PREDICTING STREAM TEMPERATURE AFTER RIPARIAN VEGETATION REMOVAL [1]

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Abstract: Removal of stream channel shading during timber harvest operations may raise the stream temperature and adversely affect desirable aquatic populations. Field work in California at one clearcut and one mature fir site demonstrated diurnal water temperature cycles and provided data to evaluate two stream temperature prediction techniques. Larger diurnal temperature fluctuations were observed in the water flowing through the clearcut than in the undisturbed area above the clearcut site. The mature fir forest also had a large diurnal water temperature variation. A 5.6°C temperature rise was observed through a 380-m clearcut that exposed the stream channel, and Brown's equation predicted a change of 6.1°C. A regression model underpredicted the maximum observed temperature by just under 2°C at the clearcut site. A technique that includes the effect of shade recovery after timber harvest is suggested for use during long-range harvest planning.

Forest management can affect water quality and aquatic life, and riparian areas are both sensitive and easily disturbed. Streamside forest canopy removal allows direct sunlight to reach first- and second-order streams that were extensively shaded before timber harvest. Direct sunlight can increase stream temperature, which effects fish and aquatic insect species composition and growth (Feller 1981). Temperature also affects water quality parameters such as dissolved oxygen and the waste assimilation capacity of a stream.

The effects of logging on stream temperature have been the subject of considerable research and numerous reviews (Brett 1956, Brown 1969, Patton 1973, Anderson and others 1976). Direct solar insolation was found to account for at least 90 percent of a stream's temperature change after clearcutting (Brown 1970). Salmon (*Oncorynchus* sp.), brown trout (*Salmo trutta*), and brook trout (*Salvelinus fontinalis*) prosper in streams that are between 10° and 18°C, and if water temperatures exceed 24°C they may die, depending on acclimation temperatures, pH, and dissolved oxygen (Patton 1973). The replacement of these high-value, cold-water fish species by warm-water fish has been associated with timber harvest.

Early research determined that an important shading and sediment filtering role was played by the vegetation along channels, and this area was termed a buffer strip (Patton 1973). Management agencies have incorporated this concept by establishing special management areas along active stream channels that include the riparian zone and some amount of the adjoining hillslope. Limited.

harvesting may be allowed in these streamside management zones (SMZ), which may vary in width depending on hillslope angle. Although equipment entry into the SMZ is discouraged, the restrictions do not prevent the removal of shade-providing vegetation from riparian zones. In addition, the Pacific Southwest Region (California) of the Forest Service, U.S. Department of Agriculture, has established Best Management Practices (BMP), which state that no adverse temperature impacts should occur to streams during harvests. The actual effectiveness of SMZ restrictions and other BMPs is not known due to the lack of detailed or long-term monitoring.

Early efforts to predict stream temperature changes focused on predicting the maximum temperatures associated with peak summer conditions and low flows (Brown 1969). These early models were based on temperature changes caused by full exposure of the stream reach to the sun at the peak sun angle. By combining the site's latitude with field measurements such as stream temperature, channel width, depth, flow velocity, and an estimate of shading with estimates of potential cover reduction, likely temperature increases can be quantified. The estimated change in temperature, when added to the pre-harvest water temperature, provide an indication as to whether post-harvest temperatures might exceed the lethal limit for the resident fish.

Other modeling approaches include empirical models that are calibrated for one geographic region, or detailed simulation models that require extensive data pertaining to the reaches to be modeled (Schloss 1985, USDA Forest Serv. 1984). The Schloss model is typical of a regression model and was developed in western Oregon to predict maximum summer temperature based on elevation, distance above the main channel, stream order, and shading. The USDA model was developed by the Forest Service to simulate stream temperature

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response to multiple alternative harvest areas in a basin. It is a physical, energy budget-based algorithm, and has a time step that can range from 15-minute to hourly or daily intervals. Both direct and indirect (diffuse) shading is incorporated, as is stream aspect, topographic shading, groundwater influx and temperature, and flow into and out of the reach. The stream network is represented by sequentially estimating the outflow water temperature in each reach and using that information as the inflow temperature in the next downstream reach. A significant advantage to this model is its ability to handle partial shade, but obtaining the copious input data requires considerable field work.

