On a Two-Dimensional Temperature Model: Development and Verification

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Abstract

Government regulators on many rivers have specified acceptable temperatures based upon habitat and biological criteria. These temperature thresholds impose constraints on reservoir operations and can limit water deliveries and power generation. Existing tools based on low-order modeling simplify a river to a simple line with limited spatial distribution of inputs and poorly represent physics of the river processes. The limited spatial extents restrict the usefulness of low-order modeling for such features as agricultural returns, gravel pits, groundwater upwelling, side channel activation, and streamside vegetation. It also imposes limitation on fish habitat assessment and reoperation outside the range of the calibration datasets.

This study develops a two-dimensional (2D) temperature module for an existing 2D hydraulic model, SRH-2D version 2. The 2D model incorporates data with both lateral and longitudinal geographic extents rather than lumping results into a point-to-point or uni-directional representation. The objective was to improve the representation of spatial features where low-order models resort to empiricism for a lumped treatment. Better representation of processes leads to increased accuracy and higher confidence.

The SRH-2D temperature model utilizes meterological data as inputs (solar radiation, cloud cover, air temperature, dewpoint temperature and wind speed). Physical processes modeled include solar radiation, terrain and vegetation shade, atmospheric radiation, water back radiation, heat exchange between water and river bed, water surface evaporative and conductive losses.

The model formulation, along with governing and process equations, is discussed first. The model is then tested and verified with simple cases having analytical solutions. The model is finally verified by applying to flows on the McKay Creek downstream of the McKay Dam.

Introduction

Water temperature is a key element for water quality studies and for some cases the most important attribute for stream analysis (Bartholow, 2002). Stream manipulation may lead to changes in water temperature which in turn may affect aquatic systems in many ways. Stream modifications may include reservoir discharge, release temperature, irrigation diversion, riparian shading, channel alteration, thermal loading, etc. Since many rivers have temperature compliance criteria for habitat and biological reasons, understanding of the temperature change due to stream manipulation becomes important. With climate change and growing emphasis on maintaining biological function in addition to water deliveries, the impact of thermal criteria in constraining water operations is expected to increase.

Assessment and prediction of stream manipulation consequences on water temperature for shallow streams are often carried out with numerical temperature models. Example models include SNTEMP (Theurer et al., 1984), SSTEMP (Bartholow, 1990), and ADYN/RQUAL (Hauser and Schohl, 2003), among others. Most existing tools are based on low-order modeling that represent a channel as a line of homogeneous longitudinal elements with limited spatial distribution of inputs. Some physical processes are poorly represented. Limited spatial extent restricts the usefulness of the model by neglecting spatial features such as tributaries and agricultural returns, gravel pits, groundwater upwelling, side channel activation, and streamside vegetation are highly parameterized or not included. The simplified picture of interactions requires inferring or estimating the real processes through conversion to lower order dimensions by the use of a number of empirical parameters used as abstract calibration coefficients. These coefficients increase the difficulty of model usage as well as the uncertainty, because most rivers do not have sufficient data to calibrate the independent effects of different features. Further, coefficients not tied to physical processes do not apply across a broad range of conditions. Predictive capability is limited to circumstances within measured ranges and cannot estimate the impact from changes on how the system operates. Example coefficients include: adjustments for estimates of velocity distributions (travel times) in the main channel, multiple flow paths, lateral inflows (surface or subsurface), and storage areas.

In this presentation, a two-dimensional (2D) temperature module is developed which incorporates geographic extents both laterally and longitudinally. A 2D representation provides a more direct and quantitative estimate of temperature impacts using the same spatially distributed area as is significant for biological characteristics. The developed 2D temperature module is then incorporated into an existing 2D hydraulic flow model, SRH-2D version 2 (Lai, 2008). The SRH-2D flow model is based on SRH-W (Lai, 2006) and has been widely applied by Reclamation and by external institutions. Many restoration projects in recent years apply 2D flow models to assess stream habitat suitability (e.g., Moir and Pasternack, 2008). Therefore, a temperature module would be a valuable addition where temperature is an important water quality element.

