Development of a Mechanistically Based, Basin-Scale Stream Temperature Model: Applications to Cumulative Effects Modeling[1]

Douglas Allen,[2] William Dietrich,[2] Peter Baker,[3] Frank Ligon,[3] and Bruce Orr[3]

Abstract

We describe a mechanistically-based stream model, *BasinTemp*, which assumes that direct shortwave radiation moderated by riparian and topographic shading, controls stream temperatures during the hottest part of the year. The model was developed to support a temperature TMDL for the South Fork Eel basin in Northern California and couples a GIS and a 1-D energy balance model. Spatially varying insolation is calculated in the GIS and heat and mass transfer processes are modeled using a simple steady-state scheme integrated with an optimization procedure which improves model predictions. *BasinTemp* can be applied to basins of varying sizes and requires minimal measured input data. Model predictions for three sub basins in the South Fork Eel yielded RMSE statistics ranging from 0.25 ºC to 0.30 ºC. The model also performed well using pooled data for all three sub basins, yielding an RMSE of 0.36 °C. *BasinTemp* has been used to assess local and downstream stream heating effects after modifying riparian shade. Model predictions for the three sub basins illustrate the importance of riparian shade provision on low order channels and show the shifts in the quality and quantity of potential coho habitat following different shade prescriptions.

Key words: stream temperature prediction, model, BasinTemp, riparian shade, cumulative effects

Introduction

The transformation of the Pacific Northwest and California landscape that followed the arrival of Europeans was accompanied by, and more often at the expense of, significant changes in the quality and quantity of terrestrial and aquatic biological habitat. Timber harvesting practices have been responsible for much of this change and particularly for the decline in salmonid habitat (for example, Beschta and others 1987, Lichatowich 1999). Degradation of water quality parameters, especially water temperature, has significantly reduced coldwater fish habitat (Lichatowich 1999). Coldwater fish species with physiological adaptations to cool freshwater conditions are especially vulnerable to temperature fluctuations.

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[2] University of California, Berkeley, Department of Earth and Planetary Science, McCone Hall, UC Berkeley, CA 94720. email: allen@eps.berkeley.edu

[3] Stillwater Sciences, 2855 Telegraph Ave., Suite 400, Berkeley, CA 94705.

Regulatory efforts to halt the decline in salmonid habitat and at the same time promote recovery and restoration, have been administered chiefly through the Endangered Species Act and the Clean Water Act (Poole and others 2001b). Towards meeting legislative requirements contained in these statutes a broad range of analytical and empirical tools have been applied to assess and quantify elevated stream temperature conditions (Deas and Lowney 2000). The model presented here, *BasinTemp* (Allen 2006), was developed to support work on a temperature TMDL (Total Maximum Daily Load) conducted for the South Fork Eel River in Northern California. The basin was listed for temperature (and sediment) under section 303(d) of the Clean Water Act primarily as a result of degradation of coho *(Oncorhynchus kisutch)* habitat. While temperature influences all coho life-stages, the summer rearing life stage is especially sensitive to change (Cafferata 1990). Coho were once abundant throughout the South Fork Eel basin, supporting a major industry well into the early 20th Century before overfishing forced its closure (U.S. Environmental Protection Agency 1999). A brief recovery was followed by a further decline in numbers in the latter half of the last century (U.S Environmental Protection Agency 1999). The TMDL objectives for the South Fork Eel (U.S. Environmental Protection Agency 1999) required locating stream reaches with elevated temperatures, identifying the source (or sources) responsible for these elevated temperatures, and developing methodologies to evaluate shade requirements necessary to meet the TMDL requirements (U.S Environmental Protection Agency 1999). Fulfilling these objectives argued for a mechanistically-based model that could be applied to large basins, that could be rapidly deployed, and required limited input data to operate. In addition, recognizing the crucial role of riparian vegetation for blocking direct insolation, we reasoned that the model needed to represent accurately the riparian shading affects, and to include the facility to modify riparian vegetation to explore the effects different shade scenarios on water temperature.