This paper reports on field work at two streams in California that evaluates Brown's stream temperature change prediction technique and an empirical equation developed in Oregon (Brown 1970, Schloss 1985). Both partial and complete riparian vegetation removal are analyzed. A modification of Beschta and Taylor's (1988) phased vegetation recovery system is proposed as part of a multireach accounting system for basins with multiple cutting areas.

Temperature Prediction

Model Selection

Model selection should be based on the size of the area of concern and on the intended use of the water temperature prediction. Because the typical forestry use is to assess the effect of timber harvest, grazing, recreation, or road construction on large land areas, the complex and data-hungry physical simulation models are inappropriate. Empirical (regression) models may be appropriate if one has been developed for the local area of interest. In most cases, however, a relatively simple model based on the physical processes relating stream surface exposure to sunlight is most appropriate.

Exposed Surface Models

Exposed surface models combine a few crucial types of field data with tabular data dependent on site location (Brown 1969). This type of model uses only physical constants and field measurements, so it is not an empirical, "calibrated" model. Changes in water temperature T(°C) increase directly in relation to new stream surface area A (m^2) that is exposed and insolation N (cal/cm^2-min), and inversely with streamflow Q (m^3/s):

$$\Delta T = \frac{AN}{Q} * .000167 \tag{1}$$

The coefficient contains the constants for the conversion of the flow, area, and insolation units to temperature.

Because this model predicts a change in temperature, pre-project temperatures should be measured wherever harvests are planned. Streams should be visited during California's low flow and peak heat times of July, August, and September. A simple pocket thermometer could yield representative data for several small basins with a moderate amount of effort, using measurements taken between noon and 1500 hours. Peak temperatures occur due to the interaction of declining streamflow and insolation, in spite of the decline of insolation after June 21.

The parameter A reflects the new channel area that will be exposed due to forest harvest, but topography, channel aspect, and harvest design also have a role in determining A, so subjective judgments may be needed. If 35 percent of the cover in a 100 m zone along the southside of a channel is to be removed, it may be reasonable to equate this to complete removal from about 30 m of channel.

Table 1 — Average values of net solar radiation absorbed by water surfaces in middle latitudes for a range of exposure times (cal/cm^2-min) (after List 1951, Brown 1974).

Water Travel Time (hours)	Latitude (degrees) 35	40	45
2	1.30	1.28	1.22
4	1.25	1.22	1.17
6	1.19	1.14	1.11
8	1.09	1.06	1.00

Solar loading N is dependent on season, latitude, and the length of time that the water is in an exposed area. California's National Forests range from 34° to 42° latitude, so N values for the appropriate latitudes have been estimated (table 1). N values could be reduced by about 1 percent for each week after July 1 to account for the seasonal decrease in insolation, but such minor adjustments are probably not warranted due to the inherent errors in area and discharge estimates. The travel times for the 160 m to 400 m openings typical of National Forest System operations and stream gradients are between 1 and 2 hours, so the N values for 2 hour travel times in table 1 should be used for most small streams.

The final requirement for equation 1 is discharge volume, and small mountain streams are difficult to gauge accurately due to shallow depths, turbulence, and sidepool areas. If a small current meter is available, measurement of cross-sectional areas and water velocities can provide reasonably accurate results. Alternately, dye or floating objects such as oranges can be used but accuracy will suffer. If objects such as sticks are used, the velocity should be multiplied by 0.8 to correct for the vertical velocity profile of the stream. Cross-sections should be selected to minimize stagnant water pools near the stream's edge or discharge can be overestimated by 50 to 100 percent.

Empirical Prediction

Empirical equations can be developed by regressing stream temperature on basin, cover, and stream characteristics (Schloss 1985):

$$T = 11.9 - 0.0013E + 0.206L + 0.676R + 1.814(S/50 + 1) \qquad (2)$$

where:
T = maximum summer stream temperature (°C)
E = midbasin elevation (m)
L = distance from junction of next higher-order stream (km)
R = stream order
S = shade percentage (percent)
Standard deviation = ±1.7°C.