2D modeling provides accurate flow hydraulics which eliminates the need for abstract travel time adjustment coefficients and flow routing. When there are multiple flow paths, such as with gravel pits or side channels, flow moves at different speeds

along the different paths and, as a results, heats or cools at different rates. The difference in flow velocities between the river centerline and banks is also captured, eliminating the need to calibrate for cross section averaging. Spatially distributed sources of heat and cooling (ground water, solar, wind, vegetation) are directly transferable to the model and do not require grouping by reach. As a result, the spatially explicit results may show acceptable areas within generally unacceptable conditions and permit compromises where simplified models might indicate temperature violations. A process model can indicate the most critical component of the more critical areas to focus solutions. Grouping and lumping with abstract coefficients obscures the actual steps preventing temperature compliance.
Multi-dimensional tools for temperature modeling of reservoirs and lakes exist, for example, the 2D laterally averaged model CE-QUAL-W2 (Cole and Buchak 1995) and three-dimensional (3D) model U^{2}RANS (Lai et al. 2004). However, they are not applicable to typical streams. 2D laterally averaged reservoir models neglect lateral effects in favor of vertical stratification and are mostly limited to impounded areas; 3D models can accurately simulate temperature but the scale limits application to small areas. This paper focuses on shallow water streams where vertical stratification is negligible and complete vertical mixing is assumed.

Governing Equations and Process Models

The 2D depth-averaged flow equations are based on the assumptions that stream flows are shallow compared to width and the effect of vertical motion is negligible. Details of the equations and their numerical solution procedure may be found in Lai (2008) and are omitted here.

Conservation of thermal energy leads to the 2D depth-averaged temperature equation expressed as:

$$\frac{\partial hT}{\partial t}+\frac{\partial hUT}{\partial x}+\frac{\partial hVT}{\partial y}=\frac{\partial}{\partial x}\left[\frac{h\nu_t}{\sigma_t}\frac{\partial T}{\partial x}\right]+\frac{\partial}{\partial y}\left[\frac{h\nu_t}{\sigma_t}\frac{\partial T}{\partial y}\right]+\frac{\Phi_{net}}{c_w\rho_w}+\frac{q_{sp}}{A_{sp}}(T_{sp}-T) \quad (1)$$

In the above, T is depth averaged water temperature [C], x and y are horizontal Cartesian coordinates [m], t is time [s], h is water depth [m], U and V are depth-averaged velocity components [m/s] in x and y directions, respectively, ν_t is the turbulent viscosity and dispersion [m^2/s], σ_t is the thermal Prandtl number, ρ_w is the water density [kg/m^3], c_w is the specific heat of water [J/kg/C], q_{sp} is the spring water flow rate [m^3/s] into the stream (zero if spring flows out), A_{sp} is the area [m^2] of the spring water inflow, T_{sp} is the spring water temperature [C], and Φ_{net} is the net heat exchange [W/m^2] between water column and its surroundings (through water surface and streambed).

The turbulent eddy viscosity (ν_t) is computed with a turbulence model (Rodi 2003). Two turbulence models may be used in SRH-2D: the depth-averaged parabolic model or the two-equation k-ε model (Lai 2008). The Prandtl number is computed as follows (Bowie et al. 1985; Fischer et al. 1979; Kim and Chapra 1997):

$$\frac{\nu_t}{\sigma_t} = C_d h u_* \tag{2}$$

where u_* is the bed frictional velocity and C_d is a constant coefficient which may be case dependent.

The net heat flux, Φ_{net}, consists of six contributions as follows:

$$\Phi_{net} = \Phi_{ns} + \Phi_{na} + \Phi_{bed} - \Phi_{br} - \Phi_e - \Phi_c \tag{3}$$

where

Φ_{ns} = net solar radiation entering water surface
Φ_{na} = net atmospheric radiation entering water surface
Φ_{br} = heat loss by back radiation from stream
Φ_e = evaporative heat loss at water surface
Φ_c = conductive heat loss at water surface
Φ_{bed} = heat flux into stream at channel bed

The net solar radiation at a water surface incorporates five thermal processes: extra-terrestrial solar radiation, attenuation due to atmosphere, correction for cloud cover, reflection by water surface, and correction due to terrain and vegetation shade. The processes are described fully in a number of reports and textbooks on hydrology (e.g., Huber and Harleman 1968; Eagleson 1970; Brutsaert 1991).

