Review #1 - Dr. Graham B. Wallis, Professor of Engineering, Dartmouth - 7/6/99

Here are some comments. I have not performed a detailed review.

This is a reasonable approach to the problem of modeling stream temperature changes. It obviously needs a lot of checking of the parts of the model, particularly the way the shading of the stream by vegetation is modeled.

1. Page 3. Equation 2-1 has strange units that are improved later in the report. It is so simple that it is not worthwhile calling it "Brown's Equation".
2. Yes, surface evaporation is important and hard to estimate. It depends on the wind direction, sheltering by vegetation etc. Winds blowing along a stream whip up waves that increase mass exchange considerable.
3. Page 7. Is downstream temperature really input? Surely it is calculated from the model.
4. Pages 8-10. I would expect an energy balance equation like 2-7. It would be better to derive it from a control volume between x and x + dx along the stream. This is much better than trying to add up separate effects. Then the evaporation losses and groundwater flows would be apparent and not added in later. Also the changes in cross section area and velocity would be faced as parameters that probably are eliminated by combining the mass and energy conservation laws.
5. On page 10 the finite difference form appears to represent $d(U_xT)/dx$ and not U_xdT/dx. I don't understand why this is done. It should be checked, as it is perhaps a source of consistent error trend.
6. It seems reasonable that D_L should be proportional to U_x in 2-4. What are W and U_s in 2-5?
7. Page 11. As mentioned before, I do not think that the downstream boundary condition is dT/dt=0. Isn't this temperature calculated?
8. Page 12. The solution procedure seems possible.
9. Page 14-24. There are many aspects to the solar energy input. How are the actual field shading parameters evaluated? It must be impractical to measure all the angles and vegetation characteristics all along a stream, so someone has to use judgement, presumably, and try sensitivity calculations. On p.20 S1S2 has dimensions of length so SUN1 would seem to be dimensionless. Is this correct?
10. Page 34. as mentioned earlier, the evaporation model has uncertainties. Proportionality to velocity is reasonable as a first estimate, but many local conditions influence the coefficient, especially if the wind is funneled along the stream.
11. Comparisons with data are quite good. Of course, the temperature changes shown on the lower graphs provide a much better test of the model. I wonder how the author(s) chose the parameters to model vegetation in each case.
12. In some instances the actual temperature change systematically lags the predicted. Is this because of the error in evaluating the derivative advective term or because there is a systematic error in the geometry or timing of the insulation terms? Why are there no readings at midnight?
13. On Page 61 the actual temperature changes appear too simple, suggesting instrument error.
14. Page 63 presents a nice comparison. Again, the temperature is predicted to rise earlier than the actual in the morning. Perhaps this is due to a "daylight-saving time" error, or to being at the extreme of a time zone. Were actual local solar times used?
15. The sensitivity studies are useful. Even if the model is not accurate in every case, it should be useful for estimating the effects of changes, such as cutting down the shade trees, or planting them.

DEQ response to comment #1

Brown's Equation was mistyped as $\Delta T = \frac{(\Phi)(A_y)}{(Q)}$ and should be changed to $\Delta T = \frac{(\Phi)(A_y)}{(Q)} \cdot C_{unit}$, where C_{unit} accounts for unit conversions and the specific heat of water. While Brown's Equation is overly simple (which is stated in the Heat Source document on Page 3), it demonstrates the fundamental heat energy, surface area and flow relationships that affect stream temperature. Further, this equation served as a starting point for temperature analysis 30 years ago in the Pacific Northwest and is still used today in USFS temperature models (SHADOW v 2.3, USDA FS Pacific Northwest Region, 1993).

DEQ response to comment #2

The current methodology does account for many parameters that affect evaporation (i.e. wind speed, relative humidity, air temperature, stream temperature, vapor pressures and latent heat of vaporization). While wave action may affect evaporative heat exchange via increased stream surface area, it is not accounted for in the model methodology. No plans exist for inclusion of this phenomenon.