Equation 2 was calibrated for forested basins in western Oregon that were below 610 m elevation. Unlike equation 1, this technique predicts maximum temperature rather than temperature change. The stream order and channel distance factors are measured on US Geological Survey 7.5° quadrangle maps. The channel length is the distance from the area of interest to that stream's juncture with the "main" channel. The shade code is the percentage of channel that has less than "complete" shade within 1600 m upstream from the point of interest.

Site Descriptions and Field Methods

McGill Creek

A clearcut site was identified 3 km north of Iron Canyon Reservoir along McGill Creek at an elevation of 915 m (figure 1). Iron Canyon Reservoir is in the Shasta National Forest and is 61 km northeast of Redding, California. McGill Creek is a south-draining second-order stream, with a slope of 3.5 percent, that passes through an 8-ha clearcut. The timber operator removed nearly all of the timber on both sides of the stream, and the slash disposal burn got out of control and destroyed most of the remaining near-stream vegetation. These actions produced a 380-m section of stream that had almost no shading.

Field instrumentation consisted of water temperature, air temperature insolation, humidity, and wind instruments. Ten water temperature probes were placed in the unshaded channel, one probe was 70 m upstream of the cut, and probes were placed 35 m and 90 m downstream of the clearcut area. Except for a hygrothermograph and rainfall collector, all readings were collected electronically at 15-minute intervals. The site was monitored for 48 hours between August 31 and September 2, 1983. Approximately 1.3 cm of rain fell during the afternoon and evening of August 31, but September 1 and 2 were warm with clear skies. Peak air temperatures were 29°C on September 1 and 32°C on September 2. The average discharge during the study interval was 18 l/s (0.6 ft³/s).

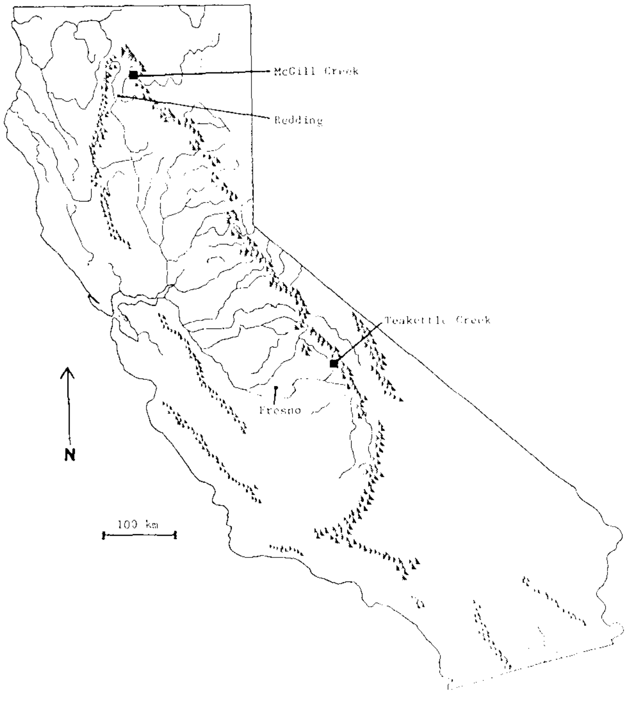

Figure 1—California map pinpointing McGill Creek clearcut site and Teakettle Creek mature fir site where field tests took place.

Table 2 - Average water temperatures and meteorological data for McGill Creek near Redding, and for Teakettle Creek near Fresno, California.

