Review #2 - Bruce Cleland, Senior Environmental Scientist - Environmental Protection Agency Region 10 (OW-134) - August 5, 1999

The review of Bruce Cleland has been typed exactly as it was received to the extent that it was practical.

As you requested, I agreed to participate in a review of the supporting documentation for Heat Source. My review focused on the substance of the methodology (e.g. definition of terms, analytical approach, support by literature and other research, etc.) and on the testing / validation of the model.

I find that Heat Source represents one of the more comprehensive accounting methods that has been developed to assess water temperature changes in streams. Heat Source incorporates methodologies developed and tested over the past 30 years. I believe that Heat Source is a major advance in the field of water temperature modeling. Simulations are focused on hourly temperature changes using current knowledge of energy sources which deliver heat to stream systems. Many other models predict only daily average and maximum water temperature values. The output form Heat Source provides hourly heat budget and temperature information. This enables a much easier cross-checking of model results with standard equations and easier comparison to actual thermograph data.

The attachment contains detailed comments prepared in conjunction with my review of Heat Source and its analytical methodology. Please call me if you have any questions regarding these comments or need additional information.

Heat Source Methodology – Review Comments

The following represents comments prepared in conjunction with my review of Heat Source and its analytical methodology.

METHODOLOGY

Development of the methodology that supports Heat Source used a literature review of past water temperature modeling efforts. The purpose of this literature review was to utilize the most current approaches towards water temperature analysis in Heat Source. A major objective of Heat Source is to highlight various components of the stream system that cause water temperature change through use of a heat budget analysis of factors that induce the change.

The review of the supporting literature is solid. Information presented in the literature review represents a good cross-section of the current state of knowledge regarding water temperature modeling. Literature cited in the Heat Source methodology that is used in other water temperature modeling efforts includes.

- Brown's equation is used as a starting point.
- Wunderlich provided a more comprehensive description of algorithms to estimate energy flux components, particularly evaporation.
- Jobson and Keefer developed a methodology to predict heat transfer on the Chattahoochee River using finite difference methods (hydro-pulsated system).
- Beschta and Weatherred contributed quantitative descriptions of heat energy flux components, particularly convection, conduction, and evaporation.
- SSTEMP used daily average temperature and estimated daily maximum temperature form an empirical simplification that correlates maximum air and water temperature.
- MNSTREM (Sinokrot and Stefan) developed a numerical model based on finite difference solution to the unsteady heat advection / dispersion equation in predicting hourly water temperatures.

- Chen used a combination of the Hydrologic Simulation Package Fortran (HSPF) and an energy balance methodology to simulate stream temperatures for various hypothetical riparian restoration strategies.

Heat Source provides a record of energy flux components and the predicted water temperature change. The flow chart in the supporting documentation (Figure 2-1) provides a good summary of the model structure and factors considered in the numerical analysis within Heat Source. Important components include:

- Finite Difference Solution
- Atmospheric parameters
- Solar parameters
- Stream parameters
- Energy balance

Finite Difference Solution

Heat Source uses a finite difference method to solve the non-uniform heat energy transfer equation. The model is structured to consider advection, dispersion, and heat energy flux. The Heat Source document clearly defines all terms used in development of the numerical solution. Heat Source accounts for the longitudinal transfer of heat energy. The document describes the role of advection / dispersion and how it is considered. The approach used is consistent with other water quality modeling efforts including methodologies applied in EPA models (e.g. QUAL2E). Heat Source also calculates the net heat energy flux at every time and distance step based on physical and empirical formulations developed for each significant energy components, again consistent with accepted approaches to water temperature modeling.

The Heat Source document also explains the approach used to define boundary conditions for the finite difference solutions and the simultaneous solution method employed. Finally, assumptions regarding spatial and temporal scale are described including limitation. With respect to the finite difference solution, I find that the Heat Source documentation does a good job in describing the overall approach. The method applied is consistent with other water temperature modeling efforts.

