Calculations are derived by using empirical relationships for various input factors based on wood supply area (e.g., bank erosion, landslides, treefall, windthrow, etc). An advantage of wood budgeting is that it can predict the potential sources of wood based on actual source availability. However, wood budgets typically represent a steady-state snapshot in time, and they are not responsive to variations in stand dynamics that strongly influence mortality processes.

Wood budgets can be useful in tracking the sources of potential wood so that specific management objectives and targets can be set. They can be limited by the need for a wide array of empirically-derived inputs that vary across the landscape and over time. Observed rates of wood recruitment from different sources vary widely, and depend on ecological and geomorphic disturbance regimes, climatic factors, stand types, the geomorphic context for each site, etc. Wood budgets tend to be backward-looking estimates of existing wood loading. They might not necessarily represent future potential, responses to management, or responses to disturbances.

Wood Recruitment Models

There are a number of wood recruitment models that have been developed, all of which have one or more weakness (Gregory et al. 2003). Wood recruitment models offer an objective tool for comparing the recruitment trajectories under existing conditions and treatment conditions. However, currently available wood recruitment models are limited in their ability to: a) accurately predict the proportional balance between various wood recruitment mechanisms (e.g., bank erosion, mortality, windthrow, etc), and b) accurately predict actual wood loading conditions into the future. Models tend to be deterministic, and are not very effective at predicting important stochastic (quasi-random) processes like floods, landslides, infestation, etc that drive these key recruitment processes.

There are also a number of input variables that models are sensitive to, and for which limited data is available. Some variables might be informed directly through onsite measurements (e.g., stand density, site index, channel width, buffer width, etc). Other factors like depletion rates (Murphy and Koski 1989; Welty et al. 2002; Gregory et al. 2003; Hassan et al. 2006), breakage (Van Sickle and Gregory 1990; Liquori 2006), and treefall direction (Bragg and Kershner 2004; Liquori 2006) can be difficult to inform locally, and might require regional databases to properly inform. Alternatively, guiding rules might be developed to minimize the reliance on these uncertain factors.

INFERENCES FOR FOREST MANAGEMENT

There is a large body of literature that examines the relative importance of the various wood recruitment processes to streams. Our review considered over 100 papers related to wood recruitment, yet it is a fraction of the information available. There are wide variations in the opinions expressed in the literature, and many of the opinions expressed are not necessarily supported by data. Studies often draw speculative or simplistic conclusions that extend beyond the data that were collected. Many studies focus on small sub-sets of issues or synthesize literature from many sources. Few papers fully integrate all the dimensions associated with wood production and recruitment in riparian forests.

There has yet to be developed a single recognized ecological endpoint for which individual streams should be managed (Young 2001), and thus effective riparian management might consider measures that provide sufficient integrity and resilience so that each riparian exchange function can persist over time (Rieman et al. 2003). Policies that establish management objectives might help to focus scientific resources to better address riparian management practices.

Despite the varied opinions expressed in the literature and the general lack of scientific consensus, there are some emerging trends in the reviewed literature, which we highlight below.

The relationship between the width of wood recruitment has been fairly extensive studied in several diverse regions in California, and is available through a database on wood recruitment specifically targeting California landscapes (Benda et al. 2002; Benda et al. 2003; Benda et al. 2004; Benda et al. 2005). These studies show that there is no single relationship between buffer width and wood recruitment because the zone of maximum effectiveness varies by contributing mechanisms, and these mechanisms vary over time and space. However, 70-90% of wood is recruited within 30-100 ft (10-30 m) in most areas.

Wood recruitment processes are highly dynamic, and there are typically wide variations in the natural rates of recruitment from each process from various locations within the landscape. Specific stream sites are prone to variations in wood recruitment rates over time in response to changes in growing space and disturbance risk.

Wood recruitment processes (i.e., bank erosion, treefall, streamside landsliding) in headwater channels are not significantly different compared to larger fish-bearing streams, however the rates associated with these processes are different, and the importance of each process can vary across the landscape.

Streamside landsliding can be an important source of woody debris at certain locations in a watershed across all physiographic areas. Headwater streams can be prone to debris flows in certain physiographic areas in California and thus can be a significant source of wood to larger fish-bearing streams (primarily Coast Ranges and Klamath Mountains). Areas prone to streamside landsliding and/or debris flows can be determined using various tools (e.g., models, maps, etc) based on geomorphic and hydrologic criteria; however such tools cannot accurately predict the risk of landslide occurrence, but might be able to estimate probability of occurrence, which might support risk-management strategies. In certain landscapes, wood in debris flow deposits can play an important ecological role (Reeves et al. 2003; May and Gresswell 2003; Benda et al. 2003; Reeves et al. 2003). Although wood delivery by debris flows occurs in California, its role in supporting instream wood loading is not well understood.

These generalizations must also be considered within the context of California's diverse physiographic regions. Wood loading is responsible for many habitat features in coastal and Klamath basins but woody debris has substantially less effect on habitat in steeper boulder bedded streams that are common in the Sierras (Ruediger and Ward 1996).

While wood recruitment is important, the long-term production of healthy and resilient riparian vegetation might be locally more important in some settings than short-term wood debris amounts and inputs into riparian systems. The risk associated with these strategies can be best offset by applying spatially variable treatments across the landscape and tracking the response to such treatments in a rigorous, scientifically valid manner (Bisson, Rieman et al. 2003; Dwire and Kaufman 2003; Rieman et al 2003; others).

The most significant constraint on the recovery of riparian wood functions is the age and structure of riparian forests, which is at least partly a function of legacy forest management practices. Complete recovery of the wood exchange function might require that the distribution of riparian forests become dominated by more mature stand conditions than currently exists in California. Recovery can be improved by managing the riparian stand to affect: 1) the dynamics between growth and mortality, and 2) maintain an appropriate distribution of disturbance regimes based on the ecological context for the site. Such strategies might require a full suite of management tools.

There can be negative consequences to unmanaged riparian buffers that might be detrimental to salmonid resources. Examples include excessive wind damage in buffers adjacent to clearcuts (Lisle and Napolitano 1998; Liquori 2006); increased risk of catastrophic (stand-replacing) riparian fire risk associated with unmitigated fuel loading (Murphy et al. 2007); and delay in recovery associated with suppressed stand growth (i.e. stagnation) (Welty et al. 2002).

INFORMATION GAPS

There are several data gaps involving wood recruitment in California streams. These include:

1. Wood recruitment related to debris flows. Although this process was observed to be locally important in several regions in California (particularly the coastal and Klamath mountains), it remains unquantified. A combination of modeling and field work could resolve this outstanding question. For example, application of debris flow models to areas such as the upper Sacramento and Klamath (using NetMap, Benda et al. 2007 as commissioned by the USFS) revealed headwater streams that might have a high potential for delivery wood to fish-bearing streams by debris flow.

2. The importance of wildfire as a wood recruitment agent in California is not known. Field studies and or simulation modeling (e.g. Benda and Sias 2002) could be used to estimate the importance of wood recruitment by post fire toppling. Simulation modeling using an estimated 150 year fire rotation indicated fire related wood loading could approach 50% (Benda and Sias 2003). Longer fire rotations (250 yrs) greatly diminish this proportion (~5 to 10%).

3. Buffer designs need to predict in-stream wood production based upon current forest structure and species composition. Regional differences in wood production are documented with Northern California and the Pacific Northwest loadings higher than other parts of the West (Harmon et al. 1987; Bilby and Bisson 1998; Lassettre and Harris 2001).

4. Future life-cycle, death and decay studies are needed to depict the regional differences with various forest structures and species compositions given endemic and epidemic mortality agents such as insects and disease (species or host specific) as well as abiotic events (e.g., fire, landslides, windstorms, etc.).

5. Supply from headwaters. The supply of wood from headwater streams is not well documented for California. Studies that document the transport distance for both fluvial and debris-flow transport processes will help to establish proper longitudinal source distance lengths.

6. The effectiveness of wood placement projects as short-term enhancements or mitigation for poorly stocked riparian

sources should be evaluated. Such studies should consider the benefit to habitat development and maintenance, the fish response, and the time for which such placement projects are effective.

7. California-specific studies that evaluate the biological benefits to specific wood loading conditions to help establish instream wood targets for managed areas. Such studies might consider geomorphic response (e.g. Montgomery and Buffington 1995; Beechie and Sibley 1997), or biological response.

GLOSSARY

Debris Flow	a form of mass wasting where landslides mix with floods to create a highly destructive slurry of water, mud, rock and debris that can scour downstream for long distances
Disturbance	any of a number of physical processes that result in premature mortality or alteration of stand structures. Disturbance processes may include fire, wind, flood, landslides, debris flows, infestation, disease, animal damage, ice breakage, avalanches, etc. The level of impact from disturbance is often related to its frequency (how often it occurs) and its magnitude (how big the disturbance is).
Fluvial Transport	movement through the channel network by way of streamflow processes
Headwater Channels	small tributaries that drain hillslopes and connect to the stream channel network. Typically non-fish bearing.
Higher-Order Streams	stream order is a way to classify segments of the channel network based on the topology of the network (the number of junctions of similar segments). Higher-order streams are typically larger streams that are fish bearing. In the case of this review, typically 3rd-5th order streams.
Hollow	an unchannelized swale (depression) on the hillslope that is immediately upstream of the channel, and which is prone to saturation. Hollows can be sources of groundwater supply and when sufficiently steep, can be sources of landslides and debris flows
Ingrowth	trees that germinate and/or are released from the understory when sufficient canopy gaps are created either through management actions or disturbance
Landslides	a failure of a hillslope in which large portions of

	the hillslope slide downslope. Typically associated with large storms.
Larger Rivers	Typically very high-order streams (>6th order)
Legacy Effects	effects associated with past forest management practices. See Section 2.2
Mass Wasting	any of a number of hillslope processes in which large volumes of sediment move together as a single fluid (or solid) mass
Stand Dynamics	the response of tree growth and mortality conditions that corresponds to the overall stand structure. Mortality and growth are dynamically linked within the stand.
Stem Differentiation	different growth rates that occur within a stand in response to its structure, age, size distribution and species. For example, during the first 100 years or so Douglas fir trees will grow more rapidly (differentiate) compared to redwood in the same stand. During differentiation, some trees will grow in height and diameter, and others may become suppressed (demonstrating little or no growth).
Stem Exclusion	a successional phase in which competition for growing space begins to cause mortality (death) in suppressed trees.
Streamside Landslides	landslides that occur in confined valleys adjacent to streams
Succession	a series of forest structures and conditions that typically occur “in succession”, following typical periods of growth and mortality. Succession concepts have given way to stand dynamic concepts

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

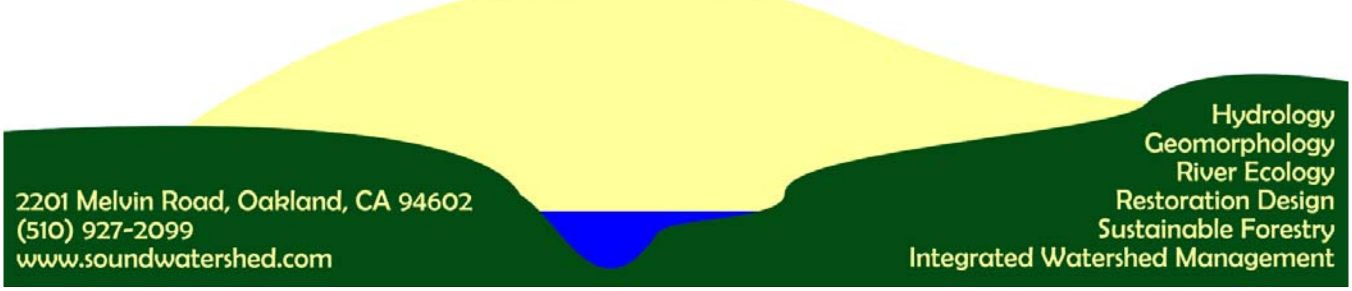
Chapter 6

SEDIMENT EXCHANGE FUNCTIONS

for

The California State Board of Forestry and Fire Protection

September 2008



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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

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September 2008

SWC Ref# 1013

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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).

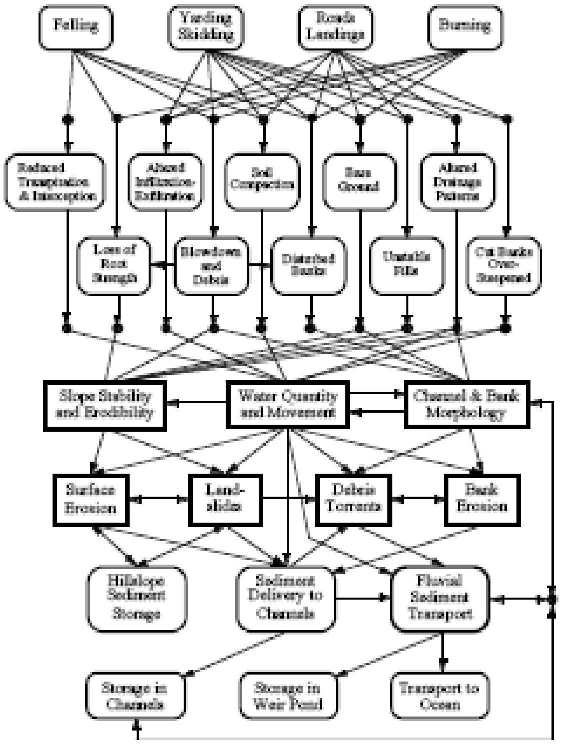


Figure 1) Conceptual pathways for forest management impacts on sediment production, delivery and transport (*from Lewis 1998*).

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).

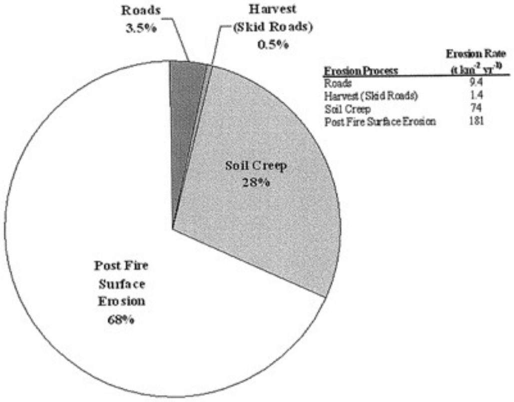


Figure 2) Estimated sediment production at Judd Creek (Southern Cascades). Soil Creep represents the "natural" rate of background sediment supply (*from Benda et al 2003*)

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.

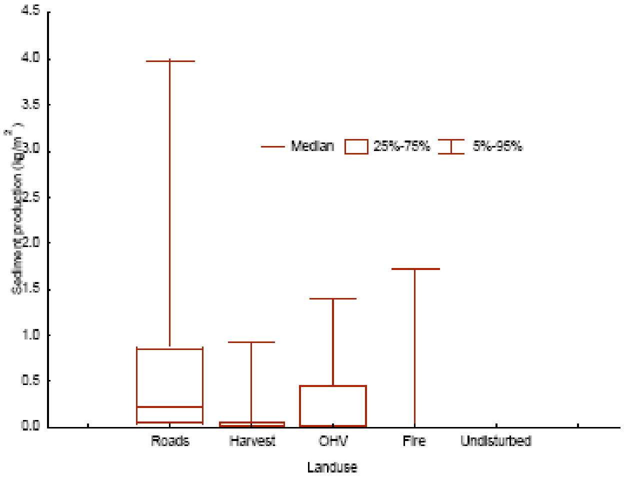


Figure 3— Sediment production by dominant land use for the 1999–2000 wet season.

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).

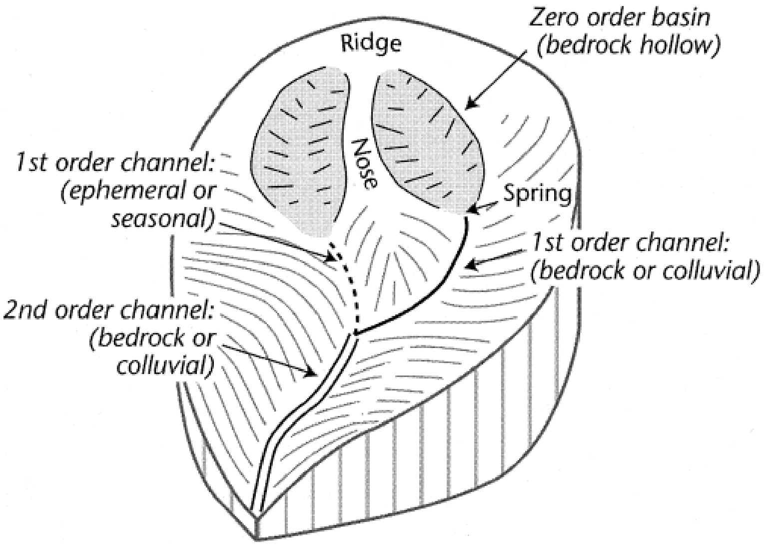


Figure 4) Anatomy of headwater drainage basins (from Benda et al 2005).

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.

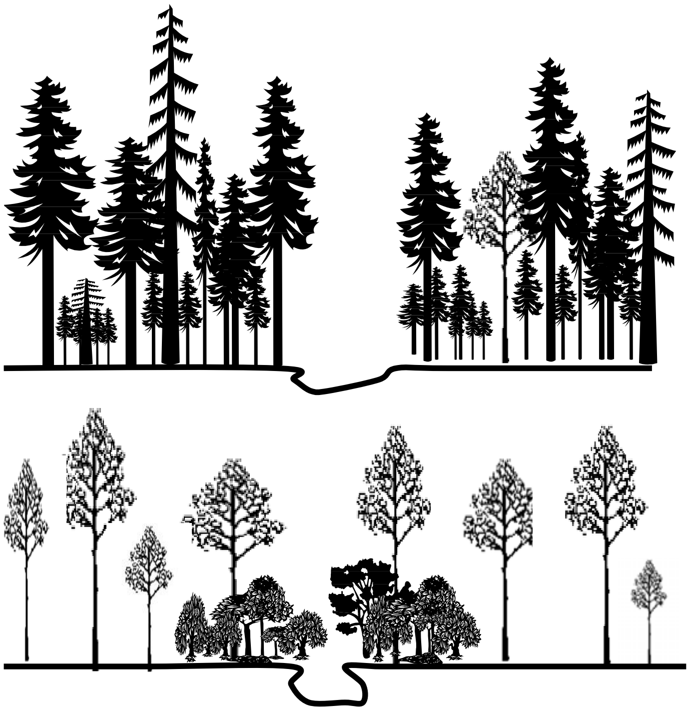


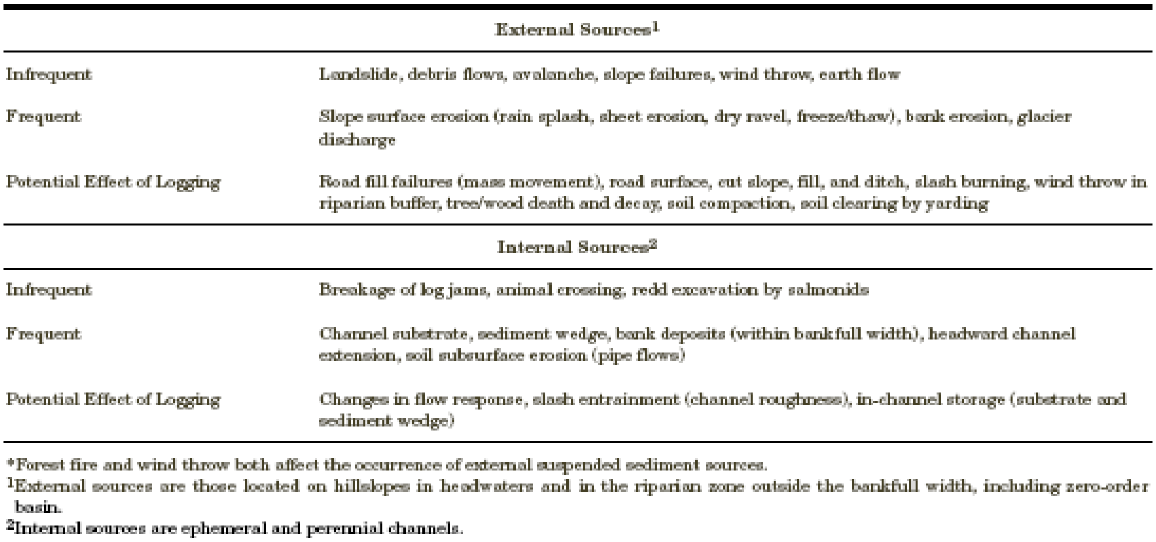
Figure 5) Schematic diagrams comparing a forested riparian area dominated by fir (top) as compared to a riparian community dominated by a scrub-shrub community(bottom). The scrub-shrub community requires an more open canopy, yet offers quality salmonid habitat conditions (from Liquori and Jackson 2001).

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.

<u>Roads</u>

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.

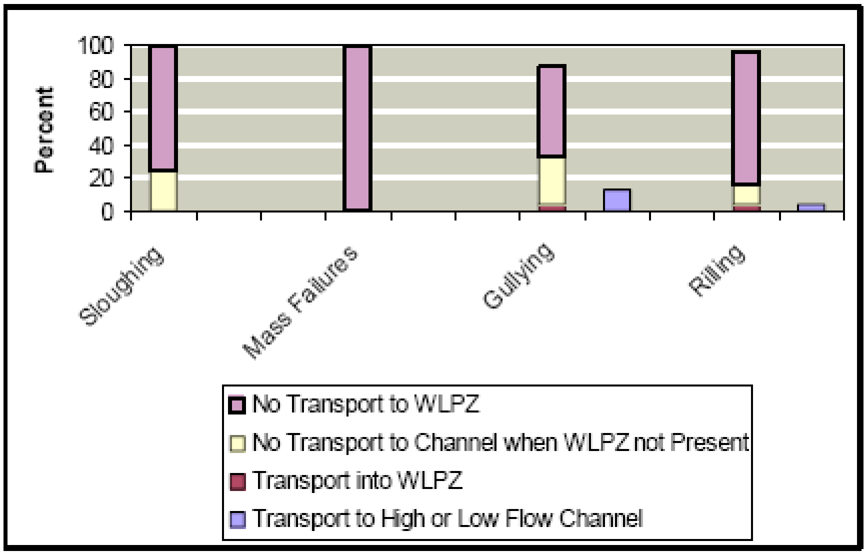


Figure 6) proportion of erosion features observed during dry season surveys of skid trails that deliver to streams and riparian areas (*from Cafferata and Munn 2002*). Note that only a small fraction of sites delivered to the stream channel (short bars next to Gullying and Rilling).

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.

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[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.*

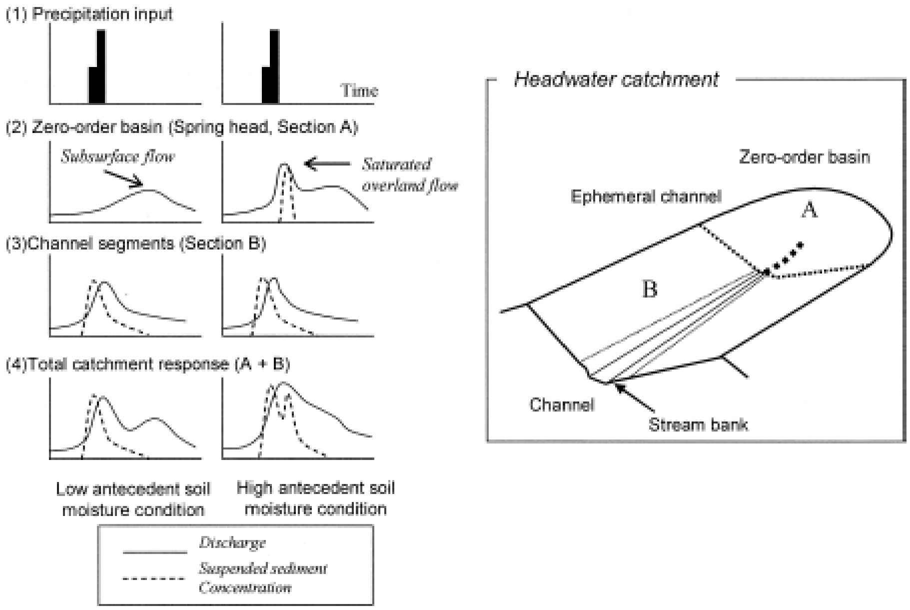

Figure 7) Hypothetical hydrologic response and suspended sediment concentrations in a zero-order (hollow) and 1st-order (channeled) catchment during low and high antecedent soil moisture conditions. The X-axis shows time and y-axis represents relative magnitude (*from Gomi et al 2006*).

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.

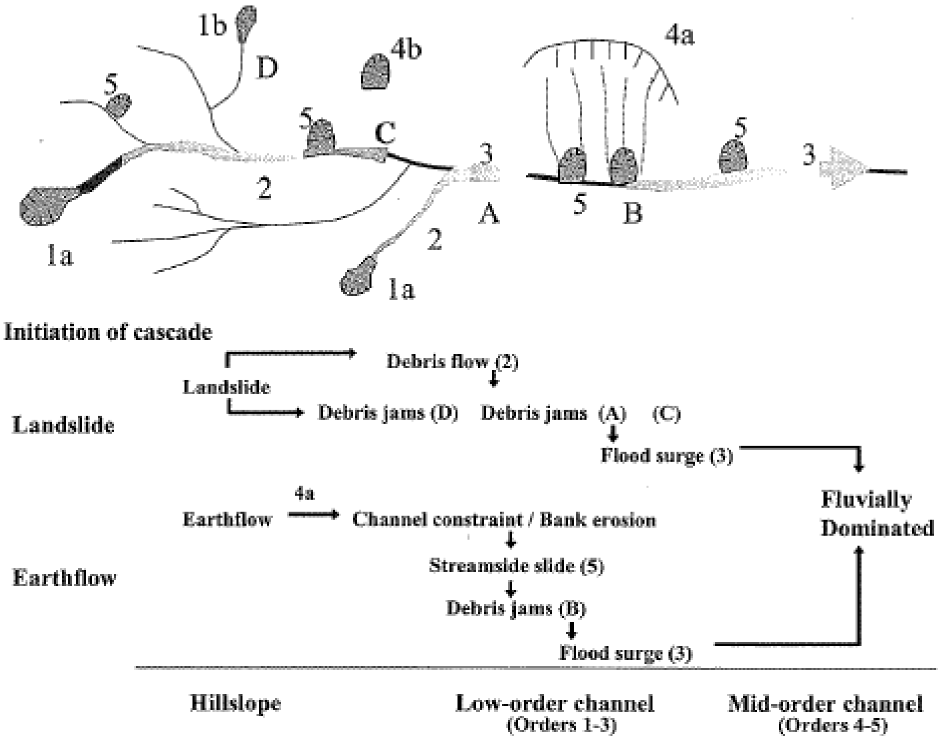

Figure 8) Example schematic diagram of a disturbance cascade, showing how processes over a channel network translate into different disturbances types as the disturbance moves downstream. For example, a landslide from a hollow (1a) becomes a debris flow in the first-order channel (2) causing a flood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

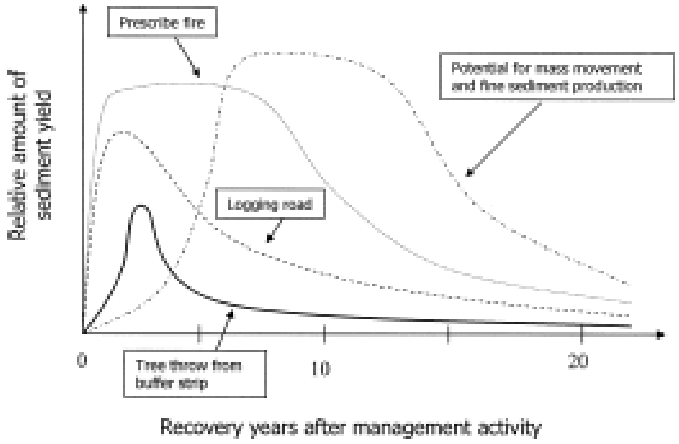

Figure 9) Relative duration and recovery rates of increased suspended sediment yield associated with forest harvesting and other disturbances (*from Gomi et al 2005*).

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.

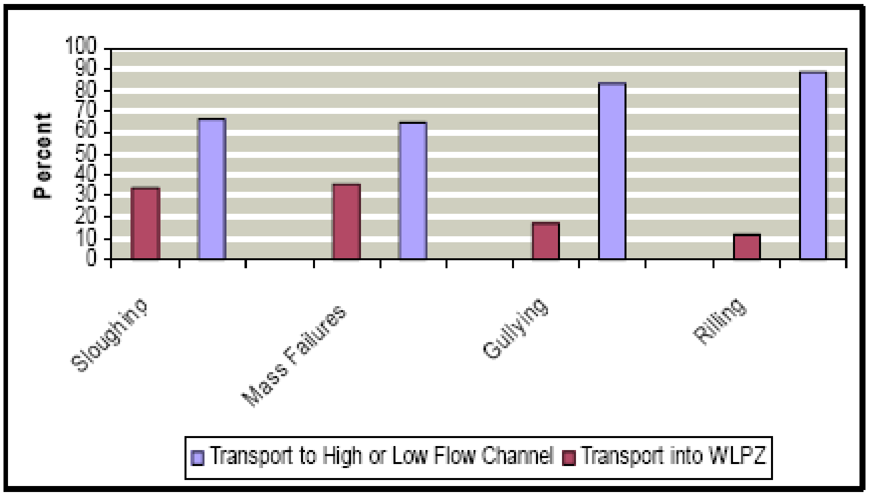

Figure 10) Percent of erosion features in riparian buffers observed during dry season surveys that deliver to streams (from Cafferata and Munn 2002). Note that in each case, most erosion features in buffers deliver to streams. However, only 37 erosion features in riparian zones were observed in 300 project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

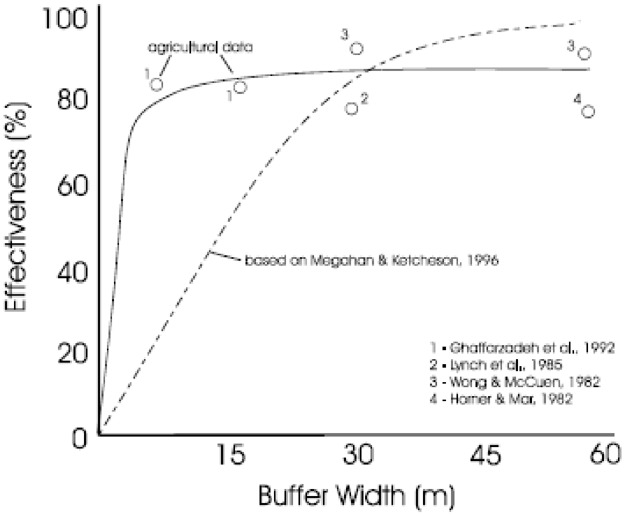

Figure 11) Source-distance relationship for sediment as reported by Castelle and Johnson (2000).

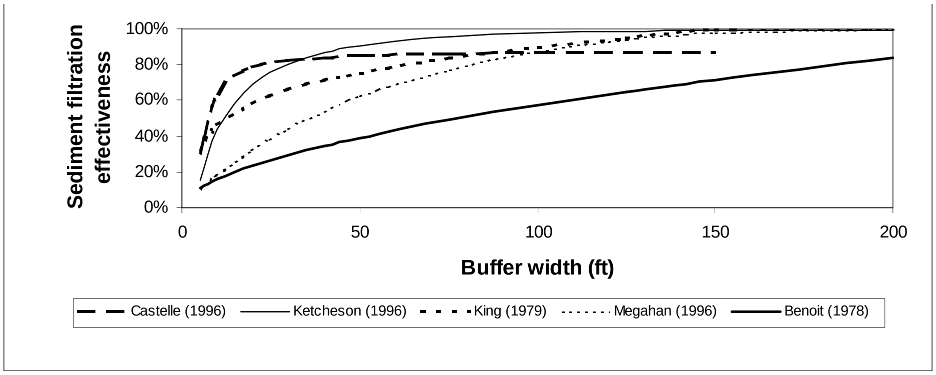

Figure 12) Source-distance relationship for sediment as reported by CH2MHill and Western Watershed Analysts (1999).

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.

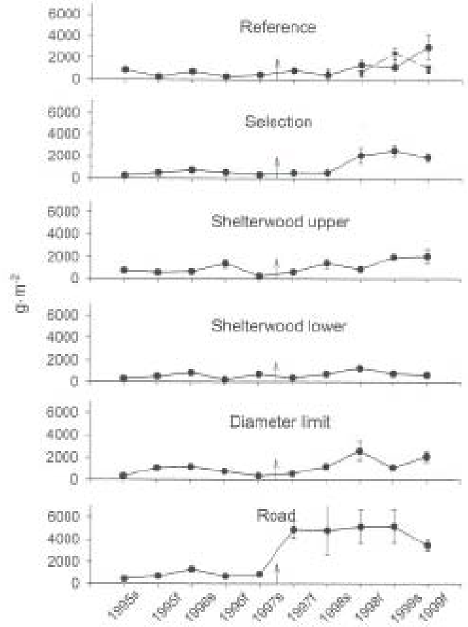

Figure 13) Sediment concentrations associated with various types of harvest treatments in low-order channels without riparian buffers (*from Kreutzweiser and Capell 2001*).