Date	Time	Entry Water Temp.(°C)	Exit Water Temp.(°C)	Temp Diff (°C)	Air Temp. (°C)	Insolation (°C)	Windspeed (cal/cm^2-min)
McGill Creek							
8/31	15-18	12.0	12.0	0.0	12.8	0.04	0.6
	18-24	11.8	10.7	-1.1	10.3	.0	.3
9/01	0-6	11.6	11.2	-0.4	9.4	-.01	.1
	6-9	11.5	11.6	0.1	10.0	.06	.1
	9-12	11.7	13.9	2.2	15.9	.65	.5
	12-15	12.2	16.7	4.5	20.6	.82	.7
	15-18	12.1	15.6	3.5	16.9	.21	.7
	18-24	11.6	12.2	0.6	7.0	-.05	.4
9/02	0-6	11.0	10.9	-0.1	5.2	.0	.6
	6-9	10.8	10.8	0.0	8.2	.02	.6
	9-12	11.3	14.1	2.8	22.9	.82	.6
	12-15	12.3	17.4	5.1	27.0	.89	.8
Teakettle Creek							
8/26	15-18	11.1	10.6	-0.5	13.8	0.01	0.5
	18-24	9.0	8.9	-0.1	6.8	.0	.8
8/27	0-6	7.5	7.4	-0.1	5.1	.0	.8
	6-9	7.1	7.0	-0.1	9.3	.02	.8
	9-12	9.5	9.2	-0.3	24.4	.69	.4
	12-15	12.0	11.3	-0.7	22.3	.38	.5
	15-18	11.3	10.8	-0.5	14.6	.0	.4
	18-24	9.2	9.0	-0.2	7.4	.0	.0
8/28	0-6	7.8	7.6	-0.2	5.8	.0	.0
	6-9	7.5	7.4	-0.1	9.1	.01	.0
	9-12	9.7	9.4	-0.3	23.4	.70	.5
	12-15	12.0	11.3	-0.7	21.2	.32	.3

Teakettle Creek

The Teakettle site is on the Sierra National Forest at an elevation of 2100 m. It is in the Teakettle Experimental Forest, on the southeast flank of Patterson Mountain and 66 km east of Fresno, California. Teakettle Creek is a southeast-facing, second-order drainage with a slope of 8 percent that passes through senescent red fir. Although some clearings exist due to the presence of 10 m by 40 m wet meadows, the combination of extensive shrub growth and the 50- to 80-m fir trees exclude most direct exposure from sunlight. A shading survey produced an estimate of 80 percent canopy cover.

The field instrumentation at Teakettle was similar to that used at McGill Creek. Approximately 380 m of stream channel was monitored with 11 water temperature probes, and the other instruments were sited along the stream channel. Peak air temperatures were 27°C on August 27 and 25°C on August 28, 1983. The average discharge during the study was 39 1/s (1.3 ft^3/s).

Measurement Accuracy

All thermistor probes were calibrated by measuring their resistances in three baths of known temperature that spanned the expected measurement interval. The agitated water baths were measured using a precision thermometer accurate to ±0.1°C. A separate polynomial equation was developed for each probe.

Replicate stream temperatures were measured by placing two probes within 2 cm of each other at a single random spot at both McGill and Teakettle Creeks. The mean difference around the replicates and the confidence limits around the difference between any two probes were as follows:

	Mean difference (°C)	95 Pct. Confidence interval (°C)
McGill	0.16 ± 0.3	
Teakettle	0.20 ± 0.4	

Based on these confidence intervals, observed water temperature values that differ by less than 0.8°C must be considered to be the same.