Atmospheric Parameters

Another component of Heat Source addresses atmospheric parameters, notably the optical air mass thickness, atmospheric pressure, and vapor pressure. As indicated by supporting literature, estimates of the atmospheric parameters are used in parts of the heat budget, e.g. heat transfer through evaporation. I find that the Heat Source document defines terms used and the literature supporting estimation techniques employed by the model. Methods are clearly stated and limitations described, such as the effect of condensation.

Solar Parameters

As stated in the Heat Source document, the dominant source of heat energy contributing to water temperature increases is solar radiation directly striking the stream surface. Any analytical tool designed to assess the effects of riparian management on water temperature must adequately address heat transfer from solar radiation. The Heat Source document contains a very thorough discussion on methods used to determine solar parameters. Derivation of model coefficients is based on methods published in the scientific literature. Areas described in the Heat Source document include the basic mechanics of shade, solar time, solar angle, routing of solar radiation to the stream surface, and solar radiation attenuation / scattering. Terms used in the Heat Source document are well defined, equations clearly described, and the supporting literature cited. I find that the description of the methodology for determining solar parameters as written in the Heat Source document actually provides very good reference on this subject, in and of itself.

A suggestion regarding the model itself (Heat Source Version 5.5) involves an input value that relates to the calculation of heat energy from solar radiation. The input value requested is the canopy coefficient (C_{veg}) as described on page 21 of the Heat Source document. The role of this parameter is to determine the attenuation and scattering of solar radiation, which is clearly described in the Heat Source document. The model itself, however, labels this input parameter as ***"Buffer Density"***. I would suggest changing this parameter label in the model ***"C_{veg}"*** or something that reflects canopy coefficient. ***"Buffer Density"*** can lead the user to believe that the value is canopy density as measured with densiometer. There is a distinction between the two values, which may contribute to confusion on the part of the user.

Stream Parameters

Stream parameters described in the Heat Source document included reflectivity and bedrock characteristics. The document describes the importance of each consideration in calculating the heat budget. Again, I find that the Heat Source document defines terms, clearly describes methods, and cites appropriate, relevant literature.

Energy Balance/Groundwater

The core of the Heat Source methodology is in the stream / river systems energy balance. The Heat Source document starts with the basic relationship between water temperature and total heat energy, then proceeds to build upon the heat energy continuity equation. Heat transfer processes considered include net solar radiation, long-wave radiation, evaporation, convection, streambed conduction, and groundwater energy exchange. Terms used in the Heat Source document are well defined, equations clearly described, and appropriate supporting literature cited. I find that the description of the methodology for calculating a heat budget to evaluate effects on water temperature as written in the Heat Source document, again, provides a very good reference on this subject.

Another suggestion regarding the model itself is the calculation of groundwater energy exchange. The Heat Source document describes development of the energy relationship which is based on stream / groundwater mixing (pages 35-36, equation 2-30). My observation in using Heat Source (Version 5.5) is that the finite difference solution may contribute to underestimating the cooling effect of groundwater. Discussions with author indicate that this concern is being addressed in an update to Heat Source.

Testing/Validation

Data Collection

Methods for collecting data to be used with Heat Source are discussed in the document. The techniques described for stream temperature and hydraulic data are standard accepted procedures. Methods to estimate atmospheric data are discussed and assumptions about cloud cover stated. With respect to shade data, techniques for gathering shade angle data are described. However, as discussed earlier, the document could be improved with some clarifying statements regarding differences between the vegetation coefficient Heat Source uses and canopy density.

Model Validation

Model validation of Heat Source is discussed in the document. The approach used is clearly described and follows techniques used in other water quality modeling efforts. In addition, supplemental information is provided for each test site that contributes to interpretation of results. Monitoring data include locations both in eastern and western Oregon

CONCLUSIONS

I find that Heat Source represents one of the more comprehensive accounting methods that has been developed to assess water temperature changes in streams. Heat Source incorporates methodologies developed and tested over the past 30 years. I believe that Heat Source is a major advance in the field of water temperature modeling. Simulations are focused on hourly temperature changes using current knowledge of energy sources which deliver heat to stream systems. Many other models predict only daily average and maximum water temperature values. The output from Heat Source provides hourly heat budget and temperature information. This enables a much easier cross-checking of model results with standard equations and easier comparison to actual thermograph data.