We determined that none of the temperature models available at the time fully met these criteria. Simple empirical models (for example, Mitchell 1999) and simple reach-based mechanistic models (for example, Brown 1969) were inadequate or inappropriate for large-basin applications. Fully-mechanistic temperature models also didn't meet our needs. Reach-based, physical models [for example, SSTEMP (Bartholow 2000); HeatSource (Boyd and Kasper 2003)] were inappropriate for basin-scale application, while the spatially distributed physical models [for example, SNTEMP (Theurer and others 1984); HSPF (Bicknell and others 1997)], require substantial field-measured input data to operate. These data were unavailable and would have been prohibitively expensive to acquire. To fulfill the TMDL requirements, we developed a physically-based, large-area assessment model, *BasinTemp*, which complements rather than competes with existing fully-mechanistic physically-based models. Temperature predictions generated by *BasinTemp* may be used to guide physically-based model applications where more detailed information about the individual mechanisms responsible for stream heating (air temperature, evaporation rate, streambed conduction, and so forth) is required.

Model Development

The temperature of a water body is a function of the total heat energy contained in a discrete volume of water,

$$\frac{E}{V} = C_p \cdot \rho \cdot T_w \qquad (1)$$

where E is heat energy (calories), V is the volume (m^3) of water, Cp is specific heat capacity of water (1000·cal/kg·K), ρ is the density of water (1000·kg/m^3), and T_W is water temperature in units of degrees centigrade. Most mechanistically-based models which are designed to explicitly quantify the various mass and heat transfer mechanisms, invest the majority of effort toward quantifying the fluxes that comprise the energy term, E (Deas and Lowney 2000).

In mid-latitude regions during the hottest time of the year, direct insolation dominates the heat energy budget (Brown 1969, Ice 2001, Sansone and Lettenmaier 2001), contributing up to 80 percent of the total radiation budget (Monteith and Unsworth 1990). In forested catchments dominated by lower order channels, riparian vegetation is the primary control on the amount of direct solar radiation received at the stream surface (Lynch and others 1984, Poole and Berman 2001). In mid-latitude regions during the summer, streamflow is almost exclusively maintained by groundwater influx which enters the stream at temperatures that are reasonably well represented by the local mean annual air temperature (Beschta and others 1987). Based on this information, we determined that the essential components of summertime stream heating could be captured in a model where solar insolation dominates the fluxes that comprise the energy term, E. The model, *BasinTemp* (Allen 2006), is a mechanistically-based approach which assumes that direct shortwave radiation drives summertime stream heating and the contribution of direct shortwave radiation reaching the stream surface is controlled by shade from local topography and riparian vegetation. Heat and mass transfer processes are represented very simply in a 1-D, steady-state numerical model which assumes that water is fully mixed in the vertical and horizontal directions. An optimization routine is integrated with the 1-D heat balance model and uses locally measured stream temperature data to improve model predictions. Data preprocessing is performed in a GIS where the data required for spatially distributed insolation modeling are assembled. A hybrid topography-vegetation digital elevation model (DEM) is merged using existing digital elevation data and vegetation information converted to tree heights for the area of interest. Model simplicity is maintained by ignoring the contribution of shortwave radiation transmitted through the canopy. While important in locally-select cases, canopy-transmitted shortwave radiation is of secondary importance compared to the direct shortwave contribution (Reifsnyder and Lull 1965). A vector-based stream channel network is discretized into uniform segment lengths, where the length of each segment is scaled to match the resolution of the source elevation and vegetation data. Low-flow channel geometry is computed using a power relationship between drainage area and field-measured low-flow widths for the area of interest. Solar insolation—comprised of direct, diffuse, and reflected shortwave radiation contributions—is computed using radiative transfer routines packaged with the Image Processing Workbench (IPW) (Dubaya and others 1990, Frew 1990). The insolation model predicts daily integrated, spatially-varying insolation for every DEM grid cell for the geographic location of interest. Insolation predictions are passed to the 1-D heat balance model which computes for every stream segment, the heat energy transferred out of the reach via stream flow. This heat energy is the sum of heat transported into a reach from upstream, heat entering the reach by groundwater seepage, and heat energy supplied by shortwave radiation (in units of W/m^2). Low-flow hydrology is treated very simply—discharge leaving each reach is computed as the sum of discharges from reaches upstream and local groundwater seepage into the reach. The rate of groundwater seepage is assumed to be a fixed, linear constant whose value is calculated so that predicted discharges at reference reaches match observed low-flow discharges at gages at the location and time period of interest.