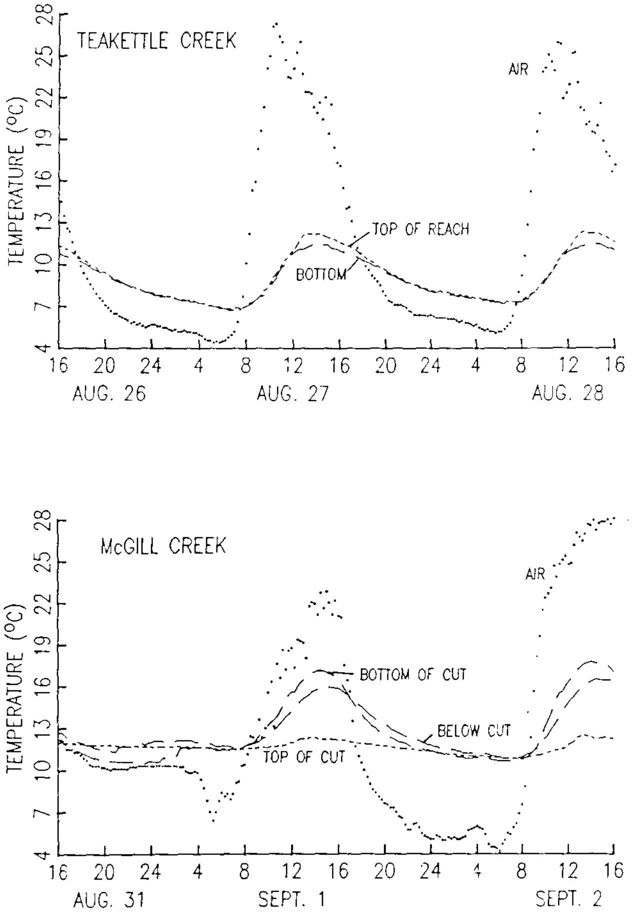

Figure 2–Recorded diurnal water temperature at the two field test sites, August 31 – September 2, 1983.

Results and Discussion

The diurnal water temperature at the two sites share a similar pattern, but there are important differences (figure 2). The air temperatures at both sites peaked at between 24°C and 28°C. The McGill Creek water temperature was 17°C on September 1 and 18°C on September 2, but Teakettle water temperatures peaked at 12°C on both August 27 and 28.

Although both sites produced a sine-shaped temperature pattern, the amplitude varied at the two sites. At McGill Creek, one can hypothesize that the diurnal variation of temperature would be very small in the natural system. Sensors 65 m above and at the upper margin of the clearcut show very small diurnal variations (figure 2). This small variation is due at least in part to the dense shade provided by the willow and alder that choked the channel upstream of the clearcut area. The mature fir forest at Teakettle Creek provided the channel with only 80 percent cover, and the overstory was much higher than at McGill. Teakettle Creek's water temperature is lower than the "natural" case at McGill, a situation that may be due in part to the 1100 m elevation difference. The higher variability at Teakettle may be due to the upstream springs that supply the stream. At McGill, side seeps were common along the channel, and their presence would add to the diurnal variation due the shallow, marshy flow that was exposed to the sun.

Average insolation, windspeed, and air and water temperatures illustrate some of the differences between the sites (table 2). The difference between the 3-hour average water temperature entering and leaving the clearcut was about 5°C at McGill, but the stream actually lost heat in the measured reach at Teakettle. The open site had both larger daytime energy inputs and larger nighttime energy losses due to the lack of a canopy. The total allwave flux was 790 cal/cm^2 at McGill and 383 cal/cm^2 at Teakettle. Windspeeds at the two sites were roughly equivalent, but little wind movement would have been possible in the natural channel areas above the clearcut at McGill due to the dense vegetation close to the water surface. The canopy at Teakettle, however, is much higher, allowing typical diurnal wind patterns.

Exposed Surface Water Temperature Prediction

The McGill Creek site was well suited to Brown's (1970) model for predicting temperature. Channel area was calculated using an average width estimated by measurements at six locations along the channel. In addition to the 1.9-m width along the 380 m of channel, there were also eight small pools that had been constructed for gradient control and to allow sediment to settle. The pools added 111 m^2 to the 483 m^2 of channel surface area, so the estimate of the total exposed area was 594 m^2. McGill Creek is at 41° latitude and the water travel time was about 1 hour (velocity = 0.1 m/s, so the N factor (equation 1, table 1 for 2 hours) equals 1.27. The average discharge, as measured by both current meter and dye velocity/cross-section measurements was 0.019 m^3/s. The calculated temperature change was 6.6°C, and the observed water temperature increase through the cut area was 5.0°C on September 1 and 5.4°C on September 2.

Both the calculated and observed temperatures are estimates that include measurement errors. For equation 1, the area term may have about a 25 percent error, the insolation error may be 20 percent, and the discharge error may be 50 percent. The combined effect of these errors suggests that the predicted value of 6.6 °C is the "best guess" in a range of predicted temperature increase that extends from 3°C to 20°C. Some decrease in the error band may be obtainable with extreme diligence during data collection. The errors associated with the probe measurements are discussed above.

Part of the difference between the predicted and observed values could be due to the decreased solar strength in early September as compared to the peak strength associated with the June 21 summer solstice. Peak insolation at the Central Sierra Snow Laboratory, near Soda Springs, California, declined by 8 percent during that interval. Assuming that the same pattern is followed at McGill Creek, the decreased solar input accounts for 0.5°C, dropping the predicted change for the actual measurement period to 6.1°C. The remaining difference could be due to the shrubby vegetation along the channel, ground water inflow, or errors in the stream area or discharge measurements.