Support for conclusions: I base the above conclusions on my education and on my experience in the field of water quality assessment. I received my B.S. degree in Computer Science from Michigan State University's College of Engineering (1972). Course work included numerical analysis and finite difference methods. I received my M.S.E. degree from the University of Washington (1978). Course work focused on water resources engineering, in particular water quality modeling. My thesis involved the use of dynamic water quality models including some of the analytical methods used by Heat Source. I have been with EPA since 1977 working in various parts of the water quality program including monitoring and assessment, water quality modeling, planning, Nonpoint source management, NPDES permits, and the development of Total Maximum Daily Loads (TMDLs).

DEQ response to Solar Parameters

The reviewer correctly points out that the canopy coefficient is mislabeled as the canopy density. The canopy coefficient was developed by Beschta and Weatherred (1984) and successfully used in the temperature model TEMP86. There is no explicit transformation of the canopy coefficient to a canopy density value.

Canopy density is preferred as model input because values can be measured in the field with a densiometer or remotely sampled from aerial photos. For this reason, DEQ has decided to replace the canopy coefficient and related methodology with algorithms derived from Beer's Law (Oke 1978) and employed by Chen (1996) in the model SHADE. This methodology relies on true canopy density values. The new methodology for calculating attenuation of direct beam solar radiation is presented below.

Shadow casting from riparian vegetation and the stream bank is calculated resulting in a percent stream surface shaded (i.e. 0% to 100%). For the portion of stream shaded, direct beam solar radiation is attenuated as function of path length through the vegetation and vegetation density.

Calculations of solar direct beam path length through riparian areas is performed via the following algorithms:

$$\text{Path}_1 = \frac{\left(W_{veg} + W_{hang}\right)}{\sin\left(\theta_{azimuth}\right)\cdot\cos\left(\theta_{altitude}\right)}, \quad \text{Path}_2 = \frac{\left(W_{veg} + W_{hang}\right)}{\cos\left(\theta_{altitude}\right)}, \quad \text{Path} = \frac{\left(\text{Path}_1 + \text{Path}_2\right)}{2}$$

Calculations of the riparian extinction coefficient is performed via the following algorithms:

$$\lambda_{veg} = \frac{\ln(1 - \rho_{veg})}{H_{veg}}, \quad \rho_{shade} = 1 - \exp(-\lambda_{veg} \cdot Path)$$

Calculations of the direct beam solar radiation after passing through the riparian area is performed via the following algorithm:

$$\Phi_{direct2} = \Phi_{direct1} \cdot \alpha_{shaded} \cdot (1 - \rho_{shade})$$

Where,

- $Path_1$: First estimate of direct beam path length through vegetation (m)
- $Path_2$: Second estimate of direct beam path length through vegetation (m)
- Path: Direct beam path length through vegetation (m)
- l_{veg}: Riparian extinction coefficient
- r_{veg}: Riparian vegetation density (%)
- r_{shade}: Shade density (%)
- a_{shaded}: Portion of stream surface shaded (%)
- H_{veg}: Riparian vegetation height (m)
- $q_{azimuth}$: Solar azimuth (rad)
- $q_{altitude}$: Solar altitude (rad)
- W_{hang}: Vegetation overhang into bankfull channel (m)
- W_{veg}: Vegetation width (m)
- $F_{direct1}$: Direct beam solar radiation before entering riparian vegetation (cal m^{-2} s^{-1})
- $F_{direct2}$: Direct beam solar radiation after exiting riparian vegetation (cal m^{-2} s^{-1})

DEQ response to Energy Balance/Groundwater

Heat Source 5.5 accounts for groundwater by divide the groundwater inflow volume between distance steps equally. 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 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.

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

Where,

T:	Stream temperature (^oC)
T_{gw}:	Groundwater temperature (^oC)
Q:	Average stream flow (cms)
Q_{gw}:	Groundwater exchange volume (cms)