State of California **The Resources Agency**

M e m o r a n d u m

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From: **Department of Forestry and Fire Protection**
Sacramento Headquarters

Subject: **Clearcut Adjacency Rule—Petition to the California State Board of Forestry and Fire Protection dated September 10, 2003 (Microclimate Rule Petition)**

Abstract

A petition has been submitted to the California State Board of Forestry and Fire Protection requesting that the Forest Practice Rules be changed to prohibit adjacent clearcut units unless trees are at least 25 years old or 25 feet tall in the existing unit. Currently the rule requires that trees must be 5 years old or 5 feet tall. The petition claims that "science now tells us that air temperature is the single most influential element governing water temperature." I conducted a brief literature review to examine the validity of this statement. There is disagreement in the literature regarding the importance of changes in air temperature on stream water temperature. It is clear that air temperatures tend to be highly correlated with average water temperatures, and in a regional context, air temperature is an important parameter for predicting water temperature. While several studies have found a cumulative effect of timber harvesting on water temperatures, this has not been linked to air temperature changes. Modeling suggests that elevated air temperature from clearcutting with buffer strips is a contributing factor to higher water temperatures, but not the dominant parameter. More important variables appear to be reduced vegetative shading (allowing more solar radiation to reach streams), changes in channel morphology, altered streamflows, and heating of unvegetated near-stream soils and alluvial substrates. It is impossible to know exactly how much benefit would be derived to stream water temperatures with a 25 year—25 feet tall clearcutting rule from the existing literature, but the preponderance of evidence suggests that the benefit would be relatively small. This literature review just addresses the air temperature—water temperature issue. The petition to the Board also mentions soil erosion and sediment yield aspects related to clearcutting, and this concern will be addressed in a subsequent review of the literature.

Introduction and Background Information

At the request of Mr. Dennis Hall, Acting Chief of Forest Practice, I conducted a brief review of the scientific literature regarding whether clearcutting large percentages of watersheds in a short time period can elevate stream water temperatures because basin air temperatures have been increased due to canopy removal.

Currently, the California Forest Practice Rules require evenaged regeneration units, including clearcut blocks, to be separated by at least 300 feet in all directions (ref. 14 CCR § 913.1[933.1, 953.1](a)(3)). The rules also state that no logical logging unit contiguous to an existing evenaged management unit may be harvested using an evenaged regeneration method (e.g., clearcutting) unless the dominant and codominant trees average at least 5 years of age or average at least 5 feet tall, and 3 years of age from the time of establishment on the site, either by planting or by natural regeneration (ref. 14 CCR § 913.1(a)(4); with a slight variation in the Northern and Southern Districts).

The petitioner requests that the five year requirement be raised to 25 years and the five foot tall rule be elevated to 25 feet, so that the rule would state: logging units contiguous to an existing evenaged management unit may be harvested using an evenaged regeneration method when the dominant and codominant trees average at least 25 years of age or average at least 25 feet tall. The petition states that "***science now tells us that air temperature is the single most influential element governing water temperature***." The petition also states that "in addition to cooling air temperature, so vital for amphibians and the water temperature for threatened and endangered fish, this rule would reduce erosion and slow down habitat loss."

Previously Summarized Literature

An earlier review prepared for Mr. Snyder (Cafferata 2002) reported that there are four environmental factors that primarily regulate heat input and output from the stream environment, and thereby determine stream temperature under any given solar loading: riparian canopy, stream depth, local air temperature, and groundwater inflow (Sullivan et al. 1990, Adams and Sullivan 1989). Riparian vegetation regulates stream temperature by providing shade that reduces direct solar heating. This is especially important in smaller streams (Murphy 1995). Diurnal fluctuations of water temperature are strongly influenced by the fluctuation of both solar insolation and air temperature. Regardless of riparian cover and stream size, air temperature influences both mean and maximum water temperature, and is an important input variable in several prediction models (Sullivan et al. 1990).

Timber harvesting adjacent to streams can lead to increases in daily maximum stream water temperatures largely due to the increased exposure of the stream surface to direct solar radiation. Typically, increases of 3 to 7° C in daily maximum temperature can be expected with removal of significant amounts of shade from the streamside zone of small streams (Sullivan et al. 1990). The magnitude of temperature change with removal of streamside vegetation varies with stream size (Brown 1969, Adams and Sullivan 1989). Daily maximum temperatures in very small streams tend to have the largest response to forest canopy removal (Doughty et al. 1991). Timber harvesting can influence stream temperature by either reducing riparian shading of a stream due to harvest or by accelerating mass wasting processes such as debris torrents (WFPB 1997).