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.

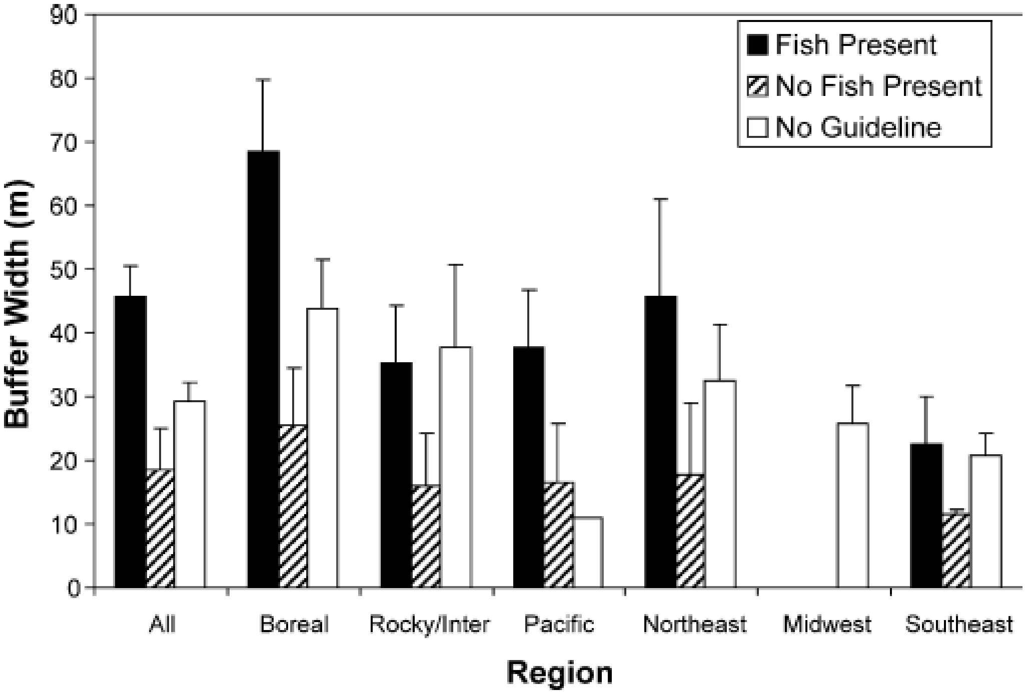

Figure 14) Mean buffer widths of large streams with fish (first bar) and without fish (second bar) for jurisdictions with fish guidelines, and jurisdictions without fish guidelines (third bar). Error bars represent standard error. (*From Lee et al 2004*).

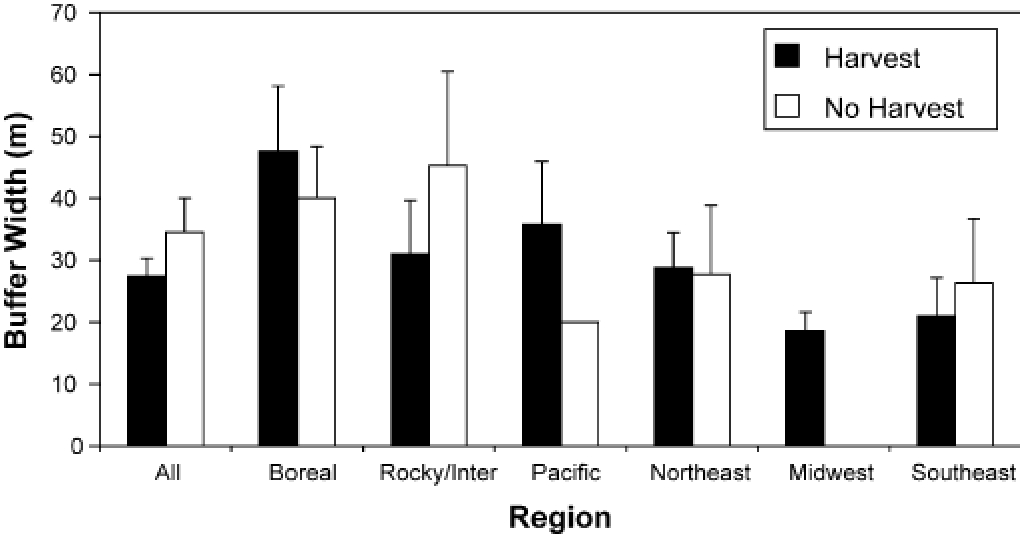

Figure 15) Mean buffer widths on large streams for jurisdictions with selective harvest (first bar) and jurisdictions without selective harvest (second bar). Error bars represent standard error (*From Lee et al 2004*).

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.

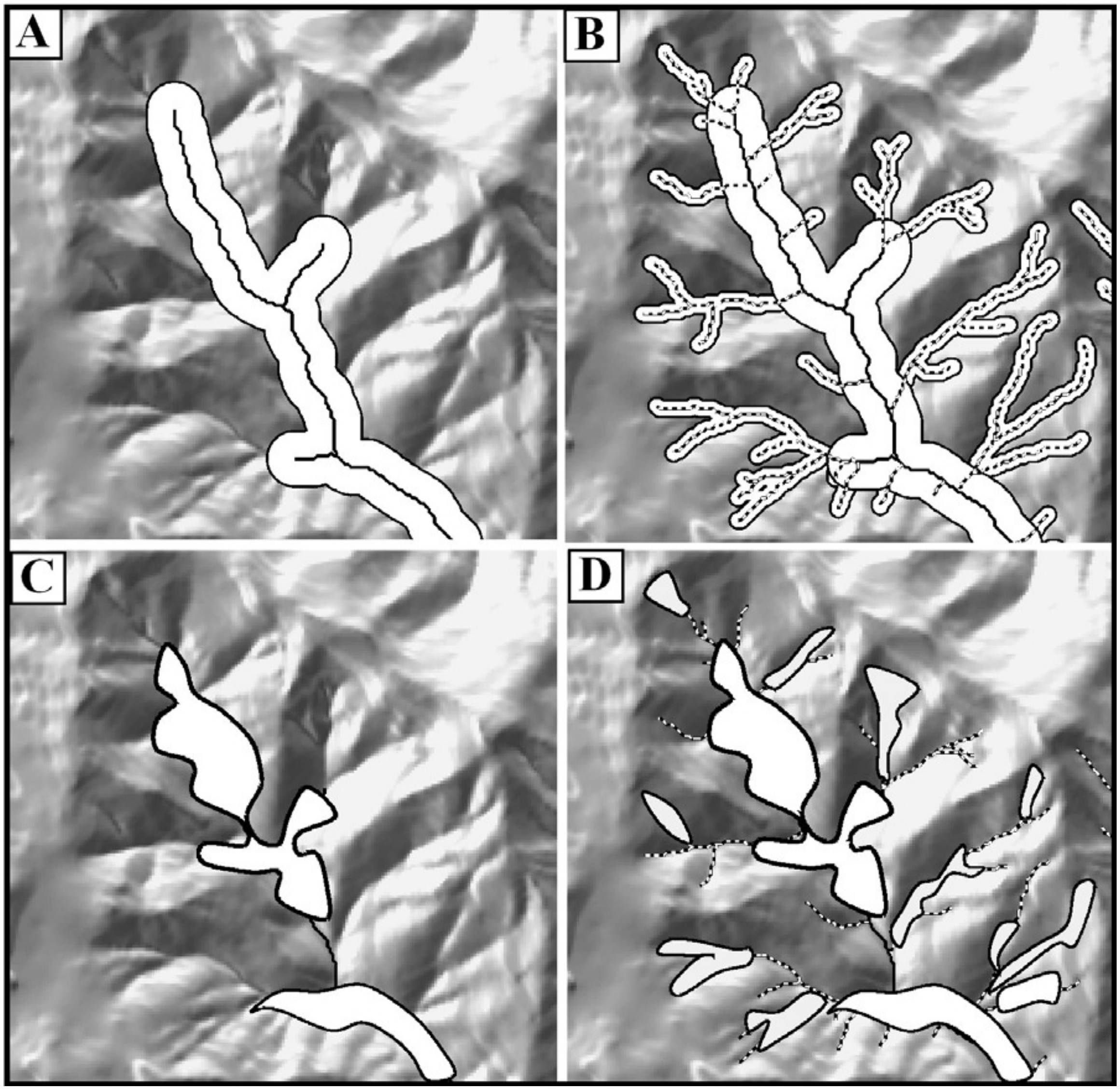

Figure 16) Example of a spatially-integrated ecological framework for riparian management. Traditional buffer approach: (A) continuous, uniform buffer, on primary streams (B) including headwaters. Spatially-integrated approach: (C) variable, discontinuous buffers on primary streams (D) and including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

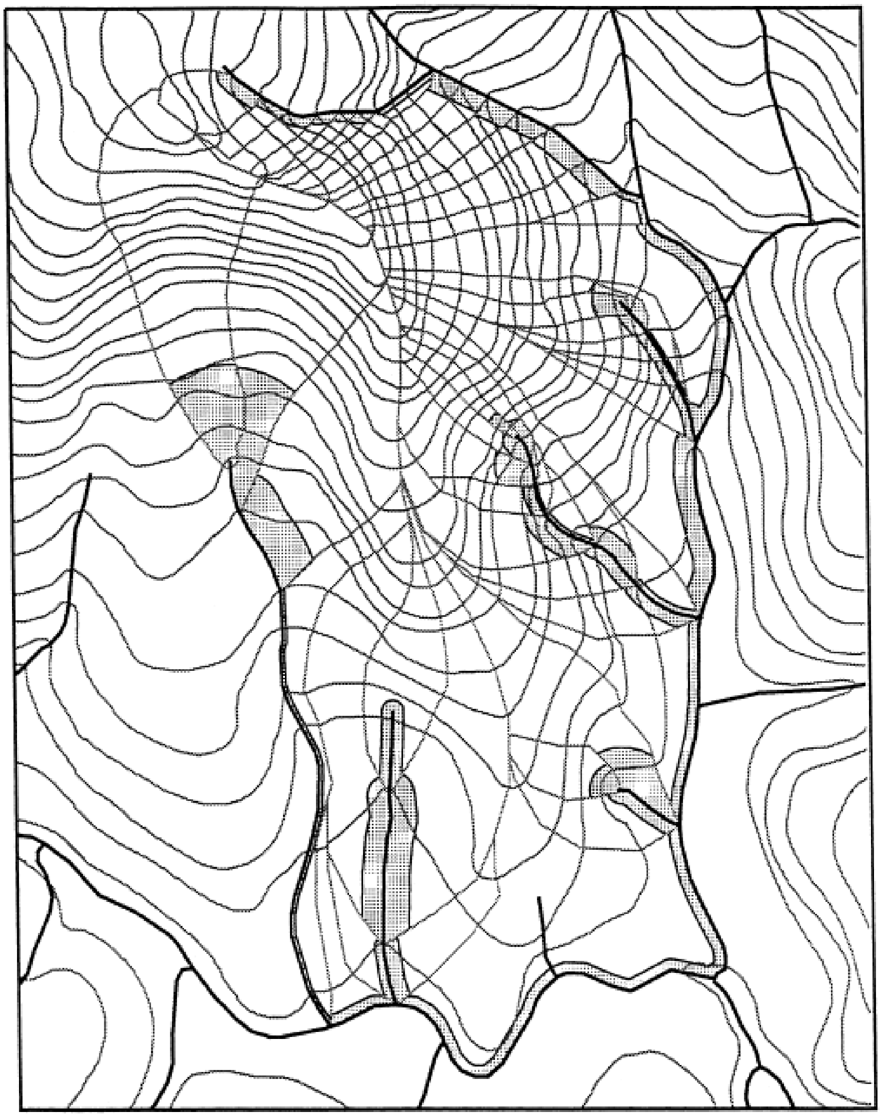

Figure 17) Example of a constant-buffer loading design that consumes 20% of the land area *(from Bren 1998*).

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.

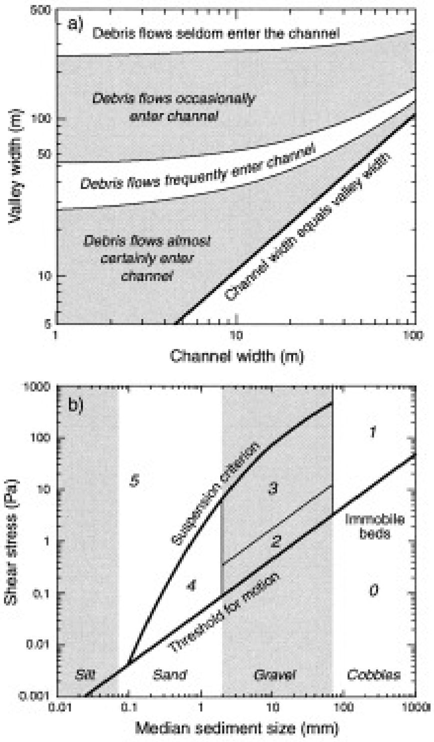

Figure 18) Process-based stream classification system characterizing the degree of hillslope interaction with the channel and the transport capacity of sediment within the channel (*from Hassan et al 2005*).

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

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Sound Watershed Consulting
Creating Functional Water Environments

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

Chapter 7

SYNTHESIS

for

The California State Board of Forestry and Fire Protection

September 2008

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Hydrology
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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

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EXECUTIVE SUMMARY

In this chapter, we discuss concepts that will help guide the Board of Forestry toward an integrated approach to riparian management that considers all forms and functions.

We've discovered four key findings throughout our review of the literature that extend across all the exchange functions. These include:

1. Spatial context is important, as it influences functional response patterns.
2. Longitudinal controls (along the channel length) on exchange functions in addition to lateral controls (buffer width) are important in maintaining the watershed-scale ecosystem structure that maintains aquatic habitats.
3. There are dynamic interactions among and between riparian exchange functions that alter the importance of exchange functions for any particular setting.
4. While riparian zones can buffer a stream from direct management impacts, they do not protect streams from disturbances, but in fact alter the disturbance regimes in ways that can affect the functional response expressed by both short-term and long-term evolution of riparian areas.

A shift in thinking from a "protection" mindset (e.g., buffering the stream) to an "ecosystem processes" mindset is consistent with several general themes in the literature in recent years (Nakamura and Swanson 2003; Reiman et al. 2003; Young 2001). These papers suggest that it may be a more appropriate management objective to ensure that the ecosystem processes and functions are maintained to provide desired riparian (and instream) conditions in managed settings.

There are three general approaches to achieve this objective that are promoted in the reviewed literature.

Riparian Reserves utilize large buffers so that mature to late-seral stand conditions are eventually achieved.

Resource Optimization seeks to balance appropriate protections against other management objectives.

Advanced Recovery/Enhancement manages growth and disturbance risks to influence ecosystem processes that create conditions favorable to salmonids over the short- and long-term.

The scientific basis for buffer widths is described in terms of source-distance relationships that relate width to the cumulative inputs (or limits) for various functions. The shape of source-distance curves are strongly influenced by the dominant mechanisms or riparian characteristics for contributing (or preventing) the key input associated with each exchange function in that setting. Seven specific limitations in using source distance relationships are described that raise questions regarding the utility and/or effectiveness of using source distance relationships as the sole basis for riparian management.

The scientific basis for longitudinal variation describes regional, watershed, and temporal scales of influence that combine to influence the context for habitat requirements. Managing for longitudinal variation requires an understanding of how different ecosystem processes act to form and maintain habitats throughout the channel network.

The scientific basis for headwater riparian management recognizes that headwaters affect functional responses in downstream reaches. The concept of longitudinal source-distances is offered here as an analog, wherein different characteristic input distances can be measured from the confluence of the headwater tributary junction with fish-bearing reaches. Data to support such source-distance relationships for headwater areas is limited in the reviewed literature.

Riparian forest structure is fundamentally a dynamic expression of growth and disturbance. It is the combination of structural characteristics and disturbance processes that influence functional relationships between riparian areas and salmonid habitats. Management of riparian zones can affect the types of disturbances and vulnerability to disturbances that deliver functional inputs. These disturbances can be beneficial, detrimental, or both.

Our synthesis of the reviewed literature leads us to the conclusion that the importance of maintaining ecosystem functions, including those associated with disturbance, dynamics, growth, and spatial variability, point to the need for an evolutionary step in the design and application of riparian management strategies. A more holistic strategy would integrate landscape-scale concepts into local decision criteria. A wide array of analytical tools for evaluating watershed-scale processes and conditions are available, and the reviewed literature suggests that there is considerable scientific data to inform such tools.

KEY THEMES

Generally speaking, riparian zone management seeks to influence exchange functions by:

- Delivering and retaining wood, nutrients and coarse sediment in streams, and
- Preventing large perturbations in the timing and amount of heat, water and fine sediment that are delivered to streams.

The processes that are responsible for meeting these objectives are sensitive to variability at the regional scale, watershed scale, and time scales.

The previous chapters of this literature review were focused around each of five riparian exchange functions, and were generally evaluated in isolation from each other. In this chapter, we discuss some concepts that will help guide the Board of Forestry toward an integrated approach to riparian management that considers all forms and functions.

What we learned

We've discovered throughout our review of the literature four key findings that extend across all the exchange function chapters. These include:

1. Spatial context is important, as it influences functional response patterns.
2. Longitudinal controls (along the channel length) on exchange functions in addition to lateral controls (i.e., buffer width) are important in maintaining the watershed-scale ecosystem structure that maintains aquatic habitats.
3. There are dynamic interactions among and between riparian exchange functions that alter the importance of exchange functions for any particular setting.
4. While riparian zones can buffer a stream from direct management impacts, they do not protect streams from disturbances, but in fact alter the disturbance regimes in ways that can affect the functional response expressed by

both short-term and long-term evolution of riparian areas.

1) <u>Spatial context is important</u> – We observed that the answers for many of the key questions depend on where one is located both geographically and geomorphically. For example, in-stream wood is more important along the coast than the Sierras (Berg et al. 1998), and is more important in mid-order channels than in headwater channels (Nakamura and Swanson 2003). Similarly, more shade for temperature sensitivity is needed for some streams but not for others (Allen 2008). The theme of spatial and geographical variability extends across most of the key issues with each exchange function.

2) <u>Longitudinal factors</u> – Spatial variability and dynamic processes show that riparian functions are not only influenced by width but by the influence of landforms and processes that change longitudinally along the channel network. The effective width for functions depends on process, which depends on location. Riparian management by width alone ignores multidimensional factors as reported in the reviewed literature.

3) <u>Interactions among and between riparian exchange functions</u> influence both the short-term and long-term suitability of habitat for salmonids. For example, canopy openings affect heat exchange, nutrient cycling, macroinvertebrate production, soil moisture, vegetative species colonization patterns and riparian stand growth in ways that both support and potentially harm conditions that are beneficial for salmonids. Similarly, the density of standing trees in riparian areas affects the diameter growth of trees that can recruit to the stream, the rate at which trees are recruited, and the risk of disturbance from fire, infestation, flood, etc. As such, the inherent response of the forest to management-induced change is extremely complex.

4) <u>Riparian buffers affect ecosystem processes and functions.</u> There is a growing recognition that a riparian zone does not "buffer" (e.g., protect) the stream from disturbances, but in fact alters the disturbance regimes in ways that both benefit and harm salmonid habitat conditions. Riparian management can affect riparian disturbance regimes by affecting the types of disturbance, the magnitude of disturbances and the frequency of disturbances. Since disturbance regimes are one of the driving factors that influence riparian stand dynamics and succession (Oliver & Larsen 1990; Naiman et al. 1998; Franklin et al. 2002), the long-term trajectory of riparian stands can be substantially influenced not only by the direct manipulation from forest management, but by the indirect effects of forest management on natural processes. For example, recently observed fire behaviors in riparian zones, where low intensity ground fires become damaging crown fires, demonstrates how some riparian buffers can harm salmonids by exposing the stream to risks it may not have experienced under a fully natural condition. Management actions within or near riparian areas are just one of many forms of disturbance that affect the evolution of the riparian stand. As management increases risks for some ecosystem processes, it also reduces risks in others, and it is the sum of effects that controls the outcome for salmonid habitats.

Where we are going in this chapter

Riparian functions can be viewed holistically by considering their ecological context as a way to identify risks and priorities for important functions, and in the process, explain some of the variability in these exchange function processes.

We have attempted to create a framework for synthesis that considers the literature in the context of the latest concepts that stress the occurrence and ecological importance of spatial variability, diversity, and dynamics. These ecological characteristics influence the range of conditions and natural mechanisms that support salmonid ecology (e.g., disturbance processes, material inputs, diversity of conditions, managing risks, etc.).

We explore each of these themes in more detail in the sections below. We follow with a discussion of the implications for forest management that might help to outline a framework for addressing these issues within public and private forest management in California.

THE CONTEXT FOR RIPARIAN ZONES

Forest structure is fundamentally a dynamic expression of growth and disturbance (Oliver and Larsen 1990; Franklin et al. 2002). Riparian areas in particular tend to be more prone to both growth and disturbance relative to upland stands. Therefore, it is a logical extension that the conditions in riparian forests responsible for supporting salmonid habitat depend primarily on the dynamic exchange between growth and disturbance processes in riparian areas.

A shift in thinking from a "protection" mindset (e.g., buffering the stream) to an "ecosystem processes" mindset is consistent with several general themes in the literature in recent years (Nakamura and Swanson 2003; Reiman et al. 2003; Young 2001;). These papers suggest that it may be a more appropriate management objective to ensure that the ecosystem processes and functions that maintain desired riparian (and instream) conditions are encouraged to persist in managed settings.

The reviewed literature offers no clear strategy for maintaining ecosystem processes. The debate amoung scientists follows along several predominant pathways, the resolution of which is a complex ecological policy issue. The positions are generalized as follows:

The Riparian Reserve Argument: Ecological processes and functions that occur in riparian areas are so complex, so poorly understood, so long-lived, and so sensitive to management, that riparian buffers should be as wide as possible to ensure that the effects of management (which can extend some distance into the upslope riparian zone edge) are minimized. This argument is often bolstered by the perspective that the best conditions for salmonids are perceived to be late-seral or old-growth conditions, and that large buffers will allow natural recovery processes over the period of centuries to eventually restore such conditions. A broad consensus of scientific reviews considers a one-site-potential tree height sufficient to provide most riparian functions in hillslope constrained channels over time (Young 2001). As indicated by source-distance relationships (see below), 100% of the potential delivery of most functions are provided in this width (e.g, FEMAT 1993).

The Resource Optimization Argument: It is inefficient (and perhaps unfair) to require large buffers because most of the benefit for salmonids are found in the zone closest to the stream, and thus there is a point where resource values associated with timber production outweigh the benefits to salmonids. This is often justified by the economic concept of diminishing returns.

The Advanced Recovery/Enhancement Argument: Active management of riparian zones may help the recovery of desired riparian conditions by promoting growth, substantially advancing recovery of late-seral conditions, and managing risks from undesired disturbances (e.g., fires, infestation, disease, etc.). Active management can create conditions that are favorable to salmonids over the short- and long-term and provide timber harvest opportunities that can offset the costs of actively managing these areas.

The Scientific Basis for Defining Buffer Widths in Fish-Bearing Streams

The scientific basis behind riparian management has historically been driven by a focus on the width of the riparian forest necessary to sustain each of the five exchange functions. The effective width has been defined by a series of generalized functional relationships originally described in FEMAT (1993), and explored by others (Castelle and Johnson 2000; Young 2001; Benda et al. 2002; Benda et al. 2003; others). These relationships were established using “source distance” curves that relate the cumulative effectiveness of each exchange function in terms of the distance from the stream bank (Figure 1). Initial debate in the literature centered around populating these curves with data from various settings (Castelle & Johnson 2000; Young 2001; others).

More recent studies lead us to conclude that there is no single curve that represents each exchange function in all settings. Instead, for any given setting, a unique curve can be generated that represents the integration of ecosystem processes and riparian structures that exist in that setting. In other words, the shape of the curve is strongly influenced by the dominant mechanisms or riparian characteristics for contributing (or preventing) the key input associated with each exchange function in that setting.

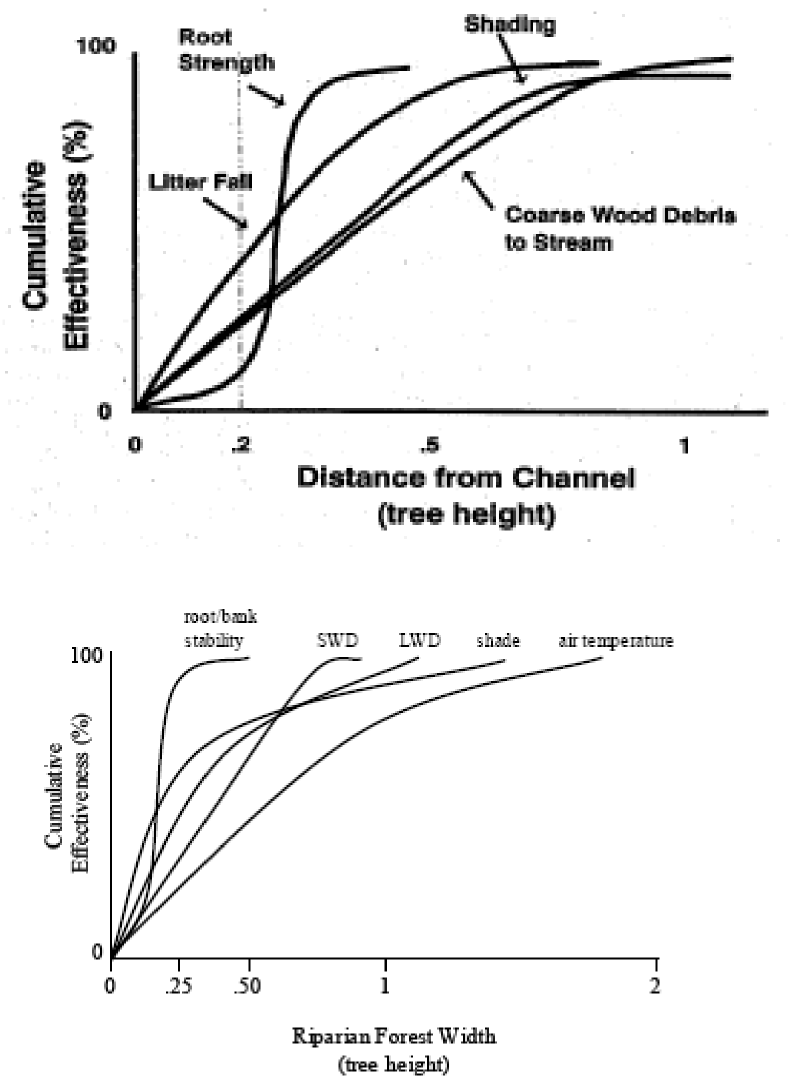

Figure 1. Examples of cumulative source distance curves A) from FEMAT (1993) and B) from Young (2001). Note the difference in the scale of the x-axis.

The source distances for wood and sediment are directly influenced by delivery processes, while the source distances for biotic and heat (and to some extent water[1]) are determined primarily by the riparian structure, which can be indirectly influenced by

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[1] *Water is a special case, because studies have not defined specific riparian effects. See Water chapter in this review.*

disturbance and growth processes. The specific variables that affect the shape of each source-distance curve include:

Wood: recruitment mechanism (bank erosion, landslide, treefall,), stand mortality (windthrow, fire, insect/disease, suppression), tree height, and valley slope/confinement;

Sediment: surface roughness, compaction, topography, soil type, geology, and local ground disturbance processes (e.g., landslides, gullies, roads, skid trails, etc.);

Heat: tree height, canopy density, topographic shading, stream orientation, and stream width;

Biotic and Nutrients: vegetative species, size, stand structure, channel morphology, and possibly valley slope/confinement.

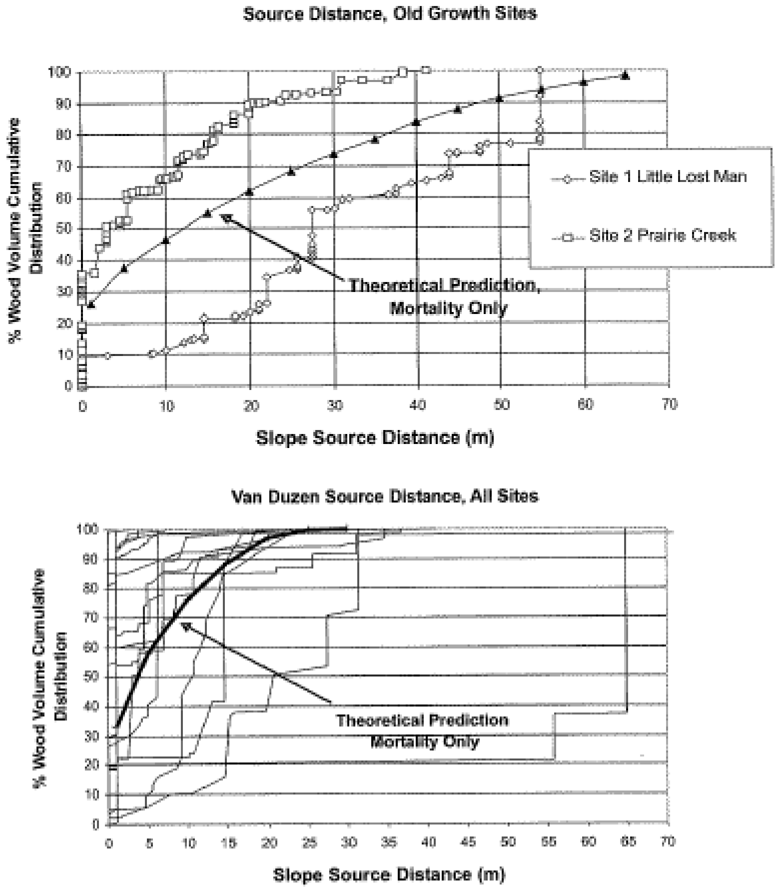

Figure 2. Source distance curves for old growth (top) and second growth (bottom) sites. In each case, the relative position of the source-distance curve can be explained by the dominant recruitment mechanism (bank erosion vs. landsliding). Note mortality in these plots refers to treefall recruitment (Benda et al. 2002).

So, for example, as described in the Wood Chapter (and Figure 2), sites that have recently experienced high rates of bank erosion express a curve that is shifted toward the stream (i.e., a greater proportion of inputs is derived from closer to the stream). Similarly, areas that recently experienced landslides or windthrow typically shift away from the stream (i.e., the source zone for wood extends further out from the stream).

The reviewed literature offers considerable data for wood source distance relationships, primarily because wood has generally required the widest source distance relative to other exchange functions, and may be the best studied (at least in the general sense – specific site conditions may vary). This data can be used to establish prescriptive relationships suitable to conditions in California.

Despite the widespread study and use of source-distance relationships, there are several limitations with using these relationships as the sole basis for setting riparian management prescriptions, such as:

The instream biological response to source distance relationships has not been established. There is little empirical information, and large degrees of variation in existing data about the biological effectiveness associated with specific riparian buffer widths (Young 2001).

Source distance relationships ignore the trade-offs between functions. In any given setting, the larger source distance may not be the limiting factor from the perspective of aquatic communities. For example, in some settings, deciduous litter inputs may be the limiting biological factor and managing to maximize wood source distance may reduce the development of deciduous understory and associated exchange functions.

Source distance relationships downplay the importance of the quality of contributed inputs. Source distance relationships describe the effectiveness of delivering (or preventing) a particular input to the stream. They do not address the quality of that input, or how the quality may be affected by the prescription.

Source distance relationships only capture the effects of some disturbances. Many of the important disturbances that are responsible for affecting supplies of wood, nutrients, and sediment occur during large events (e.g., floods, fires, etc.). While some recent studies have begun to look at disturbances associated with wind (Liquori 2006; Martin and Grotefendt 2007), landslides and bank erosion (Benda et al. 2002; Benda et al. 2003; Benda et al. 2004; Benda et al. 2005), other riparian disturbances (e.g., fire, insect/disease) are less well represented by the reviewed literature.

Source distance relationships describe the relative contribution, but not the total contribution. A higher effectiveness does not necessarily indicate a higher volume. For example, if a stream has 10 pieces of wood, and 9 result from bank erosion, then 90% of the wood comes from that process. But if a site with 50 pieces of wood has 9 from bank erosion, then only 18% comes from that process, even though the process delivered the same amount of wood. Similarly, a younger stand will typically have higher total mortality even when the rates are similar, because younger stands typically have more trees.

