Review #4 - Dr. Robert L. Beschta, Professor of Forest Hydrology, OSU - 6/30/99

Dear Mr. Pedersen:

The following comments pertain to my review of **Heat Source: Reach Analysis of Stream and River Temperature Dynamics** as requested by your office of the Oregon Department of Environmental Quality.

My approach to this review was to read through the documentation and then return to several sections of specific interest for additional comment. I did not go back to original research publications to check the accuracy of the reported equations as I assumed the author, the program committee members for the Masters of Science degree, and the DEQ have done that detail work. Hence, many of my comments are more generalized and base on my experience with developing a temperature simulation model (i.e., TEMP86), an understanding of the literature on stream temperatures, and empirical research related to stream temperatures over the last 20 years.

For anyone that has attempted to undertake the development of an energy balance model of stream and river temperatures (and I have), the multitude of site and atmospheric conditions that can influence energy transfers is somewhat daunting. Furthermore, all energy transfers must ultimately be expressed as discrete mathematical relationships that attempt to best represent what happens in the real world. From an overall perspective, I would submit that the Heat Source Model has generally done an excellent job at trying to represent the complexity of energy transfers associated with streams and rivers and represents what I would consider to be a "start-of-the-art" approach to modeling of stream temperatures. In addition, not only is the documentation clearly written and well organized, but it provides the basic equations and relationships used in the model as well as synopses of previous literature, equations, and research. I'm particularly impressed that the Heat Source model and write-up is the product of a Masters of Science degree program; there are many such programs that do not result in anything as substantial as the material presented in this documentation of the Heat Source model. The originating author of this model deserves much credit for what he has accomplished. More specific comments follow:

1. **Pages 8-10; Non-Uniform Heat Energy Transfer Equation**

   The inclusion of dispersion is an important improvement over previous temperature models. While dispersion effects over short stream reaches and high flows are likely to be insignificant, during low flows and over long reaches, dispersion may have a significant role.

2. **Page 12; Spatial and Temporal Scale**

   "The length of the defined reach is limited by the assumption that the upstream and downstream portions of the reach are relatively homogenous."

   This is an important point. Nearly all modeling efforts require some degree of generalization and simplification of a real-world situation. A stream and its attendant complexity of channel characteristics, riparian vegetation, and energy transfer processes is often much more complex that anyone can precisely measure or model. As long as the person using the model is aware of this concern and attempts to work with the context of expected levels of modeling error, perhaps that is all one can ask.

3. **Page 12; Spatial and Temporal Scale**

   "As of the time of this writing, no limits to reach length have been established. Theoretically, the only limitations to reach length are that the reach is relatively

homogeneous and that no major surface inflow from merging water bodies occurs in the defined reach."

Again, the author of Heat Source is indicating that departure from reach homogeneity is likely to create prediction errors. I would agree. However, the "reach length" issue is also an important concern if the model is to be used for evaluating temperature changes over "long reaches" or a series of shorter reaches that cumulatively effect the water temperature at some downstream location. My review of the Heat Source documentation and results indicates to me that the model has the potential for being a relatively good predictor of stream temperatures for reaches of approximately 2000 feet or less (results on pages 40-63 indicate that the stream lengths for which the model was evaluated averaged 1130 ft with a standard deviation of ± 780 ft). The more difficult question to answer is whether the model is capable of accurately predicting stream temperatures over longer reaches where the "cumulative effect" of bias in one or more heat transfer relationships may become important. Such bias may not be a problem nor apparent in the prediction of stream temperatures over relatively short reaches.

4. **Pages 14-16; the Mechanics of Shade**

   The calculation of an "effective shade" is an interesting and appealing approach. By representing the potential relative to the measured daily solar radiation at a stream surface, all of the complexities of shade effects are summarized in a single variable.

5. **Pages 18-21, Routing Solar Radiation to the Stream Surface**

   While a large number of energy transfer processes can and do occur along streams, the modeling of shade is probably the most important single component for most forested riparian ecosystems. For shrub dominated systems, I suspect that shade will also be a major factor affecting stream temperatures; less clear is the role of shade along meadow systems that are likely to be dominated by sedges and herbaceous plants adapted to moist conditions. In these later instances, the role of vegetation on stream temperatures may be most important with regard to channel morphology effects (e.g., channel width).