Assuming steady-state conditions, the energy balance is solved by a simple ordinary differential equation:

$$\frac{dh}{dx} = \alpha T_{GW} \frac{dq}{dx} + \left\{ K_0 I + K_1 + K_2 \left(K_3 - \frac{h}{\alpha q} \right) \right\} w \qquad (2)$$

h(x) is the heat flux across a surface perpendicular to the reach at a distance *x* from the reach head,
q(x) is water flux across this same surface (cms/km)
w is the reach width (m)
I is solar irradiance at the stream surface (W/m^2)
α is a constant which converts that energy in units of W/m^2 to calories, and mks units to cgs.
T_{GW} is the groundwater temperature parameter (°C), and
K_0, K_1, K_2, and K_3 are model parameters. In all runs K_0 was set to 1.0.

The predicted water temperature for each stream segment is then simply the ratio of heat energy calculated by *equation 2* and flow volume. An optimization routine applying a model trust region method (Dennis and Schnabel 1996) using full second derivative information is integrated with the 1-D heat balance model. The objective function minimized by the optimization routine is the simple root mean square error between predicted and observed reaches at calibration reaches. The routine fulfills the goals of a simple, rapid deployment model for large basins but at the expense of explicitly quantifying the various heat exchange mechanisms at the air-water, and water-streambed interfaces. *BasinTemp* was developed primarily for application to aquatic biology issues and thus justifying lumping these exchange processes into the fitting parameters. Furthermore, most physically-based models perform parameter tuning exercises, and where field measured data are sparse, the range of values used for these parameters (notably wind speed and evapotranspiration) often fall well beyond physically realistic values. Formally introducing an optimization scheme into the model allows for calibration and sensitivity analyses to be conducted objectively and reproducibly. Minimum source data required to run the model are shown in *table 1* which also lists the source data used for the South Fork Eel. In summary, the main features of the model are: (a) application to basins of varying size, (b) transferable to basins with very different characteristics than those where it was developed, (c) limited and flexible input data requirements, (d) water temperatures are predicted for every reach segment and then routed downstream, permitting assessment of local and cumulative downstream temperature effects, (e) modification of riparian tree height for all or part of the basin of interest, permitting the assessment of different land management scenarios on local and basin-scale water temperatures.

Table 1—*Minimum source data required to run* BasinTemp *and source data used for South Fork Eel sub basin predictions*

Data type	Minimum required	Data used for S. Fork Eel
Topography	30-meter digital elevation model	30-meter USGS DEM
Tree height	Vegetation tree height. Sources may include aerial photographs, field measured plot data; satellite imagery, and so forth.	Landsat TM imagery classified according to the California Wildlife Habitat Relations (CWHR) system (Fox and others 1997)
Stream network	Vector-based channel network resolved at a minimum scale of 1:24,000	1:24,000 USGS DLG blueline hydrography
Channel geometry	Low-flow channel width for entire stream network	Power-law relationship between drainage area and field measured low-flow width for reaches throughout the South Fork Eel.
Low-flow Discharge	Measured (daily averages) low-flow discharges for the MWAT week.	7-day mean daily discharge data from USGS gages at Weott in Bull Creek and on mainstem Elder Creek. Discharge data from nearby Tenmile Creek were used for Rattlesnake Creek.
Observed stream temperature data	Array of thermograph stations sufficient to account for basin size, drainage density, and vegetation and lithologic heterogeneities.	1996-1997 thermograph data compiled by Humboldt Country Resource Conservation District (Friedrichsen 1998, Lewis and others 2000)

Study Area

The South Fork Eel river basin is almost equally divided among Mendocino and Humboldt Counties in Northern California and drains an area of approximately 1,800 km^2 (see insert map in *fig. 1*). The climate is generally Mediterranean type and characterized by long, warm summers and cool, wet winters. Mean annual precipitation ranges from 1,500 mm to 1,800 mm most of which falls between October and April (James 1983). Summer high temperatures can exceed 31 °C (Mast and Clow 2000). Approximately 20 percent of the basin is owned by State Parks and the Bureau of Land Management and a small portion is owned by large timber industries, while the remainder is owned by small landholders, ranchers, and residential communities. Temperature modeling focused on three watersheds within the South Fork Eel Basin. The sub basins, Bull Creek, Elder Creek, and Rattlesnake Creek captured a broad range of topographic, lithologic, and vegetation characteristics, and landuse histories observed in the South Fork Eel basin. Elder Creek (drainage area 17 km^2) is a largely undisturbed basin containing one of the last remaining stands of old growth Douglas Fir in California. Rattlesnake Creek (drainage area 99 km^2) is characterized by gently rolling terrain and broad areas of grassland and chaparral vegetation. Bull Creek (drainage area 112 km^2) is almost equally comprised of old growth forest and disturbed areas.