Source distance relationships ignore changes over time. The data used to support these curves only capture a snapshot in time. The processes that have been active during that snapshot may not reflect the long-term trends associated with that particular setting. For example, periods of fast bank erosion tend to be followed by periods of slow bank erosion. The processes that drive these mechanisms (landslides, bank erosion, wind, fire) tend to be episodic (in the case of disturbance processes) or dynamic (in the case of riparian structure).

Source distance relationships ignore the longitudinal context. Because effectiveness is defined only by the existing potential of the riparian area, it does not account for the instream needs of the site. Not all exchange functions are important in all settings. For example, in some stream types and in some geographic settings, heat risks may be less important than other exchange functions.

Across the landscape, process domains may be used to develop an integral curve that best represents the risk profile and thus the long-term average curve shape. Geomorphically-defined process domains reduce some of the variation in these curves, as certain processes can be inferred from them. For example, heat risk can be defined based on geomorphic (e.g., topographic shading) and geospatial factors (e.g., elevation, climatic zone) that can be mapped with a fair degree of confidence.

In the next section, we describe the benefit in longitudinal variation as a way to provide a mix of riparian conditions so that some exchange functions are not compromised by the effort to support another function.

The Scientific Basis for Longitudinal Variation

One of the legacies of the source-distance relationship is that the debate about impacts from forest management has primarily focused around buffer strip width. This has lead to prescriptive strategies that tend to ignore the site's context within the channel network, at least in the absence of more detailed and costly analytical study (e.g., watershed analysis).

The science community has long recognized that longitudinal variations are an important ecological component of natural environments (Naiman and Bilby 1998). Variation occurs in nature in response to differences in geomorphic and geographic context that control the magnitude, frequency and intensity of natural disturbance processes. Since forest management imposes its own characteristic disturbance signature, it is reasonable to consider that variation in management might lead to greater diversity, richness and reduced risk.

Regional variability is expressed in the different ways that salmonid habitats are established and maintained. For example, Coast Range habitats are driven by wood and sediment loading that are predominantly influenced by landslides, flooding disturbances, and in some locations wind. By contrast, the Sierra's appear less responsive to wood and sediment loading, and more strongly influenced by fire disturbances.

Watershed variability is expressed in the different risks, rates and characteristics of ecological processes and their distribution across the landscape. Small headwater streams are influenced by different sets of processes, functional inputs, and habitat requirements than are larger rivers.

Time variability establishes the trajectory of recovery processes, the timing and frequency of disturbances, and the extent of risk in riparian forests. Time also influences the changing distribution of habitat types across the landscape as systems respond to ecological, geomorphic and biological processes.

In order to effectively outline general trends for any exchange function, it's important to understand these scales of variability. For example, there are forms of regional, watershed and temporal variability in ambient air temperature, vegetation type, sediment sources and characteristics, controls on topographic shading, stand growth and mortality dynamics, biological productivity, and hydrological process.

Debates remain as to how to implement variations across the landscape in a way that doesn't compromise salmonids. This section describes some common themes of longitudinal variation that are widely held within the scientific literature, and which may be captured by management strategies (Figure 3).

Variability is expressed throughout the channel network in several ways:

River Continuum – One of the fundamental concepts in aquatic ecology is that there are generalized trends in functional processes and representative biota that occur as one moves downstream along the channel network (Vannote et al. 1980). For example, dominant aquatic invertebrate types change from shredders in the headwater streams to grazers in larger mainstem channels. These biological variations exist primarily in response to different ecological processes domains that influence patterns of stream energy inputs (i.e., heteotrophic and autotrophic production) along the river continuum.

Geomorphic Context – Different landscape conditions contribute to differences in the stream environment. Such differences influence the dominant instream processes that are affected by inputs from riparian functions. The geomorphic context can be described by various stream classification systems (Rosgen 1994; Montgomery and Buffington 1997) that generalize stream conditions based on channel gradient, confinement, sediment supply, etc. Inherent in these systems is a recognition that different processes contribute to the organization of the stream and its suitability to various aquatic communities.

Biological Hotspots – There are certain landscape features that can offer rich and diverse habitat conditions where salmonids and other aquatic communities can thrive. Such features include floodplains, confluence zones, alluvial fans, side channels, off-channel habitats, etc. The locations, distribution, and size of these features are generally predictable as they are a result of interactions among landforms and geomorphic processes.

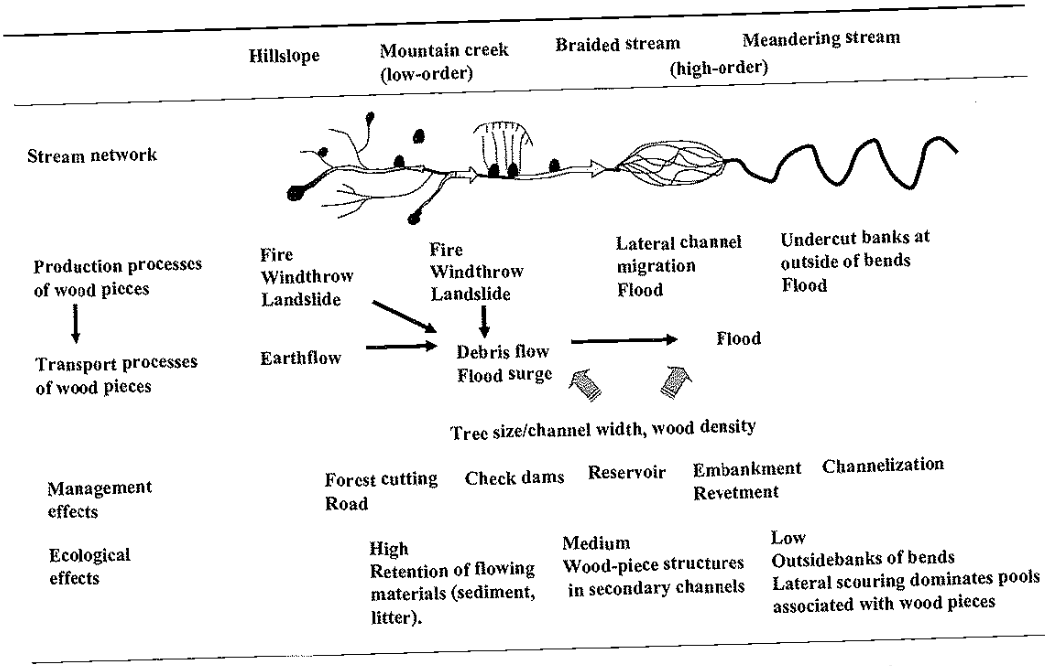

FIGURE 10. A framework for applying results in different geographic and management settings.

Figure 3: A framework for applying results in different geographic and management settings (Nakamura and Swanson 2003).

Recent perspectives of aquatic ecosystems are also focusing on spatial heterogeneity of habitat forming processes and associated physical habitat features at the scale of feet to miles, driven by alternating canyons and floodplains, tributary confluences, landslides, and log jams etc. (e.g., Montgomery 1999, Nakamura and Swanson 2003). The perspective of patchy habitat formation and its related variability driven by landscape disturbances and inherent spatial variability of landscapes and stream systems has influenced much current thinking in riverine ecology (e.g., Bisson et al. 2003; Benda et al. 2004).

The Scientific Basis for Headwater Riparian Management

Headwater streams comprise the majority of the stream network, in some landscapes as much as 80% of the entire channel length. This extensive distribution of channels creates a high edge to area ratio for small streams that result in tight coupling of the riparian functions to the aquatic environment (Richardson et al. 2005).

The general concept of source distances or influence zones applies to headwater riparian management, just as it does for fish-bearing reaches. However, the importance of riparian inputs in headwater systems depends on two factors:

- **Local requirements** – what does the headwater stream itself require to support aquatic organisms and what are the resource management goals for these streams, and
- **Downstream inputs** – what inputs are important to support downstream fish-bearing reaches?

There is very little information to inform the first topic in the reviewed literature. Therefore, our discussion is focused on the downstream importance of headwater stream functions and the length of headwater buffers, or influence zone that affects export materials from headwater streams.

Longitudinally, the buffer length should be sufficient to limit certain key inputs (heat, sediment, water), while promoting others (invertebrates, smaller wood, organic litter). Downstream transport of material inputs is more relevant for some functions than for others. As in the fish-bearing streams, the width of the headwater buffer might benefit by understanding the specific objectives relevant to the site. For example, wood inputs appear less relevant than limiting sediment inputs in headwater streams that are fluvially controlled (MacDonald et al. 2004), but wood may be more relevant in streams where debris-flow processes influence long-term processes (May and Gresswell 2003; Reeves et al. 2003).

There are different longitudinal source distances for systems dominated by fluvial transport versus debris-flow transport. The distribution of debris-flow risks can be determined based on geomorphic criteria.

Similar to lateral (width-based) source-distance relationships, we envision that there are longitudinal source-distance relationships that are relevant to headwater functions. To our knowledge, these have not yet been developed, however, we have some indication of the relative scale for given inputs. These were discussed in more detail in the exchange function chapters, but general examples include the following:

- Sediment transport distances tend to vary depending on the size of material delivered to the stream. Fine sediment typically has transport distances from headwater areas that are relevant at a scale of about 30,000 feet, sand transport is relevant at about 6000 feet, and coarse sediment is relevant at about 300 feet (NCASI 1999). These distances can be influenced by the volume of instream debris, the type of stream, and valley gradient, among other factors. Sediment sources can come from instream erosion (Lewis et al. 2001), roads (Megahan and Ketchison 1996), and upslope erosion (Rashin et al. 2006).

- Wood transport distance from headwater streams is typically short (< 200 m) in fluvially dominated landscapes (Benda et al. 2005; Martin & Benda 2001). Also, the majority of fluvially transported LWD pieces are smaller than the channel width (Martin and Benda 2001, May and Gresswell 2003). In debris-flow dominated landscapes, the instream wood loading tends to be concentrated near confluences and channel gradient transitions where sediment and wood from debris flows are deposited (Benda et al. 2003; others).

- Invertebrate production is strongly influenced by local riparian conditions (Romero et al, 2005) and insect drift distance is less than 100 m (300 ft) during low-flow conditions (Danehy unpublished MS). Therefore most of the invertebrates delivered to larger streams originate in close proximity to the headwater stream junction. Similarly, coarse litter (leaves and twigs) is processed locally and fine particulate is transported out of headwaters.

- As discussed in the heat chapter, we know that downstream temperature influence is typically mitigated in 500 to 650 feet (150-200 m) (Caldwell et al. 1991).

To summarize, fine sediment and fine litter may be derived from along the entire headwater channel. But wood, coarse sediment, coarse litter, invertebrates are primarily derived from within several hundred feet of tributary junctions. Management of the adjacent headwaters can influence habitat and aquatic production immediately downstream. Thus, it appears that headwater streams might benefit by focusing on the following functional objectives:

- supporting inputs for nutrients, invertebrates, litter and small wood;

- limiting inputs of fine sediment and, where relevant, heat;

- considering the role of canopy interception in regulating storm effects in colluvial hollows (zero-order channels)[2]; and,

- supporting functions important in biological hotspots (e.g., tributary confluences, alluvial fans) (Benda et al. 2004).

It may be reasonable to note that discontinuous buffers may provide sufficient protection for headwater systems.

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[2] *There was very little relevant discussion addressing these issues in the reviewed literature.*

THE INFLUENCE OF MANAGEMENT ON DISTURBANCE AND DYNAMIC PROCESSES

We've established that the riparian structures and landforms influence source distance relationships and the inputs provided by exchange functions. Riparian structure and growth conditions are particularly responsive to two classes of ecological processes:

Disturbance –We define disturbance broadly as those processes that physically alter the structure of the riparian community, or otherwise cause premature stand mortality. They include fire, wind, ice-breakage, flooding, erosion, landslides, debris flows, avalanches, insect and disease infestations, animal damage, harvest activities, etc.

Dynamic Processes – These are systems of two or more functional processes and/or disturbance processes that interact in ways that are either self-reinforcing or self-limiting. For example, substantial coarse sediment inputs to streams can increase rates of bank erosion, which can recruit more wood to the streams, which can further increase rates of bank erosion. Similarly, wood acts to store and sort coarse sediment in ways that form complex salmonid habitats.

There is increasing recognition that disturbances and dynamic functional processes act in combination to create and maintain certain attributes of aquatic condition over time (e.g., Benda and Dunne 1997, Benda et al. 1998; others).

The Role of Disturbance Dynamics

Management of riparian buffers (or lack thereof) influences vulnerability to natural disturbance. The location and intensity of management may influence the type and potential distribution of disturbances.

In natural forests unimpacted by management, risks of disturbance are influenced by landforms, climate, and the spatial distribution of forests. Therefore, stand patterns tend to reflect the frequency, magnitude and distribution of disturbance. Management causes a shift in the distribution of these disturbance processes that may increase the risk (vulnerability) in some settings (Figure 4). In so doing, management (or lack thereof) can modify the local disturbance regime in such a way that the normal type and distribution of disturbances is altered.

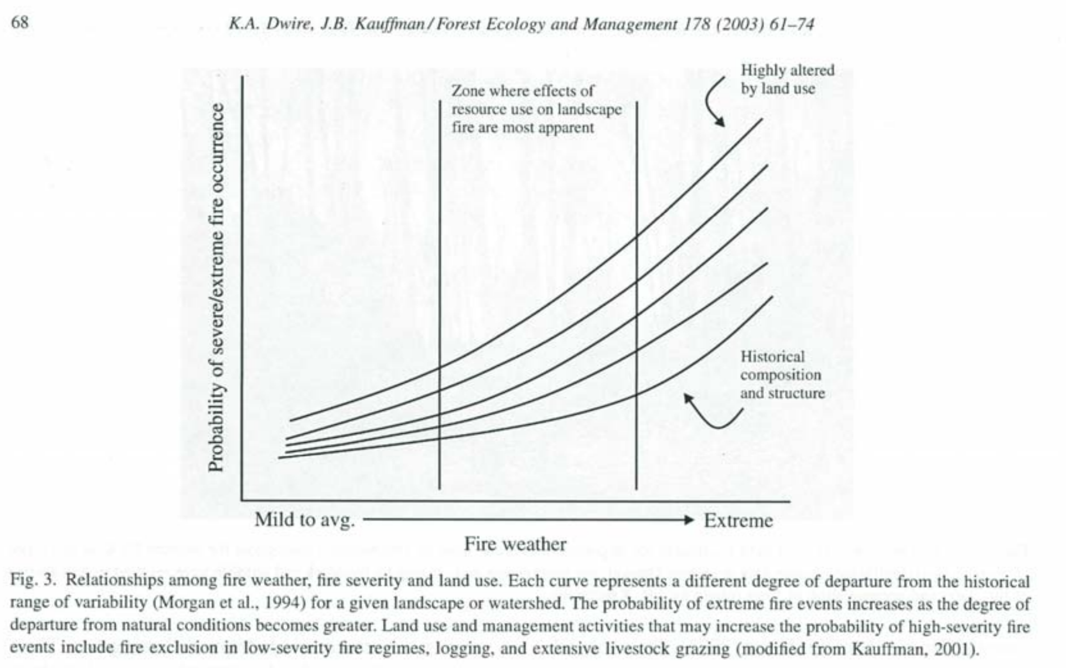

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Fig. 3. Relationships among fire weather, fire severity and land use. Each curve represents a different degree of departure from the historical range of variability (Morgan et al., 1994) for a given landscape or watershed. The probability of extreme fire events increases as the degree of departure from natural conditions becomes greater. Land use and management activities that may increase the probability of high-severity fire events include fire exclusion in low-severity fire regimes, logging, and extensive livestock grazing (modified from Kauffman, 2001).

Figure 4) Conceptual depiction of fire risk response to landscape-scale management regimes (*from Dwire and Kauffman 2003*).

Strategies that "protect" sites from disturbance may alter the type, frequency and magnitude of disturbance, and can create conditions over time that lead to markedly different riparian structures and thus different rates of delivery for various functions (Dwire and Kauffman 2003; Liquori 2006; Martin and Grotefendt 2007). This is one of the reasons that thinking has shifted from "protecting streams" to maintaining functional processes. For example:

- Fire suppression in uplands combined with increased fuel loading in riparian areas may increase the occurrence of crown fires in riparian zones, causing preferentially more disturbance in riparian areas. This pattern has been observed in several recent California fires (e.g., Angora, Trabing, Antelope fires).

- Risks of windthrow are increased when edges are exposed along riparian zone margins, where trees have not previously been exposed to wind stresses (Liquori 2006; Lisle and Napolitano 1998; Martin and Grotefendt 2007).

- The magnitude and frequency of streamside landslides have been altered by legacy forest management practices in ways that alter the expected future frequency of streamside disturbance (Benda and Dunne 1997).

Size distributions of trees in unmanaged coniferous forests are strongly related to disturbance history and the timing and frequency of disturbance (Oliver and Larson 1990). Typical patterns of size distribution can be identified, although many stands will deviate from idealized patterns. In centuries-old, late successional forests, tree inventory information often indicates that multiple disturbance events are responsible for the stand's development (Franklin et al. 2002). Low to intermediate disturbances such as partial fires can remove understory and overstory trees, altering horizontal and spatial pattern of canopy foliage, and may be a key long-term structural component supporting aquatic communities (Agee 1993; Bisson et al. 2003).

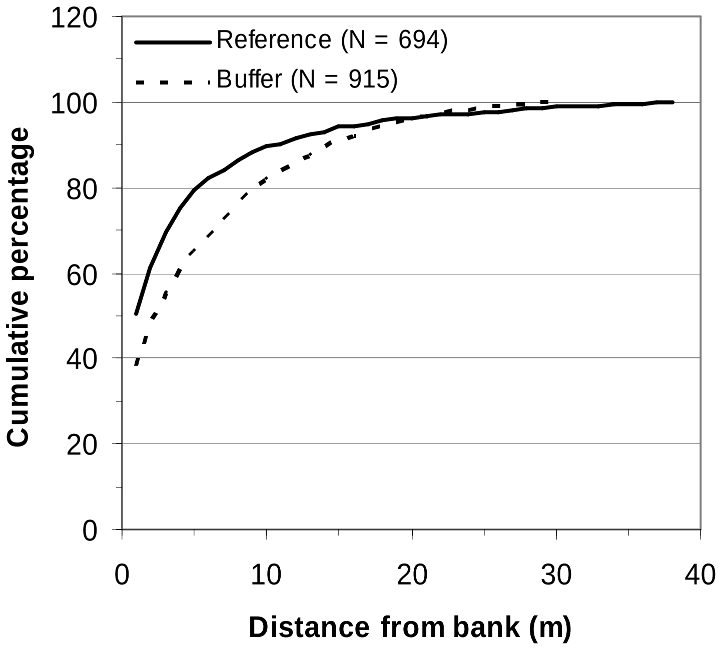

Figure 5) Cumulative distribution of source distances for downed trees in buffered and reference streams. The shift in source distance can be attributed to changes in disturbance dynamics in buffers relative to reference sites (in this case, wind). (*from Martin and Grotefendt 2007*).

One of the growing observations is that not only do disturbances affect riparian zones, but that riparian management can influence the characteristics of disturbances that occur in the landscape (Figure 5). For example, the retention of buffers in wind disturbance landscapes causes an increase in mortality within the buffer (both frequency and magnitude) that exceeds natural background (Martin and Grotefendt 2007; Liquori 2006). We can generally classify two end-members along a continuum of disturbance process dynamics:

Primarily Natural Disturbance Processes: Certain disturbance processes occur without regard to forest condition. Factors such as landsliding, bank erosion, flooding, wind and channel migration can occur primarily in response to natural processes, although in some cases they may be somewhat influenced by management. The geographic domain in which these processes are dominant can be predicted with a reasonable degree of accuracy (Montgomery 1999). For example, it is possible to identify areas prone to landsliding based on various factors (soil type, topography, geomorphic expression, hydrologic regime, etc.). Similar mapping capabilities exist for channel migration, flood prone areas, thermal loading, and wind prone areas.

Primarily Management-Influenced Disturbance Processes: Other processes can be strongly influenced by management activities, even if they are initiated by natural events. For example, fire risk is widely accepted to be a function of fuel loading, structure, and spatial arrangement of the forest (Agee 1993). Similar conditions can exist with infestation and to some extent wind. Thus vulnerability to such disturbance processes can be influenced by forest management (i.e., timing, location, and configuration of harvest units), and the relative vulnerability is also predictable over time and space, given the distribution of stand and landscape characteristics.

Disturbance processes often operate at time scales of decades, and can thus be affected not only by current management practices, but also by legacy practices.

MANAGING FOR ECOSYSTEM PROCESSES

There are a growing number of opinions expressed in the literature that suggest that managing for ecosystem processes may be the key to effective riparian management (Young 2001; Bisson et al. 2003; Nakamura and Swanson 2003; Reiman et al. 2003; others). These papers tend to argue for management strategies that are developed at watershed or landscape scales, yet specific guidance tends to be limited about how to relate such strategies back to the site scale, where management decisions are ultimately implemented.

We discovered during our literature review that while the science has advanced in many areas, our improved knowledge has potentially added complexity to management. However, landscape-level complexity and spatial variation should be one of the strategies of riparian management.

Policy should define goals and objectives for riparian strategy. However, it can be difficult for policies to explicitly define the specific tools and methods for implementing strategies, especially when the details of implementation can be so complex. Some fundamental policy alternatives are:

1. Apply the Riparian Reserve concept (at the risk of reduced economic efficiency), or

2. Define a relatively large array of prescriptions that are targeted to specific landscape conditions (at the risk of having some conditions that may be difficult to classify), or

3. Simplify the prescriptions (at the risk simplifying riparian conditions, and reducing landscape complexity in a manner that may not meet important functions), or

4. Codify the science into regulatory prescriptions (at the risk of creating a logistical nightmare), or

5. Develop a series of objective, collaborative, science-based, decision support tools that can be expressed to managers in the form of user-friendly maps, models, equations, monographs, etc. (at the risk of asking scientists to accept some responsibility for developing management tools).

Our synthesis of the reviewed literature leads us to the conclusion that the importance of maintaining ecosystem functions, including those associated with disturbance, dynamics, growth, and spatial variability, point to the need for an evolutionary step in the design and application of riparian management strategies. A more holistic strategy would integrate landscape-scale concepts into local decision criteria. A wide array of analytical tools for evaluating watershed-scale processes and conditions are available, and the reviewed literature suggests that there is considerable scientific data to inform such tools.

We suggest that it is possible, given the advances in our understanding of riparian functions, to develop objective, science-based, decision support tools. Such tools can provide sufficient spatial context for local management that targets the right riparian functions to the right landscape condition. Such tools could be informed by a framework that:

a) Establishes objective science-based criteria for determining specific, site-based input objectives that are consistent with the specific landscape context, and

b) Understands that there are landscape-scale controls that can broadly define disturbance regimes and dynamic processes regimes that contribute to (or retard) riparian structure, growth, and functional response, and

c) Recognizes patterns in the growth trajectory of stands and how management might affect the processes responsible for stem distributions (diameter, height, species and density) and mortality processes that naturally regulate exchange functions, and

d) Addresses risks at larger spatial and temporal scales, and

e) Is informed by a collaborative, applied scientific support infrastructure, including the capacity for research, monitoring, and adaptive management.

We believe that these components would form a nexus that integrates all five exchange functions in virtually every relevant landscape in California in a way that is spatially diverse and ecologically sound.

Over time, this approach would result in a greater understanding of the effects of forest management on aquatic ecosystems, including salmonids and other sensitive species. It would reduce the risk of further salmonid habitat declines, and should promote opportunities for recovery. It would provide an infrastructure for translating science into applied management tools that could dramatically simplify the permit application process. It could help support jobs in many of the rural economies of California, and it could spread the effort for species protection among agencies, private companies, consultants and academics.

KEY LITERATURE GAPS

- **Longitudinal Source Distance Relationships** – Very limited information is available on the relative source distances appropriate in the various regions in California. Empirical studies that help to develop these relationships will help calibrate local source-distance curves, and can support management.

- **Dynamic Processes in Fish-Bearing Channels** – There are known trade-offs that exist in the various inputs from riparian management. For example, concerns over long-term wood loading is often preferred over nutrient support, although there is growing evidence that nutrient support could provide more short-term benefits for salmonids. Developing better strategies for assigning these relative values and trade-offs in a way that reduces risks would greatly improve riparian management practices.

- **Dynamic Processes in Headwater Channels** – Dynamic processes in headwater streams are not well understood. For example, trade-offs between heat and nutrients, dynamics between water availability and habitat response, etc. Understanding these processes would support a stronger scientific basis for headwater riparian management.

- **Biological Response to Buffers** – Very little information is available about the biological response to riparian management. Much of the discussion of source-distance relationships is predicated on the assumption that in the inputs are provided, fish will benefit. More empirical support for this assumption would help improve management practices, and validate the state of the science. In headwater streams, the biological dependence on these riparian exchange functions to support local communities (e.g., amphibians, macroinvertebrates, etc.) has not been well established.

GLOSSARY

Autotrophic	Literally, self-feeding. Refers to organisms that obtain energy from sunlight or inorganic compounds or elements, such as nitrate, sulfide or reduced iron
Dynamic	Processes that change in response to other process or inputs
Heterotrophic	Literally, other-feeding. Refers to organisms that obtain energy from reduced carbon (dead or living plant or animal tissue)
Source distance	The lateral distance from the stream bank that supplies functional inputs. Source-distance curves typically compare the horizontal distance to the cumulative inputs provided to the stream between the bank and the reported distance.
Site-Potential Tree Height	A statistically-derived height that dominant trees can expect to achieve for a given site condition

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2. PRIMERS

Primer
on
Biotic & Nutrient Riparian Exchanges Related to Forest Management in the Western U.S.

Prepared by the
Technical Advisory Committee
of the
California Board of Forestry and Fire Protection

May 2007

Version 1.0

Technical Advisory Committee Members

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PRIMER: BIOTIC AND NUTRIENT RIPARIAN EXCHANGE FUNCTION

The riparian vegetation area (zone) along forested streams serves critical biotic and nutrient transfer and exchange functions that directly and indirectly control the survival and growth of juvenile salmonids (e.g. Wilzbach et al. 2005, Jones et al. 2006). Therefore, the timing, magnitude, and qualitative aspects of these biotic and nutrient riparian influences are not only among the very best predictors of overall stream ecosystem health and the condition of the component salmonid populations (e.g. Naiman and Dechamps 1997, Gregory et al. 1991, Meyer et al. 2003, Moore and Richardson 2003), but they also constitute significant potential for management procedures to sustain and/or enhance these salmonid populations (e.g. Bilby and Bisson 1992).

The riparian biotic and nutrient transfers and exchanges are directly or indirectly important to the growth and survival of juvenile salmonids. These can be categorized into: 1) light and nutrients (including dissolved organics), and 2) inputs of particulate organic matter and terrestrial invertebrates (see Figure 1). The general characteristics of the biotic and nutrient exchanges and transfers differ in a predictable way along a west to east gradient. For example, temperature is moderated by coastal climate and has less seasonal effect on in-stream metabolic rates of the resident organisms than in eastern drainages where both daily and seasonal temperature excursions are significantly greater.

Shading by Riparian Vegetation Cover Over, and Transfer of Nutrients into, Streams

Light and nutrients regulate in-stream plant growth, primarily algae. The periphyton assemblage on surfaces in running water constitute the food resource for a group of aquatic invertebrates termed scrapers, after their behavior of scraping loose their attached algal food resource. Light has been shown to be limiting for algal growth in some shaded forest streams even under conditions of very low nutrient concentrations (Gregory 1980, 1983). Limitation of algal growth whether by nitrogen or phosphorous is primarily a function of the parent geology in a watershed (Allan 1995). If light and/or nitrogen and/or phosphorous nutrients become available in significant excess over natural conditions, the algal community can move through a succession from a single cell and small colony community, largely of diatoms and green algae, to a filamentous colony dominated by blue-green (cyanobacteria) and green algae (Stockner and Shortreed 1978, Shortreed and Stockner 1983). The former provides a suitable food resource for scraper invertebrates, the latter does not (e.g. Dudley et al. 1986). Therefore, management actions that shift the periphyton to domination by filamentous forms has a severe negative impact on scrapers, some of which are important prey of juvenile salmonids. Increase of nutrients and light, especially if combined with the deposition of fine sediments, can favor the development of rooted vascular aquatic plants (Clarke 2002). These vascular hydrophytes, including aquatic mosses, if they are present, function primarily as habitat for many invertebrates (e.g. Fisher and Carpenter 1976). That is, they are sites for attachment and concealment, and serve as a food resource for only a very few, and these invertebrates are not commonly consumed by juvenile salmonids (Merritt and Cummins 1996). However, many of the invertebrate taxa that utilize vascular hydrophytes as a habitat are consumed by fish (Svendsen et al. 2004). When filamentous algae and vascular hydrophytes die, they enter the detrital cycle and are consumed by gathering collector invertebrates, many of which are important food organism for juvenile salmonids (Svendsen et al. 2004). A simple and effective bioassay for nitrate and/or phosphate nutrient limitation of algal growth in streams has been developed and well tested (Fairchild and Lowe 1984). Diffusing substrates are used which can be evaluated visually (or by chlorophyll analysis) to determine if a given riparian condition is fostering light and/or nutrient limitation, and, if the latter, which nutrient is most limiting.

Along with nitrogen and phosphorous, dissolved organic matter (DOM) can stimulate the growth of microorganisms that are responsible for the direct decomposition of particulate organic matter (POM) (Ward and Aumen 1986). These microbes also serve as the most important component of the coarse particulate organic matter (CPOM) food source of shredder macroinvertebrates and some of these are prey for juvenile salmonids (Cummins et al. 1989, Svendsen et al. 2004).

Transfer of Riparian Litter and Terrestrial Invertebrates into Streams

Litter derived from riparian vegetation is the dominant base of food chains in forested streams of orders 0 through 3. (Cummins et al.198, Cummins 2002). Up to 90% of the energy flow in such streams is attributable to this litter (Fisher and Likens 1973, Richardson et al. 2006). The processing times (normalized for temperature by expressing it as degree-days) of coarse litter, primarily leaves and needles, is known for a wide range of riparian plant species (Petersen and Cummins 1974, Webster and Benfield 1986, Cummins et al. 1989, Richardson et al. 2004). Riparian litter can be classified according to its processing rate, that is, the turnover time required to convert the material to some other form once it is in the stream. Most hard woods (e.g. alders, vine and big-leaf maples and some shrubs such as salmon berry and elder berry) have short processing times and are referred to as fast (turnover) litter (Petersen and Cummins 1974). By contrast, most conifers (e.g. redwood, Douglas fir) and broad-leaf evergreens (e.g. rhododendron and laurel), oak hardwoods, and willows have long processing times and are termed slow (turnover) litter (Petersen and Cummins 1974). Processing is defined as the sum of leaching of DOM, decomposition by microbes, feeding by shredder invertebrates, and mechanical fragmentation (Cummins et al. 1989). The majority of leaching of soluble organics from wetted litter is rapid with the litter losing 20-40% of it’s dry mass in 24 to 72 hours (Petersen and Cummins 1974). This portion of litter processing is non-biological and and fairly independent of temperatures from 5 to 20 ºC (Petersen and Cummins 1974, Dahm 1981). After the initial loss rapid loss of weight due to leaching, small amounts of DOM continue to leach slowly from litter and large woody debris (LWD; Cummins et al. 1983). The riparian terrestrial soil and litter also continuously leach small to moderate amounts of DOM into streams (Allan 1995).

In order for riparian litter to be processed by microbes and shredders it must be retained in place in a given reach for a sufficient period for microbial conditioning and shredder feeding to take place. Small woodland streams have been shown to be quite retentive, providing that sufficient wood debris and other obstructions are present. Once it is wetted, the major portion of the riparian litter introduced into a small stream is retained within the range of 100 meters (Cummins et al. 1989). The percent cover by species of riparian vegetation has been shown to be a good predictor of the percent composition of the litter entrained in a reach of stream. Linked to this, the hatching and major feeding by resident shredder invertebrates is keyed to the timing of the drop and entrainment of the different riparian species (Grubbs and Cummins 1986; Cummins et al. 1989, Richardson 2001)

The end result of litter processing is microbial and invertebrate biomass and fine particulate organic matter (FPOM, <1mm>0.5 µm particle size) (Cuffney et al. 1990). FPOM transported in suspension is the major food of filtering collector invertebrates and, when it settles out on or into the sediments it is the food of gathering collector invertebrates (Merritt and Cummins 1996). These two invertebrate groups contain the most important prey items for juvenile salmonids (Wilzbach et al. 2006).