   The approach adopted by Heat Source for routing solar radiation through streamside vegetation is that presented by Beschta and Weatherred (1984). When that original approach for routing solar radiation was developed, we based it on theoretical considerations of how streamside vegetation, particularly forest vegetation, might route incoming solar radiation over a wide variety of canopy densities, canopy heights, buffer widths, and solar angles. Unfortunately, we were unable to test and verify their approach with actual field data. Thus, this represents an area of continuing research need—empirical measurements at stream surfaces of solar energy that has been routed through various canopies of riparian vegetation.

6. **Page 21; Local Dawn/Dusk**

   It appears that "" and "<" symbols were inadvertently left out of the relationships in parentheses.

7. **Pages 22-24; Stream Parameters**

   This section also utilizes many of the relationships and equations presented by Beschta and Weatherred (1984). The results of this approach are a mixture of theoretical considerations and available empirical relationships; it was reasonable in 1984 and I have no reason to suspect it is not a reasonable approach today. To my knowledge, the measurement of heat absorption by a streambed has never been directly measured. Because the water column absorbs most solar energy, any errors in these relationships are likely to have minor effects on stream temperatures except where water depths are inordinately shallow.

8. **Pages 32-35: Evaporation Flux**

   Brown's early research in western Oregon indicated that evaporative heat loss was not a major concern for predicting the temperatures of small forest streams. However, recent research for streams in eastern Oregon (Beschta, unpublished) indicate that an evaporative heat loss term needs to be considered. While a variety of equations exist for predicting evaporation flux (summarized on page 34), I would agree that the equation presented by Bowie et al. (1985), and which is used in Heat Source, probably represents the best approach that is currently available. Even so, the use of the Bowie et al. (1985) equation requires the use of vapor pressure and wind speed data; such information can be estimated or approximated but is seldom directly available for a particular stream reach.

9. **Pages 35, 36; Stream Temperature Data**

   If groundwater discharge into a stream is occurring along a reach, the simple mixing equation approach used by Heat Source is likely adequate for the vast majority of situations. An exception might occur if the groundwater discharge is localized (i.e., a spring) and it occurs at either the upstream or downstream end of the reach.

10. **Pages 36-39; Stream Temperature Data**

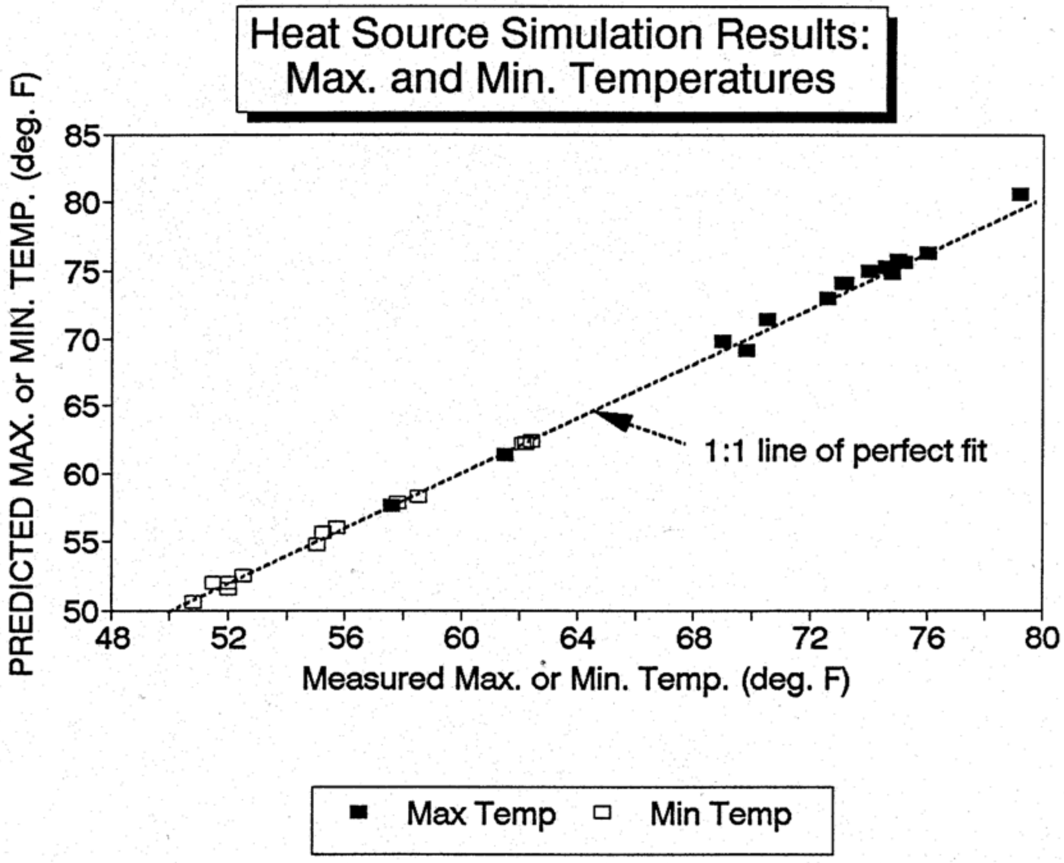
    I appreciate the inclusion of thermistor calibration data. It helps provide an important context regarding the precision and accuracy of the field measurements.