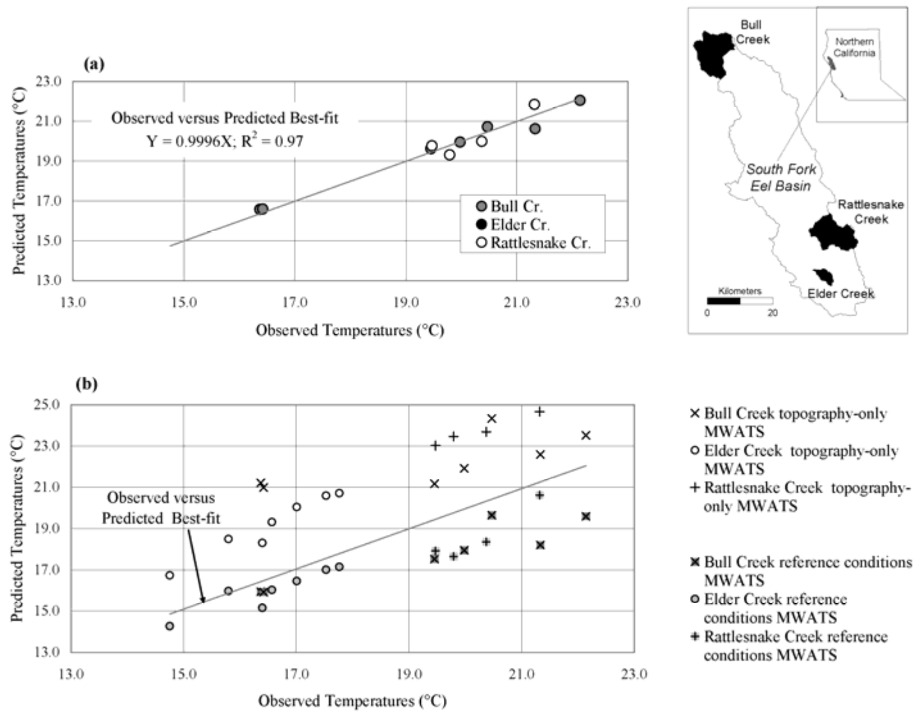

Figure 1—Simultaneous fit to observed 1996 and 1997 temperatures for Bull, Elder and Rattlesnake Creeks for, (a) current vegetation conditions, and (b) topography-only and reference vegetation conditions

Input data used for the three sub basins are shown in *table 1*. Sources for these data are identical to those used in the South Fork Eel TMDL (U.S. Environmental Protection Agency 1999), however the availability of higher resolution digital elevation data and improvements in processing capability (allowing for improved drainage area and low-flow width calculation) means that some of the results reported here differ from the results reported in the original TMDL (U.S. Environmental Protection Agency 1999). Most of the changes between the original predictions and those reported here are the result of significant changes to the 1996 thermograph data used in the calibration and optimization exercise. These data underwent several significant changes from the original 1998 report (Friedrichsen 1998) to the final report (Lewis and others 2000), which was published after work on the TMDL had been completed. The nature of these changes and effects on model predictions are discussed in detail elsewhere (Allen 2006).

The hybrid vegetation-topography DEM is comprised of 10-meter USGS (resampled to 30-meters) digital elevation data and Landsat Thematic Mapper (TM) imagery classified according to a modified California Wildlife Habitat Relations scheme (Fox and others 1997). Tree heights are computed using published diameter-at-breast-height (DBH) relations (Burns and Honkala 1990, Fowells 1965, Mayer and Laudenslayer 1988, Sawyer and Keeler-Woolf 1995, Whitney 1985). The blueline hydrography channel networks for the three sub basins were discretized into 25-meter long reaches, approximately matching the pixel resolution of the Landsat TM data. Every stream segment is attributed with a low-flow width calculated using a power relationship between drainage area and field-measured low-flow channel widths for the South Fork Eel (Stillwater Sciences 1998[4]). Shortwave radiation is computed for every grid cell for the time period of interest (week-ending July 31, 1996 and 1997). Atmospheric transmission parameters were assigned values appropriate for clear-sky, rural conditions. The groundwater seepage constant was computed for each sub basin by iteratively adjusting the rate until the predicted mean low-flow discharge for the stream segment nearest to a local USGS gage station matched the measured mean low-flow discharge for the time period of interest. No gage station exists in Rattlesnake Creek so low-flow data from a (now obsolete) gage in nearby Tenmile Creek were used to calculate the groundwater seepage rate. Thermograph data collected by the Humboldt County Resource Conservation District (Friedrichsen 1998, Lewis and others 2000) were used for calibration and optimization of model predictions. The model predicted the 7-day running Mean Weekly Average Temperature (MWAT) for every stream segment. Several researchers have shown that salmonid growth rates (Brungs and Jones 1977) and salmonid presence/absence (Welsh and others 2001) are closely correlated with the MWAT metric and the metric is also used by the National Marine Fisheries Service and the U.S. Fish and Wildlife Service (NMFS and USFW 1997).