The aquatic invertebrates that depend upon periphyton, plant litter, and FPOM as their food resources, and constitute important prey for juvenile salmonids in forested streams are tightly coupled to the riparian area, because of the restriction of algal populations by shading and organic matter transfers. The aquatic insects among these can be characterized as having deterministic life cycles that are adapted to stochastic environmental conditions such as flow and temperature regimes and the timing of riparian litter inputs. The general pattern is one in which the most vulnerable life stages are matched to the seasonal periods during which environmental conditions have the highest probability of being favorable (e.g. Fisher et al. 1982). Stream flows suitable to allow eggs and newly hatched nymphs and larvae to maintain their location and the availability of food for feeding nymphs and larva are seasonally timed (Grubbs and Cummins 1996, Richardson 2001). For example, invertebrate shredders lay their eggs in late summer and early fall when stream are at base flow. This timing leads to hatching of larvae and nymphs at the time of abscission of deciduous riparian hardwoods that are in the fast processing category and the food supply of the autumn-winter shredders (Grubbs and Cummins 1996, Cummins et al. 1989). Spring –summer shredder populations rely on litter with longer processing times, such as conifer needles, as their food resource (Cummins, et al.1989, Robinson et al. 2000).

Terrestrial invertebrates also constitute transfers from the riparian area into the stream ecosystem. Included are canopy insects and their frass, annelids, spiders, and ants from the soil and terrestrial litter mat (Nakano and Murakami 2001, Allan et al. 2003). Among the terrestrial invertebrate inputs from the riparian area are the adult (and in some cases pupal) stages of aquatic insects. All of these transfers of terrestrial invertebrates to the stream can serve as important food sources for juvenile salmonids, at least seasonally. Aquatic invertebrates are more abundant in the winter and terrestrial forms are more abundant in the summer in juvenile salmonid diets. (Shigeru and Murakami 2001, Allan et al. 2003).

The activities of the microbes and invertebrate shredders on leaf litter, the resulting FPOM that is generated, and the ensuing effect on invertebrate collectors in the smallest streams is transmitted down stream (e.g. Vannote et al. 1980, Webster et al. 1999, Cummins and Wilzbach 2005, Meyer et al. 2007). Woody debris is also a source of FPOM, although it is released more slowly (Ward and Aumen 1986). These cumulative effects from small headwater streams to larger tributaries constitute an important delivery system to juvenile salmonid populations down stream (e.g. Wipfli and Gregovich 2002, Wipfli and Musselwhite 2004) and constitute a basis for their protection (Cummins and Wilzbach 2005).

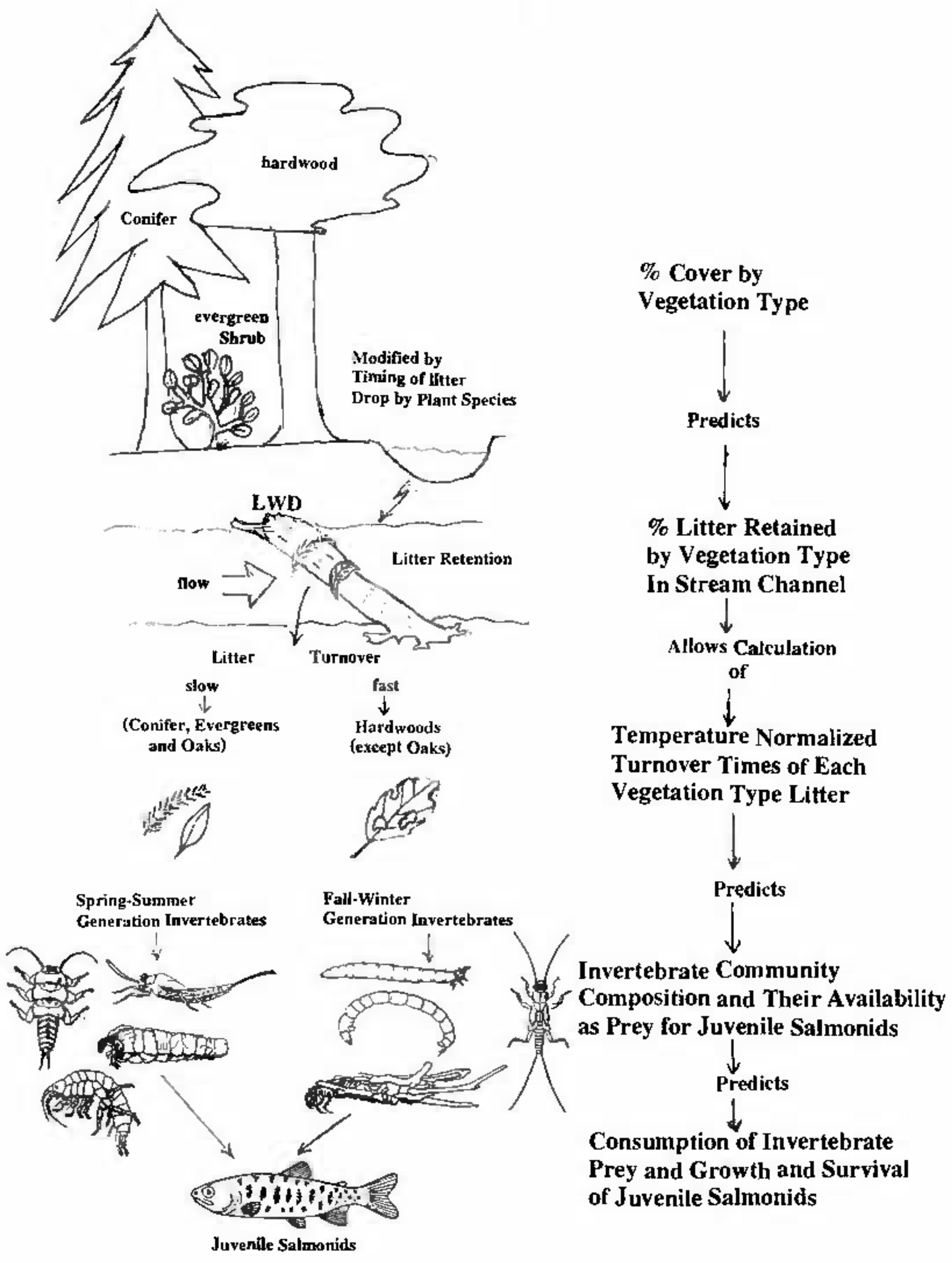

Figure 1: Riparian biotic and nutrient transfers and exchanges process relative to growth and survival of juvenile salmonids

KC 1/23/07

Primer
on
Wood
Riparian Exchanges Related to Forest Management in the Western U.S.

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May 2007

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PRIMER: WOOD RIPARIAN EXCHANGE FUNCTION

(Abstracted from Hassan, Hogan, Bird, May, Gomi, and Campbell, Spatial and temporal dynamics of wood in headwater streams of the Pacific Northwest, Jour of the Amer Water Res Assn., Aug 2005.)

In general, wood within the channel boundary significantly alters flow hydraulics, regulates sediment transport and storage, and influences channel morphology and diversity of channel habitat (e.g., Swanson and Lienkaemper, 1978; Hogan, 1986; Bisson *et al.,* 1987; Montgomery *et al.,* 1995, 1996).

In-channel wood plays an important role in determining aquatic habitat conditions and riparian ecology (e.g., Bisson *et al.,* 1987; Bilby and Bisson, 1998).

Wood is introduced to the stream channel through a variety of processes including mass wasting, tree fall (blowdown), and bank erosion.

Fluvial and nonfluvial processes transport and redistribute wood introduced in upstream areas to downstream locations (e.g., Keller and Swanson, 1979; Lienkaemper and Swanson, 1987; Nakamura and Swanson, 1993; Hogan *et al.,* 1998; Johnson *et al.,* 2000a; Benda *et al.,* 2002, 2003; Lancaster *et al.,* 2003).

However, wood exerts its greatest geomorphic influence in channels with physical dimensions similar to or smaller than the size of wood (e.g., Bilby and Ward, 1989; Bilby and Bisson, 1998);
therefore, wood plays a disproportionately large role in small headwater streams.

Although wood dynamics and channel morphology of streams in the PNW have been studied in some detail, most of the research has occurred in relatively large streams and rivers (> third-order streams on 1:50,000-scale maps). Such results may not be applicable in headwater streams where episodic sediment and wood supply from adjacent hillslopes dominate channel dynamics and where fluvial transport of wood is restricted due to insufficient streamflow and narrow channels. The practical need to understand the physical and ecological roles of small streams has recently been highlighted by interest in restoring downstream ecosystems and the assessment of land management practices in relatively small watersheds (Moore and Richardson, 2003).

Interest in wood dynamics in headwater channels stems from the recognition that these channels represent a distinct class of stream, with characteristic morphologies, processes, and dynamics (see Benda *et al.,* 2005; Hassan *et al.,* 2005).

The focus is on the steeper portion of the channel network where episodic wood inputs and sediment from adjacent hillslopes exert significant control on channel dynamics and morphology. In these channels wood tends to accumulate, and sediment is stored upstream of accumulations, transforming steep bedrock channels into alluvial reaches

(Massong and Montgomery, 2000; May and Gresswell, 2003b; Montgomery *et al.,*2003b).

In these streams, wood controls channel morphology by regulating the temporal, spatial character and the quantity of sediment stored within the channel zone, and this influences channel stability (e.g., Swanson *et al.,* 1982; Bilby and Ward, 1989).

The paper begins by defining small streams and addressing wood scaling issues relative to channel size. Then the paper reviews the current knowledge regarding each component of the wood budget in small streams. Next the paper discusses the spatial and temporal variability of wood in small streams, with special attention to geographic variability. Then an assessment of available models for the predicting wood dynamics in small streams is provided. The effect on wood dynamics of timber harvesting and riparian management on wood dynamics is considered. Finally, gaps in the knowledge are identified for future research on the wood dynamics in small streams. Due to the limited available information on small forested streams, certain information obtained from larger mountain rivers will be included in this review, and its applicability to small streams is assessed.

Table 1 – Definition of relative wood size and relative channel size. Matrix thresholds are arbitrary until further analysis justifies these classes. This scaling of wood to channel size allows use of studies in larger channels.

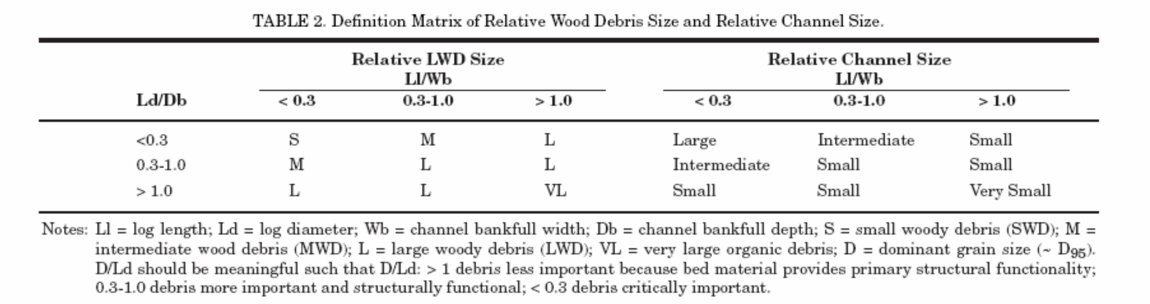

TABLE 2. Definition Matrix of Relative Wood Debris Size and Relative Channel Size.

	Relative LWD Size Ll/Wb			Relative Channel Size Ll/Wb		
Ld/Db	**< 0.3**	**0.3-1.0**	**> 1.0**	**< 0.3**	**0.3-1.0**	**> 1.0**
<0.3	S	M	L	Large	Intermediate	Small
0.3-1.0	M	L	L	Intermediate	Small	Small
> 1.0	L	L	VL	Small	Small	Very Small

Notes: Ll = log length; Ld = log diameter; Wb = channel bankfull width; Db = channel bankfull depth; S = small woody debris (SWD); M = intermediate wood debris (MWD); L = large woody debris (LWD); VL = very large organic debris; D = dominant grain size (~ D_{95}). D/Ld should be meaningful such that D/Ld: > 1 debris less important because bed material provides primary structural functionality; 0.3-1.0 debris more important and structurally functional; < 0.3 debris critically important.

Value of, need for, a wood budget to determine where wood comes from, where it is delivered to, where it is stored, how it is transported or depleted from a given drainage basin or stream reach.

From a forest management context there is potential to affect each component of the budget, so it is important to know the relative importance of each component and which are most susceptible to impact.

Wood Recruitment

The potential of landslides in mountainous landscapes can be increased by logging, road building, wind throw wildfire, earthquakes, and volcanic activity (Harmon *et al.,* 1986; Lienkaemper and Swanson, 1987; Nakamura and Swanson, 2003).

Research in the PNW has shown that landslides can provide a substantial quantity of wood to headwater streams (Keller and Swanson, 1979; Schwab, 1998; Hogan *et al.,* 1998; May, 2002; May and Gresswell, 2003a; Reeves *et al.,* 2003).

In contrast, other studies in Alaska, California, and Washington have found that mass movements may be of limited importance in supplying wood to larger streams (Murphy and Koski, 1989; Johnson *et al.,* 2000a; Martin and Benda, 2001; Benda *et al.,* 2002; Gomi *et al.,* 2004; May and Gresswell, 2004).

Another wood source into small streams is snow avalanches, a process that commonly destroys forest stands in the runout pathway. Repeated avalanches down established pathways prevent the growth of mature forests, so this process may be associated with the recruitment of relatively small wood. Where snow avalanches are an important landscape process, they provide the greatest wood recruitment in areas where the channel and hillslopes are coupled (Dave McClung, The University of British Columbia, January 6, 2005, personal communication) (see Figure 1 below)

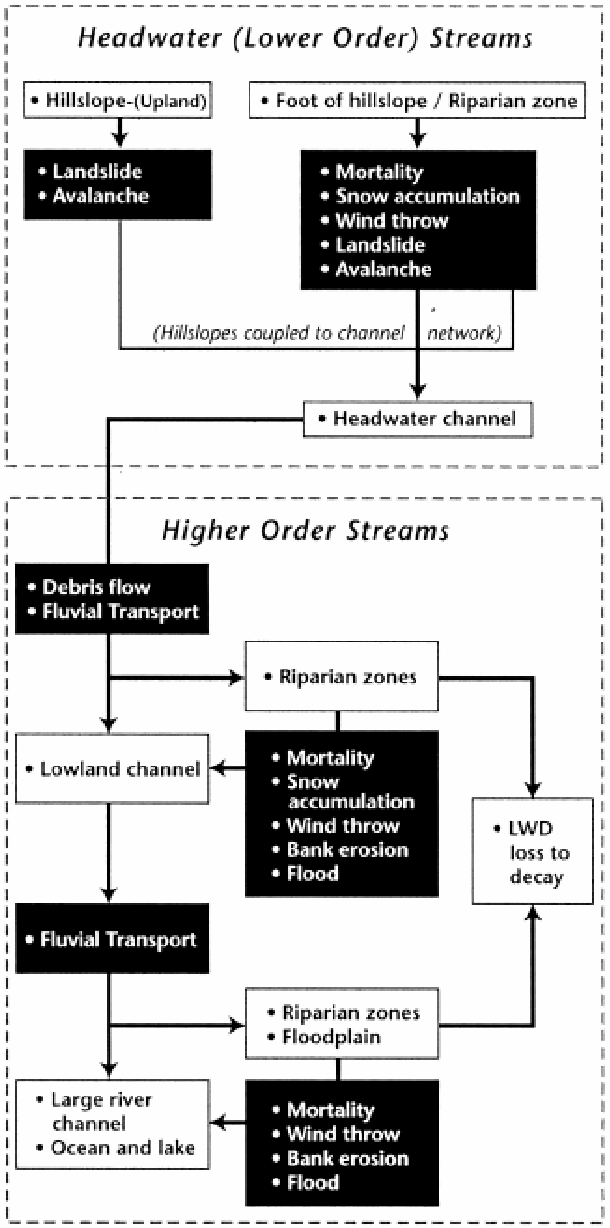

Figure 1. Flow Diagram for a Wood Budget in a Watershed. Open squares represent geomorphic areas related to locations for the sources and storages of wood, and filled squares represent processes that affect wood transport.

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Fires, insect infestations, and disease outbreaks are other processes that influence the recruitment of wood to streams.

If high severity fires burn extensive areas around headwater streams, the amounts and characteristics of wood input to streams may be altered for long periods; wood inputs are likely to increase immediately after fires (Nakamura and Swanson, 2003). Burned wood may also break into smaller pieces that can choke the channel, thereby increasing channel instability and downstream fluvial transport of wood (e.g., Berg *et al.,* 2002). The degree of fire damage to stands depends on fire severity, type (ground, surface, or crown), and spatial extent (Agee, 1993). Patterns of mortality due to forest fire vary among regional fire regimes, season, and topography.

Compared to floodplains, upland areas, including small streams and riparian zones, are more frequently affected by forest fires because of their relatively dry conditions and strong winds (Agee, 1993). Fire can also affect the wood budget by altering the age structure of the forest, initiating episodic pulses of wood recruitment, consuming existing dead wood, and influencing the mobility of instream wood (Young, 1994; Tinker and Knight, 2000; Zelt and Wohl, 2004).

Finally, insect infestations and disease outbreaks can episodically affect stand mortality in large areas. In the PNW, many disease and insect outbreaks appear to be related to fire suppression or exotic pathogens (Hessburg *et al.,* 1994; Swetnam *et al.,* 1995; Dwire and Kauffman, 2003). However, most insects and diseases affect only a single tree species, so the net effect on wood recruitment will depend upon the composition of the stand (Harmon *et al.,* 1986).

Streambank erosion may not significantly contribute wood to steep headwater streams because the channel is constrained by the adjacent hillslopes (Nakamura and Swanson, 2003) and banks are often semi- or non-alluvial (e.g., Halwas and Church, 2002). Actual rates of bank erosion in headwater constrained streams are poorly documented but are believed to be minimal. However, in gentler areas with less bedrock constraints, bank erosion is likely (expected) to be a significant source of wood into channels. In headwater streams, wood is often suspended above the channel banks due to relatively narrow channel widths (relative to tree heights and diameters) and hillslope confinement. Direct input to the channel may not occur until a log is either broken or fragmented (Nakamura and Swanson, 1993).

Wood storage

Once delivered to the stream system, wood is stored for various durations in several different nvironments; these include areas in riparian zones and associated floodplains and within the channel boundaries (Figure 1, Table 3).

few studies have referenced the criterion used to determine that portion of the wood actually interacting with the stream and fluvial processes. Robison and Beschta (1990a) examined the storage of wood in distinct zones within the stream system and developed a classification system in which they identified and distinguished between wood within the channel and wood on the banks.

Storage of wood within a system can be likened to a wood reservoir that has a characteristic residence time (Keller and Tally, 1979; Hogan, 1989). Wood reservoirs can be used to study wood dynamics over a range of temporal and spatial scales. In headwater streams, the temporal scale is likely to be a function of the frequency and magnitude of the wood mobilizing events (see the following section).

Wood output

Wood stored in the fluvial system is transferred out of a reach by downstream transport or lost through abrasion or *in-situ* decomposition.

Log stability in channels is controlled by many factors, including piece dimensions (length and diameter) relative to the channel, wood integrity, attached root wads, and degree of anchoring in the channel bed and bank (e.g., Montgomery *et al.,* 2003a,b).

Braudrick *et al.* (1997) suggested three mechanisms of wood transport: floating in a congested manner (high concentration) by streamflow, floating in an uncongested manner, and debris flows (for more details see the section on modeling).

Field studies show that log movement is more likely to occur as channel size increases and when logs are shorter than bankfull width, implying that fluvial transport of wood is more significant in higher order streams (e.g., Bilby and Bisson, 1998).

Wood temporal and spatial variability

Tthreshold occurs that corresponds to channels approximately 5 m wide, which is similar to the pattern observed by Jackson and Sturm (2002).

(Excerpted from Lassettre and Harris, 2002, The Geomorphic and Ecological Influence of Large Woody Debris in Streams and Rivers)

Timber harvest activities in streamside forests can directly affect wood input (Table 2, Swanson and Lienkaemper 1978, Bilby and Bisson 1998).

Table 2. The effect of certain management practices on the characteristics and abundance of LWD within stream systems. Timber harvest temporarily reduces input or changes the physical characteristics of subsequent inputs. Flood control and road maintenance activities generally result in the removal of in-channel wood.

MANAGEMENT PRACTICE	EFFECT	REFERENCES
Timber harvest	• Temporary reduction in LWD input	Bryant 1980, Andrus 1988, Murphy and Koski 1989
	• Second growth input smaller, less rot resistant with less profound effects on physical habitat	Bilby and Ward 1991, Wood-Smith and Buffington 1996, Ralph et al. 1994
	• Removal of logging residue simplifies physical habitat by failing to distinguish between naturally occurring habitat-forming logs and leftover material	Swanson et al. 1976, Swanson and Lienkaemper 1978, Beschta 1979, Bryant 1980, Keller and MacDonald 1983, Bilby 1984, Bisson et al. 1987, Bilby and Ward 1989
	• Extremely large amounts of logging material reduces intragravel flow, increases biological oxygen demand, reduces space available for invertebrates, and blocks fish migration	Hall and Lantz 1968, Narver 1970, Brown 1974
	• Destabilization of hillslopes and increase in debris avalanches	Swanson and Lienkaemper 1978
	• Narrow buffer strips (<20 m to 30 m) potentially reduce wood input	McDade et al. 1990, Van Sickle and Gregory 1990
	• Buffer strips adjacent to clearcuts have higher occurrence of windthrow and are depleted of large wood sources rapidly	Reid and Hilton 1998
Flood control and road maintenance	• Remove wood to decrease channel roughness, increase conveyance, and maintain flood capacity	Marzolf 1978, Young 1991, Gippel et al. 1996
	• Remove wood and clear jams to keep culverts and bridges free of debris and reduce structural damage during storms	Singer and Swanson 1983, Diehl 1997

The harvesting of streamside forests may temporarily reduce or eliminate LWD recruitment to the stream (Bryant 1980).

The recovery time for input to return to pre-harvest conditions may be quite long. Fifty years after logging, debris from the current stand of a western Oregon stream contributed only 14% of total LWD volume and only 7% of the wood from the current stand contributed to pool formation (Andrus et al. 1988).

The results indicate that some second growth stands must grow at least 50 years before trees contribute LWD in sizes and amounts similar to old growth forests. A decay model calibrated in southeastern Alaska predicted a 70% reduction in wood 90 years after clear-cutting, and that full recovery exceeded 250 years (Murphy and Koski 1989).

Streams flowing through second growth forests have a lower frequency of LWD associated pools and fewer channel spanning logs than old growth streams, leading to a scour pool dominated system (Bilby and Ward 1991). Thus, in low to mid-order streams the percentage of LWD formed waterfalls and the control of wood on gradient is decreased by timber harvest.

Old growth logs are larger and retain more bedload sediment and fine organic debris.

Fine organic debris influences the physical characteristics of large jams and may contribute to an increased diversity of pool types in old growth streams (Bilby and Ward 1991).
Changes in wood loading and abundance significantly alter stream morphology. Wood-Smith and Buffington (1993) showed that pool frequency, pool depth, and local shear stress were significantly different in logged versus unlogged streams.

Near-stream logging influences natural LWD input processes. Depending on the method, harvest activities destabilize hillslopes and increase the likelihood of debris avalanches (Swanson and Lienkaemper 1978).

Buffer strips are a common technique to reduce logging effects on forests and streams. Most LWD inputs come from within 20 m to 30 m of the stream channel and buffers more narrow than this zone of input potentially reduce the amount of available logs (McDade et al. 1990, Van Sickle and Gregory 1990).

Buffer strips adjacent to clearcuts are exposed to higher wind velocities, increasing the occurrence of windthrown logs to the stream channel (Reid and Hilton 1998).

In moderate to high gradient streams, logs play an important role in bedload storage (Figure 2), and the removal of LWD eliminates potential storage sites (Beschta 1979, Bilby 1984, Bilby and Ward 1989).

The decrease in storage capacity and subsequent release of sediment simplifies physical habitat by filling in the deepest pools, reducing pool area, and smoothing channel gradient (Sullivan et al. 1987, Dominguez and Cederholm 2000).

Debris removal affects salmonid populations by decreasing the amount of available hydraulic cover available during winter high flows, and by reducing stream wetted width and perimeter (Dolloff 1986, Elliott 1986).

Alternatively, an excessive amount of logging material left in the stream may be damaging to fish populations. Fine debris lying on the gravel surface impedes interchange between intragravel flow and surface water, reducing subsurface dissolved oxygen levels (Hall and Lantz 1969, Narver 1970, Brown 1974).

Reduced oxygen availability retards the development of salmonid embryos within the gravel. The decomposition of wood increases biological oxygen demand, further reducing available dissolved oxygen (Narver 1970).

Small pieces of wood and bark occupy interstitial pores, reducing the available living space for stream invertebrates (Narver 1970).

Very large human induced accumulations of wood prevent upstream migration of anadromous salmonids (Brown 1974). Much historical management of LWD in logged streams concentrated on the removal of excess debris to allow fish passage (Bilby and Bisson 1998).

In systems influenced by human infrastructure, road maintenance and flood control activities affect the abundance of large wood. Logs and riparian vegetation increase channel roughness, reduce conveyance, and are commonly removed by managers to maintain flood capacity (Marzolf 1978, Singer and Swanson 1983, Young 1991, Gippel et al. 1996).

Possibly the first step in improving the management of LWD in California stream systems is to recognize the different roles it plays in different parts of the watershed. The stream classification proposed below explicitly does that.

Table 3. The gradient range and general characteristics of reach morphologies in alluvial channels (Data taken from Bisson and Montgomery 1996 and Montgomery and Buffington 1997).

	CASCADE	STEP-POOL	PLANE-BED	POOL RIFFLE
GRADIENT	• 0.08 to 0.30	• 0.04 to 0.08	• 0.01 to 0.04	• 0.001 to 0.02
BED MATERIAL	• Boulder	• Cobble/boulder	• Gravel/cobble	• Gravel
CONFINEMENT	• Confined	• Confined	• Variable	• Unconfined

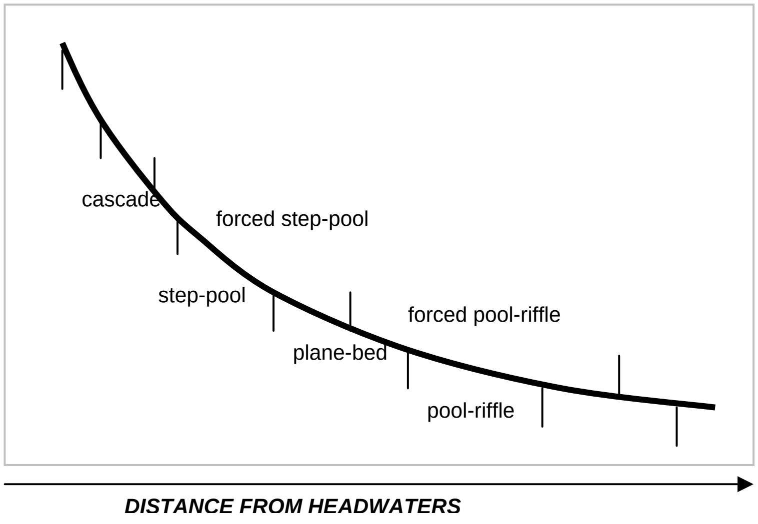

Figure 2. Generalized long profile of alluvial channels showing spatial arrangement of reach morphologies, including forced step-pool and forced pool-riffle morphologies. Forced morphologies extend beyond the gradient range of free-formed counterparts. Gradient ranges of forced morphologies

depicted above are interpreted from Montgomery et al. (1995) and Beechie and Sibley (1997). The classifications are based on geomorphic processes and reflect basin wide trends in sediment transport and storage (Figure adapted from Montgomery and Buffington 1997).

To ensure future supplies of LWD to stream channels, buffer strips serving as reservoirs of wood supply should be wide enough to encompass the zone of LWD input, typically within 20 m to 30 m of the stream channel (Lienkaemper and Swanson 1987, McDade et al. 1990, Van Sickle and Gregory 1990).

Some researchers have argued for larger buffers, based on susceptibility of buffer strips next to clear-cuts to blow-down and rapid depletion of available streamside wood (Reid and Hilton 1998).

The use of a selectively logged fringe buffer adjacent to the streamside buffer may serve to reduce abnormally high rates of windthrow and preserve natural input rates. Any selective cutting within buffer strips should leave an abundant supply of the largest trees for recruitment (Murphy and Koski 1989, Abbe and Montgomery 1996).

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Species, diameter, and wood decay rates influence the amount of wood recruitment potentially necessary (Murphy and Koski 1989).

Along with the diameter and length of pieces of large wood, the riparian plant species involved largely determine the processing (turnover) time of large wood in streams. (e.g. Anderson et al. 1978; Anderson and Sedell 1979). The actual rate at which large wood of a given species is processed in a stream is a function of temperature, oxygen, moisture, microbial metabolism, invertebrate ingestion, and mechanical abrasion. Completely submerged wood is processed a great deal more slowly than damp wood , on which terrestrial fungal and invertebrate agents can act. (Harmon et al. 1986). In general, wood of hard wood species is processed more rapidly than that of coniferous species. For example, red alder is among the most rapidly and Douglas fir is among the slowest (Anderson et al. 1978). These differences is disappearance rates of the wood types are primarily dependent upon the relative activities of biological agents (microbes and invertebrates) on the wood (Harmon et al. 1986).

Table 4. The possible management implications of preserving LWD input, transport, and presence within the stream channel.

MANAGEMENT PRACTICE	IMPLICATION	REFERENCES
Timber harvest	• Buffer strips should be wider than zone of LWD input	McDade et al. 1991, Van Sickle and Gregory 1990
	• Fringe buffers can protect streamside buffers from premature wood depletion	Reid and Hilton 1998
	• Selective management in buffers should consider future input required based on instream surveys	Bilby and Ward 1989, Murphy and Koski 1989

	• Selective management should leave large trees that will be stable and influence channel morphology	Fetherston et al. 1995, Abbe and Montgomery 1996
	• Active management of buffer zones can increase recruitment of certain species and sizes of wood	Beechie and Sibley 1997
	• Removal of logging debris best dealt with by selective removal	Bryant 1983, Bilby 1984, Gurnell et al. 1995
	• Knowledge of habitat conditions, and the size and abundance of LWD required to maintain conditions must be considered when removing instream wood	Bryant 1983, Bilby 1984
	• Characteristics of unmanaged streams should guide re-introduction of wood	Smith et al. 1993a, b, Montgomery et al. 1995, Abbe and Montgomery 1996, Beechie and Sibley 1997, Montgomery and Buffington 1997
Flood control and road maintenance	• Must gain quantitative understanding of effect of wood on flood heights and how moves through a system	Young 1991, Braudrick et al. 1997, Braudrick and Grant 2000
	• Design and modify bridges and culverts to allow for passage of woody debris	Diehl 1997, Flanagan et al. 1998
	• Develop management that recognizes ecological value and impact of wood on human infrastructure and public safety	Singer and Swanson 1983, Piegay and Landon 1997

Forest managers should seek to increase the recruitment of certain species, primarily conifers which produce the largest and longest lasting LWD. This may involve active management of deciduous riparian zones to promote conifer establishment and growth (Beechie and Sibley 1997). This strategy should be considered in relation to position within the channel network. Small channels (<10 m width) can form pools around smaller pieces of wood (<20 cm), such as alder logs. Large to intermediate channels require greater diameter logs to form pools (>60 cm). Data on variations in the size and amount of woody debris with changing stream size could be used to develop plans for numbers and sizes of trees to be achieved (Bilby and Ward 1989).

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Primer
on
Heat
Riparian Exchanges Related to Forest Management in the Western U.S.

Prepared by the
Technical Advisory Committee
of the
California Board of Forestry and Fire Protection

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Version 1.0

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PRIMER: HEAT RIPARIAN EXCHANGE FUNCTION: The Status of Knowledge for Heat Transfer Affecting Stream Temperature and Microclimate within Riparian Forest Buffers

This primer discusses the processes of heat transfer within riparian ecosystems and the effect on water temperature and microclimate. These interactions have been thoroughly and thoughtfully reviewed in a recent article by R.D. Moore, D.L. Spittlehouse, and A. Story that appeared in the Journal of the American Watershed Resources Association (2005). This article was part of a compendium of review articles by leading researchers in the field. This review paper provides a very strong discussion of the mechanics of heat transfer and the role of riparian forests and stream factors in determining water temperature and microclimate characteristics in managed and unmanaged forest streams. The TAC adopts this review paper as the primary basis for the heat and microclimate primer.

The Moore et al. review paper (2005) does not thoroughly cover several topics important to the discussion of T&I rules in California. These include the effects of water temperature on salmon, and watershed-level temperature patterns. The TAC committee authored a primer on these topics that follows that reviews the scientific literature in some depth. Finally, the TAC developed a set of questions that are the meant to guide and focus the BOF literature review on the subject of riparian forests, heat transfer, microclimate, and salmon health.