11. **Pages 39; Shade Data**

    The actual estimation of shade characteristics of riparian vegetation canopies (e.g., height, width, canopy density) is somewhat of an "art-form" and needs to be done judiciously because it can have important effects on temperature predictions. Furthermore, I suspect that the potential variability of such estimates for inexperienced individuals using Heat Source can be quite large. This situation seems to be somewhat analogous to that of estimating Mannings "n" roughness coefficients in hydrology. While there can be disagreement between individuals as to the exact "n" failure for a particular stream, coefficient estimates have proven to be useful approach for a wide variety of engineering modeling uses. Such may also be the case with regard to estimation of riparian canopy characteristics and geometry; individual observers may have somewhat different values but the approach has merit if done carefully and results are checked against field data whenever possible.

12. **Pages 40-64; Results**

    On page 64, a summary of model accuracy is presented in tabular form for the various site evaluations. An average SE (Standard error of the estimate??) of approximately 0.35° F was found for both temperature profiles and temperature changes comparisons. This level of accuracy would appear to be quite good.



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To further evaluate model accuracy, I simply plotted the measured maximum and minimum temperatures at the downstream end of a reach for each simulation against its corresponding predicted maximum and minimum temperature. These results are shown in the enclosed Figure. I chose maximum temperatures because they are basis for the current stream temperature standard for the State of Oregon. I also include the minimum temperatures because they are an important feature of a streams daily thermal regime. Subtraction of the daily minimum from the daily maximum provides an important perspective on the effect of the various energy transfers upon stream temperatures. In any event, the attached Figure simply indicate that the model, when applied to reaches generally 2000 feet long or less, does a good job predicting measured temperatures.

13. **Pages 65-70; Sensitivity Analysis**

This is a well-organized section and provides important insights into model dynamics when individual variables are altered. While model responses that seem to match current dogma regarding stream temperatures is gratifying and supportive of a conclusion that the model "seems to work", by itself such results cannot conclusively prove that the model is necessarily correct. Nevertheless, the results presented here do largely demonstrate important relationships between selected input variables and their effect on modeled temperatures. The results also largely seem to match current "dogma" regarding how stream temperatures are likely to respond when specific inputs are varied.

While various questions can be asked regarding the effect of each independent variable upon stream temperature, the direction (i.e., ±) and magnitude (slope) are probably the most important. Although the response relationships (presented in graphical form) are quite clear, interpretation is still needed because the % increases or decreases indicated for each variable do not represent "equivalent" changes. For example, a 10% increase in windspeed (Figure 3.16) cannot be constructed as being similar in magnitude as a 10% increase in relative humidity, or a 10% increase in relative humidity, or a 10% increase in air temperature even though all are represented similarly along the X axis. It’s not that I necessarily have a better way of presenting the sensitivity analysis, but readers should be cautioned that the indicated relative changes in input variables (i.e., as a percentage of some base condition) are done primarily for purposes of presentation (i.e., getting several variables on the same graph). To help clarify this situation, I would recommend that an addition be made to the each of the graphs in this section so that the absolute value of each input variable be shown at ± `00%. In other words, along the bottom of the X-axis of Figure 3.16, the windspeed for a –100%, 0% and +100% should be shown as 0mph, 5 mph, and 10 mph, respectively. Similar units should be included for all independent variables. I realize these can be calculated from Table 3.10, however their inclusion at the bottom of Figures 3.16, 3.17, 3.28, and 3.19 would help maintain clarity. Furthermore, I would recommend those absolute changes in "maximum stream temperature change be used on each Y axis instead of the percentages that are currently presented.