DEQ response to comment #3

The model calculates downstream temperatures, while measured downstream temperature values are used for model validation (i.e. to assess model accuracy).

DEQ response to comment #4

DEQ decided to use Equation 2-7 as the governing equation because it is physically based as opposed to statistical or black box derived methods. DEQ is largely concerned with the distinguishing effects of parameters such as groundwater, channel geometry, riparian vegetation, flow volume and evaporative cooling from the exposed stream surface. Therefore, Heat Source uses physically based algorithms, instead of deriving and/or lumping the effects of several mass and heat energy transfer parameters.

Equation 2-7 Non-Uniform One-dimensional Heat Energy Transfer

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

Steady Flow: $\frac{\partial U_x}{\partial t} = 0$

Non-Uniform Flow: $\frac{\partial U_x}{\partial x} \neq 0$

Where,

c_p: Specific heat of water (cal kg^{-1} K^{-1})

D: Average stream depth (m)

D_L: Dispersion coefficient (m^2/s)

F: Heat energy flux (cal m^{-2} s^{-1})

r: Density of water (kg/m^3)

T: Stream temperature (^oC)

t: Time (s)

U_x: Longitudinal flow velocity (m/s)

x: Longitudinal position (m)

DEQ response to comment #5

The finite difference form has been changed from an implicit solution to an explicit solution. Advection, dispersion and heat energy transfer is calculated below. Transformation of the *non-uniform heat transfer equation* into a central difference explicit form will now be demonstrated.

Recall Equation 2-7,

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

Which can be expressed in a central difference form as:

$$\frac{\left(T_i^{t+1} - T_i^t\right)}{\Delta t} = U_x \cdot \frac{\left(-T_i^t + T_{i-1}^t\right)}{\Delta x} + D_L \cdot \frac{\left(T_{i-1}^t - 2T_i^t + T_{i+1}^t\right)}{\Delta x^2} + \frac{\Phi}{c_p \cdot \rho \cdot D_i}.$$

Which can be rearranged as:

$$\left(T_i^{t+1} - T_i^t\right) = \frac{U_x \cdot \Delta t}{\Delta x} \cdot \left(T_{i-1}^t - T_i^t\right) + \frac{D_L \cdot \Delta t}{\Delta x^2} \cdot \left(T_{i-1}^t - 2T_i^t + T_{i+1}^t\right) + \frac{\Phi \cdot \Delta t}{c_p \cdot \rho \cdot D_i}$$

Define: $\delta = \frac{U_x \cdot \Delta t}{\Delta x}$, $\lambda = \frac{D_L \cdot \Delta t}{\Delta x^2}$, $\sigma_i = \frac{\Phi \cdot \Delta t}{c_p \cdot \rho \cdot D_i}$

Which simplifies to Equation 2-8 Non-Uniform Heat Transfer Equation (Explicit Form)

$$T_i^{t+1} = T_i^t + \delta \cdot \left(T_{i-1}^t - T_i^t\right) + \lambda \cdot \left(T_{i-1}^t - 2T_i^t + T_{i+1}^t\right) + \sigma_i$$

Known Stability Constraints,

$$\delta = \frac{U_x \cdot \Delta t}{\Delta x} \le 1$$

$$\lambda = \frac{D_L \cdot \Delta t}{\Delta x^2} \le \frac{1}{2}.$$

DEQ response to comment #6

The longitudinal dispersion coefficient can also be determined from stream dimensions with a relationship developed from roughness and flow (Fischer et. al. 1979).