The TAC has developed other individual materials to support the BOF literature review/Primer for the Heat transfer function. This information is shown in item 3) below of the contents of the Heat transfer Primer.

Contents of Materials Provided by the TAC to the BOF on the subject of Heat Transfer, Microclimate, and Riparian Forests

1) **Primer on the basic science and understanding of the interaction of riparian forests and heat transfer processes.**

   Moore, R. D, D.L. Spittlehouse, and A. Story. 2005. Riparian Microclimate and stream temperature response to forest harvesting: a review. Journal of the American Water Resources Association 41(4): 813-834.

2) **Summary without references of key points of Moore et al. and TAC primers**

3) TAC Primer on Temperature and Salmon and Watershed Patterns (The Physiological Basis for Salmonid Temperatures)

1) Primer on the basic science and understanding of the interaction of riparian forests and heat transfer processes.

See: Moore, R. D, D.L. Spittlehouse, and A. Story. 2005. Riparian Microclimate and stream temperature response to forest harvesting: a review. Journal of the American Water Resources Association 41(4): 813-834.

2) Summary Without References Of Key Points Of Moore Et Al. And TAC Primers

This summary follows the organization of the Moore, Spittlehouse, and Story (2005) review of Temperature and Microclimate published in the Journal of the American Water Resources Association in 2005. Key points are taken from this paper as bullets. The key points of the TAC-developed Temperature biological effects and watershed temperature patterns are appended at the end of the summary of Moore et al.

The bulletized points in this document faithfully summarize the key findings of the Moore et al.paper, and the TAC addendum. These concepts were developed with thorough referencing to original research in the Moore et al. review article and the TAC primer. For ease of reading, no referencing is included in this summary.

Introduction

- There have been many studies of stream temperature.
- There have been some excellent reviews previously.
- Still a lively debate about how to manage riparian zones.
- Most states require a riparian buffer to protect stream temperature and microclimate.
- Moore et al review concentrates on small streams, Pacific Northwest.

Riparian Microclimate

Characteristics of Forest Microclimates

- Forest canopies affect the microclimate and ultimately stream temperature because canopies intercept the transmission of radiation.
- Tree species and stand densities affect evaporation processes, wind and light transmission.

- Riparian areas typically have elevated water tables and higher soil moisture than adjacent upland areas.

- Forest canopies tend to reduce the diurnal air temperature range compared to open areas (also reduce the soil temperature range).

- Lower air temperatures under a canopy will also create higher humidity as well.

- Relationship of riparian forest stands to topography will influence the extent, climate within, and effect on streams.

Edge Effects and the Microclimate of Riparian Buffers

- The magnitude of harvesting related changes in riparian microclimate will depend on the width of riparian buffers and how far edge effects extend into the buffer.

- There have been studies of microclimate effects in forests, and to a more limited extent, riparian areas, around the world.

- Much of the change in microclimate takes place within about 1 tree height (15 to 60 m) of the edge.

- Solar radiation, wind speed, and soil temperature adjust to interior forest conditions more rapidly than do air temperature and relative humidity.

- Edge orientation can be important, particularly when south facing.

- Studies of microclimate in riparian areas are more limited. (Cites Ledwith from CA 1.6 deg C decrease in air temperature per 10 m of buffer up to 30 meters and 0.2 deg C per 10 m for widths from 30 m to 150 m.

- Only one pre-harvest/post-harvest study (Washington). Gradients from stream into upland existed for all variables except solar radiation and windspeed. May have been enough affect to influence riparian fauna.

Thermal Processes and Headwater Stream Temperature

- An understanding of thermal processes is required as a basis for understanding stream temperature dynamics, in particular for interpreting and generalizing from experimental studies of forestry influences.

- As a parcel of water flows through a stream reach, its temperature will change as a function of energy and water exchanges across the water surface and the streambed and banks.

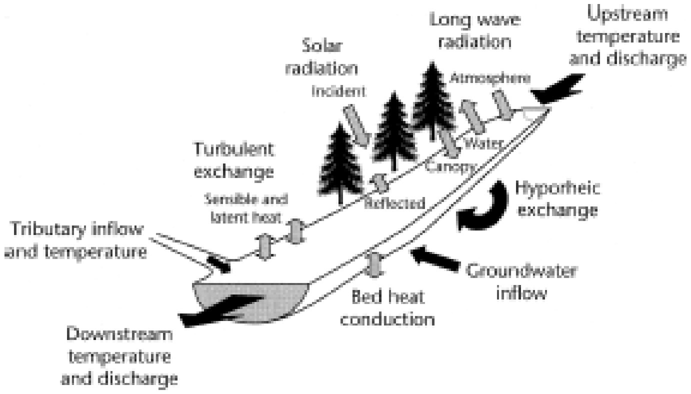


Figure 1. Factors Controlling Stream Temperature. Energy fluxes associated with water exchanges are shown as black arrows.

- Can be defined as a heat balance with expression of the radiation and advective exchange components.

- A form of the energy balance equation

Radiative Exchanges

- Radiation inputs to stream surface include incoming solar radiation (direct and diffuse) and long-wave radiation emitted by the atmosphere, forest canopy and topography.

- Canopy will reduce the direct component of solar radiation and will redistribute some of the diffuse component.

- Channel morphology (wide, narrow, and topographically shaded) will influence how much energy exchange occurs. Orientation can also affect how long the stream "sees" the direct solar during the day.

- When direct radiation comes from +30 degrees above the horizon, most of it can be absorbed within the water column and by the bed, and thus is effective at stream heating.

- Low solar angles at dawn and dusk, and during much of the annual solar cycle are not effective at stream heating because direct radiation comes in at too low an angle to be absorbed effectively.

- Incoming longwave radiation will be a weighted sum of the emitted radiation from the atmosphere, surrounding terrain, and the canopy, with the weights being their respective view factors.

Sensible and Latent Heat Exchanges

- Transfers of sensible and latent heat occur by conduction or diffusion and turbulent exchange in the overlying air.

- Sensible heat exchange depends on the temperature difference between the water surface and overlying air and on the wind speed.

- Where the stream is warmer than the air, heat transfer away from the stream is promoted by the unstable temperature stratification. Where the air is warmer than the stream, the heat transfer from the air to the stream is dampened by the stable air temperature stratification.

- Latent heat exchange also depends on atmospheric stability over the stream.

- Under intact forest cover, especially over small streams, lack of ventilation appears to limit the absolute magnitude of sensible and latent heat exchanges.

Bed Heat Exchanges and Thermal Regime of the Streambed

- Radiative energy absorbed at the streambed may be transferred to the water column by conduction and turbulent exchange and into the bed sediments directly by conduction and indirectly by advection where water infiltrates into the bed. Given that turbulent exchange is more effective at transferring heat than conduction, much of the energy absorbed at the bed is transferred into the water column, and the temperature at the surface of the bed will generally be close to the temperature of the water column, except where there may be local advection.

- Bed heat conduction depends on the temperature gradients within the bed and its thermal conductivity.

- The bed will normally act as a cooling influence on summer days and a warming influence at night, thus tending to reduce diurnal temperature range.

- Bed temperatures may be important biologically.

- The degree to which post-logging bed temperatures reflect changes in surface temperature depends on the local hydrologic environment.

Groundwater Inflow

- Groundwater is typically cooler than the streamwater during daytime, and warmer during winter and thus tends to moderate seasonal and diurnal stream temperature variations.
- Forest harvesting can increase soil moisture and ground water levels
- Increases in gw volume could act to promote cooling, or at least ameliorate warming.
- Some have argued cutting could increase groundwater temperature.
- There are no published research that has examined ground water discharge and temperature both before and after harvest as a direct test of the hypothesis of ground water warming.

Hyporheic Exchange

- Hyporheic exchange is a two-way transfer of water between a stream and its saturated sediments in the bed and riparian zone.
- Stream water typically flows into the bed at the top of a riffle and re-emerges at the bottom of a riffle.
- Hyporheic exchange can create local thermal heterogeneity and it can be important in relation to both local and reach scale temperature patterns in headwater streams.
- There are significant methodological problems associated with quantifying rates of hyporheic exchange and its influence on stream temperature.

Tributary Inflow

- Effects of tributary inflow depend on the temperature difference between inflow and stream temperatures and on the relative contribution to discharge and can be characterized by a simple mixing equation.

Longitudinal Dispersion and Effects of Pools

- Longitudinal dispersion results from variation in velocity through the cross-section of a stream. Not well studied, but could smooth and damp effects downstream.
- Deeper pools may have incomplete mixing creating thermal stratification.

Equilibrium Temperature and Adjustment to Changes in Thermal Environment

- For a given set of boundary conditions (e.g., solar radiation, air temperature, humidity, wind speed) there will be an “equilibrium” water temperature that will produce a net energy exchange of zero and thus no further change in temperature as water flows downstream.

- There is a maximum possible temperature a parcel of water can achieve as it flows through a reach at a given time, assuming that boundary conditions remain constant in time and space.

- Equilibrium conditions may not be achieved because the boundary conditions may changes in time and space before the water parcel can adjust fully to the thermal environment.

- Equilibrium temperature will be lower where there is substantial groundwater inflow, and will be higher for unshaded reaches.

- The rate at which a parcel of water adjusts to a change in the thermal environment depends on stream depth because for deeper streams, heat would be added to or drawn from a greater volume of water.

- Shallow streams adjust relatively quickly to a change in thermal environment.

- Flow velocity influences the length of time the parcel of water is exposed to energy exchanges across the water surface and the bed, and thus the extent to which the parcel can adjust fully to its thermal environment.

- Given that the depth and velocity of a stream tend to increase with discharge, the sensitivity of stream temperature to a given set of energy inputs should increase as discharge increases.

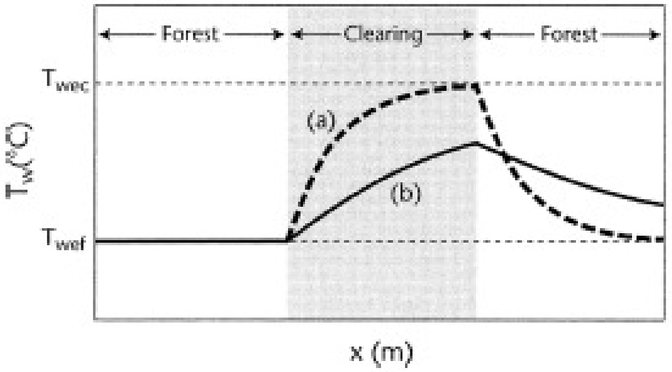


Figure 2. Schematic Temperature Patterns Along a Stream Flowing From Intact Forest, Through a Clear-Cut, and Back Under Intact Forest for (a) Shallow, Low Velocity, and (b) Deep, High Velocity Conditions (T_{wef} = equilibrium temperature in forest; T_{wec} = equilibrium temperature in clearing).

Thermals Trends and Heterogeniety Within Stream Networks

- Small streams tend to be colder and exhibit less diurnal variability than larger downstream reaches
- Small streams are more heavily shaded, will have a higher ratio of groundwater inflow, and are located at higher elevations (cooler air).
- Local deviations from a dominant downstream warming tend may occur as a results of ground water inflow, hyporheic exchange, advection of water from other sources, or even changes in dominant variables such as air temperature.
- Thermal heterogeneity has been documented at a range of spatial scales: with a pool, within a reach, within a river system.

Stream Temperature Response to Forest Management

- Studies have occurred.
- Some BACI, some not
- Most studies in PNW in rain-dominated climates

Influences of Forest Harvesting Without Riparian Buffers

- Almost all streams that have buffers removed increase in summertime temperature.
- Harsh treatment yields high temperature response.
- Results appear to be more mixed in more recent years.
- Response in snowmelt not well studied. Still get increases.
- Winter temperatures have also not been well studied.

Influences of Forest Harvesting With Riparian Buffers

- Studies in rain-dominated catchments suggest that buffers may reduce, but not entirely protect against increases in summer stream temperature.
- A few studies in snow-dominated in Canada showed increase in temperatures.
- The protective effect of buffers can be compromised by blow-down.

Thermal Recovery Through Time

- Post-harvest temperatures should decrease through time as riparian vegetation recovers.
- Effects seem to last 5-10 years if riparian vegetation is allowed to recover.

Comparison With Studies Outside The Pacific Northwest

- Studies conducted elsewhere in the world are in many ways consistent with results from the PNW.
- However, difference in important environmental variables limit the comparability of results.

Effects of Forest Roads

- Some evidence for very small streams that even a road-right-of-way cut can be of sufficient length to cause local heating.

Downstream and Cumulative Effects

- You can get watershed level response—upstream to downstream translation

- Downstream transmission of heated water would increase the spatial extent of thermal impacts.

- Debate about whether down-stream cooling (how much, how fast) can have a significant effect.

- Streams can cool in the downstream direction by dissipation of heat out of the water column or via dilution by cool inflows. Dissipation to the atmosphere can occur via sensible and latent heat exchange and long wave radiation from the water surface and evaporation.

- Reported downstream temperature changes below forest clearings are highly variable. Some reports streams cooled, some report streams continued to warm in the downstream direction.

- Whether cooling occurs may depend on ambient temperatures (only occurs when temperature is at a maximum)

- Little process work to understand the mechanisms that allow cooling to occur.

- Three factors may mitigate against cumulative effects of stream warming. 1) dilution could mitigate temps to be biologically suitable, 2) the effects of energy inputs are not linearly additive throughout a stream network due to systematic changes in balance of energy transfer mechanisms. 3) Intercepting environments (lakes, reservoirs)

- May be secondary impacts like widening and shallowing from sedimentation

Monitoring and Predicting Stream Temperature and its Causal Factors

Monitoring Stream Temperature

- Most recent studies have used submersible temperature loggers

- Forward-looking infrared radiometery from helicopters has been used for investigating stream temperature patterns in medium to large streams. The application of this technology to small streams limited. Method can identify cool water areas.

Measuring Shade

- Many different ways to measure shade (view-factor).

Predicting the Influences of Forest Harvesting on Stream Temperature

- There are empirical models (a few environmental variables can usually predict maximum temperature within a degree or two with about r^2 of 0.60 to 0.70)

- There are physically-based models. There are a variety of them with different assumptions, formulations, variables to inform, complexity. Most, including the simplest, predict temperature accurately.

Discussion and Conclusions

Summary of Forest Harvesting Effects on Microclimate and Stream Temperature

Biological Consequences and Implication for Forest Practices

- Briefly discusses non-fish potential effects

- A better understanding is required of how changes in the physical conditions in small streams and their interactions with chemical and biological processes influence their downstream exports.

- One tree height should cover it.

Issues For Future Research (Moore et al. 2005)

- Riparian microclimates have been relatively little studies, both in general and specifically in relation to the effects of forest practices.

- Shade is the dominant control on forestry-related stream warning in small streams.

- Determining shade in small streams is difficult and refined and consistent methods are needed.

- Hemispherical photography might be the way to go to solve subjectivity and methods problems.

- The effects of low and deciduous vegetation in controlling temperature in very small streams is not well understood.

- Further research should address the thermal implications of surface/subsurface hydrologic interactions, considering both local and reach scale effects of heat exchange associated with hyporheic flow paths.

- Bed temperature patterns in small streams and their relation to stream temperature should be researched in relation to stream the effects on benthic invertebrates and nonfish species.

- The hypothesis that warming of shallow ground water in clearcuts can contribute to stream warming should be addressed, ideally by a combination of experimental and process/modeling studies.

- The physical basis for temperature changes downstream of clearings needs to be clarified. Are there diagnostic site factors that can predict reaches where cooling will occur. Such information could assist in the identification of thermal recovery reaches to limit the downstream propagation of stream warming. It could also help identify areas within a cut block where shade from a retention patch would have the greatest influence.

The Physiological Basis for Salmonid Temperature Response

- Water temperature governs the basic physiological functions of salmonids and is an important habitat factor.

- Fish have ranges of temperature wherein all of these functions operate normally contributing to their health and reproductive success. Outside of the range, these functions may be partially or fully impaired, manifesting in a variety of internal and externally visible symptoms. Salmon have a number of physiologic and behavioral mechanisms that enable them to resist adverse effects of temporary excursions into temperatures that are outside of their preferred or optimal range. However, high or low temperatures of sufficient magnitude, if exceeded for sufficient duration, can exceed their ability to adapt physiologically or behaviorally.

- Salmon are adapted over some evolutionary time frame to the prevailing water temperatures in their natural range of occurrence, and climatic gradient are among the primary factors that determine the extent of a species' geographic distribution on the continent.

- Salmon are considered a “cold water” species, and generally function best within the range of ambient temperatures in water bodies within their natural range of occurrence. This range is 0-30^{o}C for salmonids, where end temperatures are lethal and mid range temperatures are optimal. The southern limit of the natural range of salmonids coincides with the occurrence of summer water temperatures of 30^{o}C.

- The effects of temperature are a function of magnitude and duration of exposure. Exposure to temperatures above 24^{o}C of sufficient continuous duration can cause mortality.

- Salmon can tolerate each successively lower temperature for exponentially increasing intervals of time. Temperatures above 22^{o}C are stressful. Lengthy exposure to higher temperatures include loss of appetite and failure to gain weight, competitive pressure and displacement by other species better adapted to prevailing temperatures, or disease.

- Growth occurs best when temperatures are moderate and food supplies are adequate. High and low temperatures limit growth. Optimal temperatures for growth are in the range of 14 to 17^{o}C, depending on species.

- Salmon have been shown to increase growth in streams where riparian canopy rwas removed due to increased light and food availability, despite the occurrence of warmer temperatures.

- Larger size generally increases survival and reproductive success.

- Growth rates are important for anadromous salmonids, who must reach minimum sizes before they are able to migrate to the ocean. Missing normal migration windows by being too small or too large may have negative effects on success in reaching the ocean.

- The temperature of rivers and streams ranges over the full range of temperatures within the range utilized by salmonids during the course of the year. The summer maximum temperatures are generally those of most concern.

- The most thermally tolerant salmonid species occur in California (steelhead, chinook and coho). Of these species, coho are the most thermally sensitive.

Temperature Exposure in Natural Streams and Potential Effects of Forest Practices

- Water temperature generally tends to increase in the downstream direction with stream size as a result of systematic changes in the important environmental variables that control water temperature. As streams widen, riparian canopy provides less and shade until some point in a river system where it provides no significant blocking effect. Cooler groundwater inflow also diminishes in proportion to the volume of flow in larger streams.

- The lowest order streams have the coolest water temperatures near groundwater temperature (11-14^{o}C). Higher order streams are near ambient air temperatures (20-26^{o}C). The range of water temperature from lower to higher orders in California rivers and streams during the warmest period in the summer spans much of the tolerable temperature range for salmonids. Water temperature typical of higher order streams are within stressful levels for salmonids.

- Removal of riparian vegetation may increase stream temperatures up to the ambient air temperature, depending on the natural extent of shading and the proportion of canopy removed. Thus, temperatures typically observed only in downstream reaches may occur in tributary streams.

- Salmonid distribution within stream systems and within the region reflects temperature tolerance. Coho are found in the cooler waters associated with headwater streams and within the coastal zone where climate is strongly influenced by the Pacific Ocean. Steelhead have somewhat higher thermal tolerance, and are more widely distributed.

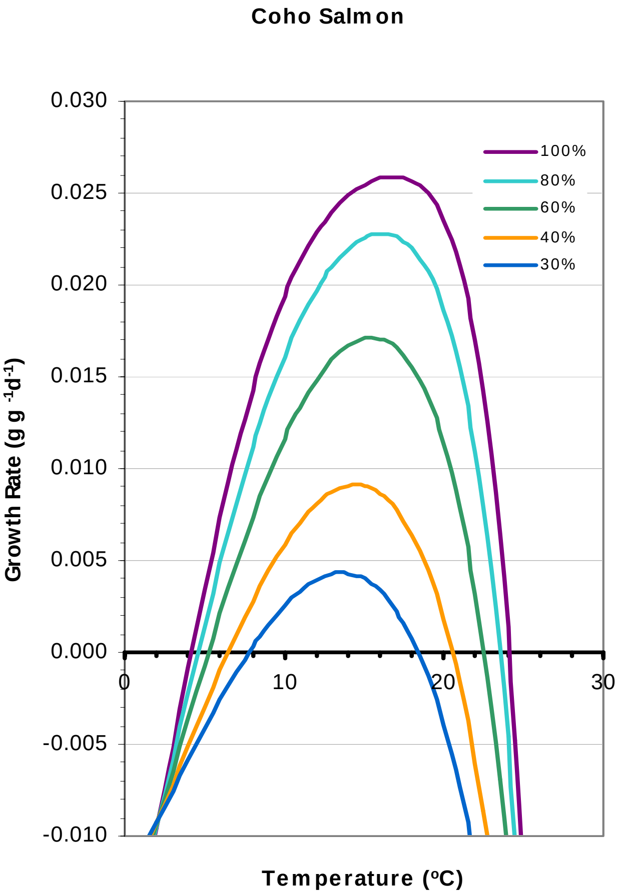
3) TAC Primer on Temperature and Salmon and Watershed Patterns (The Physiological Basis for Salmonid Temperatures)

The Physiological Basis for Salmonid Temperature Response

Water temperature is a dominant factor affecting aquatic life within the stream environment (Hynes 1970). Water temperature affects important stream functions such as processing rates of organic matter, chemical reactions, metabolic rates of macro-invertebrates, an cues for life-cycle events (Sweeney and Vannote 1986). Water temperature plays a role in virtually every aspect of fish life, and adverse levels of temperature can affect behavior (e.g. feeding patterns or the timing of migration), growth, and vitality.

Water temperature governs the rate of biochemical reactions in fish, influencing all activities by pacing metabolic rate (Frye 1971). Fish are poikilothermic or "cold-blooded". This means that fish do not respond to environmental temperature by feeling hot or cold. Rather, they respond to temperature by increasing or decreasing the rate of metabolism and activity. Water temperature is the thermostat that controls energy intake and expenditure.

Figure 1. Coho salmon daily growth rate as a function of temperature and daily food ration.



The role of temperature in governing physiologic functions of salmonids has been studied extensively (Brett 1971; Elliott 1981; reviewed in Adams and Breck 1990; Brett 1995, McCullough 1999). The relationship between energetic processes and temperature have been quantified for many fish species with laboratory study. Energetic processes are expressed as functions of activity rate in relation to temperature. The relationships between energy-related functions and temperature follow two general patterns: either the rate increases

continuously with rise in temperature (e.g., standard metabolic rate, active heart rate, gastric evacuation), or the response increases with temperature to maximum values at optimum temperatures and then decreases as temperature rises (e.g., growth rate, swimming speed, feeding rate) (Brett 1971, Elliott 1981). Each function operates at an optimal rate at some temperature and less efficiently at other temperatures.
For example, daily growth as a function of temperature is shown in Figure 1. Beginning with the coolest temperatures (0^{o} C), growth increases with temperature up to the optimal due to increasing consumption and food conversion efficiency. At temperatures above the optimal, growth rates decline as consumption declines in response to temperature and metabolic energy costs increase (Brett 1971, Elliott 1981, Weatherly and Gill 1995). Because the shape of growth curves is relatively broad at the maximum, there is little or no negative effect of temperature several degrees above optimum. Some investigators define the optimal temperature as the temperature at which maximum growth occurs, and refer to the range of temperature where growth occurs as “preferred” temperatures (Elliott 1981).

The general form of this relationship is similar for all salmonid species, varying somewhat in the details of growth rates and optimal temperatures. All salmonids have a similar biokinetic range of tolerance, performance, and activity. They are classified as temperate stenotherms (Hokanson 1977) and are grouped in the cold water guild (Magnuson et al. 1979). Significant differences in growth rate and temperature range exist among families of fish (Christie and Regier 1988). Some families grow best in colder temperatures (e.g. char), and many grow better in warmer temperatures (e.g. bass). Differences in the specific growth/temperature relationships among species in large measure explain competitive success of species in various temperature environments.

The range of environmental temperature where salmonid life is viable ranges from 0-30 ^{o}C, with critical temperatures varying somewhat by species. Salmonid physiologic functions operate most effectively in the mid regions of the range where growth is also optimized. Physiological functions are impaired on either end of the temperature range so that the geographic distribution of prevailing high or low temperatures ultimately limits the distribution of the species in the Salmonidae family (Eaton 1995).

The effects of temperature are a function of magnitude and duration of exposure. Figure 2 from Sullivan et al. 2000 summarizes the general relationship of salmonid response to temperature exposure. Salmon species are similar in this pattern, but vary somewhat in the temperatures zones of response.

Exposure to temperatures above 24^{o}C can elicit mortality with sufficient length of exposure. The temperature where death occurs within minutes is termed the ultimate upper incipient lethal limit (UICL). This temperature is between 28- 30^{o}C, varying by salmon species. Clearly, salmon populations are not likely to persist where this temperature occurs for even a few hours on a very few days each year (Eaton 1995).

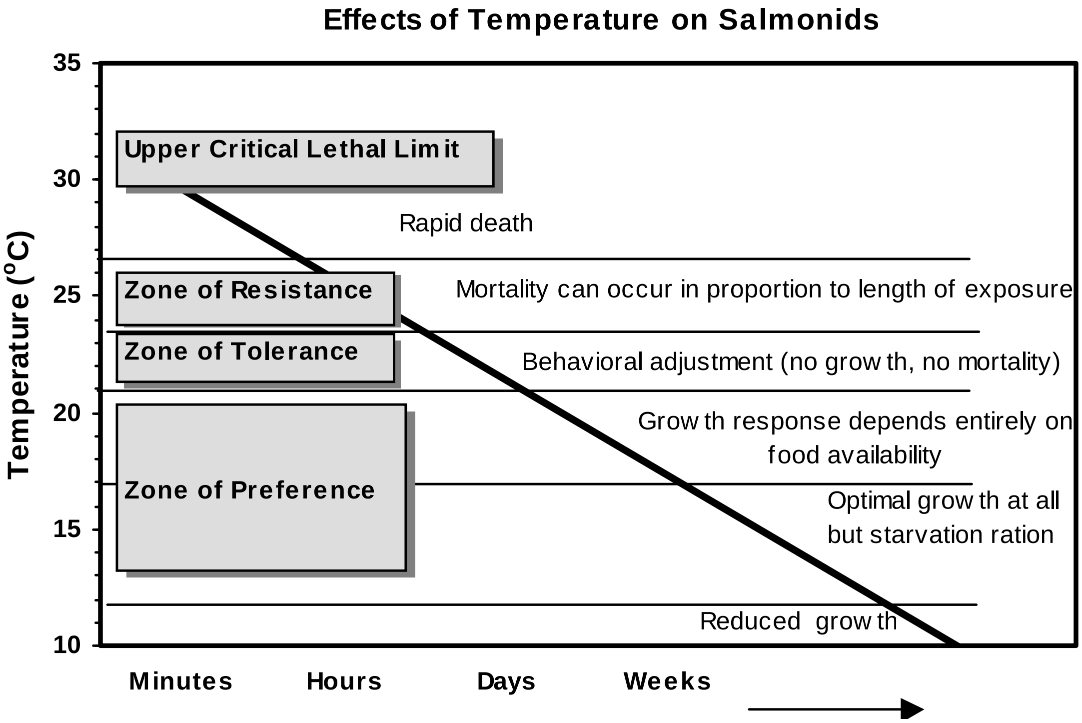
Lethal exposure is defined as up to 96 hours of continuous exposure to a given temperature.

Salmon can tolerate each successively lower temperature for exponentially increasing intervals of time. They do so by altering food consumption and limiting the metabolic rate and scope of activity (Brett 1971, Elliott 1981, Weatherly and Gill 1995). This resistance to the lethal effects of thermal stress enables fish to make excursions for limited times into temperatures that would eventually be lethal (Brett 1956; Elliott 1981). The period of tolerance prior to death is referred to as the “resistance time” (Figure 2) (Hokanson 1977, Jobling 1981). Salmon can extend their temperature tolerance through acclimation. Brett (1956) reported that the rate of increase in ability to tolerate higher temperatures among fish is relatively rapid, requiring less than 24 hours at temperatures above 20^{o}C. Acclimation to low temperatures (less than 5^{o}C) is considerably slower.

Laboratory and field studies have repeatedly found that salmon can spend very lengthy periods in temperatures between 22 and 24^{o}C without suffering mortality (Brett 1995, Bisson et al. 1988; Martin 1988). Temperatures within this range may be stressful, but are not typically a direct cause of mortality (Brett 1956). Temperatures that cause thermal stress after longer exposures, ranging from weeks to months, are termed chronic temperature effects. Endpoints of lengthy exposure to temperature that are not physiologically optimum may include loss of appetite and failure to gain weight, competitive pressure and displacement by other species better adapted to prevailing temperatures (Reeves et al. 1987), change in behavior, or susceptibility to disease. Werner et al. (2001) documented correlations between stream temperature, size of juvenile steelhead and heat shock protein expression.

Fish may be able to avoid thermal stress by adjusting behavior, such as moving to cooler refugia. Numerous observers have observed behavioral adjustment by seeking cool water refugia when temperature in normal foraging locations reaches 22°C (Donaldson and Foster 1941; Griffiths and Alderdice 1972; Wurtsbaugh and Davis 1977; Lee and Rinne 1980; Bisson et. al. 1988; Nielsen et al. 1994, Tang and Boisclair 1995; Linton et al. 1997; Biro 1998). Fish resume feeding positions when temperatures decline below this threshold. At very low temperatures, salmonids cease feeding and seek cover under banks or within stream gravels (Everest and Chapman 1972).

Figure 2. General biological effects of temperature on salmonids in relation to duration and magnitude of temperature (from Sullivan et al. 2000).



Less quantifiable in a dose-response context are relationships involving temperature and disease resistance, and temperature effects on sensitivity to toxic chemicals and other stressors. (Cairns et al. 1978). For temperature to affect the occurrence of disease, disease-causing organisms must be present, and either those organisms must be affected by temperature or fish must be in a weakened state due to the effect of temperature. Some disease-causing organisms may be more prevalent at high temperature, others are more prevalent at low temperature, and some are not temperature-related. Thus, the interaction of temperature and disease is best evaluated on a location-specific basis.

If energy intake is adequate to fuel the physiological energy consumption, mediated in large part by the environmental temperature, then the organism can live in a healthy state and grow. Growth is a very important requirement for anadromous salmon living in fresh water. Salmon emerge from gravels in their natal streams measuring approximately 30 mm in length and weighing approximately 0.5 gram. Adults returning to spawn 3 to 5 years later typically measure 500 to 1000 mm in length and weigh from 5 to 20 kg depending on species. This enormous increase in body mass (greater than 5000 times) must be accomplished within a very limited lifespan. Salmon have evolved from a fresh water origin to spend a major portion of life in a marine habitat where there is far greater productivity and where the majority of growth occurs (Brett 1995).

Juvenile salmon must achieve the first six times increase in weight in their natal stream before they can smolt and migrate to the ocean (Weatherly and Gill 1995). Coho and steelhead generally smolt within 1 year, but can require as long as 3 years to achieve sufficient size to begin the transition to salt water. The long-term exposure of salmonids to temperature during their freshwater rearing phase has an important influence on the timing of smoltification and the ultimate size fish achieve (Warren 1971, Brett 1982, Weatherly and Gill 1995, Sullivan et al. 2000).

The size of salmonids during juvenile and adult life stages influences survival and reproductive success (Brett 1995). Larger size generally conveys competitive advantage for feeding (Puckett and Dill 1985, Nielsen 1994) for both resident and anadromous species. Smaller fish tend to be those lost as mortality from rearing populations (Mason 1976; Keith et al. 1998). Larger juveniles entering the winter period have greater over-wintering success (Holtby and Scrivener 1989; and Quinn and Peterson1996). Growth rates can also influence the timing when salmon juveniles reach readiness for smolting. Missing normal migration windows by being too small or too large, or meeting a temperature barrier, may have a negative effect on success in reaching the ocean (Holtby and Scriverner 1989).

How large a salmon can grow in a natural environment is fundamentally determined by environmental and population factors that determine the availability of food. Water temperature regulates how much growth can occur with the available food. Brett et al. (1971) described the freshwater rearing phase of juvenile salmon as one of restricted environmental conditions and generally retarded growth. Many studies have observed an increase in the growth and productivity of fish populations in streams when temperature (and correspondingly) food is increased. This tends to occur even in the cases where temperatures exceed preferred and sometimes lethal levels (Murphy et al. 1981, Hawkins et. al., 1983, Martin 1985, Wilzbach 1985, Filbert and Hawkins 1995).

Table 1 summarizes results from laboratory and field studies of coho and steelhead temperature response (from Sullivan et al 2000). Steelhead and coho are similar, though not identical, in the temperatures at which various functions or behaviors occur. Importantly, Sullivan et al (2000) showed that even though the laboratory optimal growth temperatures for steelhead are within a narrower and cooler range than those of coho (e.g. their “growth curves”), steelhead grow better than coho when exposed to higher temperatures in natural streams. These authors suggest that this disparity results from a greater efficiency in obtaining food in natural environments by steelhead, thus allowing them to generally obtain a higher ration of food. Bisson et al (1988b) showed that the body form of these two fish differ, enabling steelhead to feed efficiently in riffle habitats where food supply is more abundant. Thus, steelhead have a higher “net temperature tolerance” than coho.