Results

The model was initially calibrated using Bull Creek data where observed MWATs for July 31, 1996 were available for seven thermograph stations within the basin. Daily integrated insolation predictions for this period are computed for each grid cell and passed to the heat balance model. The groundwater temperature parameter, T_{GW}, is constant and set to a physically realistic temperature (11.8 °C), approximately matching the mean annual air temperature. The coefficient of insolation parameter, K_0, is fixed at 1.0 for all model runs. The parameter can be varied during the fitting process, however considerable effort is devoted to characterizing accurately the shortwave flux reaching the stream surface and the local vegetation regime that control the amount reaching the surface, and so ideally this parameter should be fixed at 1.0. Sensitivity analyses (Allen 2006) indicate that when allowed to vary, this coefficient remains at or very close to unity. The remaining three parameters, K_1, K_2, and K_3, are all used to optimize model predictions but only two are allowed to vary at any one time. The MWAT predictions generated by the model for Bull Creek, were very satisfactory (root mean square error equal to 0.25 °C and R^2 = 0.99), and appeared to validate the simplifying assumptions embedded in the model.

To test the robustness and reliability of *BasinTemp* predictions, we applied the model to Rattlesnake and Elder Creeks. Thermograph data for these basins for both 1996 and 1997 were far more limited. Neither station contained sufficiently reliable observed MWAT data for 1996 and 1997, however both basins included an adequate number of thermographs recording the seven-day running mean of the daily average (Weekly Average Temperature or WAT) for the week ending July 31, 1997, and this is the metric the model was used to predict both for Elder and Rattlesnake Creeks. The model performed well for Elder Creek, with an RMSE of 0.30 °C and an R^2 of 0.91. Results for Rattlesnake Creek were less successful yielding an RMSE of 0.93

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[4] Unpublished data. Thirty-five low-flow widths were measured during July and August, 1998 from sites throughout the S.F. Eel basin.

°C and an R^2 of 0.18. WATS predictions from two thermographs were primarily responsible for the diminished model performance. When these two thermographs are eliminated from the calibration exercise, model predictions improve significantly, yielding an RMSE of 0.26 °C and an R^2 of 0.87. Both stations are located immediately downstream of tributary junctions, and thus if the combined flow from the tributary and mainstem channels are not fully mixed, the thermographs may record unrepresentative temperatures. The groundwater seepage rate used for Rattlesnake Creek computed from low-flow discharge data from the adjacent Tenmile Creek basin is almost certainly inaccurate. Furthermore, our assumption of a linear groundwater seepage rate is an oversimplification. Relief, lithologic, and structural heterogeneities, and vegetation variation across a basin guarantee that seepage rates and hence low-flow discharge must also vary spatially. An application of *BasinTemp* to Canton Creek (Allen 2006), a 164 km^2 basin which drains into the North Umpqua River in Southern Oregon has revealed the limitations of the basin-wide, linear groundwater accretion rate assumption. Spatially varying low-flow discharges across the Rattlesnake Creek basin may also explain the poorer model performance.