Local air temperature is the single most important parameter influencing the daily **mean** stream temperature at equilibrium, and mean stream temperature will always be very near the mean air temperature (Adams and Sullivan 1989). Similarly, Lewis et al. (2000) reported mean water temperature is generally within a few degrees of mean air temperature measured at stream-side. Shallow streams reach equilibrium much more rapidly than deep streams (Adams and Sullivan 1989). Removal of riparian vegetation has relatively modest impact on the **mean** stream temperature because the energy gain due to increased solar radiation influx is partially offset by increased energy loss by radiation to the sky (back radiation) (Adams and Sullivan 1989).

Direct solar radiation affects the magnitude of stream temperature **diurnal** variations (i.e., daily maximums)—with a relatively small impact on mean stream temperature at equilibrium. Riparian vegetation influences direct solar radiation and primarily influences the diurnal temperature fluctuation and, therefore, **maximum** stream temperature (Beschta et al. 1987).

A general warming of water temperatures in the downstream direction has also been observed in Washington and Oregon (Sullivan et al. 1990, Zwieniecki and Newton 1999). Reasons for this include: 1) air temperatures increase with decreasing elevation, 2) river widening results in less shading, and 3) groundwater flow decreases in importance compared to the volume of flow already in the channel. Sullivan et al. (1990) found that the two dominant factors correlated to stream temperature that could be used to reliably predict temperature sensitivity are shading and elevation (indicating an air temperature regime). This resulted in the development of a temperature sensitivity screen for Washington. Riparian shade is unlikely to have a significant influence on stream temperatures where the natural low flow stream width exceeds 100 feet (Sullivan et al. 1990), while at higher elevations, streams are not likely to exceed water quality standards for maximum temperature due to cooler mean air temperatures (Sullivan et al. 1990).

In California, Lewis et al. (2000) reported that air temperature has a significant influence on stream temperatures. Air temperatures, however, did not strictly follow expected elevational cooling trends across the northwestern California study area. Near the coast, air temperature was more a function of distance from the ocean. In interior areas, air temperatures did decrease with increasing elevation. In addition, air temperatures measured very near water temperature monitoring sites showed greater correlations with water temperatures than remote air temperature data. Water temperature was also found to increase with both increasing distance from the watershed divide and increasing drainage area. These geographic position factors are largely surrogates for air temperature and stream size.

A few studies have documented changes in air temperature with vegetation removal in the vicinity of streams. Sullivan et al. (1990) reported that comparisons between air temperatures within and outside buffer strips in Washington revealed that buffer strips do reduce air temperature changes in the riparian zone compared to clearcut areas. In paired measurements, they found that air temperature following harvest increased about 5% within the vegetated buffer, and jumped to 15% greater beyond the boundary between the cutover area and the buffer. In California, some authors have reported that the use of stream buffers allow air temperatures to increase and relative humidities to decrease over undisturbed conditions in riparian zones, with potential adverse impacts on terrestrial riparian flora and fauna (Ledwith 1996, Erman and Erman 2000). Ledwith (1996) studied air temperatures and relative humidities in riparian zones at two sites that had been clearcut with buffers in the Six Rivers National Forest. Measurements were collected for buffer widths of 150 m, 90 m, 60 m, 30 m, 15 m, and 0 m. Air temperatures above the stream increased exponentially with decreasing buffer width, with a 6.5° C increase in mean air temperature along the riparian zone between the 150 m and 0 m buffer width sites. Ledwith (1996) concluded that buffer strips wider than 30 m will still affect microclimate in the riparian zone, but at a lower rate of change than narrower zones (e.g., 1° C or 2° C), and that buffer strips at least 100 feet wide (30 m) are necessary to avoid significant alteration of microclimate.

Erman and Erman (2000) studied microclimate conditions in eight small stream basins in the Sierra Nevada Mountains. Temperature sensors recorded data at three heights on five transect grids to a maximum distance of 128 m from the stream in 1997 and 176 m in 1998. Air temperature varied by distance from the stream, density of canopy cover, height above ground, aspect of stream banks, time of year, weather conditions, and elevation. Temperatures increased gradually to the maximum distance in basins with dense canopy. Openings in canopy were directly related to higher temperature and lower relative humidity.