Table 1. The spectrum of coho salmon and steelhead response at temperature thresholds synthesized for field and laboratory studies in Sullivan et al (2000). Threshold values are approximations, due to lack of consistency in reporting temperature averaging methods among studies. Temperature thresholds are standardized to the average 7-day maximum to the extent possible to allow comparison of field and laboratory study observations.

Biologic Response	**COHO Approximate Temperature ^{o}C**	**STEELHEAD Approximate Temperature ^{o}C**
Upper Critical Lethal Limit (death within minutes)-Lab	29.5	30.5
Geographic limit of species—Stream annual maximum temperature (Eaton 1995)	30	31.0
Geographic limit of species—Warmest 7-Day Average Daily Max Temperature (Eaton 1995)	23.4	24.0
Acute threshold U.S. EPA 1977—Annual Maximum	25	26
Acute threshold U.S. EPA 1977— 7-day average of daily maximum	18	19
Complete cessation of feeding (laboratory studies)	24	24
Growth loss of 20% (simulated at average food supply)	22.5	24.0
Increase incidence of disease (under specific situations)	22	22
Temporary movements to thermal refuges	22	22
Growth loss of 10% (simulated at average food supply) (7-day average of daily maximum)	16.5	20.5
Optimal growth at range of food satiation (laboratory)	12.5-18	10-16.5
Growth loss of 20% (simulated at average food supply) 7-day average of daily maximum	9	10
Cessation of feeding and movement to refuge	4	4

Optimal temperatures for both Chinook salmon fry and fingerlings range from 12   C to 14   C, with maximum growth rates at 12.8   C (Boles 1988). [These numbers seem much to low compared to other studies. Need reference.] With the exception of some spring-run Chinook salmon, most Chinook juveniles do not rear in streams through the summer and are therefore not typically exposed to late-summer conditions. A significant portion of spring-run Chinook salmon, however, reside in streams throughout the summer. These salmon are also the only salmonid that must cope with summer water temperatures as adults. They typically enter the Sacramento River from March to July and continue upstream to tributary streams where they over-summer before spawning in the fall (Myers et al. 1998). Adult spring-run Chinook salmon require deep, cold pools to hold over in during the summer months prior to their fall spawning period. When these pools exceed 21 C adult Chinook salmon can experience decreased reproductive success, retarded growth rate, decreased fecundity, increased metabolic rate, migratory barriers, and other behavioral or physiological stresses (McCullough 1999).

There has been some suggestion that there may be genetic adaptations by local populations that confer greater tolerance to temperatures. However, literature on temperature thresholds for salmonids, as summarized in Table 1 is remarkably consistent despite differences in locations of subject fish (Sullivan et al. 2000, Hines and Ambrose 2000, Welsh et al. 2001).

One problem encountered in synthesizing laboratory and field studies is how to characterize the widely variable stream temperature characteristics of a stream in either a physically or biologically meaningful way is lack of standardization on reporting summary statistics. The measures of 7-day maximum values have been shown to have biological meaning (e.g. Brungs and Jones 1977). These types of metrics also provide useful indices for comparing temperature among streams. Sullivan et al (2000) showed that all of the short-term high temperature criteria relate closely to one another when calculated from the same stream temperature record (7-day mean and maximum, annual maximum temperature, and long-term seasonal average). However, longer-term measures are better indicators of general ecologic metabolism. For example, degree-summation techniques sum duration of time (days, hours) above a selected threshold temperature.

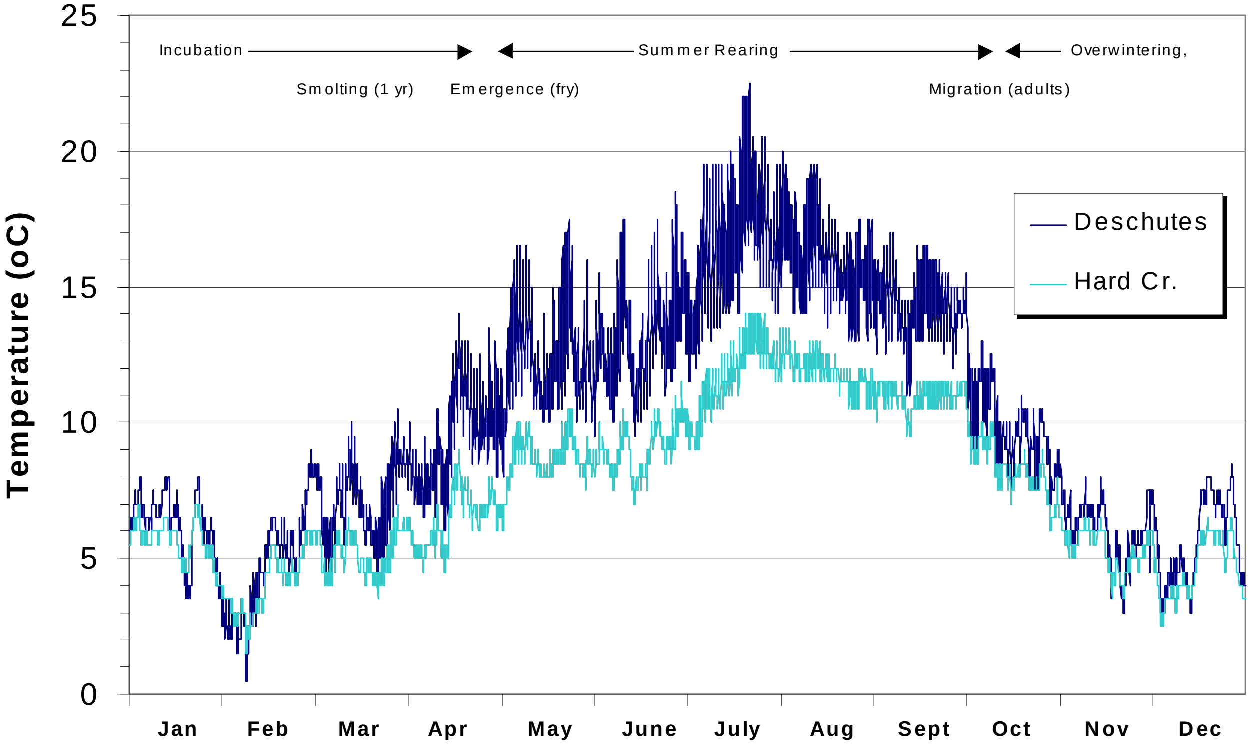
Temperature Patterns and Salmonid Species Distribution Within Watersheds

Temperatures supporting the physiologic functions of fish species reflect the ambient temperatures likely to be found in streams in each species' natural range of occurrence (Hokanson 1977). For salmonids, this range is from 0 to less than 30^{o}C (see Table 1). Within the range of distribution of salmonids in the Pacific Northwest, there is a west to east climatic gradient reflecting the marine influence at the coast and the orographic effects of interior mountain ranges. Coastal zones are characterized by maritime climates with high rainfall that occurs during the winter and dry warm summers. Interior zones are dryer, and rainfall may occur as rain or snow. Summers are very dry, and temperatures often hotter than coastal zones, although elevation can have a significant cooling effect. Comparison of river temperatures associated with forested regions throughout Washington, Oregon and Idaho show generally consistent occurrence of temperatures within the temperature tolerance of salmonids (Sullivan et al. 2000).

The temperature of streams and rivers within the range of distribution of salmonids in the Pacific Northwest and California typically vary widely on both temporal and spatial scales. For example, the range of hourly temperature over a year period for a smaller headwaters stream and larger mainstem river located within a forested watershed in Washington are shown in Figure 3. (The figure also shows the typical phase and migration timing for coho and steelhead salmon.) Similar patterns are observed in forested regions of California.

Active feeding and positive growth can occur at any time during the year when temperature is within the positive growth range illustrated in Figure 1. Juvenile salmon experience preferred temperatures for much of the year, and may experience stressful temperature conditions for relatively little time during the year. Water temperatures between 8 and 22°C tend to be the most prevalent temperatures observed in natal rivers and streams in the Pacific Northwest (Sullivan et al. 2000). Temperatures high enough to directly cause mortality are rare within the region where salmon occur. Temperatures high enough to cause stress (>22°C) may be common, especially in higher order streams.

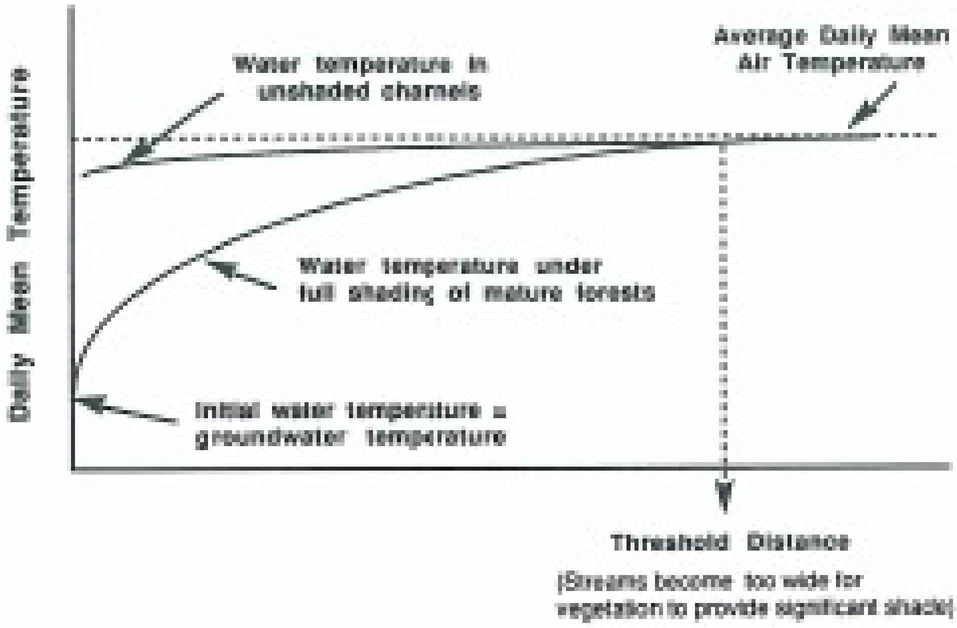
Figure 3. Water temperature of the Deschutes River (148 km^2) and Hard Creek (2.3 km^2), a headwater tributary, near Von. Data are hourly measurements.



Watershed Temperature Patterns

Stream temperature tends to increase in the downstream direction from headwaters to lowlands. (Hynes 1970, Theurer et al 1984). The dominant environmental variables that regulate heat energy exchange for a given solar loading, and determine water temperature are stream depth, proportional view-to-the-sky, rate and temperature of groundwater inflow, and air temperature (Moore et al, 2005). Increasing temperature in the downstream direction reflects systematic tendencies in these critical environmental factors. Air temperature increases with decreasing elevation (Lewis et al. 2000). Riparian vegetation and topography shade a progressively smaller proportion of the water surface as streams widen (Spence et al. 1996), until at some location there is no effective shade at all (Beschta et al. 1987, Gregory et al. 1991). Streams gain greater thermal inertia as stream flow volume increases (Beschta et al. 1987), thus adjusting more slowly to daily fluctuations in energy input. The typical watershed temperature pattern is illustrated in Figure 4.

Figure 4. General pattern of temperature at the watershed scale and potential range of response to forest removal. (from Sullivan et al. 1990).



Low order streams tend to be the coolest within the stream system. Low order streams are close to source areas and emerge near groundwater temperatures. They are typically shallow, steep and narrow, and are well-shaded, depending on overstory vegetation. Mid-order streams have wider channels and therefore less shade, greater flow volume, and moderate gradient. Tributary inflow is the main source of external flow contribution (as opposed to groundwater inputs). Higher order streams characteristically have low gradients, wide channels, and large volumes of water. Riparian vegetation and topography provide little insulation. The thermal inertia of the large volume of flow, and rapid mixing by turbulent flow generally overwhelms any lateral inputs (tributaries or phreatic groundwater) relatively quickly, allowing only isolated pockets of colder water. These streams may have large alluvial aquifers that may create significantly cooler zones from hyporheic flow; particularly in streams with complex channel features.

Water temperature in larger rivers without riparian shading is in equilibrium with, and close to, air temperature. In smaller streams, water temperature is depressed below air temperature due to the cooling effects of groundwater inflow and the shading effects of the forest canopy (Sullivan et al. 1990; Moore 2005). The minimum temperature profile in Figure 4 indicates the general pattern of water temperature in streams in a fully forested watershed. The coolest temperatures will be observed in the smallest streams and will be near prevailing groundwater temperature. As the effects of these insulating variables lessens in the downstream direction, water temperature moves closer to air temperature until the threshold distance where riparian canopy no longer provides effective shade and the water temperature is closely correlated with air temperature alone (Kothandaraman 1972). It is likely that the shape of the minimum line varies both with basin air temperature and with differences in natural vegetation.

Various authors have reported the likely summertime temperatures that mark the highest and lowest temperatures on this curve for streams and rivers of the Pacific Northwest and California used by salmonids. Minimum groundwater temperatures are approximately 10-13^{o}C (Sullivan et al. 1990, Lewis et al. 2000). Maximum temperatures typically range from 20 to 26^{o}C (Sullivan et al. 2000, Lewis et al. 2000) depending on location.

Removal of vegetation in headwater streams may allow temperature to increase up to (but not exceed) the basin air temperature maxima. Thus, the potential response of water temperature to forest harvest may be large in small streams, but only small, and difficult to detect in mid to large size watersheds.

Fish Species Distribution Within Watersheds

Salmonid species found in California include Chinook (O. tshawytscha), coho (O. kisutch), and steelhead (O. salmo). These species are the most temperature tolerant of the anadromous species in the salmonidae family. The southern-most extent of the natural range of salmon is found at latitude approximately equal to San Francisco, dipping further south along the coast. Eaton (1995) showed a strong relationship between prevailing summertime maximum temperatures and the end of the range of occurrence.

Salmon species throughout their range have evolved to use different parts of the river system during their freshwater rearing phase. Systematic changes in the occurrence or dominance of species within river systems in part reflects the temperature patterns as one important component of habitat. Differences among species can confer competitive advantages in relation to environmental variables that influence the species' distribution (Brett 1971, Baltz et. al. 1982, Reeves et al. 1987, DeStaso and Rahel 1994).

Steelhead have higher net temperature tolerance, are widely distributed within the northern region of California and occupy a broader range of habitats including larger rivers and smaller streams. Coho have the lowest net temperature tolerance of the salmonids found in California, and are found primarily where temperatures are coolest for most of the year. They primarily occur in the low to mid-order tributaries within the coastal zone. (reference for distribution).

Chinook salmon are perhaps the most temperature tolerant of all salmon species. They have the highest optimal temperatures for growth and fastest growth rates of all the salmonids. Fall run chinook emerge from gravels in spring and move to the larger (warmer) rivers where their growth rate allows them to migrate to the ocean with weeks to a few months. They migrate out of the river before the warmest summer temperatures occur. An exception are spring-run Chinook salmon. Some juveniles reside in streams throughout the summer. These salmon are also the only salmonid that must cope with summer water temperatures as adults. They typically enter the Sacramento River from March to July and continue upstream to tributary streams where they over-summer before spawning in the fall (Myers et al. 1998). Adult spring-run Chinook salmon require deep, cold pools to hold over in during the summer months prior to their fall spawning period. When these pools exceed 21 C adult Chinook salmon can experience decreased reproductive success, retarded growth rate, decreased fecundity, increased metabolic rate, migratory barriers, and other behavioral or physiological stresses (McCullough 1999).

California Regional Temperatures

To date, there has been no California-wide water temperature study or synthesis of available information. A regional stream temperature study was conducted within the Coho ESU by the Forest Science Project at Humboldt State University (Lewis et al. 2000). The area where coho occur within California is delineated by the Coho ESU includes the northern coast zone and portions of the interior Klamath region. Water temperature was measured at hundreds of sites in a variety of streams and rivers well distributed within the area from approximately San Francisco northward to the Oregon border, and from the coast to approximately 300 km inland. Stream size varied from watershed areas as small as 20 to a maximum of over 2,000,000 hectares. The assessment included new data and historical analysis of historic temperature assessments, augmented with recently measured temperature at the same locations as earlier measurements.

Results of the study provide some general insight into maximum summer stream temperatures within this region of California.

- The regional study confirmed the general increasing trends in temperature from watershed divide to lowlands.

- The annual maximum temperature ranged from 12-25^{o}C in the coastal zone and 14-32^{o}C inland beyond the coastal influence. Temperature as high as 32^{o}C occurs, but is rare.

- The cooling influence of the coastal fog belt on air temperature extends as far inland as 50 km in some rivers, and is significant enough to affect water temperature within a distance 20 km from the coast in some locations. The effect of the cool air is sufficient to reduce some river temperatures by as much as 5-7^{o}C degrees by the time water reaches the ocean. These help prevent prolonged exposure to stressful temperatures. The coast fog zone is the dominant zone for coho productivity in the state.

- Maximum temperature in rivers in the coastal fog belt can exceed 20^{o}C

- No one geographic, riparian, or climatic factor explains water temperature with high precision. Multiple regression models developed from the data explain about 65% of the variability, similar to finding in other parts of the Pacific Northwest (Sullivan et al. 1990).

- The coolest maximum temperatures (<18^{o}C) are most likely to occur where:

    - Distance from divide is less than 10 km.

    - Canopy cover is >75%

- The probability of achieving temperature of <20^{o}C decreases at 1) lower canopy closure, 2) distance from divide as an indicator of stream size, and 3) with distance from the coast.

- There is relatively small difference in maximum water temperatures between interior and coastal streams of similar watershed areas in basins less than 100,000 hectares in size.

What needs to be understood better for California:

- the availability of cool water at the watershed and population scale

- the overall cumulative effect of temperature on the annual basis.

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Primer
on
Sediment
Riparian Exchanges Related to Forest Management in the Western U.S.

Prepared by the
Technical Advisory Committee
of the
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PRIMER: SEDIMENT RIPARIAN EXCHANGE FUNCTION:
Erosion and Erosion and Sediment Processes in California's Forested Watersheds

Erosion is a natural process that is well described for California in several college textbooks (Norris and Webb 1990, Mount 1995). California's evolving landscape reflects the "competing processes of mountain building and mountain destruction", with landslides, floods, and earthquakes working as episodic forces which often create major changes (Mount 1995). In general, the land surface is sculpted by the forces of erosion: water, wind, and ice. The physical and chemical composition of the rock determines how it weathers by these forces. The role of running water in shaping the earth's surface is considered the most important of all the geologic processes and has received the greatest attention by researchers (Leopold et al. 1964; Morisawa 1968).

The rates of natural erosion are very high in the State's regions having greater amounts of rain and snow, such as the geologically young mountains of the Northern Coast Ranges, Klamath Mountains, and Sierra Nevada (Norris and Webb 1990). Mean annual precipitation was shown to be a relatively precise indicator of climatic stress on sedimentation in Northern California (Anderson et al. 1976).

Soil erosion processes on upland watersheds include: a) surface erosion (e.g., dry ravel, sheet and rill), b) gullying, and c) mass movement or wasting (e.g., soil creep and landslides, such as slumps, earthflows, debris slides, large rotational slides). These can occur singly or in combination. Falling raindrops can be a primary cause of surface erosion, especially where soils have little vegetative cover (Brooks et al. 1991). Erosion products deposited by water become "sediment", brought to a channel by gravity and erosive forces. The water-related, or "fluvial", processes active within the stream channel and floodplain are: 1) the transport of sediment; 2) the erosion of stream channel and land surface; and 3) the deposition or storage of sediment.

Sediment Sizes, Transport & Measurement

Sediment is any material deposited by water, but research usually describes sediment according to its size, means of transport, and method of measurement (MacDonald et al. 1991, Leopold 1994). Inorganic sediment ranges in size from very fine clay to very large boulders. Particle size classes tend to be split into a different number of size categories by physical scientists (AGI 2006) and by biologists (Cummins 1962). The Modified Wentworth Scale is commonly used by biologists (Waters 1995) and includes 11 particle sizes and names: clay, silt, sand (five classes), gravel, pebbles, cobbles, and boulders. In addition, sediment includes particulate organic matter, composed of organic silts and clays and decomposed material. Grain size terminology can also vary:

- *Fine-grained sediment* ("fines") includes the smaller particles, such as silt and clay (usually <0.83 mm in diameter). The largest size class for this category varies, sometimes including sand and small gravel (1-9 mm) (Everest et al. 1987).

- *Coarse-grained sediment* represents the larger particles, such as gravels and cobbles. It makes up the bed and bars of many, if not most, rivers. The smallest size class for this category varies, and sometimes includes sand and small gravel (1-9 mm).

Whatever the term used, it is important to understand the sediment definition and particle size that each research article is using before extrapolating the results.

Sediment is transported by streams as either *suspended load* of the finest particle sizes (from clay to fine sand <2.0 mm) that are carried within the water column, or as *bedload* of the larger particles (from coarse sand to boulders) that never rise off the bed more than a few grain diameters. Higher velocity and steeper streambed slope can transport larger grain size, for example.

Since the measurement of sediment transport levels can be problematic, it is done in several ways. (For detailed descriptions of common methods, including the strengths and limitations of each, see MacDonald et al. 1991, Gordon et al. 1992, and Waters 1995.)

Suspended sediment samplers measure direct suspended sediment concentration (SSC) in milligrams of sediment per liter of water (mg/l). Since most sediment transport takes place during high flows, samples must be taken during these periods to develop long-term averages. Many samples are needed near peak discharges to determine the error margin. Two types of samplers can be used: depth-integrating and point-integrating.

Turbidity is a measure of the ability of light to be transmitted through the water column (e.g., the relative cloudiness). Turbidity sampling and meters are often used as a substitute for the direct measurement of the suspended sediment load of a selected stream reach, but the relationship may vary and requires a careful study design to make accurate correlations Turbidity is frequently higher during early season runoff and on the rising limb of a storm’s runoff; automated data collection is now being used to more accurately capture such infrequent events (Eads and Lewis 2003). Turbid water may also be due to organic acids, particulates, plankton, and microorganisms (which can be ecologically beneficial); interpretation must therefore be carefully done. In redwood-dominated watersheds of north coastal California, Madej (2005) found the organic content of suspended sediment samples ranged from 10 to 80 weight percent for individual flood events. Turbidity is not a good indicator for movement of coarse-grained sediments, such as sand in granitic watersheds, since these larger grain sizes move at the bottom of the water column or as bedload (Morisawa 1968; Sommarstrom et al. 1990; Gordon et al. 1992).

Bedload measurement can be a difficult method since this larger-sized sediment must be collected manually during high flows when bedload is in transport. While there are different types of methods and equipment, the Helley-Smith bedload sampler has become the standard for bedload measurement, especially for coarse sand

and gravel beds. Multiple samples must be taken per cross-section of stream. Bedload cannot be collected automatically as readily as suspended sediment can. Bedload as a percentage of suspended load can range from 2-150 percent; 10 percent bedload would be a conservative estimate for a storm event with muddy-looking water in a gravel-bed stream.

Sediment that is deposited within stream channels can be measured by changes in channel characteristics. The most common methods include: a) channel cross-sections, b) channel width / width-depth ratios; b) pool parameters (e.g., fines stored in pools (V*)), c) bed material (particle-size distribution, embeddedness, surface vs. subsurface particle size); d) longitudinal profiles in upstream-downstream directions (e.g., using the “thalweg”, the deepest part of the stream channel).

Fluvial Processes and Sediment

Stream reaches can be defined by the dominant fluvial processes: erosion /transport / storage (Schumm 1977; Montgomery and Buffington, 1997; Bisson, *et al,* 2006). The steep headwaters tend to be the source of erosion, the middle elevation streams are the transfer zone, and the low elevation streams are the depositional zone. However, any given stream reach demonstrates all three processes over a period of time; the relative importance varies by location in the watershed.

Natural Sources of Sediment

Within the riparian zone, natural sediment sources and the effects of the riparian zone tend to vary by the type of channel reach (Montgomery and Buffington, 1997; Bisson, *et al,* 2006). The uppermost parts of many source reaches are characterized by exposed bedrock, glacial deposits, or colluvial valleys or swales. Stream reaches in bedrock valleys are usually strongly confined and the dominant sediment sources are fluvial erosion, hillslope processes, and mass wasting. The colluvial headwater basins have floors filled with colluvium which has accumulated over very long periods of time. Such channels as may exist are directly coupled with the hillslopes, and their beds and banks are composed of poorly graded colluvium. Stream flow is shallow and ephemeral or intermittent. The colluvial fill is periodically excavated by debris flows which scour out the stream channels and delivery large quantities of sediment and large woody debris to downstream reaches (Montgomery and Buffington, 1997; Bisson, *et al,* 2006). There is often is no distinctively riparian vegetation bordering the channels.

A bit further downstream, transport reaches commonly still have steep gradients, are strongly confined and subject to scouring by debris flows. Stream beds are consequently characterized either by frequent irregularly arranged boulders or by channel-spanning accumulations of boulders and large cobbles that separate pools. The boulders move only in the largest flood flows and may have been emplaced by other processes (e.g., glacial till, landslides). Streams generally have a sediment transport capacity far in excess of the sediment supply (except following mass wasting events). Dominant sediment sources are fluvial and hillslope processes and mass wasting (Montgomery and Buffington, 1997; Bisson, *et al,* 2006). The transition between transport and response reaches is especially likely to have persistent and pronounced impacts from increased sediment supply (Montgomery and Buffington, 1997).

In the higher response reaches, stream gradients and channel confinement become more moderate. Incipient floodplains or floodprone areas may begin to border the channels, so they are not so coupled to hillslope processes. The typical channel bed is mostly straight and featureless with gravel and cobble distributed quite evenly across the channel width; there are few pools. Where the bed surface is armored by cobble, sediment transport capacity exceeds sediment supply, but unarmored beds indicate a balance between transport capacity and supply. Dominant sediment sources are fluvial processes, including bank erosion, and debris flows are more likely to cause deposition than scouring (Montgomery and Buffington, 1997; Bisson, *et al,* 2006). There is usually distinctively riparian vegetation along the channel.

Also in low to moderate gradients, braided reaches may form where the sediment supply is far in excess of transport capacity (e.g., glacial outwash, mass wasting) and/or stream banks are weak or erodible (Buffington, *et al*, 2003). Channels are multi-threaded with numerous bars. The bars and channels can shift frequently and dramatically, and channel widening is common. The size of bed particles varies widely. Banks are typically composed of alluvium. Bank erosion, other fluvial processes, debris flows, and glaciers are the dominant sediment sources. Distinctively riparian vegetation is common, and is especially important in providing root strength to weak alluvial deposits (Bisson, *et al*, 2006).

In lower-elevation, lower-gradient response reaches, channels are generally sinuous, unconfined by valley walls, and bordered by floodplains. Beds are composed of gravel or sand arranged into ripples or dunes with intervening pools. Sediment supply exceeds sediment transport capacity, so much of the finer sediment is deposited outside the channel onto the floodplain. The dominant sediment sources are fluvial processes, bank erosion, inactive channels, and debris flows. Distinctively riparian vegetation typically grows on the floodplain where it plays important roles in: i) reinforcing weak alluvial banks and floodplains, and ii) providing hydraulic roughness to reduce erosion during overbank flooding (Montgomery and Buffington, 1997; Bisson, *et al,* 2006).

Natural sediment production in undisturbed watersheds can vary significantly, depending upon soil erodibility, geology, climate, landform, and vegetation. Delivery of sediment to channels by surface erosion is generally low in undisturbed forested watersheds, but can vary greatly by year (Swanston 1991). Annual differences are caused by weather patterns, availability of materials, and changes in exposed surface area. Sediment yields for surface erosion tend to be naturally higher in rain-dominated than in snow-dominated areas. Soil mass movement is the predominant erosional process in steep, high rainfall forest lands of the Pacific Coast. The role of natural disturbances in maintaining and restoring the aquatic ecosystem is becoming more recognized by scientists using interdisciplinary approaches (Reeves et al. 1995).

California Examples

Landslides are an important sediment source in northern coastal ranges of California, particularly where they were active in the wet period of the late Pleistocene and have remained dormant for long periods. If reactivated by undercutting at the toe, these slides can deliver immense amounts of sediment to channels (Leopold 1994). Kelsey (1980) found in the Van Duzen River basin that avalanche debris slides accounted for headwater erosion storage, but that natural fluvial hillslope erosion rates were quite low. In the North Coast range, small headwater streams tend to aggrade their beds during small storms and degrade during large, peak flow events. However, in larger streams, sediment aggrades during large events and gradually erodes during smaller ones (Janda et al.1978).

Sediment budgets offer a quantitative accounting of the rates of sediment production, transport, storage, and discharge (Swanson et al. 1982; Reid & Dunne 1996). They are performed in California by academic researchers (Kelsey 1980; Raines 1991), consultants (e.g., Benda 2003), and agencies. In a review of sediment source analyses completed for agency-prepared Total Maximum Daily Load (TMDL) allocations in nine north coast California watersheds, the amount of the “natural” sediment source contribution ranged from a low of 12% to a high of 72% over the past 20-50 year period (Kramer et al. 2001). An evaluation of sediment sources in a granitic watershed of the Klamath Mountains found 24% of the erosion and 40% of the sediment yield to be natural background levels in 1989 (Sommarstrom et al. 1990). Post-fire erosion can be a major component of sediment budgets in semi-arid regions of California (Benda 2003).

Role of Riparian Vegetation

Forested riparian ecosystems influence sediment regimes in many ways. First, riparian plant species are adapted to flooding, erosion, sediment deposition, seasonally saturated soil environments, physical abrasion, and stem breakage (Dwire et al. 2006). Sediment transported downslope from overland flow passes by riparian vegetation, where it can accumulate or be transported through the riparian area (USEPA 1975; Swanson et al. 1982b). The significance of vegetation’s role in providing bank stability and improving fish habitat was first recognized as early as 1885 (Van Cleef 1885). Riparian plant roots help provide streambank, floodplain, and slope stability (Thorne 1990; Abernathy and Rutherford 2000; NRC 2002) and can bind bank sediment, reducing sediment inputs to streams (Dunaway et al. 1994). Bank material is much more susceptible to erosion below the rooting zone, but vegetated banks are typically more stable than unvegetated ones (Hickin 1984). Soil, hydrology, and vegetation are interconnected in bank stability, though the understanding has developed more slowly

(Sedell and Beschta 1991; NRC 2002). For example, the effect of riparian vegetation roots on the mass stability of stream banks may be overestimated in erosion models, according to recent research (Pollen and Simon 2005). In a study on the Upper Truckee River, California, a willow species provided an order of magnitude more root reinforcement than lodgepole pine and reduced the frequency of bank failures and sediment delivery (Simon, Pollen, and Langendoen 2006).

Riparian vegetation patterns appear to indicate specific landforms and local hydrogeomorphic conditions; the patterns differ by geographic location and climate, such as semi-arid versus humid regions (Hupp and Ostercamp 1996). Since streamside areas tend to have high moisture and low soil strength, they are vulnerable to compaction and physical disturbance (Dwire et al. 2006). For some sediment processes originating from upslope of the riparian zone, vegetation may have little influence. Large, deep-seated landslides are probably not affected by streamside plants and downed wood, for example (Swanson et al. 1982b). Current conditions of riparian plant communities need to be viewed in the context of the historical alterations to the landscape, including land management (NCASI 2005).

Effects of Sediment on Aquatic Life of Streams

While erosion processes can provide sources of gravels for fish spawning, excessive sediment deposition can be harmful to aquatic life. Habitat needs for anadromous salmonid fish of the Pacific Coast are well described by Bjornn and Reiser (1991), with a review of the effects of fine sediment on fish habitats and fish production compiled by Everest et al. (1987), Furniss (1991), Walters (1995), Spence et al. (1996), and CDFG (2004). A brief summary of the effects of sediment on critical life stages of salmon and trout is as follows:

- <u>Spawning</u>: Fine sediment can become embedded in spawning gravels, reducing the abundance and quality available for spawning and possibly preventing the female from excavating her nest (redd); excessive sediment loading can cause channel aggradation, braiding, widening, and increased subsurface flows, all reducing spawning gravel abundance; excess sediment can fill pools that are needed for rest and escapement of adults migrating upstream to spawn.
- <u>Egg Incubation</u>: Excessive fine sediments can suffocate or impede egg development or developing alevins by reducing or blocking intragravel water flow, oxygenation, and gas exchange. Organic sediment, however, can provide valuable food (e.g., bugs) for fish (Madej 2005).
- <u>Juvenile Rearing</u>: Coarse and fine sediment can fill pools, which reduces the volume of habitat available for critical rearing space and the population that can be sustained; fine sediment can cover the streambed and suffocate benthic macroinvertebrates, reducing availability of important food source (Suttle et al. 2004). Chronic turbidity from suspended fine sediment interferes with feeding effectiveness of fry and smolts, reducing their growth rate or forcing them to emigrate (Sigler et al. 1984; Newcombe and Jensen 1996; Rosetta 2004).