Most of the sensitivity results seem reasonable. However, unless I’ve misread the figures, there are a couple of them that present questionable relationships. For example, the generally linear decrease in "% maximum stream temperature" relative to a "% change in channel width" is not what I would have expected. Small decreases in channel width from the origin (i.e., the 0, 0 position in Figure 3.17) would be expected to cause small consequent changes in depth and therefore small adjustments to the "change in stream temperature" variable. However, in the neighborhood of –70% to –90%, each percentage change in width should have relatively large changes in depth and relatively large changes in the "change in stream temperature". Because depth is such an important variable relative to stream temperature responses, a curvilinear relationship was expected, perhaps something like that shown for streamflow in Figure 3.18 but inverted in shape. What am I missing?

Also I don’t understand why maximum temperatures are essentially unresponsive to a change in flow velocity (the nearly flat line shown on Figure 3.18). A simple evaluation of Brown’s Equation (Brown et al., 1971) indicates that ΔT is directly proportional to exposed surface area (A) divided by stream discharge (Q). Since exposed surface area is the product of reach length (L) times average width (W), and stream discharge is a product of average velocity (V), stream width (W), and average depth (D) at a cross-section, we can indicate the following:

$$\Delta \mathrm{T} \; \alpha \frac{A}{Q} \, and \, \frac{LW}{WDV}$$

Simplifying, we get:

$$\Delta \mathrm{T} \alpha \frac{L}{DV}$$

Where L/V is travel time. Thus, increasing V should have a strong effect on decreasing $\Delta \mathrm{T}$. Why isn't this the case in Figure 3.18?

14. **Pages 71-76, Model Application**

This is an important section as it allows a user to explore the effects of selected changes/treatments upon expected stream temperature responses. The Heat Source model is a powerful tool for addressing such questions. It allows answer and conclusions to be developed that often cannot be obtained in any other way. The development and inclusion of this section is an important component of the Heat Source model documentation.

With regard to figure 3.25, I still don't understand why a linear relationship between stream width and change in maximum stream temperature occurs. For example, let's suppose that 10cfs are flowing down a channel that is 10 feet wide, 1 foot deep, and an average velocity of 1 ft/sec. If the channel width is decreased to 5 ft and we keep the velocity of 1 ft/sec, then the channel depth would be 2 feet. Using Brown's Equation, and holding energy transfers per unit area at the surface constant, this would indicate a $\Delta \mathrm{T}$ approximately ½ that encountered for the original channel. If we keep the velocity thee same 1ft/sec and collapse channel width to a dimension of 1 ft (I realize this amount of change may not be realistic but I am simply trying to understand the response of the model), then a depth of 10 feet is what we would expect.

According to Browns Equation, we now expect a $\Delta \mathrm{T}$ to be 1/10th that of the original condition. Why do I not see a curvilinear response (an inverted version of figure 3.24) to changing channel width in figure 3.25?

With regard to Figure 3.27, is it assumed that same level of stream discharge and other conditions (i.e., shading levels, channel characteristics, meteorological variables) are experienced by the stream in a downstream direction? It would also be interesting to plot the changes in minimum stream temperatures that are predicted at various locations. At a flow of 1 ft/sec, the 7 mile reach represents about 10 hours of travel time that the water has been exposed to incoming solar radiation; 4 miles represents nearly 6 hours of travel time. Is the flattening of the curve at about 4 miles primarily a result of reduced solar energy levels once the period of exposure exceeds about 6 hours or a result of feedback mechanisms (e.g., increased long-wave energy loss with higher water temperatures, higher evaporation rates, deeper water columns) that tend to stabilize maximum temperatures. This figure implies that water temperatures will tend to stabilize, yet the causative factor(s) for such "stability" were apparently not explored or explained in the text.

In summary, I feel that the Heat Source model represents a state-of-the-art approach for modeling the daily temperature regimes of specific reaches using an energy balance approach. While questions regarding any single component of the model can always be raised, and there is always room for additional research to improve specific relationships, in total the model provides researchers and practitioners a significant advancement in their ability to assess the effects of alternative environmental factors or management regimes on specific stream temperatures (e.g., daily maximum) and temperature patterns (daily and seasonally). Not only can it be used to evaluate existing stream reaches or the effects of past management practices (e.g., removal of riparian forests, water withdrawals), but it can also provide insights into the potential temperature benefits associated with restoration of degraded riparian zones or improved flow levels. Given that riparian and/or channel systems for many of Oregon’ streams have been impacted by historical and ongoing land uses, one of the major questions often asked of researches is—what was the natural thermal regime of a particular stream? Because there is general lack of stream temperature data from historical periods, we cannot answer such a question empirically. However, through modeling approaches such as those demonstrated by Heat Source, these questions can be addressed.