Equation 1 is sensitive to errors in discharge estimation, especially on small streams with low total flows. If the 0.019 m^3/s value is varied by ±10 percent, the initial predicted temperature change (6.1°C) changes to 5.6°C or 6.8°C. Typical current meters are accurate to approximately ±5 percent (USDI Bur. Reclam. 1975), and errors as large as 50 percent are likely in small channels due to lateral turbulence and shallow depths.

The largest 3-hour average insolation values in table 2 for McGill Creek are 35 percent less than a solar loading value of 1.26 estimated for a site at 41° latitude from table 1. The instantaneous net allwave values measured at McGill Creek peaked at 1.1 cal/cm^2-min. If the tabular value is reduced by the 8 percent seasonal factor, the value becomes 1.16 cal/cm^2-min, a value that is only 0.06 cal/cm^2-min different than the observed value.

The Teakettle Creek site is not as well suited for the application of Brown's technique as was McGill Creek. Although no new channel area had been exposed due to harvesting, the 80 percent canopy cover implies that 20 percent of the stream is exposed to insolation. The channel survey yielded an average width estimate of 3.3 m and a length of 380 m, so there is 1254 m^2 of surface area and 251 m^2 of the total is exposed. The insolation value for a 2-hour travel time at 37° latitude, corrected by the 8 percent seasonal factor, is 1.19 cal/cm^2-min. The observed discharge was 0.037 m^3/s, so the predicted temperature increase was 1.4°C. The field results show a top-to-bottom temperature decrease of almost 1°C on both days. Due to the measurement and prediction error factors mentioned above, there is no difference between estimated and observed values, but the divergence is interesting. The decreasing water temperature is counterintuitive in that no large open areas above the measurement site were present from which the stream was recovering. Further, the water temperature at the top of the reach was already rather low for the peak summer heat period.

The diurnal variations at the two sites were markedly different. The Teakettle site had diurnal variations of 4°C, but the undisturbed portion of the McGill site had diurnal variations of 1.2°C. This difference may be due to the lack of low shrub cover at Teakettle versus very dense willow and alder at McGill Creek. The water temperature at Teakettle declined markedly during the night, and this pattern was not seen at McGill in spite of similar air temperatures.

Empirical Temperature Prediction

McGill Creek's elevation is 915 m (E), it is a second order stream (R), and the site is 2.4 km (L) from Iron Canyon Reservoir. The 380 m of clearcut area produces an S value of 24 percent because the remainder of the channel was shaded. It is likely that there would be less overall effect if the clearcut area was split into two portions at either end of the 1600 m effective distance, but this method lumps all partial or unshaded areas into a single ratio. Equation 2 predicts a summer maximum temperature of 15.3 °C. Compared with observed maxima of 17°C and 18°C, the predicted values are surprisingly close.

As a second test at McGill Creek, a prediction can be made for the undisturbed area above the clearcut. The shading factor becomes zero and the channel length changes to 2.5 km. The predicted maximum water temperature is 14.4°C , and the observed maximum was less than 12°C.

Teakettle Creek is at 2100 m elevation, is a first-order stream, and the site is 3 km from the Kings River. Using a shade factor of 20 percent, the predicted summer maximum was 13°C with a standard deviation of 1.7°C. The observed maximum water temperature was 12.3°C, not significantly different than the predicted value. Because Teakettle is further from Oregon and higher than McGill, plus has no real clearcut areas, the correspondence between the observed and predicted temperatures is surprising.

Although these three cases are not an adequate evaluation of Schloss' equation, they do show both the promise and the danger associated with an empirical approach. An equation that was calibrated for a geographic area could be very useful and reasonably accurate. Indiscriminant use, however, could conceal problem situations that deserve closer attention.