The review by Everest et al. (1987) demonstrated that the effects of fine sediment on salmonids are complex and depend on many interacting factors: species and race of fish, duration of freshwater rearing, spawning escapement within a stream system, presence of other fish species, availability of spawning and rearing habitats, stream gradient, channel morphology, sequence of flow events, basin lithology, and history of land use (Furniss et al. 1991). It also should be noted that research on the effect of “fine sediment” on salmonid reproduction (e.g., percent survival of fry emergence from eggs) varies in the definition of sediment size, ranging from 0.85mm to 9.5 mm, but tends to focus on 2.0 millimeters or less (Everest et al. 1987). One needs to be careful in interpretation of the literature when comparing the effects of differently defined “fines” (Sommarstrom et al. 1990.)

The first major literature review on the aquatic effects of human-caused sediment was published in 1961 by California Dept. of Fish and Game biologists Cordone and Kelley, who concluded that sediment was harmful to trout and salmon streams. Productive streams, at every trophic level, contain stored sediment and large organic debris and are more productive than channels with too little or too much sediment (Everest et al. 1987). An early California study of streams with increased sedimentation found that fish biomass decreased in some streams and increased in others (Burns 1972). Stream macroinvertebrate diversity was significantly decreased in stream reaches below failed logging road crossings, implying the effect of higher sediment levels (Erman et al. 1977). In a review of stream characteristics in old-growth forests, the authors noted that many streams in California have naturally high sediment loads, including an abundance of fines less than 1 mm, but historically these streams supported healthy populations of salmonids (Sedell and Swanson 1984).

Forest Management & Sediment Effects

The literature on the erosion and sediment impacts of forest operations is quite extensive, though much of it comes out of the Pacific Northwest. Most of the California research on private forestland has focused on the north coastal redwood region, particularly in the Caspar Creek Experimental Watershed of the Jackson Demonstration State Forest in Mendocino County (e.g., Zeimer 1998; Rice et al. 2004) and in the Redwood Creek watershed as part of Redwood National Park related research (e.g., Best et al. 1995; Madej 2005).

Historic Logging Practices

Certain mid-20th century logging practices were clearly identified as harming water quality. Clearcut logging, of large portions of a watershed down to the edge of streams, and the logging road system, were noted as a major source of sediment in earlier studies in Oregon (Brown and Krygier 1971; Swanson and Dyrness 1975) and California (Cordone and Kelly 1961; Burns 1972). Cordone and Kelley in 1961 perceived that the bulk of stream damage was caused by carelessness and could be prevented “with little additional expense”, they thought at the time. Over thirty years ago, Burns (1972) examined logging and road effects on juvenile anadromous salmonids in northern California streams, with all streams showing sediment increases following logging. Evidence was also gathered to show that good logging practices could reduce sedimentation problems in the western region (Haupt and Kidd 1965; Brown 1983).

Sediment and other impacts led to a series of increasingly protective measures for forestry operations on public and private lands in the U.S. In 1973, California's State Water Resources Control Board recommended improved timber harvest and road construction methods at the time of the passage of the State Forest Practice Act but prior to the adoption of the Forest Practice Rules in 1975 by the Board of Forestry (SWRCB 1973). Tighter stream protection rules were later required by the State, as described under Riparian Buffers below. Berbach (2001) describes the evolution of such measures for private forestland in California.

Roads as a Major Source of Sediment

Logging roads have historically been the largest, or one of the largest, sources of forest management-related sediment (Trimple and Sartz 1957; Megahan and Kidd 1972; Burns 1972; Anderson et al. 1976; Adams & Ringer 1994). One study found that roads can contribute more sediment per unit area than that from all other forestry activities, including log skidding and yarding (Gibbons and Salo 1973). Roads can affect streams directly through the acceleration of erosion and sediment loadings, the alteration of channel morphology, and changes in the runoff characteristics of watersheds. Sedimentation was often greatest when major storm events occurred immediately after construction, while surface erosion usually declined over time with revegetation of roadsides and natural stabilization (Beschta 1978). A long-term study in Caspar Creek in Mendocino County found similar results, but also a lag of sediment transport as material only moved during periods of high runoff and streamflow (Krammes and Burns 1973). In landslide prone terrain, road-related erosion could continue unless certain design, construction and maintenance practices were carried out, or high erosion hazard areas were avoided. Much of the research of logging road effects was on roads that had been constructed in the 1950's, 60's and 70's, before improved road location and design to minimize potential slope stability and erosion problems were applied. By the early 1990s, steps were being taken to minimize the negative effects of roads on streams through both construction and maintenance practices (Furniss et al. 1991; Weaver and Hagans 1994).

Channel crossings, within the riparian area, are often the primary cause of water quality problems associated with roads and the resultant ecological impacts (USFS 1976; Erman et al. 1977; Forman and Alexander 1998). Debris blockages of undersized culverts and flood flows can cause the failure of the logging road stream crossing, delivering large volumes of crossing-fill sediment directly into the channel. In a long-term erosion evaluation of the Redwood Creek watershed, researchers found significant gullying problems due to logging roads, particularly due to diversions at plugged stream culverts or ditch relief culverts (Hagans et al. 1986). These diversions created complex channel networks and increased downslope drainage density, yet 80% of all gully erosion was avoidable, the authors stated, through minor changes in road construction techniques.

Heavily used, unsurfaced logging roads also can produce significantly more sediment and turbidity than abandoned roads, with one study in Washington State showing a 130 fold increase (Reid and Dunne 1984). Road surface sediment can drain into roadside ditches and then into streams, delivering fine sediment detectable by turbidity sampling below the road (Bilby et al. 1989). The problem can be effectively minimized, the authors noted, by draining the ditch onto the forest floor in small quantities to infiltrate, by using better road construction and surfacing material, and by leaving woody debris within the stream. Ketcheson and Megahan (1996) evaluated the potential sediment filtration effectiveness of the riparian zone below road fills and culverts in granitic terrain, finding that road sediment travel distance increased with increasing volume of eroded material.

In some locations, road placement within the stream riparian zone can encroach on the floodplain and channel and force streamflows to the opposite bank, potentially destabilizing the hillslope and causing increased landsliding. Roads located within the landslide-prone inner valley gorge, where very steep slopes are adjacent to streams, are at high risk of frequent or iterative failure (Furniss et al. 1991). A study in the Klamath Mountains of northwestern California noted this relationship (Wolfe 1982). If roads must be located in a valley bottom, a buffer strip of natural vegetation between the road and the stream is recommended (Furniss et al. 1991).

High quality roads and better maintenance are likely to reduce the amount of material supplied to channels from hillslopes, reduce the amount of sediment mobilized along low order streams, and reduce the sediment delivery rate to high order streams (Furniss et al. 1991; Slaymaker 2000). In the past decade, methods to inventory logging road drainages for their potential to deliver sediment have become more standardized (Flanagan et al. 1998; CDFG 2006). Road erosion studies need to be examined in the context of geology and soil types, such as the highly erosive granitics (e.g., Megahan and Kidd 1972).

Some studies have compared the effects of old to new forest practices. Cafferata and Spittler (1998) compared the effects of logging in the 1970s to the 1990s in the Caspar Creek watershed in Mendocino County found that “legacy” roads continue to be significant sources of sediment deca des after construction. Recent Total Maximum Daily Load (TMDL) studies in north coastal California watersheds assessed sediment sources over multiple decades, but the analyses did not distinguish whether logging road-related sediment originated from roads constructed before or after the Forest Practice Act in 1973 (Kramer et al. 2001). However, timber operations under the “modern” Forest Practice Rules produced an estimated erosion rate one-tenth that of pre-1976 practices on a tributary of Redwood Creek (Best et al. 1995). Rice (1999) cautioned about direct comparisons of different studies with different objectives, but concluded that road-related erosion in Redwood Creek was significantly reduced due to improved road standards (e.g., better sizing and placement of culverts). In 1999, the Scientific Review Panel on California Forest Practice Rules and Salmonid Habitat made nine recommendations on road construction and maintenance, including the removal of legacy roads within the riparian zone (Ligon et al. 1999).

Riparian Buffers in Forest Management

The concept of using vegetation and/or obstructions to form buffer strips to minimize or retard downslope sediment movement has been applied to agricultural and forestry operations for many years (Broderson 1973; USEPA 1975). Buffer strips are defined as riparian lands maintained immediately adjacent to streams or lakes to protect water quality, fish habitat, and other resources (Belt et al. 1992). Limiting mechanical harvesting activities within streamside zones is appropriate to protect their vulnerability to compaction and physical disturbance, due to high moisture and low soil strength factors (Dwire et al. 2006).

The U.S. Forest Service adopted the Streamside Management Zone (SMZ) in the 1970s as a Best Management Practice (BMP), for closely managed harvesting, to act as an effective filter and absorptive zone for sediment, to protect channel and streambanks, and other benefits (USFS 1979). Each National Forest's Forest Plan also has Standards and Guidelines for the protection of riparian areas, including specific BMPs (Belt et al. 1992). In 1975, the California Board of Forestry first adopted the Stream and Lake Protection Zone (SLPZs) as part of the state's Forest Practice Rules (FPRs); these riparian zone protections were later expanded by the Watercourse and Lake Protection Zone (WLPZ) in 1983, 1991 and 2000 (Berbach 2001). While the benefits of such riparian protections are not challenged, the extent of the buffer strips (i.e., upslope and upstream) to balance ecological, water quality, and management needs continues to be debated (Dwire et al. 2006).

Direct physical disturbance of stream channels and soils within the riparian area by timber harvest activities can increase sediment discharge (Everest et al. 1987). In a 1975 California field study, physical damage to streambanks during logging was caused by equipment operating through streams, by yarding and skidding timber through channels, and by removal of streamside vegetation. Failed road crossings deposited sediment into the streams, reducing the diversity of the aquatic invertebrate community (Erman et al. 1977). Grant (1988) identified a method, primarily through aerial photograph analysis, to detect possible downstream changes in riparian areas due to upstream forest management activities.

More recent studies have looked at the design of forest riparian buffer strips to protect water quality. The authors of one literature summary stated, "we cannot overemphasize the importance of maintaining the integrity of the riparian zone during harvest operations" in relation to erosion and sedimentation processes (Chamberlin et al. 1991). The use of riparian buffers and BMPs has generally decreased the negative effects of forest harvest activities on surface water quality (Belt et al. 1992; Norris 1993). However, even an intact riparian buffer strip cannot prevent significant amounts of hillslope sediment from entering a stream via overland flow (due to infiltration and saturation excess in severely disturbed soil) or from debris slides originating outside the riparian zone (Belt and O'Laughlin 1994; O'Laughlin & Belt 1995).

One area of research receiving more attention is the riparian zone within headwater and low order streams (e.g., first and second). Sediment deposited in low order streams (which tend to be Class III under FPR rules) may be delivered to high order streams (e.g., third and fourth) that are usually Class I and II. Moore (2005) summarizes the latest results of this headwater research in the Pacific Northwest. MacDonald and Coe (2007) have recently investigated the influence of headwater streams on downstream reaches in forested areas, including the connectivity and effects of sediment. These recent research papers and others on this topic need to be thoroughly examined before consensus can be reached on the conclusions.

In recent years, the use of riparian buffer zones as a management tool has increased. For public lands in the Pacific Northwest, Riparian Reserves (RR) were set aside under the Northwest Forest Plan in 1994, where silvicultural activities were not allowed for multiple reasons, including water quality (Thomas 2004). For private forest lands, stream protection zones have increased in importance and restrictions in the past decade due to the federal and state listings of anadromous salmonid species as threatened or endangered (Blinn and Kilgore 2001; Lee et al. 2004). The current WLPZ rules for California were tightened from the 1991 Rules to protect listed fish species under the "Threatened or Impaired" (T/I) Rules, adopted as Interim Rule Requirements by the BOF in 2000, based in part on the recommendations of the Scientific Review Panel (Ligon et al. 1999; Berbach 2001). Research is now needed on the effects of these newer riparian protection zones, with comparisons made to previously designated zones.

Recent Sediment Evaluations of Forest Practices

Evaluations of forest practices producing and delivering sediment, as a nonpoint pollution source, revealed that Best Management Practice (BMP) implementation was generally good across the U.S., but cases of noncompliance persisted (especially for road and skid trail BMPs (SWRCB 1987; Binkley and Brown 1993). The authors recommended compliance and effectiveness monitoring must therefore be an ongoing activity.

The Board of Forestry's Monitoring Study Group (MSG) has overseen two recent evaluations of the effectiveness of the Board's Forest Practice Rules (FPRs). The Hillslope Monitoring Program (Cafferata and Munn 2002) evaluated monitoring results from 1996 through 2001, while the Modified Completion Report (Brandow et al. 2006) continued analysis of data from 2001 through 2004. Both studies found that: 1) the rate of compliance with the FPRs designed to protect water quality and aquatic habitat is generally high, and 2) the FPRs are highly effective in preventing erosion, sedimentation and sediment transport to channels when properly implemented. The 2006 report concluded the following:

> In most cases, Watercourse and Lake Protection Zone (WLPZ) canopy and groundcover exceeded Forest Practice Rule (FPR) standards. With rare exceptions, WLPZ groundcover exceeds 70%, patches of bare soil in WLPZs exceeding the FPR standards are rare, and erosion features within WLPZs related to current operations are uncommon. Moreover, in most cases, actual WLPZ widths were found to meet or exceed FPR standards and/or widths prescribed in the applicable THP…
>
> When properly implemented, road-related FPRs were found to be highly effective in preventing erosion, sedimentation and sediment transport to channels. Overall implementation of road-related rules was found to meet or exceed required standards 82% of the time, was marginally acceptable 14% of the time, and departed from the FPRs 4% of the time. Road-related rules most frequently cited for poor implementation were waterbreak spacing and the size, number and location of drainage structures…
>
> Watercourse crossings present a higher risk of discharge into streams than roads, because while some roads are close to streams, all watercourse crossings straddle watercourses. Overall, 64% of watercourse crossings had acceptable implementation of all applicable FPRs, while 19% had at least one feature with marginally acceptable implementation and 17% had at least one departure from the FPRs. Common deficiencies included diversion potential, fill slope erosion, culvert plugging, and scour at the outlet…

Attention has recently focused on riparian management of low order streams by management agencies, the public, and scientists. Gaps in knowledge are still being identified for the Pacific region and the diversity of riparian management standards continue to be debated (Young 2000; Moore 2005).

What We Do Not Know or Do Not Yet Agree Upon:

- The need for buffer strips along low order (e.g., 1st, 2nd) streams to prevent or minimize the delivery of sediment to higher order streams during forestry operations.

- The amount of forest management that can be performed within a designated riparian buffer zone without accelerating sediment production and delivery.

- The sediment effects of the newer, riparian protection zones for forest management, with comparisons made to previously designated zones.

- The relevance of forest management research on sediment relationships in riparian zones in other western states to California, and the relevance of such research in California's north coastal redwood region to other region's of the state.

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Primer
on
Water
Riparian Exchanges Related to Forest Management in the Western U.S.

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PRIMER : WATER RIPARIAN EXCHANGE FUNCTION

Salmonid Life-Cycle Needs Related to Water

Important habitat characteristics for salmonids in streams include minimum streamflow, obstructions to flow that create debris dams and have other effects on stream shape, and gravel necessary for spawning (Botkin and others 1994). The riparian zone along streams influences all of these factors. Streamflow, and the sediment this flow transports, interact with large wood, boulders, and bedrock outcrops to produce physical characteristics of streams required by fish, including side channels in floodplains, and pools and riffles in small main-stream channels.

The amount, velocity, and depth of water required by salmonids varies depending on the life stage. Bjornn and Reiser (1991) present a comprehensive review of this topic for North American salmonids. Migrating fish require water depths that allow upstream passage [e.g., minimum water depths of 0.09 m to 0.12 m for chum salmon, depending on substrate particle size (Sautner and others 1984)]. Streamflow affects the amount of spawning habitat available by regulating the area covered by water and the velocities and depths of water over gravel beds [e.g., velocities ranging from 0.3 to 3.0 m/s and a minimum depth of 0.18 m (Thompson 1972)]. Stream discharge, followed by water velocity, are the most important factors in determining the amount of suitable living space for rearing salmonids [e.g., velocities < 10 cm/s for newly emerged salmon and trout fry (Everest and Chapman 1972); depths ranging from water barely deep enough to cover juveniles to > 1 m (Bjornn and Reiser 1991)].[1] In general, salmonid carrying capacity increases as streamflow increases up to a point, and then levels off or declines if velocity becomes excessive (Bjornn and Reiser 1991, Murphy 1995).

Minimum streamflows in both summer and late fall are critical for juvenile rearing and successful spawning for salmonids, respectively. Murphy (1995) reported that minimum streamflow in summer limits salmonid carrying capacity on a broad scale. For example, total commercial catch of coho salmon off of Washington and Oregon was found to be directly related to the amount of summer streamflow when the juveniles were in streams two years before (Smoker 1955, Mathews and Olson 1980). Botkin and others (1994) found that streamflow, especially the minimum flow in November three and four years prior to adult returns, accounted for most of the variation in adult spring Chinook adult salmon returning to spawn in the Rogue River in Oregon.

Effects of Forest Management on Peak Flows, Low Flows, and Water Yield

The effects of forest management activities on streamflow have been studied since the early 1900's and are summarized in Ziemer and Lisle (1998) and Moore and Wondzell (2005). Changes in peak flows, low flows, and water yield resulting from forest removal are very complex. The magnitude of change to both water yield and peak flows depends on the amount and location of the harvest, the stand age and composition of the vegetation removed, soil and lithologic characteristics, topography, and climatic conditions. The persistence of the effect is largely determined by the rate and composition of vegetation re-occupying the disturbed site.

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[1] Note that in an area with numerous deep pools and cool groundwater contribution, discharge and velocity can be very low, compared to an area without pools.

In terms of aquatic habitat, key hydrologic concerns relate to changes in summer low flows, and in peak flows and their effects on channel stability and sediment transport (Moore and Wondzell 2005). In a comprehensive review of forestry impacts on aquatic habitats, Botkin and others (1994) concluded that there is no evidence or reason to believe that changes in flow due to forest harvest would be deleterious to fish. They state that increases in flood peaks would be expected to cause a slight increase in channel mobility and an increase in the transport of bed sediment (factors that relate to spawning and rearing habitat), but there do not appear to be field studies relating changes in flooding to degradation of fish habitat.

Peak Flow Changes

Ziemer and Lisle (1998) provide a comprehensive description of how changes in peak flows associated with forest management vary with watershed size, type of precipitation, season, and flood magnitude. In general, the effects of forest practices are more pronounced and easier to detect in small watersheds, greater in areas where rain-on-snow events occur, greater in the fall months, and greater for frequent runoff events. More detailed information on these principles and specific examples and are provided in the paragraphs that follow.

Substantial (e.g., $\geq$30-50% clearcut) harvesting in small to medium-sized watersheds[2] over short time periods is required to noticeably increase small to medium recurrence-interval peak flows associated with timber harvesting. Limited harvesting in riparian areas alone cannot affect flood frequency or magnitude.

Ziemer (1998) reported a 9 percent increase in 2-year peak flows following clearcutting approximately 50 percent of the North Fork Caspar Creek watershed (5 km^2), located near Fort Bragg, California.[3] Ziemer and Lisle (1998) state that: "There is little evidence that forest practices significantly affect large floods produced by rain. However, it is possible that clearcutting exacerbates some rain-on-snow floods, although the magnitude of such an effect is highly variable and difficult to measure or detect."[4] They also explain that the greater the size of the flood or basin being investigated, the less likely that there will be any detectable changes caused by forest practices.

Specific peak flow studies in the Pacific Northwest confirm these conclusions. Thomas and Megahan (1998) found that treatment effects decreased as flow event size increased and were

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[2] Ziemer and Lisle (1998) define small basins as having drainage areas $\leq$ 1 km^2 (~250 ac) and large basins as >100 km^2 (~25,000 ac). Medium-sized basins can be considered be on the order of 10 km^2 (~2,500 ac).

[3] The WLPZ Forest Practice Rules tested in the North Fork Caspar Creek watershed were those in effect from 1983 to 1991 (e.g., Class I buffer strips of 200 ft for slopes >70%). In 1991, maximum Class I WLPZs were reduced to 150 feet for slopes >50%.

[4] Snow accumulation tends to be higher in openings than under forest canopies, with cut blocks typically accumulating about 30 percent to 50 percent more snow. Removal of the forest canopy exposes the snow surface to greater incident solar radiation as well as to higher wind speeds, which can increase sensible and latent heat inputs. During mid-winter rain-on-snow events, melt rates are typically governed by sensible heat transfer from the relatively warm air, condensation of water vapor onto the snowpack, and in some cases by the sensible heat of rainfall. Under these conditions, snowmelt may significantly augment rainfall, increasing the magnitude of flood peaks (Moore and Wondzell 2005).

not detectable for flows with 2-year return intervals or greater for small treated watersheds that were either clearcut or patchcut with roads in the H.J. Andrews Experimental Forest, located in the western Cascade Mountains of Oregon in the rain-on-snow zone. Beschta and others (2000) analyzed the same data and concluded that treatment effects were unlikely for peak flows with recurrence intervals of approximately 5 years or greater, and that a relationship could not be found between forest harvesting and peak discharge in the large basins.

In a broad summary of the literature, Moore and Wondzell (2005) reported that peak flows increased following forest harvesting in most studies in coastal catchments, with increases ranging from 13 percent to over 40 percent based on the original analyses. They also found that in coastal watersheds, the magnitude of forest practice-related peak-flow increases declined with increasing event magnitude in most cases, with the greatest increases typically associated with autumn rain events on relatively dry catchments. Moore and Wondzell (2005) state that peak flow change does not appear to be related in any simple way to the percentage of basin area cut or basal area removed, and that estimates of post-treatment recovery rates varied among studies.

Timber harvesting affects the amount of interception loss that takes place in forested watersheds. This, in turn, may influence changes in winter peak flows. Interception loss has been reported as approximately 20% in coastal California forests (Reid and Lewis, in press), and more generally as about 10 to 30 percent of total rainfall, depending on canopy characteristics and climatic conditions (Moore and Wondzell 2005). Differences in interception loss between logged and unlogged areas are likely to explain the majority of the observed increases in larger winter peak flows, when transpiration is at its annual minimum (Ziemer 1998, Lewis and others 2001).

Small increases in peak flows (≤ 10%) for 2-5 yr return interval events have been found to be relatively benign and have not been judged to be capable of substantially modifying the morphology of the stream channels (Ziemer 1998). This is due to the fact that the magnitude of peak flow changes is substantially less than the within-a-year and year-to-year variability in streamflows. The changes are within the normal range of variability of streamflows (Grant and others 1999).

In addition to harvesting effects, roads can have significant hydrologic impacts (Coe 2004). Several studies have shown that logging roads can intercept shallow subsurface flow and rapidly route it to the stream network, potentially leading to increased peak flows in headwater basins (Moore and Wondzell 2005), or possibly delayed peaks in larger watersheds due to desynchronization of peak flows from tributary basins. Pathways linking the road network to stream channels include roadside ditches draining directly to streams, and roadside ditches draining to culverts that feed water into incised gullies (Wemple and others 1996). Accelerated runoff at the road segment scale also results since haul roads have compacted surfaces with low permeability that generate overland flow in even moderate rainstorms (Coe 2004, Moore and Wondzell 2005).

At the basin scale, paired-watershed studies have not shown strong evidence to support road-induced increases in peak flows. Studies may have been hampered by insufficient pre-treatment calibration data, lack of treatment replication, and poor experimental control (i.e., road building and timber harvesting have often occurred simultaneously or in quick succession) (Thomas and Megahan 1998, Coe 2004). Modeling studies have shown that increases in peak flows due to roads were approximately equal to the effects from timber harvesting (i.e., canopy removal) in an experimental watershed in western Washington (Bowling and Lettenmaier 2001). The effect of both activities declined as the flow recurrence interval increased. Additionally, modeling studies suggest that roads can decrease baseflow during the critical summer months (Tague and Band 2001). However, much uncertainly still exists regarding the hydrologic effects of roads at the watershed scale (Coe 2004, Royer 2006). If there are impacts from road building on peak flows, these effects will be more pronounced and easier to detect in smaller basins (Ziemer and Lisle 1997).

Channel aggradation, or filling of the channel bed with sediment, can have a significant effect on flood height or flooding. Where aggradation is severe, it is more important for overbank flooding than changes in runoff due to logging operations (Lisle and others 2000). Widespread channel aggradation can occur in low gradient reaches of watersheds if the sediment production rate has been significantly accelerated above background rates by mass wasting and surface erosion and delivery processes. If this happens, similar magnitude peak flows to those which would have occurred earlier can cause more extensive over-bank flooding downstream because of reduced channel capacity. These flood events would be the consequence of rainfall/runoff/channel aggradation interactions, rather than rainfall/runoff interactions. The area flooded would be changed by the altered channel configuration, even if the amount of water remained the same.

Low Flow Changes

Forest removal in mountainous watersheds will increase low summer and early fall streamflows, as well as total water yield. Botkin and others (1994) reported that while total water flow in a stream is important to salmon, flow increases during summer and early fall that can augment streamflow at a critical season for juvenile rearing are more important than the changes in magnitude of total annual flow. Nearly all published reports on timber harvesting and resulting changes in summer low flows have shown that streamflow will either increase or remain unchanged in proportion to the amount of vegetation removed in the watershed. Harvested areas contain wetter soils than unlogged areas during periods of evapotranspiration, and hence higher groundwater levels and greater late-summer streamflow (Chamberlin and others 1991).

Studies have documented that the post-treatment recovery rates are highly variable depending on the severity of the treatment and the vegetation reoccupying the site, along with physiographic and climatic characteristics. Often increases are fairly short-lived, as regeneration begins to utilize surplus soil moisture and intercepts precipitation. After approximately 10-30 years, baseflow (and peak flow rates) have returned to normal or decreased below pre-harvest levels due to rapidly growing hardwoods that transpire more water than mature conifer trees (Murphy 1995, Moore and Wondzell, 2005). Long-term effects of logging on summer low flows likely depends primarily on species composition before and after harvest (Spence and others 1996, Moore and Wondzell 2005). In general, summer low flows are more sensitive to transpiration from riparian vegetation than from vegetation in the rest of the catchment (Moore and Wondzell 2005).

One example in California of documented water yield changes with both selective harvesting and clearcutting has taken place in the Caspar Creek watershed. The effects of selective logging on low flows were examined in the South Fork Caspar Creek watershed, where 64 percent of the second-growth stand volume of coast redwood and Douglas-fir was tractor logged from 1971 to 1973. Statistically significant summer low flow enhancements were evident for 7 years after logging. Minimum discharge increases averaged 38 percent after the selective harvesting and summer low flow volumes increases averaged 29% between 1972 and 1978 (Keppeler and Ziemer 1990, Rice and others 2004). The average length of the part of the low flow period when flow in the South Fork was less than 0.2 cfs was shortened by 43 days form 1972 to 1978, a 40% reduction. As in previous studies, most of the enhanced streamflow (average annual water yield) increase (approximately 90 percent) was realized during the rainy season while greater relative increases were witnessed during the summer low flow period (Keppeler 1986).

In the North Fork Caspar Creek watershed, approximately 50 percent of the watershed was clearcut harvested over about 7 years (1985 to January 1992).[5] Minimum discharge increases averaged 148 percent at the North Fork weir and flow enhancement persisted through hydrologic year 1997 with no recovery trend observed. The larger increases in the North Fork were probably due to wetter soils in the clearcut units, where little vegetation was present to use the additional moisture (Keppeler 1998). This data suggests that water yield effects will persist longer after clearcutting than when a similar timber volume is removed from a watershed with selective cutting. These differences in water yield recovery are probably related to changes in rainfall interception and evapotranspiration (Rice and others 2004). Enhanced summer low flows improve aquatic habitat in stream channels. In the Caspar Creek study, higher discharge levels increased habitat volumes and lengthened the flowing channel network along logged reaches during the summer and early fall months (Keppeler 1998).

The amount of increased water flow caused by forest management activities on summer low flows of large rivers is unknown, but Botkin and others (1994) state that based on studies extrapolated elsewhere, it is reasonable to assume that there would be a small positive effect. Given the importance of low flow increases to salmonid production, however, this change may be significant.

Annual Water Yield Changes

For total annual water-yield changes with forest management, most small-watershed studies have shown that in areas with significant precipitation (>100 cm/yr or ~40 in/yr), increases in streamflow are proportional to the reduction in forest cover. This is due to reduced losses from evapotranspiration by the trees in rain-dominated systems. Moore and Wondzell (2005) reported that in rain-dominated small catchments, clearcutting and patch-cutting increased yields by up to 6 mm for each percentage of basin harvested, while selective cutting increased yields by up to about 3 mm for each percentage of basal area removed. Increased water yield, however, is not uniformly distributed seasonally or throughout the rotation in the Pacific Northwest and California. Most of the annual increase occurs in the winter high-runoff season and during the wetter years, rather than during the summer season and drought years, when the

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[5] Most of the clearcut harvesting (45.5%) took place from the spring of 1989 to January 1992 (Henry 1998).

additional water is needed (Ziemer 1987).[6] When vegetation reduction in a watershed is less than 20 percent, the expected water-yield increase is not measurable and the remaining trees will likely use as much water as the original stand (Bosch and Hewlett 1982).

Ziemer (1987) summarized the literature on this subject and reported that total water yield increases resulting from management in larger basins would be very small and not measurable. For example, Kattelmann and others (1983) estimated that for National Forest lands in Sierra Nevada watersheds, streamflow could only be increased one percent if multiple use/sustained yield guidelines were followed.

While there is some evidence in the arid southwestern United States that expansion of the phreatophytic riparian forests along rivers can contribute to streamflow declines (Thomas and Pool 2006), this does not appear to be a significant concern for most California watersheds with coniferous forests. For forest streams with narrow strips of riparian forest, riparian vegetation water use is usually a small portion of the overall water budget and probably has minor influence on annual water yield (Dr. Julie Stromberg, Arizona State University, Tempe, AZ, personal communication). As an example, complete felling of a strip of riparian vegetation in a small watershed at Coweeta Hydrologic Laboratory in North Carolina produced only very minor water yield increases (Hewlett and Hibbert 1961). With the limited harvesting in riparian zones that is allowed under the current forest practice rules in California, water-yield increases are not expected to be measurable.

Stormflow Generation

Water is transferred through riparian zones to channels by surface and subsurface flow. Shallow or lateral subsurface flow from hillslopes in steep forested watersheds in the western United States is widely recognized as a main contributor to stream flow generation; however, processes that control how and when hillslopes connect to streams are still being studied. Much of the difficulty in deciphering hillslope response in the stream is due to riparian zone modulation of these inputs (McGuire and McDonnell 2006).

A key concept for forested watersheds is that there is great temporal and spatial variability in how water is transferred to the channel. Streamflow in small forested headwater basins is usually generated from an expanding and contracting source area, often denoted as the variable source area, representing a fraction of the total basin area. The source of streamflow is usually that part of the basin nearest the perennial, intermittent, and ephemeral channels. Source areas (the hydrologically-active areas that contribute directly to stormflow) can vary from only one percent of the total basin area in small storms to 50 percent or more in very large storms. The percentage of saturated source area in a watershed is topographically sensitive (i.e., higher percentages occur with gentler slopes). The source areas within a watershed are very dynamic, expanding and contracting during events as the influx of precipitation progresses and then ends.

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[6] This was observed in areas with rain-dominated winter periods, where summer storms are infrequent, as is found in California. In contrast, experimental studies on eastern U.S. watersheds (rain-dominated) have shown that peakflow and water yield increases dominate during the growing season months, since approximately half of the annual precipitation (in the form of higher-intensity convective storms) occurs from May through October.

Moisture redistribution continues following the rain event as slower lateral hillslope drainage supplies additional moisture to lower slope positions. Direct runoff and its source area increase due to channel expansion and slope water movement (Hewlett and Nutter 1970, Troendle 1985). Riparian areas associated with perennial and larger intermittent streams remain at or near saturation during the winter and hence are hydrologically active for transporting water by saturated overland flow and rapid subsurface flow via soil macropore and/or displacement flowpaths. Smaller intermittent and ephemeral streams are only active when the hydrologic network expands sufficiently to incorporate steeper-gradient channels. Ephemeral first order channels (typically Class III watercourses) flow only in response to direct rainfall, and, although they are part of the hydrologic network, they do not generally have riparian zones because hydrophilic (water-dependent or water-loving) plants are usually absent.