James (2003) has collected detailed information on microclimate and water temperature changes associated with different levels of harvest in buffer strips and differing buffer strip widths at the Southern Exposure research site in the Cascade province of northern California. Microclimate results revealed that edge effects from adjacent upslope clearcut harvest units had no discernible impact within 40 ft. (12.2 m) of the stream bank. Timber operations conducted in the summers of 2000 and 2001 resulted in ± 1.5° C changes in daily maximum water temperature pattern along the experimental reach. The average and maximum daily air temperature patterns within the riparian zone harvest units (stream bank out to 40 ft.) were increased at most up to 0.5 °C due to the adjacent upland experimental harvest treatments. Average and maximum daily air temperatures were increased up to 5 °C beyond 40 ft. from the stream bank within the harvested blocks. When the buffer was reduced from 150 ft. to 100 ft., the average daily soil temperature increased up to 2 °C for the microclimate station located between 80 ft. to 175 ft. from the stream bank. No change in the average daily soil temperature pattern was found in the riparian zone adjacent to the harvest units (stream bank out to 40 ft.) after the two experimental harvest treatments during the three-year study.
In small to intermediate sized streams, incoming solar radiation is the dominant form of energy input during summer months (Spence et al. 1996). Therefore, key factors for predicting water temperature **changes** (i.e., increases in daily maximums) are the surface area of the stream exposed to sunlight in summer months and stream discharge. Water temperature increase is directly proportional to the area opened to sunlight and inversely proportional to stream discharge (Beschta et al. 1987).

Effective temperature control is achieved by buffer strips with trees and shrubs that actually shade the stream during the critical summer months of the year. For small forest streams, about 80 percent of the effective riparian shade is produced by vegetation within approximately 0.6 site-potential tree heights (Steinblums et al. 1984, Broesfske et al. 1997—as displayed in CH2M-Hill and Western Watershed Analysts 1999). For a 170 foot site potential tree, this distance would be about 100 feet. Similarly, Murphy (1995) states that, in general, 30 m (approximately 100 feet) wide buffer strips provide nearly the same shade as in old-growth forest (where old-growth canopy density varies from 80 to 90%). Shade effectiveness is also influenced by site specific conditions, including density and height of vegetation, stream width, stream reach orientation, and latitude and sun angle (CH2M-Hill and Western Watershed Analysts 1999).

Cafferata (2002) concluded that:

- Shading from riparian vegetation has an important effect on preventing stream heating, but this varies with site elevation and stream size. Other local environmental factors including air temperature, stream width, and stream depth have an important influence on stream temperature.
- In a regional context, air temperature is an important parameter for predicting water temperature.
- In a local setting, mean stream temperatures will largely follow mean air temperature, given time for equilibrium to occur.
- For large rivers, water temperature is more a function of air temperature than riparian shading.
- For small streams, maximum diurnal variation occurs with low levels of shading.
- Buffer strips over 30 m reduce air temperature increases when compared to clearcut areas, but some small air temperature increase (e.g., 0.5° C to 2° C) still is likely to occur (James 2003 and Ledwith 1996).
- Buffer strips of 30 m will generally provide adequate shading to reduce solar radiation inputs and prevent significant changes in daily maximum water temperatures on small forested streams.

Additional Information

The following additional information addresses the claim in the petition submitted to the Board that air temperature in a heavily harvested basin is the single most important element governing water temperature.

Beschta et al. (1987) state that incoming solar radiation is the principle source of energy heating a stream and exposed streams receive more solar heating. Energy transfers via convection or evaporation are less important. Both require wind movement at the stream surface to be effective, and temperature and vapor pressure gradients. Vapor pressure and temperature gradients close to the water surface are small and wind speeds are usually low. In addition, energy transfers involving convection and evaporation tend to counterbalance each other (Beschta et al. 1987). ***They state that warm air temperatures tend to be highly correlated with water temperatures, but the former are not the cause of the latter***. Similarly, Stillwater Sciences (2003) state that daily maximum air temperatures are strongly correlated with stream temperature, but this does not imply any causal mechanisms between high air temperature and water temperature.