Heat Source was originally developed as a "reach scale" approach to stream temperature modeling. And, based on the presentation of various components and methodologies in this report as well as model validation runs, sensitivity analyses, and applications, it generally appears well suited to the task. However, using this model to address larger scale temperature issues (e.g., the cumulative effects of multiple management practices or conditions for "long" stream reaches or at the mouth of a basin) may require additional model development or a basin-by-basin calibration.

I do have some concerns regarding some of the model sensitivity relationships and application results, as indicated in my specific comments about. It is not clear to me whether these are a "significant flaw" in the Heat Source model as currently formulated, a misrepresentation of modeling results, or my misunderstanding of what the presented relationships are trying to convey.

I trust these comments will be useful for your purposes. Should you have any questions, regarding my comments, please feel free to contact me.

Sincerely

Dr. Robert L. Beschta

Professor of forest Hydrology

Enclosure: Figure showing simulation results

DEQ response to Comment #5

These review comments, as well as points made by Bruce Cleland, EPA (Review #2, Solar Parameters)and William C. Krueger (Review #3, review comments #1 through #4) suggest that canopy density should be described with a more physically based approach. DEQ has made changes that are detail in responses to Review #2 and Review #3. Please refer to either of these responses.

DEQ response to comment #7

DEQ agrees with the reviewer's comments regarding streambed absorption and conduction. To date, DEQ has not found a method superior to that developed by Beschta and Weatherred (1984). Further, when considered with the other energy processes, streambed conduction is a rather small component for two reasons:

- Water tends to absorb solar rapidly resulting in relatively little heat energy loading of the submerged streambed, and
- Streambed materials have high conduction rates that tend to return absorbed heat energy back to water column relatively quickly.

DEQ response to comment #8

Local atmospheric data availability has been a constant challenge to this methodology. Specifically, hourly air temperature, relative humidity and wind speed data are usually collected at municipalities or weather stations that may or may not provide data that reflects conditions similar to that experienced by the stream surface. DEQ has placed data loggers in near stream areas to collected needed continuous atmospheric data in selected Oregon river basins. However, it is not practical to sample atmospheric parameters (i.e. relative humidity and wind speed) more than two or three sites per river basin during critical summertime periods.

DEQ response to comment #9

Dr. Beschta points out the same potential problem with groundwater mixing as that identified by Bruce Cleland (Review #2). Heat Source 5.5 accounts for groundwater by divide the groundwater inflow volume equally between distance steps. The result is that groundwater mixes along the entire stream reach. Forward Looking Infrared Radiospectrometry (FLIR) data recently collected in the Umatilla and Grande Ronde river basins show that groundwater may behave more locally and occur at specific points. For this reason the methodology has been changed to allow the user to define the longitudinal position of groundwater inflow, the volume of groundwater inflow and temperature of groundwater inflow. Complete transverse mixing is assumed at each longitudinal groundwater inflow site.

$$T_i^{t+1} = \frac{\left(T_i^t \cdot Q\right) + \left(T_{gw} \cdot Q_{gw}\right)}{\left(Q + Q_{gw}\right)}$$

Where,

T: Stream temperature (^{o}C)

T_{gw}: Groundwater temperature (^{o}C)

Q: Average stream flow (cms)

Q_{gw}: Groundwater exchange volume (cms)

DEQ response to comment #11

DEQ has struggled with the difficult task of describing vegetation characteristics that often are quite variable. In an effort to increase riparian vegetation parameter resolution, stream segmentation (i.e. stream reach length) has been dramatically decreased. Segmentation is based on either vegetation characteristics, stream aspect, hydrology (tributaries or groundwater) or channel morphology changes. Vegetation height, width and density values are derived from either:

- Riparian area mapping with stereoscopic measurements from aerial photography, or
- Landsat imagery overlaying Digital Orthophoto Quads (DOQs).

Vegetation characteristics are ground checked for accuracy.