Water Exchange and Transfer within the Riparian/Floodplain Zone

Water is exchanged in riparian zones, and larger floodplains in several ways. Streams either gain water from inflow of groundwater (i.e., gaining stream—moving water from the riparian zone to the channel) or lose water by outflow to groundwater (i.e., losing stream—moving water from the channel into the riparian zone). Many streams do both, gaining in some reaches and losing in other reaches. Input of cold groundwater to the bottom of pools can be a key refugia feature for anadromous fishes in summer months (Osaki 1988).

The riparian zone has been conceptualized as a zone of transmission of ground water and hillslope water to the stream channel, as well as a direct router of precipitation and snowmelt when the riparian water table rises to the ground surface. Between storms, and even during small storms with dry antecedent conditions, subsurface inputs from adjacent hillslopes are often minimal. At these times, two-way exchanges of water between the stream and the riparian aquifer (hyporheic exchange) can become important (Moore and Wondzell 2005). The hyporheic zone is an area adjacent to the channel and below the floodplain (if present) where surface water and groundwater mix. Hyporheic zones link aquatic and terrestrial systems and serve as transition areas between surface water and groundwater systems. The hyporheic zone contains species common to both surface and subsurface systems, including a diverse community of macroinvertebrates. Few hyporheic studies have focused on unconstrained headwater streams in the Pacific Northwest. Consequently, the knowledge of hyporheic hydrology draws largely upon studies of larger, unconstrained streams.

Transpiration by vegetation in the riparian zone may extract groundwater from the riparian aquifer, producing a diurnal decrease in riparian water-table level and in streamflow, followed by recovery at night. Lundquist and Cayan (2002) report that diurnal cycles are evident in many western river records and that daily variation in streamflow is often 10-20% of the daily mean flow. Harvesting in the riparian zone can have a significant influence on riparian-zone hydrology through its effect on transpiration and water-table drawdown, potentially dampening or eliminating diurnal fluctuations in discharge and increasing low-flow discharges (Bren 1997). During extended periods of low flow, sections of small streams dry up wherever stream discharge is insufficient to both maintain continuous surface flow and satisfy water losses through the bed and banks. Stream drying may occur frequently in the headmost portions of the channel network, interrupting connectivity (Moore and Wondzell 2005). Also, forestry-related changes in channel morphology can substantially influence stream-aquifer interactions. Channel incision and simplification of channel morphology during large floods can substantially lower water tables and reduce exchange flows of water between the stream and the riparian aquifer (Wondzell and Swanson 1999).

Neither the effect of forest harvesting nor the effect of riparian buffer strips on hyporheic exchange flows has been directly examined in small headwater streams (Moore and Wondzell 2005). Moore and Wondzell (2005) hypothesize, however, that because channel morphology strongly controls hyporheic exchange, it is reasonable to assume that timber operations that lead to losses in channel complexity would reduce interactions between the stream and the riparian aquifer. In contrast, they state that efforts to minimize management impacts on channels, such as retention of riparian buffer strips, would help preserve stream-aquifer interactions. The ecological implications of decreased stream-aquifer interactions are stated as being difficult to predict with current knowledge. Moore and Wondzell (2005) report that Wondzell and Swanson's research (1996) suggests that such decreased interactions could lead to reduced nutrient cycling and reductions in stream productivity.

Forest Management Impacts on Water Transfer/Exchange Processes

Forest management activities include timber falling, timber yarding, road and crossing construction and use, site-preparation activities, herbicide applications, forest thinning, etc. Forest operations on a watershed-basis can influence surface and subsurface runoff in several ways. For example, decreased interception loss increases the amount of water infiltrating the soil, leading to higher water-table levels during storms (Moore and Wondzell 2005). Limited timber falling and tree removal in riparian zones alone will reduce interception loss and evapotranspiration, but will likely have little impact on streamflow (low flows, peak flows, or annual water yield), as discussed previously. In contrast, ground-based yarding activities in riparian zones and floodplains of larger river systems can adversely impact important overflow channels used by salmonids during high winter storm discharges. Additionally, riparian areas are vulnerable to both compaction and physical disturbance during ground harvesting operations due to areas of high soil moisture and low soil strength that are common within streamside zones. These concerns, along with riparian and aquatic habitat protection, provide a basis for limiting mechanical harvesting activities within riparian zones (Dwire and others 2006).

Considerably less is known about forest management impacts associated with small headwater channels when compared to larger fish bearing watercourses. Even though streamflow is sporadic in ephemeral first order channels (typically Class III watercourses), it is capable of transporting fine sediment down to fish-bearing streams. Rashin and others (2006) found that at several study sites in Washington, delivery of sediment to unbuffered tributaries resulted in adverse impacts to fish-bearing streams that were otherwise adequately protected by riparian buffers.

Field evidence from the Caspar Creek watershed suggested that unbuffered, headwater stream channels, particularly in burned areas, contributed significantly to suspended sediment loads. Lewis and others (2001) state that sediment increases in the North Fork Caspar Creek tributaries probably could have been reduced by avoiding activities that denuded or reshaped the banks of the small headwater channels. Much of the post-harvest increases in sediment yield in the North Fork were attributed to harvest-induced storm flow volume increases (Lewis and others 2001), suggesting that the hydrologic changes can be practically and not just statistically significant (Moore and Wondzell 2005). Therefore, there is evidence that increased flows in small headwater channels, as well as disturbance of these channels, can produce increased downstream sediment transport. Further discussion of sediment delivery is provided in the California State Board of Forestry and Fire Protection's Technical Advisory Committee (TAC) Sediment Primer.

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Chapter 1

INTRODUCTION

Stream temperature has been and continues to be of concern in watersheds throughout Northern California. There has been a heightened interest in the potential effects of altered stream temperatures on salmonids and other aquatic/riparian species. Several regulatory measures have been promulgated to mitigate impacts of increased water temperatures on aquatic biota. Restoration activities have been initiated, conservation measures developed, and land use practices altered to minimize potential alterations in stream temperatures throughout the state of California and the Pacific Northwest. Land stewards in the private and public sector have been gathering temperature data for several years. With the onset of continuous temperature sensor technology, large volumes of stream temperature data are now being assembled and analyzed. More and more state and federal agencies and private landowners are choosing continuous stream temperature monitoring devices over thermometers because of the need for diurnal and seasonal water temperature data.

Stream temperature is an important factor in aquatic ecosystems for several reasons. Water temperature directly and indirectly influences fish physiology and behavior in several ways (Spence et al., 1996):

- Metabolism
- Food requirements, appetite, and digestion rates
- Growth rates
- Developmental rates of embryos and alevins
- Timing of life-history events, including adult migrations, fry emergence, and smoltification
- Competitor and predator-prey interactions
- Disease-host and parasite-host relationships

Stream temperature may also influence other aquatic and riparian species such as reptiles, amphibians, and macroinvertebrates. Collection of stream temperature data is driven largely by the concern for aquatic biological resource protection. Monitoring of stream temperature to assess diurnal and seasonal variation is a prerequisite to assessing potential acute and chronic thermal impacts to aquatic biota. The seasonality of life histories of the species of interest must also be considered when monitoring stream temperatures. Thus, monitoring that captures the temporal trends in stream temperature is needed to assess thermal exposures of different life stages.

Background

With the onset of continuous temperature sensor technology, large volumes of stream temperature data are available and are continuing to be gathered. Despite the hundreds of gigabytes of stream temperature data collected by various groups and agencies throughout California, no regional synthesis and assessment of these data has been published and no clear understanding of temperature regimes and their association with natural resource management exists. This regional stream temperature assessment focuses on a well defined geographic area of interest (AOI), namely the California portion of the Southern Oregon Northern Coastal California (SONCC) and the Central California (CC) evolutionarily significant units (ESUs) for coho salmon (*Oncorhynchus kisutch*). It is unknown whether all streams in the AOI are temperature sensitive in relation to the California Forest Practice Rules or other pertinent land management treatments (i.e., Northwest Forest Plan).

To identify sensitive streams in the AOI, characterization of stream temperature regimes in the various watersheds, basins, and ecoregions comprising the AOI is essential. A characterization of contemporary thermal regimes across a broad geographic area was the primary goal of the Forest Science Project's regional stream temperature assessment.

State and federal agencies are lacking information on what range of stream temperatures are physically achievable in a stream reach, watershed, or basin, given the prevailing management prescriptions and climatic conditions. Provided with this information, agencies would be able to (1) set reach- or watershed-specific temperature standards that are scientifically defensible, (2) assess the relative contributions of natural and human-induced factors to non-attainment of stream temperature standards, (3) identify and prioritize stream reaches that are grossly out of compliance and most in need of remediation, and (4) establish realistically attainable temperature-reduction goals for streams, watersheds, and basins that may have naturally high water temperatures. The Forest Science Project's regional stream temperature assessment provides agencies, land stewards, and landowners with the information needed to make important decisions regarding adaptive management, remedial measures, and restoration goals.

Scope

The watersheds and basins within the California portion of the SONCC and Central California ESUs were defined as the geographic area of interest. This area extends from the Oregon border south to San Francisco and eastward to the Central Valley (Figure 1.1).

This assessment report is based on data gathered by numerous private landowners, and various state and federal agencies. Approximately 1100 sites with stream temperature records spanning nine years were assembled and analyzed. Predominantly, results from analyses of 1998 data are included in the various chapters found in this report since 1998 was the most complete data set with which to work.

The assessment is restricted to data collected using continuous sensor technology. Snapshot (synoptic) data using hand-held thermometers or min-max thermometers were not included in statistical analyses in the regional assessment. Some synoptic data were used in qualitative comparisons of recent stream temperatures to historical stream temperatures. Hourly (or other time interval) data from continuous sensors were obtained from the various data contributors. Data that were aggregated to a particular temporal or spatial level prior to submission to the Forest Science Project were not used due to potential differences in statistical analytical procedures and aggregation approaches. Consistent data verification, validation, and spatial and temporal aggregation were deemed critical for increasing the likelihood of data comparability for statistical comparisons (i.e., comparing apples with apples).

The amount of site-specific information provided by data contributors was limited. In some instances, analyses on a reduced subset of the data were performed to explore important site-level or landscape-level relationships. In such cases, the number of sites and their geographic distribution are illustrated for evaluation. In some instances, Geographic Information System (GIS)-derived (e.g., elevation, distance to coast) or regional data (e.g., air temperature, flow, degree day) were used to perform analyses. As mentioned previously, 1998 had the most complete data set in terms of stream temperature and site-specific attribute data. Thus, many of the analyses presented in the report are based on 1998 data.

The majority of data contributors collected stream temperature data during the summer months (June through September). Some investigators allowed temperature recorders to remain in the stream for longer or shorter periods of time. Inasmuch as the preponderance of data was gathered during the summer season, the assessment report focused on summertime stream temperatures. The juvenile life stage of coho salmon and other anadromous species is the stage most commonly encountered during the summer. Thus, the report places stream temperature analyses in the context of potential thermal stress on summer juveniles of coho salmon primarily, with some reference to other anadromous juvenile salmonids. This is not to imply that juvenile and adult

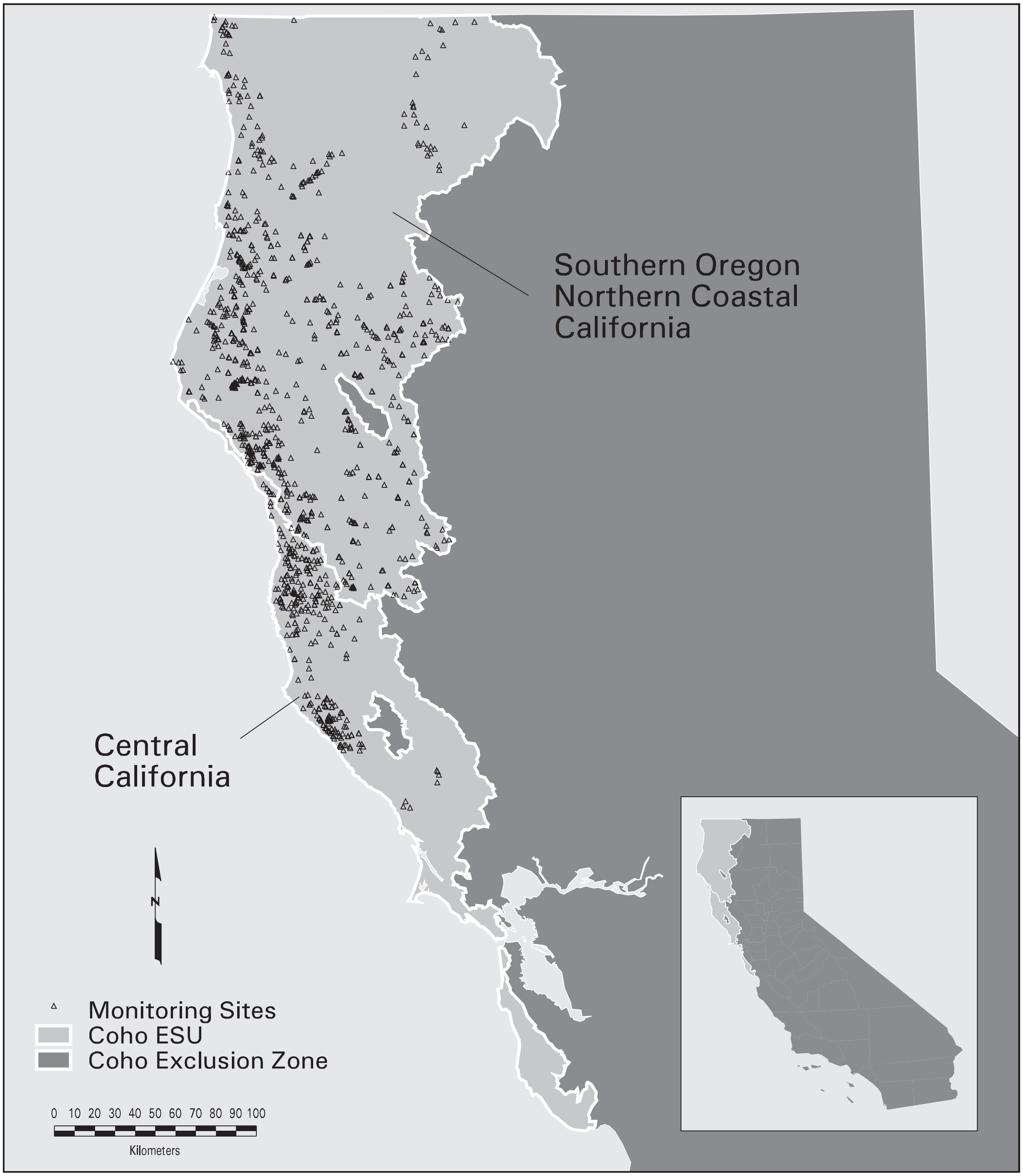

Figure 1.1. Area of interest for FSP's Regional Stream Temperature Assessment as defined by the Southern Oregon Northern Coastal California and Central California evolutionarily significant units.

Table 1.1. Seasonal Occurrence of Adult, Embryonic, and Juvenile Anadromous Salmonids in Freshwaters of Western Oregon and Washington. Modified from Everest et al. (1985).

		Month											
Species	Life Stage	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Coho Salmon	Adult	■	■										
	Young	■	■	■	■	■	■	■	■	■	■	■	■
	Eggs	■	■	■									
Winter steelhead trout	Adult	■	■	■	■	■							
	Young	■	■	■	■	■	■	■	■	■	■	■	■
	Eggs	■	■	■	■								
Summer steelhead trout	Adult	■	■	■	■	■	■	■	■	■	■	■	■
	Young	■	■	■	■	■	■	■	■	■	■	■	■
	Eggs	■	■	■									
Spring chinook salmon	Adult			■	■	■	■	■	■	■	■		
	Young	■	■	■	■	■	■	■	■	■	■	■	■
	Eggs	■	▌								■	■	■
Fall chinook salmon	Adult	■							■	■	■	■	■
	Young	■	■	■	■	■	■	■	■	■			
	Eggs	■	■								■	■	■
Sea-run cutthroat trout	Adult	■	■							■	■	■	■
	Young	■	■	■	■	■	■	■	■	■	■	■	■
	Eggs	▐	■	■									

stages of various species are not present in the various systems in the AOI during the summer months, e.g., chinook salmon and steelhead trout. However, juvenile stages are known to be the most sensitive to thermal stress, hence the reason for this focus. Table 1.1 can be used as a reference tool to determine other species of interest and the life stages that may inhabit systems in the AOI during the summer temporal window of interest assessed in this report.

Objectives

The objectives of this stream temperature assessment report were:

1. Compile available stream temperature data in a verified and validated database for purposes of regional assessment
2. Assess status and trends in stream temperatures across the region
3. Evaluate the influence of regional scale factors (e.g., climate, geographic location, watershed position, etc.) and site-specific factors (e.g., canopy closure, channel orientation, etc.) on status and trends in stream temperatures
4. Through the assessment process identify areas where improvements in existing protocols and analysis and synthesis are needed
5. Identify knowledge gaps in site-specific information that should be collected on a routine basis to improve our assessment capabilities and move us closer to a regional stream temperature sampling design
6. Identify knowledge gaps between stream temperature monitoring and information on the distribution of coho salmon and other aquatic species

Chapter 2

METHODS

Study Design

There was no study design in place for this stream temperature assessment. Land stewards that submitted data for the assessment collected stream temperature data under a multitude of objectives and assumptions. These diverse objectives can be grouped into three broad categories:

- Pre- and post-timber harvest plan monitoring
- Thermal reach monitoring
- Characterization of thermal refugia

Forest Science Project cooperators and other parties that submitted stream temperature data can be characterized as forested landowners and stewards. Therefore, the population of stream temperature monitoring locations fell predominately in forested catchments or on lands zoned as Timber Protection Zone (TPZ) or Agriculture Exclusive (AE). Some mainstem river sites were exceptions. Data from both private landowners and public resource management agencies were acquired. Thus, the land management prescriptions were dependent upon whether monitored streams were on private or public lands.

Site Selection

The stream temperature data available for analysis and assessment were entirely dependent upon the willingness of the cooperator to provide the data. The data collected reflects a broad spectrum of climatic, hydrological, topographical, and ecophysiographical conditions. As a consequence, an array of sites reflecting a range of riparian conditions across the region allowed for post-stratification of variables by hierarchical spatial scales for statistical analyses. Site selection was not based on a probabilistic or random sampling design. Rather, the sites reflect a multitude of cooperator interests and monitoring objectives in a particular stream or watershed. Table 2.1 lists the various data contributors whose data were included in this assessment.

Data were accepted from contributors for inclusion in the assessment if they met all required criteria. Additionally, many data contributors submitted one or more of the optional criteria.

Required

- Stream temperature measured with a continuous monitoring device capable of taking an integrated or instantaneous reading every 2.5 hours (as opposed to a hand-held thermometer or max-min thermometer read infrequently)

- Site coordinates provided (lat/long, UTM, state plane, or hard copy maps)

- Monitors placed in Class I streams (data from some Class II streams were received)

Optional

- Air temperature measured simultaneously at the water temperature monitoring site

- Site-specific characteristics (e.g., slope, aspect, canopy closure, habitat type) measured for a (thermal) reach. Thermal reach defined as approximately 600 m for this study.

Table 2.1. Stream Temperature Data Sources for the Forest Science Project's Regional Stream Temperature Assessment.

					YEAR				
Source	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**
Barnum Timber Company								12	23
Bureau of Land Management							2		
CA Dept. Fish & Game								4	
Elk River Timber Company								6	4
Fruit Growers Supply								14	18
Georgia Pacific West, Inc.				63	54	66	64	64	75
Gualala Redwoods, Inc.					17	27	27	26	28
Humboldt County RCD							152	159	113
Humboldt State University									12
Jackson State Forest							49	34	27
Louisiana Pacific Corporation					16	15	53	36	
Mattole Salmon Group							16		
Natural Resources Cons. Serv.						11	14	13	4
NRM Corporation						3	15	23	26
Pacific Lumber Company					4	10	25	54	27
Pacific SW Experiment Station					7	7	13		
Pioneer Resources								41	39
Redwood National Park						1	1	11	10
Russ Ranch & Timber Company							2	4	9
Shasta-Trinity National Forest	15	18	17	10	23	14	6	16	13
Sierra Pacific Industries							14	24	17
Simpson Timber Company					40	30	10	29	44
Six Rivers National Forest				3	5	12	26	42	42
Soper/Soper-Wheeler Company					1				
Stimson Redwood Company					4		7	6	7
Timber Products Company							4	9	10
TOTAL	15	18	17	76	171	196	500	627	548

- Microclimatic data such as relative humidity, evaporation, sky cover, available in association with water temperature

The regional stream temperature assessment data base included 2168 site-years representing 1090 spatially unique continuous stream temperature monitoring sites. Site coordinates were available for all sites used in the assessment report. In most cases, coordinates were provided by the cooperator with the stream temperature data. In some cases, location of monitoring sites were denoted on maps that were provided by the cooperators. Coordinates were assigned to these sites using heads-up (interactive, on-screen) digitizing techniques and 1:24,000 scale digital raster graphic (DRG) topographic quadrangles. A spatial accuracy assessment was performed in January of 1999. The procedures used for the spatial accuracy assessment are described below.

Spatial Accuracy Assessment

Site coordinates provided by the project cooperators were evaluated using 1:24,000 scale DRG images. DRGs are an accurate, georeferenced digital representation of United States Geological Survey (USGS) topographic quadrangles. Note, USGS 1:24,000 scale data are purported to meet National Map Accuracy Standards for 1:20,000 or smaller scale, which state that 90% of well-defined features are within 40 ft of their true position.

An initial examination yielded varying degrees of displacement from the hydrographic component ranging from a few meters to 63 kilometers. The sources of these errors may include: base mapping sources other than USGS 1:24,000 quadrangles, transcription, digitizing and geocoding anomalies, projection and datum differences. While the potential problems arising from an error in position of 63 kilometers are quite obvious, errors of less than 10 meters can cause misleading analytical results. Small positional errors within a stream network, especially near a tributary confluence, can cause the incorrect association of a mainstem temperature site with a tributary site or visa versa. This leads to invalid relationships between sites, errors in drainage area and aspect computation, and other erroneous results. Large displacement errors will lead to the incorrect association of elevation, ownership, basin membership and other attributes necessary for spatial stratification and reporting which are critical to a regional assessment.

From the initial site survey, it was determined that a 100% site location validation strategy be developed. Stream temperature site locations were divided into groups by cooperating organization. ArcView projects consisting of site locations, DRG images, and other relevant geospatial data were developed for each group. Office visits with each cooperator were scheduled with the individual having the most knowledge of the site location to assist in the repositioning process.

There were 817 out of 1090 total sites that included both before and after site coordinate validation. The remaining 273 sites had their initial coordinates derived during office visits and were not used in the spatial accuracy analysis.

Examination of the horizontal displacement exposed 294 sites with errors greater than 50 m. A frequency distribution graph of the horizontal spatial error for 817 sites is shown in Figure 2.1. This level of spatial displacement can have severe adverse effects. Stream network position can be altered by changing a site's relationship to a tributary-mainstem confluence. Since many temperature sensors are located within 50 m of a confluence, many mainstem sites were incorrectly located above, below, or on the tributary. This will have deleterious effects when modeling the influence of a tributary's temperature input.

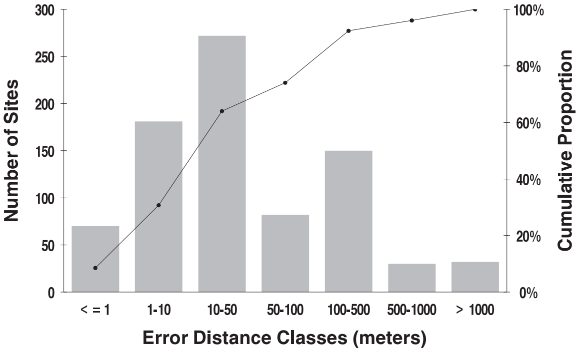

Figure 2.1. Frequency and magnitude of inaccuracies in the spatial location of stream temperature monitoring sites before site coordinate validation.

Of these 294 sensor sites, 62 sites had horizontal errors of greater than 500 m. These positional errors located many sites in the wrong drainage basin.

Upon completion of this process, the database was updated with the upgraded position and additional GIS-derived attributes.

Determining and Documenting Location

As discussed above, establishing and documenting the correct site location was critical. Key to this process was determining the required level of accuracy necessary for analysis. Digital data at a scale of 1:100,000 were found to be both lacking in spatial quality and quantity. Many stream temperature monitoring sites were located on streams represented only on 1:24,000 scale data. Hence, it was determined that the majority of GIS-based analyses would be undertaken at a scale of 1:24,000.

Two important considerations of site location are absolute positional accuracy and network topology. A high degree of absolute positional accuracy can be achieved by obtaining the site location coordinates using the Global Positioning System. This system of 28 satellites and a ground-based receiver can typically locate a site to within several meters of the true location. However, this will not ensure that a site's network topology is correctly established. Due to the spatial error in 1:24,000 scale data, a site with a high degree of absolute positional accuracy may well be incorrectly located within the network topology. Network topology describes a site's relative location within a network, in our case a hydrological network, e.g., the site is on the mainstem of the Mad River, 20 m downstream of confluence with Mill Creek.

Characterizing a site's network location with reference to well-defined features in addition to locating the site on a 1:24,000 scale topographic quadrangle will ensure that the spatial relationships between sites are maintained and that a site can be located and reestablished in the future.

GIS-Derived Variables

Once the spatial accuracy of stream temperature monitoring locations was confirmed, certain attributes were derived in GIS using standard overlay principles, raster modeling, and other methods facilitated by Arc macro language (AML) and Avenue script programs. The AML and Avenue script code can be found in Appendix A. The GIS- and Avenue-script-derived attributes were:

AML-derived
coho ESU
steelhead ESU
chinook ESU
ecoprovince
hydrologic unit (HUC)
CAL planning watershed
total maximum daily load (TMDL) Consent Decree Basin
elevation
shortest distance to coast
watershed area
distance to watershed divide

Avenue-derived
channel orientation
channel gradient
channel sinuosity

Watershed area and distance to divide were acquired by applying a simple hydrologic model to a compiled and edge-matched 1:24,000 scale digital elevation model (DEM). The compiled DEM was created by mosaicing more than 400 U.S. Geological Survey (USGS) 7.5-minute tiles. DEMs are generally available from the USGS in two distinct levels of quality. DEMs classified as Level I are created using a manual profiling procedure or the Gestalt Photo Mapper. Typically, Level I DEMs have inherent errors exhibited by elevation shifts in bands along the east-west axis. Level II DEMs are elevation data sets that have been processed for consistency and edited to remove identifiable systematic errors. Level II DEMs are created using hypsographic (contours) and hydrographic (streams) data which produce a somewhat smoother more continuous surface model. Where Level II DEMs did not exist, one of two procedures were used to create the necessary tiles. Several 30-meter DEMs were created in-house from 1:24,000 scale vector contour data while others were created by resampling USGS Level II 10-meter DEMs to a 30-meter spacing.

The compiled DEM was processed to remove spurious sinks, i.e., areas of undefined flow, by filling these to a surrounding outlet elevation. The assembled DEM was evaluated for internal and along-tile boundary errors by computing a flow-direction and flow-accumulation model for each logical basin within the Area of Interest (AOI). Any break in flow within a logical basin before reaching the natural outlet (Pacific Ocean) was determined to be an error requiring an appropriate correction. Once a flow corrected DEM existed, upstream watershed (drainage) area and divide distance were derived for each temperature monitoring site.

Using 1:24,000 scale digital raster graphics (DRGs) and USGS 30-meter digital elevation models ArcView (Environmental Systems Research Institute, Redlands [ESRI], CA) combined with Avenue scripts were used to acquire the necessary information to compute the desired attributes. Channel orientation was calculated by tracing a 600-meter reach upstream of each temperature sensor location. From this point a straight-line distance and bearing was calculated back to the sensor location. Channel orientation represents this bearing in compass degrees where north equals 0 degrees. Elevation was acquired from the DEM for the sensor site and the location 600 meters upstream. Channel gradient was calculated as the difference in elevation between these two sites divided by the reach length. Channel sinuosity was calculated by dividing the reach length (600 meters) by the straight-line distance between the two locations. Very straight reaches yielded sinuosity values nearly equal to 1.

It is important to be aware of and understand the associated errors of these products and how these errors can affect results. For example, gradient values of less than or equal to zero were occasionally acquired from sites located along channels with little natural elevation change. While a negative upstream gradient may be disconcerting, these sites can confidently be described as very low gradient reaches. Since our application was at a regional scale and we were looking at general classifications (e.g., flat, sloped, very sloped, steep), the realized error was considered acceptable.

Calculated Water Temperature Metrics

Various water temperature metrics were calculated from the data. These metrics were considered important in characterizing the thermal regimes in water temperature across Northern California. These included:

- daily minimum
- daily mean
- daily maximum
- seven-day moving average of the daily minimum
- seven-day moving average of the daily mean
- seven-day moving average of the daily maximum

The above six metrics comprise the core set of statistics that were used throughout the regional assessment. Other metrics, representing both chronic and acute thermal stress, are presented in subsequent chapters and are therein defined.

Daily and weekly temperature metrics were further reduced to single statistics for each site for each year. For example, for a given site, the highest daily maximum temperature for the year was used as a temperature index that was compared to various climatic, landscape, and site-specific attributes. Similarly, the highest seven-day moving average of the daily average was compared to similar independent variables. A list of the yearly summary statistics calculated from the daily and weekly data and most commonly used in our analyses is presented in Table 2.2.

A naming convention was developed for assigning variable names to yearly temperature metrics. While the abbreviations may seem unwieldy upon first encounter, they become second nature once an understanding of the naming convention is acquired. The first letter denotes that the yearly statistic is the ma**X**imum (**X**), **A**verage (**A**), or m**I**nimum (**I**) for the year. The second letter denotes that the statistic is a **Y**early statistic (**Y**). While a complete year (i.e., January 1 through December 31) of temperature is not used to calculate the yearly statistic, the value

Table 2.2. Most Commonly Used Yearly Temperature Statistics Calculated from Daily and Weekly Data Sets.

Yearly Site-Level Statistic	Abbreviation
highest daily maximum	XY1DX
lowest daily minimum	IY1DI
highest seven-day moving average of the daily average	XYA7DA
highest seven-day moving average of the daily maximum	XYA7DX

represents the maximum, average, or minimum for the defined sampling window in a given year. Obviously, the minimum for the year is not captured in the defined sampling window. For seven-day moving averages, the third letter specifies that the statistic is the ma**X**imum (**X**), **A**verage (**A**), or m**I**nimum (**I**). If the metric is based on a daily value, e.g., the daily average, daily minimum, or daily maximum, the third character in the variable name is a one ('1') and the fourth is a 'D' for **D**aily. If the statistic is based on a seven-day moving average the fourth and fifth characters in the variable denote this by '**7D**'. The last character specifies that the statistic is the daily value or seven-day moving average of the ma**X**imum, **A**verage, or m**I**nimum.

Some examples will help clarify the naming convention. The ma**X**imum (or highest) daily (**1 D**ay) ma**X**imum for the **Y**ear would be represented as **XY1DX**, where

X = ma**X**imum for the year
Y = a **Y**early statistic
1D = **1 D**ay or daily
X = ma**X**imum.

The m**I**nimum (or lowest) daily (**1 D**ay) m**I**nimum temperature for a site in a given **Y**ear would be denoted as **IY1DI**, where

I = m**I**nimum for the year
Y = a **Y**early statistic
1D = **1 D**ay or daily
I = m**I**nimum.

The ma**X**imum (or highest) **7-D**ay moving **A**verage of the daily **A**verage for a site in a given **Y**ear would be encoded as **XYA7DA**, where

X = ma**X**imum for the year
Y = a **Y**early statistic
A = **A**verage
7D = **7 D**ay moving average
A = **A**verage.

Potential Errors in Calculating Water Temperature Metrics

In calculating summary statistics for the various temperature metrics it was found that a potential error was inherent in the data. The highest daily minimum and lowest daily maximum were influenced by daily records that did not contain a complete number of observations due to removal of anomalous readings, e.g., ambient air spikes. If only a portion of the daily observations were removed, an incomplete daily record resulted. For example, if the sampling frequency of a device was set to take an instantaneous reading every hour, 24 observations per day should be found for each daily observation. However, if anomalous readings were removed from the daily record, less than 24 observations were observed for certain days. When the daily minimum and daily maximum temperatures were calculated using Statistical Analysis System (SAS) (SAS, 1996), days that had an incomplete number of observations had elevated daily minimum and depressed daily maximum temperatures, depending on the time of day data were missing.

Due to errors introduced in the data due to missing observations, a SAS program was written to search the hourly data set for days where the number of observations was less than the maximum number of daily observations or the maximum number of daily observations minus one. The ***maximum minus one*** provision was used to compensate for sites where the