Long-term stream temperature data for Salmon Creek, an 80,000 ac tributary to the Middle Fork of the Willamette River in western Oregon Cascades shows that maximum temperatures increased 6° C or more for the 10 warmest days of each year over the 30-year study period from 1955 to 1984 (Beschta and Taylor 1988). Air temperature trends show a small decline over the period of study, and hence cannot explain the observed increases. The authors state that "*Based on energy balance considerations, Brown (1983) indicated that convective heat exchanges between air and water have little effect on the temperatures of streams draining forested watersheds. Thus long-term trends in maximum air temperatures (if any) should be independent of stream temperatures and cannot be used as a basin for predicting long-term changes in stream temperature. To test this conclusion, we selected maximum air temperatures associated with the 10 days of each year having the highest stream temperatures. A slight decrease in maximum air temperatures was found for the 30-yr period of record, even though stream temperatures were generally increasing. This result appears to confirm the expected independence between maximum air and stream temperatures.*" Regressing maximum stream temperatures against a 30-yr index of cumulative harvesting revealed a strong relationship (r^2=0.65, significant at p<0.01). Maximum temperatures also tended to increase for several years following major peak flow events, and may be in response channel changes caused by mass failures (e.g., increased channel width) and associated with high flows. Water temperature data were taken from the basin outlet of the Salmon Creek watershed, and daily maximum temperature values were likely more extreme in the smaller headwater streams. Recent records for the watershed show a reduction in stream temperatures, with likely reasons related to reductions in logging activity, absence of major storms (and associated mass movements), recovery of streamside vegetation, and changes in a wide range of management practices that came into effect since 1970 to reduce environmental impacts.

Brosofske et al. (1997) sampled five streams before and after clearcutting in western Washington, with stream buffers that ranged from 55 feet to 235 feet. They concluded that a buffer at least 45 m (~150 ft.) on each side of the stream is necessary to maintain the natural riparian microclimatic environment along streams in their study area. Air temperature at the stream was raised by 2–4°C after harvesting, and changes in temperature variability from the stream to the upland, as measured by the coefficient of variation (CV), were significantly higher after harvesting (Dong et al. 1998). Soil temperatures were strongly correlated (r^2 = 0.75 to 0.98) with stream temperatures for pre-harvest conditions. The relationship persisted for post-harvest areas, but r-squared values were slightly lower than those at pre-harvest sites. Regression analyses between stream water temperature and air temperatures revealed intermediate effects (r^2 = 0.20 to 0.70).

A sensitivity analysis of the U.S. Fish and Wildlife Service's Stream Network Temperature Model (SNTEMP) in Bartholow (1989) illustrates which input variables are most important in predicting stream temperatures. This shows that water temperature is very sensitive to changes in air temperature when stream flow is low, inflow temperature is low, width-to-depth ratio is high, relative humidity is high, and wind speed is high (Bartholow 1989). Water temperature will not be as sensitive to air temperature when these conditions are not present. This paper also shows SNTEMP model predictions of mean and maximum daily water temperature with changes in various input mechanisms and air temperature is clearly the most sensitive factor.

In a more recent paper, Bartholow (2000) states that while physical models have been applied to predict stream temperature as a function of shading, little modeling work has gone into exploring the cumulative effects of vegetation removal on the streamside ecosystem. Therefore, Bartholow (2000), used the Stream Segment Temperature Model (SSTEMP, a Microsoft Windows application which has been used extensively and validated) to model the cumulative effects of large scale clearcutting on stream temperature from a hypothetical stream segment from the Pacific Northwest. This work was used to determine the relative contribution of the various physical changes for elevating stream temperature. Bartholow (2000) reviewed the literature and summarized the impacts of clearcutting to mechanisms known to influence water temperature, including air temperature, relative humidity, wind speed, ground temperature, solar radiation, ground reflectivity, groundwater inflows, and stream width. The model was run for a 6 mi. (10 km) reach in both a fully forested area and for a clearcut case on August 1st, recording differences in predicted maximum daily water temperature for each single variable change, and for the whole set. A riparian buffer strip with stream shading decreasing from 55% to 45% was assumed for the clearcut case, and air temperature was assumed to increase 2° C near the stream channel. Overall, clearcutting increased mean daily temperatures by 2.4° C and maximum temperatures by 3.6° C over the 6 mi. reach. Stream shading was the most sensitive variable, accounting for 1.48° C of the increase in maximum daily temperature, stream width increase was second (1.35° C) and air temperature was third, adding 0.61° C. Stream widening was assumed to occur due to elevated erosion and sediment yields associated with timber operations. **Bartholow (2000) concluded that stream temperature increases due to large-scale timber harvest is controlled by a complex set of factors, not simply a single factor (i.e., air temperature, stream shading, etc.).**
He also states that air temperature did not appear to be as important in governing the increase in maximum daily water temperature as direct solar radiation.

After a phone discussion with Mr. Barthalow, I reran this model for both conditions, holding stream width (and Manning's n) constant. With this scenario, clearcutting increased mean daily temperatures by 1.2° C and maximum temperatures by 1.9° C over the 6 mi. reach. Change in shading accounted for approximately 77% of the increase and change in air temperature accounted for about 32% of the increase (see Figure1).