Heat Loss

Elevated water temperature may decrease once the heat input disappears. At McGill Creek, a sensor was located 130 m below the clearing. After the Creek flowed under the dense canopy cover for this distance, the peak temperature listed above and shown in figure 2 decreased by 1 or 1.5°C. Heat was lost to the streambed or to the air, but it is not known if this rate of heat loss continued or if the water returned to its original temperature at some downstream point. Many streams lose heat and return to their elevation-, flow-, and groundwater-influenced base temperature within 1.6 km of their exit from a disturbed area (Schloss 1985).

Multiple Harvest Areas

Although one harvest may have only a small effect on stream temperature, multiple harvests within a few years might produce a "cumulative effect" on downstream temperature. For an Oregon watershed following clearcut harvesting, little shade recovery occurred within 5 years after stream banks were cut, but a linear and total recovery occurred during the subsequent 15 years (Beschta and Taylor 1988).

Although some stream temperature models have multicut, multiyear capability, the data requirements preclude their use on basins with miles of channels and numerous subbasins (USDA For. Serv. 1984). A tabular recovery analysis for basins could aid the harvest planning by explicitly incorporating shade recovery information (table 3). The table incorporates a 20-year vegetation growth cycle, and the procedure uses an index that varies from 1 (full effect) to 0 (no effect) to represent the loss of shading due to harvest if any canopy cover is removed from the riparian zone. After 20 years, the index returns to zero as stream shading recovers. In table 3, harvest E occurred near 1960, A occurred near 1965, and B and D occurred near 1970. The column labeled "Total" is the sum of the horizontal coefficients, but the value that should be considered to be a cumulative effect threshold is unknown. If the average riparian timber removal is 50 percent along the associated 300 m of channel and five harvests occurred within a 5-year period, a value of five in the "Total" column might represent 750 m of clearcut stream channel.

The incorporation of this technique during the harvest plan could provide a feedback system such that predicted increases in estimated stream temperatures would increasingly restrict the removal of shading vegetation. A monitoring plan that proceeded concurrently with the harvest would provide valuable information on temperature effects.

Table 3 - Shade recovery calendar for aiding the scheduling of timber harvests within a basin (after Beschta and Taylor 1988).

Harvest Year[1]	Harvest Event									
	A	B	C	D	E	F	G	H	I	Total
1960	1	-	-	-	1	-	-	-	-	2.0
65	1	1	-	1	.6	-	-	-	-	3.6
70	.6	1	-	1	.3	-	-	-	-	2.9
75	.3	.6	-	.6	0	1	-	-	-	2.5
80	0	.3	-	.3	-	1	1	-	-	2.6
85	-	0	1	0	-	.6	1	1	-	3.6
90	-	-	1	-	-	.3	.6	1	1	3.9
95	-	-	.6	-	-	0	.3	.6	1	2.5
2000	-	-	.3	-	-	-	0	.3	.6	1.2
05	-	-	0	-	-	-	-	0	.3	0.3
10	-	-	-	-	-	-	-	-	0	-

[1] Assign harvests to nearest 5-year date.

Conclusions

The exposed surface area model (Brown 1970) for predicting stream temperature may be a good choice for land managers because it requires a minimum of field data that are relatively simple to obtain. If a sufficient data base exists within a region or can be collected over time, an empirical model will simplify maximum temperature prediction associated with shade removal.

Field data from both a clearcut and a mature fir site were used. A predicted temperature change of 6.1°C compared well with an observed change of 5.4°C at a 380 m clearcut site. The prediction equation is sensitive to streamflow, a factor that is known to be difficult to measure with less than at least ±5 percent error. The 80 percent-shaded Teakettle site yielded a predicted increase of 1.4°C compared to an observed decrease of almost 1°C.

Results from the empirical model were 2°C lower than the observed water temperatures in the clearcut portion of McGill Creek and 2°C higher than the undisturbed area (Schloss 1985). The regression model's prediction nearly matched the fir site's water temperature of 12°C. If data were collected for several areas of California and used to calibrate a model with similar structure, greater consistency might be achieved. This type of model has the advantage of requiring no additional field data once the coefficients are estimated.

A shade recovery accounting system was proposed for use during the National Forest System harvest planning process. The system assumes channel cover is regained in 20 years and offers the planner a way to avoid overscheduling harvests in a basin and producing an adverse cumulative temperature effect.

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