DEQ response to comment #13

It should be noted that portions of the methodology have been modified based on the results of this review process. Therefore, DEQ intends to perform a new sensitivity analysis using the "improved" version of Heat Source that may reveal modified parameter sensitivities.

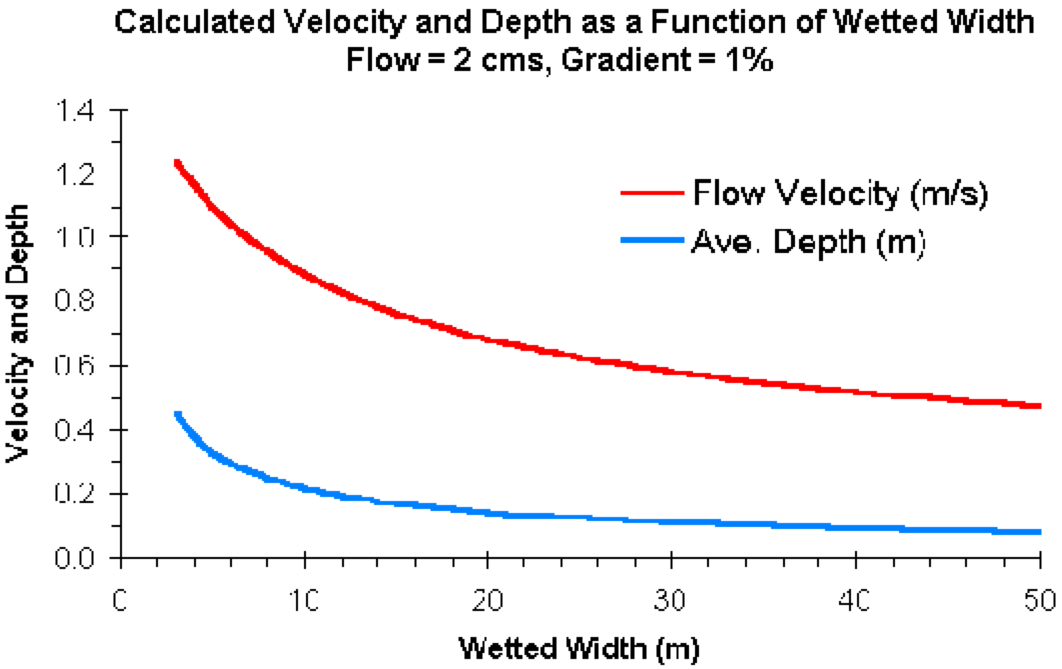
Dr. Beschta questions the results of analysis related to the sensitivity of wetted width, depth and flow velocity. The Heat Source methodology calculates wetted width (W) with Leopold's Power Functions. Depth (D) and velocity (U_x) are derived with Manning's Equation. As the Equations below depict, width (W) adjustments result in changes in both depth (D) and velocity (U_x).

Leopold Width Power Function: $W = a \cdot Q^b$

Manning Equation Derived Depth: $D = \left(\frac{Q \cdot n}{\sqrt{S_o} \cdot W} \right)^{\frac{3}{5}}$

Manning Equation Derived Velocity: $U_x = \frac{1}{n} \cdot R_h^{\frac{2}{3}} \cdot S_o^{\frac{1}{2}} = \frac{1}{n} \cdot \left(\frac{A}{P_w} \right)^{\frac{2}{3}} \cdot S_o^{\frac{1}{2}} = \frac{1}{n} \cdot \left(\frac{W \cdot D}{(W + 2 \cdot D)} \right)^{\frac{2}{3}} \cdot S_o^{\frac{1}{2}}$

If gradient (S_o) and Manning's n remain unchanged, then: $\uparrow W \propto \downarrow D \propto \downarrow U_x$.


Calculated Velocity and Depth as a Function of Wetted Width
Flow = 2 cms, Gradient = 1%

Where,

A: Cross-sectional area (m^2)

a: Leopold coefficient a

b: Leopold coefficient a

D: Stream depth (m)

n: Manning's n

P_w: Wetted perimeter (m)

R_h: Hydraulic radius (m)

Q: Stream flow (cms)

S_o: Stream gradient

W: Wetted width (m)

U_x: Stream velocity (m/s)

With this perspective, Dr. Beschta's review comment can now be addressed.

$$\frac{\partial T}{\partial t} = -U_x \cdot \frac{\partial T}{\partial x} + D_L \cdot \frac{\partial^2 T}{\partial x^2} + \frac{\Phi}{c_p \cdot \rho \cdot D_i}$$