Equation 2-4 Physical Dispersion Coefficient (Method 1)

$$D_L = C \cdot K_d \cdot n \cdot U_x \cdot D^{\frac{5}{6}}$$

Equation 2-5 Physical Dispersion Coefficient (Method 2)

$$D_L = C_{eff} \cdot \frac{U_x^2 \cdot W^2}{U_s \cdot D}$$

Where,

C: Unit conversion

D: Average stream depth (m)

D_L: Dispersion coefficient (m^2/s)

K_d: Dispersion constant (unitless)

n: Manning's coefficient (unitless)

U_x: average flow velocity (m/s)

U_s: Shear velocity (m/s)

W: Mean width (m)

DEQ response to comment #7

The downstream boundary condition is assumed to equal that of the second to last finite difference cell (T_n^t). The model compensates by calculating one extra finite difference cell (T_{n+1}^t). The downstream Boundary condition is then $T_n^t = T_{n+1}^t$.

DEQ response to comment #8

The solution method has now been changed as detailed in DEQ response to comment #5

DEQ response to comment #9

The model calculates shade levels every minute for one full day length. Riparian and channel morphology parameters that are utilized in the model methodology for calculating stream surface shade production are:

- Elevation (m): Measured from Digital Elevation Model (DEM) at upstream and downstream reach boundaries and then averaged
- Gradient (%): Is the difference between the upstream and downstream elevations divided by the reach
- Aspect (decimal degrees from North): Measured from DEQ 1:5,000 rivers layer and rounded to the nearest 15^o
- Bankfull Width (m): The width of the entire stream channel measured from 1:1,500 Digital Orthophoto Quads (DOQs)
- Channel Incision (m): Depth of the active channel below riparian terrace or floodplain. Often assumed to be zero due to lack of data
- Topographic Shade Angle (decimal degrees): The angle made between the stream surface and the highest topographic features to the west, east and south as calculated from DEM and 1:5,000 DEQ rivers layer for each stream reach
- Riparian Height (m): Derived from aerial photo stereoscopic measurements and/or Landsat Vegetation/Ground Cover Imagery overlaying DOQs at 1:5,000. Where heterogeneity exists, values are averaged along reach length
- Canopy Density (%): Values are derived via aerial photo interpretations, Landsat Vegetation/Ground Cover Imagery overlaying DOQs at 1:5,000 or ground level densiometer measurements
- Riparian Overhang (m): Distance of riparian vegetation intrusion over bankfull channel. Assumed to be zero where data is limited.
- Wetted Width (m): Derived from Manning's equation and Leopold power functions calibrated to measured wetted width data

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 lengths through riparian areas are performed via the following algorithms:

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

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)
$q_{azimuth}$:	Solar azimuth (rad)
$q_{altitude}$:	Solar altitude (rad)
W_{hang}:	Vegetation overhang into bankfull channel (m)
W_{veg}:	Vegetation width (m)

DEQ response to comment #10

Clearly the effects of wind over the stream surface will influence evaporation rates. Stream surface wind exposure will vary across a watershed due to differential heating, topography and riparian effects. The climate data used by DEQ is recorded at sites (i.e. municipalities and weather stations) that may not be indicative of conditions in the near stream microclimate. However, continuous weather data (including wind speed/direction), represents the best available data.

DEQ response to comment #11

Vegetation parameters represent ground level reach averaged measurements. Reaches simulated in the model validation section were selected for homogeneity in vegetation characteristics.

DEQ Response to comment #12

The model is adjusted for daylight savings time and no timing errors appear to be occurring. Further, systematic timing errors are not apparent (at least to this author). If the advection term was creating a systemic error, changes to the finite difference solution should correct such a problem. Midnight simulation data is not presented in the graphical output due to a graphing error.

DEQ response to comment #13

The simplicity of the actual temperature data is results from the limitations of the thermistor (i.e. temperature data recording device). The thermistor will not record a temperature change unless that change is greater than the manufacturer listed device error (0.25^{o}C). Therefore, the data listed in Figure 3.14, page 61, represents a very small diurnal temperature fluctuation.

DEQ response to comment #14

Local solar times were calculated from longitude, latitude, and day angle (i.e. the daily rotation of the earth). No timing errors were found.