An additional test of model performance and reliability was conducted by generating temperature predictions using combined data for all three sub basins. The various components of this validation exercise included predicting temperatures using source data for three basins each characterized by different lithologies, vegetation coverage, and landuse histories. Groundwater seepage rates were computed from two different water years, 1996 for Bull Creek, and 1997 for Elder and Rattlesnake Creeks. The calibration data used in the fitting exercise were comprised of two different temperature metrics, 1996 MWATS for Bull Creek (for the week ending July 31), and 1997 WATS (also for the week ending July 31) for Elder and Rattlesnake Creeks. We added an additional test by permitting only two fitting parameters (K_2 and K_3) to be used during the optimization exercise, only one of which was allowed to vary for any given iteration. Individual sub basin results and the combined results are shown in *figure 1(a)*. The model performed well for the individual basin predictions and for the combined basin prediction. These results provide further support for the simple assumptions incorporated into the model and for the parsimonious model structure. The results illustrate the very different thermal characteristics of each sub basin while also having indirect implications for land management strategies. The predictions for Elder and Rattlesnake Creek occupy the lower left and upper right portions of the graph respectively with no overlap. Bull Creek model predictions bracket the entire temperature range, reflecting the broad range of physical conditions and landuse activities characteristic of that basin. The implications from these results are that improved temperature conditions (exemplified by Elder Creek results) can be achieved by improved riparian shading, and hence shifting temperatures from right-to-left on the graph.

Discussion

A critical feature built into the model is the facility to perform scenario testing by modifying the riparian shading regime. These modifications, which involve changing tree heights, can be performed for an entire basin or selected areas within a basin. The impacts on stream temperatures can be assessed at individual reach scales up to entire basin scales, providing the capability to examine local and cumulative temperature effects after modification of the riparian environment. Predictions for two scenarios which bracket the range of potential riparian shading scenarios were performed for the three sub basins. The topography-only scenario predicts temperatures where shade is supplied solely by local topography, and the reference-state scenario assumes natural, undisturbed conditions where trees are assigned representative late seral heights. The insolation predictions for these scenarios are passed to the 1-D heat balance model which uses the fitting parameters computed for current conditions predictions. *Figure 1(b)* shows results for these scenarios using eighteen thermograph calibration sites in Bull, Elder, and Rattlesnake Creeks. As expected, temperature predictions in Elder Creek change little from the current conditions to the reference state scenario. Predictions for all three sub basins for the topography-only scenario show significantly elevated temperatures above the current condition predictions, and well exceeding 4 °C for several stations. Interestingly, predictions for Rattlesnake Creek illustrate that warm temperatures predicted for current conditions are only slightly decreased for the reference state condition, suggesting that for some naturally warm basins, shade prescriptions may result in only minor temperature reductions. The results for Rattlesnake Creek also support the argument for applying basin-specific criteria to water quality regulation rather than applying a single temperature metric or a temperature threshold for entire basins.

The model has also been used to predict temperatures for sub basin scenarios in Bull Creek, following shade modification on first and second order channels. The results from these sub basin tests provide additional support for the body of work illustrating cumulative temperature effects while indirectly contributing to the debate over timber harvesting impacts on aquatic habitat quality and quantity and the effectiveness of forest practice rules for protecting habitat (SRP 1999). A wealth of research has demonstrated the deleterious impacts of timber harvesting on water temperature and aquatic habitat (for example, Beschta and others 1987, Beschta and Taylor 1988, Brown 1969, Johnson and Jones 2000, Kopperdahl 1971, and others). In some cases, recovery to pre-harvest levels can take up to two decades (Beschta 1989). While there is general agreement over the various mechanisms responsible for stream heating, a vigorous debate persists over which are the controlling mechanisms (Bartholow 2000). A few studies have suggested that a local warm environment and ambient conditions control water temperature and have also rejected the role of cumulative downstream heating (for example, Caldwell and others 1991; Larson and Larson 1996, 1997; Sullivan and others 1990; Zwienicki and Newton 1997). However, several authors have suggested that most of these studies are based on inconsistent assumptions, flawed experimental designs, or both (see Beschta 1997, Beschta and others 2003, NCASI 2001, Poole and others 2001).

Figure 2 shows results for four Bull Creek tributaries following shade modification on first and second order channels. In addition to showing current predictions, each graph shows temperature predictions for full reference vegetation shading on first and second order channels, and topography-only shading. The right ordinate on each graph displays four temperature categories originally applied in the South Fork Eel TMDL (U.S Environmental Protection Agency 1999) and which categorize salmonid habitat conditions as a function of temperature. In an effort to delineate potential coho habitat, slope thresholds for 10 percent and four percent (if present) channel gradients are also indicated. These thresholds correspond to the furthest upstream extent of the connected channel network at gradients equal to or less than four percent and 10 percent slope and provide a quantitative indicator of potential coho habitat. The four percent threshold identifies the approximate upstream limits of coho spawning habitat (Reeves and others 1989), and the 10 percent threshold is an approximate indicator for the maximum upstream extent of coho rearing habitat (Meehan and Bjornn 1991). Results for the four tributaries very clearly demonstrate elevated downstream heating for the topography-only shading scenario for all tributaries, and especially for the East-West orientated creeks (Cow Creek and Mills Creek). For the reference vegetation scenario, downstream temperatures are notably suppressed on all four tributaries.