If we ignore the effects of dispersion ($D_L = 0$), we can simplify to:

$$\frac{\partial T}{\partial t} = -U_x \cdot \frac{\partial T}{\partial x} + \frac{\Phi}{c_p \cdot \rho \cdot D_i}$$

And the following relationships can be assumed when combined with width, depth and velocity relationships (i.e. $\uparrow W \propto \downarrow D \propto \downarrow U_x$)

$$\downarrow \frac{\partial T}{\partial t} \propto \uparrow U_x \propto \downarrow W \propto \uparrow D \propto \downarrow \Phi$$

In summary, one would expect to see a decreased rate change in temperature (T) with increased flow velocity (U_x), decreased wetted width (W), increased depth (D) and decreased heat energy flux (F). The sensitivity analysis would confirm all of these relationships, with exception of velocity. Further sensitivity analysis should be performed. This work is in progress.

DEQ response to comment #14

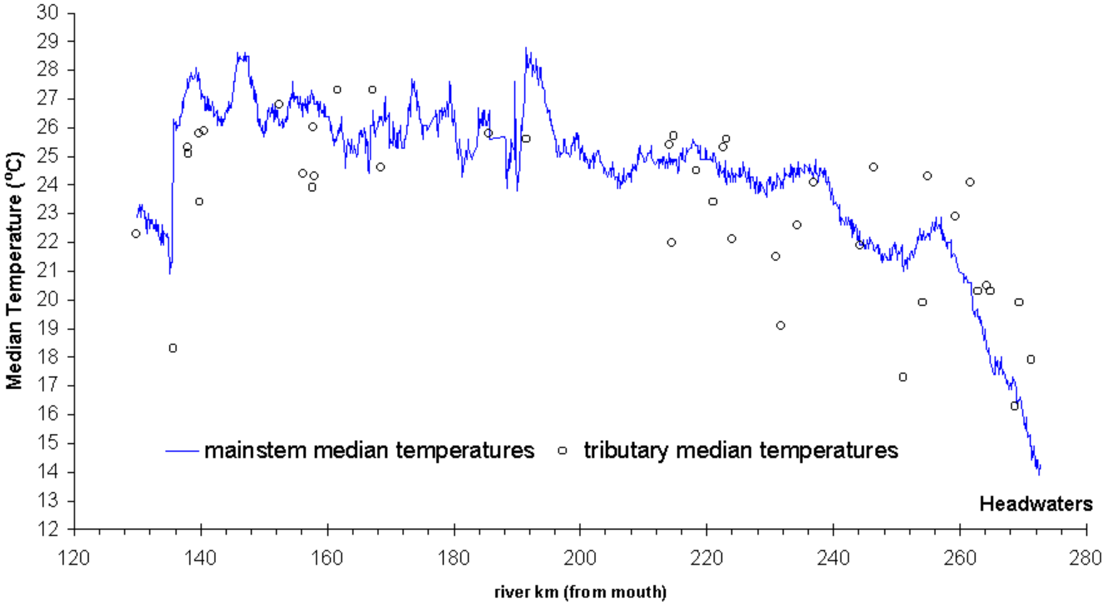
Regarding Figure 3.25 - Stream wetted width is utilized in the following ways in the methodology:

- Serves as a Manning's input for hydraulic radius (R_h), wetted perimeter (P_w), velocity (U_x) and depth (D) determination
- Determines the transverse distance across which shadows are cast for determination of portion of stream surface shaded
- Determines the surface area of the stream reach