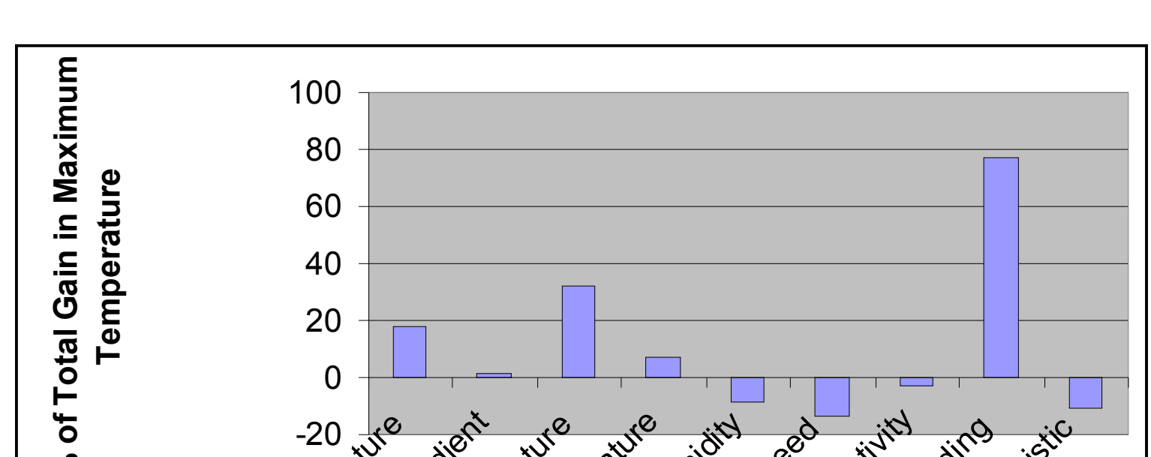

Figure 1. Bartholow's (2000) Figure 1 recalculated for constant channel width and Manning's n. Stream shading is assumed to decrease from 55% to 45%, air temperature is assumed to increase 2° C.

Tank experiments have also demonstrated the importance of shading over air temperature in regulating water temperature. For example, Moore et al. (1999) (as cited in Ice 2001) measured water temperature in 4 tanks, 2 of which were shallow and 2 deep. One of each depth tanks was shaded with plywood, but with a 12-inch headspace for air exchange. The rate of heating and cooling increased, given the same surface area, as depth increased. It was concluded that air temperature had
relatively little influence on the rate of heating and cooling of the tanks, based on the pattern of when warming and cooling occurred relative to air temperature and solar radiation patterns.

Poole and Berman (in press) discuss anthropogenic impacts on stream water temperature and report that the primary determinants of stream temperature are climatic drivers (such as air temperature and wind speed), stream morphology, groundwater conditions, and riparian canopy condition. This paper "focuses on the importance of stream morphology, groundwater influences, and riparian canopy conditions as factors that both markedly influence stream temperature and are also substantively altered by various human activities" and finds that stream temperature may respond differently to anthropogenic impacts in different parts of the stream. For example, stream temperatures may be dominated by groundwater temperature in the headwaters and by mean daily air temperature near the stream's mouth. The most dramatic change may occur in the middle reaches where the stream's temperature regime transitions from being dominated by groundwater temperatures to be being dominated by air temperature. "Restoration of historic channel structures, channel-forming processes, sediment delivery, and flow regimes may be critical to the re-establishment of historic temperature regimes in large rivers." They stress that modification of in-channel streamflows, altered riparian vegetation structure, changes in groundwater dynamics, and altered channel morphology are mechanisms that change water temperatures. Restoration of riparian vegetation alone will likely not be sufficient to meet temperature standards in streams where degraded channel morphology is the largest cause of undesirable stream temperatures.

Similarly, Ice (2001) reported that the Oregon Independent Multidisciplinary Science Team (IMST) held an experts' workshop to determine the influence of human activities on stream temperature. They concluded that the factors that human activities can affect to influence stream temperature are: 1) vegetation, 2) streamflow (hydrology), 3) channel morphology, and 4) subsurface/surface interactions (factors not listed in order of importance). They also concluded that solar radiation is the principle energy source that causes stream heating.