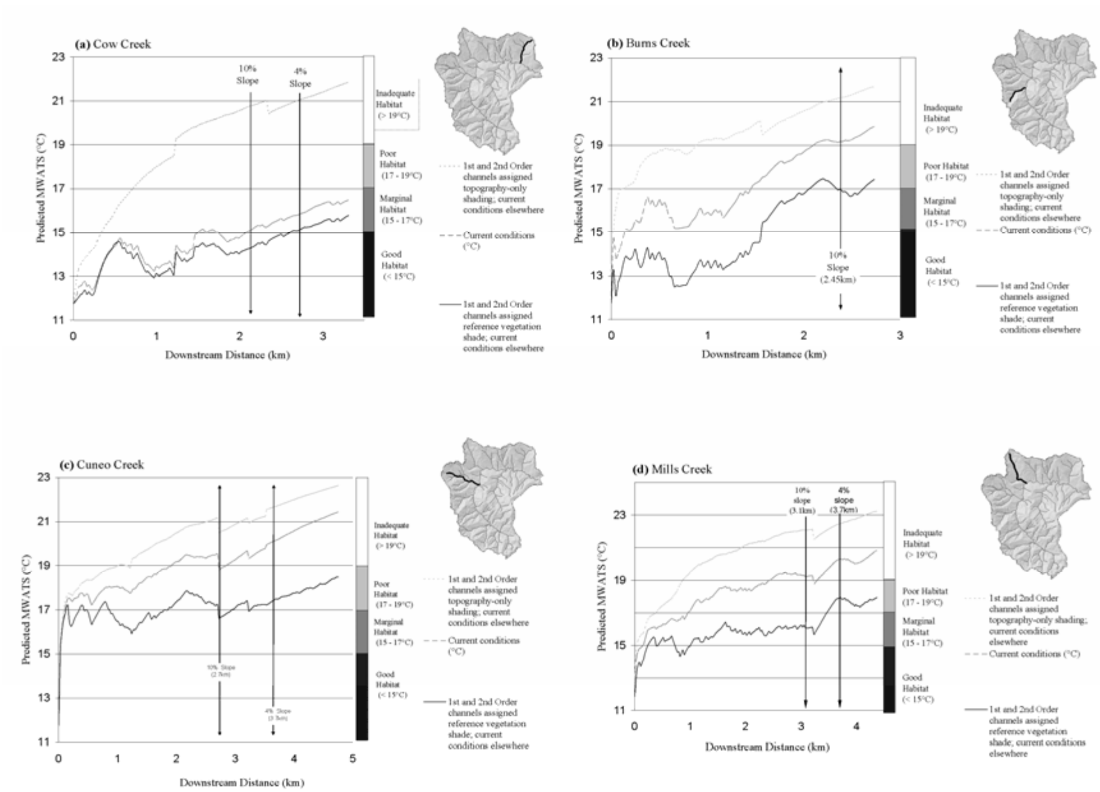

Figure 2—Downstream temperature changes following upstream shade modification on first and second order channels for four Bull Creek Tributaries.

Conclusions

We present a mechanistically-based model which assumes that direct shortwave radiation drives summertime stream temperatures and that emphasizes the importance of riparian shading for controlling insolation received at the stream surface. The model performs well for basins of varying sizes and with different vegetation, topographic, and lithologic characteristics. However, where low-flow discharges show significant spatial variability, the model performs less well. The steady-state assumption embedded in the model precludes predicting diurnal and instantaneous maximum and minimum temperatures. The model shows considerable promise, however, for temperature assessments for large watersheds and thus complements the existing physically-based models currently applied in the regulatory framework. Sub basin applications illustrate significant downstream cumulative heating effects after modifying riparian shading on low order channels, lending further support to the body of work demonstrating the role of cumulative effects (for example, Bartholow

2000, Beschta and Taylor 1988, Rowe and Taylor 1994). These results also support the arguments for providing greater protection to low order, non-fish bearing streams (Ligon and others 1999) which receive minimal protection under current California Forest Practice Rules (CDFG 1999).

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