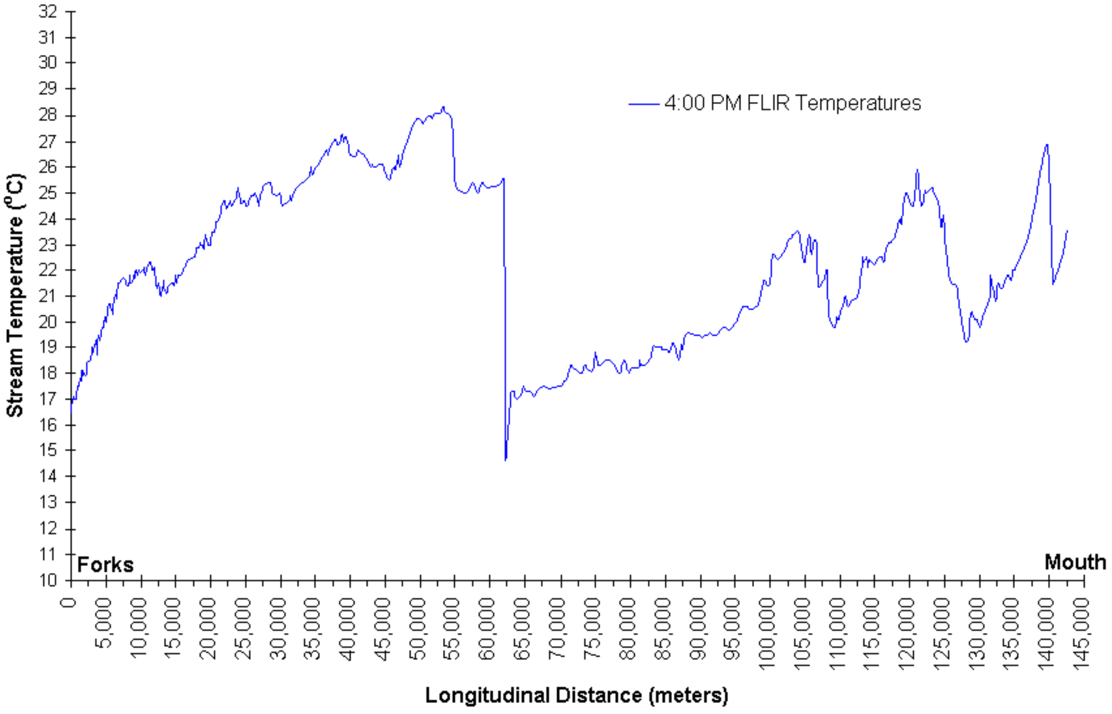
Wetted width is an important parameters for hydrologic processes, shading characteristics, as well as, surface area exposed to heat energy processes. The role of the wetted width dimension is more complicated than that reflected in Brown's Equation. With that said, the reviewer has a valid point in questioning the apparent linear sensitivity of wetted width. Further sensitivity analysis will be performed.

Regarding Figure 3.27 - Model sensitivity to reach length demonstrates that given homogenous low flow stream reach (i.e. homogenous hydrology, channel morphology and riparian characteristics) several miles in length that a stream will reach a temperature at which there is little change with respect to distance $\left(\frac{dt}{dx} \neq 0\right)$. This occurs when the rate of heat loss balances the rate of heat gain. Evaporation, longwave radiation, convection and conduction rates are partially functions of stream and air temperatures. As stream temperatures warm, heat dissipation rates increase via increased back radiation rates, convection/conduction rates may approach zero assuming the gradient between steam and air temperature is small, and evaporative heat loss rates dramatically increases. In fact the only heat energy process that is not a function of air or stream temperature is solar radiation. In essence, an equilibrium temperatures where $\left(\frac{dt}{dx} \neq 0\right)$ can only be attained when the sum of back radiation, convection/conduction and evaporation heat transfer rates balance radiant heat input rates.

Equilibrium temperatures are derived from theory. Sullivan et al. (1990) describes an equilibrium temperature that is closely related to mean basin air temperature. Although equilibrium temperatures can be developed mathematically (as demonstrated by Figure 3.27), the equilibrium temperature theory is largely unsupported by spatial stream temperature data sets (i.e. FLIR derived temperature data). Stream temperatures respond to the hydrologic and heat energy environments in the longitudinal downstream direction. These hydrodynamic and thermodynamic conditions vary with longitudinal distance (kilometers, meters) and time (annually, seasonally, daily, hourly, etc.) resulting in variable stream temperatures that are rarely in equilibrium with their environment. On a sub-basin 4th field hydrologic unit code (HUC) scale, stream temperatures rarely reach or maintain equilibrium for long distances. At best, ranges of temperatures emerge that can be referred to as the local equilibrium temperatures. Below are the longitudinal temperature profiles for the Grande Ronde River and the Umatilla Rivers. These data sets suggest that spatial temperature patterns are far more complex and variable than the Sullivan and Adams (1990) simple equilibrium theory suggests.



Longitudinal Temperature Profile from FLIR for Grande Ronde River
(Wallowa River to Tanner Creek)



Longitudinal Temperature Profile from FLIR for Umatilla River
(Columbia River to Forks)