Recovery of stream water temperatures has been studied by Johnson and Jones (2000) in the H.J. Andrews Experimental Forest in the western Cascade mountains of Oregon, where elevated stream temperatures in small experimental watersheds resulted from harvesting and debris flows in the 1960's. Factors evaluated in this study included stream temperature, discharge, air temperature, precipitation, solar radiation, and soil temperature data. Their results support the hypotheses that stream temperatures are driven by changes in shortwave solar radiation that can be modified by riparian shading and that heat conduction from near-stream soils and alluvial substrates is of greater importance than generally recognized. This occurs because direct solar radiation in forest gaps or disturbed riparian areas increases the temperature of soils and alluvial substrates that could conduct heat to streams. The rate of heat transfer between water and substrates is three orders of magnitude greater than the rate between water and air.

Hatten and Conrad (1995) compared summer stream temperatures in unmanaged and managed sub-basins of Washington's western Olympic peninsula. In this study, the temperatures of 11 streams in unmanaged subbasins and 15 streams in logged subbasins were monitored continuously during the summer of 1992. No significant differences in mean air temperatures were found between the monitoring sites in managed and unmanaged subbasins. Significant differences were found, however, between group means of variables used to characterize water temperatures. The managed group of basins had significantly warmer mean temperatures than the unmanaged group, and the best variable to explain this difference was the percentage of late seral stage forest present in the basin. Managed sites with high values of stream shade generally had warmer temperatures than unmanaged sites with similar shade values. They concluded that managing for stream temperature at the reach level will not be successful unless logging activity throughout a sub-basin is considered.

Holtby and Newcombe (1982) examined stream temperature increase in the Carnation Creek experimental watershed in coastal British Columbia. The effects of logging on stream temperatures were larger than expected from clearcutting 41% of the 2500 ac basin. Summer temperature increases were proportional to the basin area logged. Elevated air temperature was not thought to be an important factor for increased water temperatures, while changes in direct solar radiation input appeared to be a significant factor. The Carnation Creek data was reanalyzed by Holtby (1987), and it was concluded that summertime stream temperature increases were proportional to the length of streambank logged and directly related to the increased penetration of sunlight to the stream (Teti 1998). Stream temperatures were correlated with air temperatures before logging from a proximal weather station. Following logging, this correlation was significantly reduced, and multiple regression analysis indicated that increased stream temperatures, up to 3° C above historical maxima during summer, were attributable to logging impacts (Holtby 1988).

Conclusions

There is disagreement in the literature regarding the importance of changes in air temperature on stream water temperature (Bartholow 2000, Stillwater Sciences 2003). Some authors have concluded that it is very important, while others have stated that air temperature has little impact on water temperature. Several examples are found in the literature indicating that cumulative timber harvest is associated with elevated water temperatures, but air temperature changes do not generally appear to be the main contributor to this effect. As stated by Brown (1983) and Beschta et al. (1987), the physics of heat transfer from air to water do not support a contention that elevated air temperatures are the primary reason for increased water temperature. Modeling by Bartholow (2000) found that changes in air temperatures were a component of increased water temperatures, but were less significant than changes in solar radiation input. In a recent review, Stillwater Sciences (2003) reports that the view that a warm environment and ambient air temperature control stream heating is not well supported with data.

If air temperature change is not the dominant variable responsible for elevated water temperatures when a large percentage of a basin is clearcut, what other factors are left to explain the observed water data? While different authors attribute observed increases in stream water temperature following logging to different causes, it appears that important human influenced mechanisms include:

1) cumulative decreased stream shading throughout a basin;
    a. due to lack of buffer strips
    b. due to inadequate buffer strips
        i. too narrow, especially if second-growth stands have been clearcut immediately above the buffer strip—allowing solar radiation input,
        ii. too few trees due to thinning,
        iii. too short of trees, since second-growth trees are often less tall than old-growth trees,
2) increased mass and surface erosion resulting in channel widening that allows more solar radiation input;
3) disturbance in riparian areas resulting in heating of near-stream soils and alluvial substrates that can conduct heat efficiently to stream water; and
4) in some cases, altered stream flows or groundwater conditions.

The literature also suggests that modern timber harvesting practices, including improved riparian buffer strips, better road construction and maintenance, and greater use of aerial harvesting systems may be decreasing the cumulative stream water temperature increases noted within large basins with extensive, past harvesting. Many of these effective practices are requirements under the California Forest Practice Rules, which currently address impaired watersheds in part through expanded stream buffer widths, additional special operating zones adjacent to evenaged units, and increased canopy retention standards within the buffer. Further collection of data in these types of watersheds would allow more definitive conclusions to be reached.

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