If measured solar radiation (Φ_{Sm}) at water surface is available, the net solar radiation is computed as (Hauser and Schohl 2003):

$$\Phi_{ns} = \Phi_{Sm} R_S \tag{4}$$

where Φ_{Sm} is measured solar radiation (shade free solar radiation at the water) and R_S is reflection and terrain and vegetation shading factor which is computed by the following equations (Hauser and Schohl 2003):

$$R_S = R_{sm} \qquad \text{if } X_n \le B \text{ (shade free)} \tag{5a}$$

$$R_S = 0.2 \qquad \text{if } X_n > B + W \text{ (full shade)} \tag{5b}$$

$$R_S = R_{sm}\frac{B + W - X_n}{W} + 0.2\frac{X_n - B}{W} \qquad \text{if } B < X_n \le B + W \text{ (partial shade)} \tag{5c}$$

In the above:

$R_{sm} = 1 - a(57.3\alpha)^{-b}$ = shade-free reflection factor (a and b see Table 1)

α = solar altitude in radians
W = width of the stream cross section
B = distance from trees to water edge
$X_n = H_b \cos\beta / \tan\alpha$ = normal distance from trees to shadow edge
H_b = tree/bank height from water surface
$\beta = \left|\theta - \frac{90}{57.3}\right|$ = angle between sun and stream axis normal in radian
$\theta = \left|A_{zs} - \frac{A_{zr}}{57.3}\right|$ = angle between sun and stream axis in radian
A_{zr} = river azimuth, clockwise from north to direction of flow in degree
$\cos(A_{ZS}) = -\frac{\sin(\phi)\sin(\alpha) - \sin(\delta)}{\cos(\phi)\cos(\alpha)}$ = sun azimuth in radian

Table 1. Coefficients of solar radiation reflection

Cloud Cover	a	B
0-0.05	1.18	0.77
0.05 – 0.5	2.20	0.97
0.5 – 0.92	0.95	0.75
0.92 – 1.0	0.35	0.45

The solar altitude (α) is computed, assuming a spherical geometry, as follows (Huber and Harleman, 1968):

$$\sin\alpha = \sin\phi \sin\delta + \cos\phi \cos\delta \cos h \tag{6}$$

where ϕ is site latitude in radians, δ is sun declination (between the sun and equator) in radians, and h is the sun hour angle in radians.

If solar radiation is not measured, it can be computed using semi-empirical relationships. The approach follows Huber and Harleman (1968) is described in detail by Lai et al. (2004).

The net long-wave radiation emitted by the atmosphere is computed as:

$$\Phi_{na} = 5.16432 \cdot 10^{-13}(1 + 0.17C^2)(T_a + 273.16)^6 \tag{7}$$

where $C = (1 - S/S_0)^{3/5}$ is cloud cover and T_a is dry bulb air temperature [C].

The outgoing black-body radiation emitted from the water surface is a function only of the water temperature, and it is given by (Huber and Harleman 1968):

$$\Phi_{br} = \varepsilon_w \sigma (T_w + 273.16)^4 \tag{8}$$

where T_w is water-surface temperature [C], ε_w is emissivity (0.97 by Huber and Harleman 1968 and 0.98 by Tung et al. 2006), and σ is Stefan-Boltzman constant (5.672e-8 W/m^2/K^4).

The evaporative heat loss is computed by:

$$\Phi_{evp} = \rho_w L(a1 + b1W_a)(e_s - e_a) \tag{9}$$

where:

$L = (597 - 0.57T_w) * 4184$ = the latent heat [*J/kg*]

T_w = water temperature in Celsius

a1, b1 = constants: a1=0.0 to 4.0e-9; b1=1.0e-9 to 3.0e-9

$e_a = 2.171 \cdot 10^8 \exp\left[\frac{-4157}{T_d + 239.09}\right]$ = saturation vapor pressure [mb]

T_d = dewpoint temperature in Celsius.

$e_s = \alpha_j + \beta_j T_w$ = saturation vapor pressure [mb] with coefficient in Table 2

Table 2. Coefficients to compute saturation vapor pressure

T	j	αj	βj
0-5	1	6.05	0.522
5-10	2	5.10	0.710
10-15	3	2.65	0.954
15-20	4	-2.04	1.265
20-25	5	-9.94	1.659
25-30	6	-22.29	2.151
30-35	7	-40.63	2.761
35-40	8	-66.90	3.511

The conduction heat loss is:

$$\Phi_{cond} = \rho_w L(a1 + b1W_a) \cdot 0.61 \cdot 10^{-3} P(T_w - T_a) \tag{10}$$

where P is air barometric pressure in mb.

Heat exchange between stream bed and stream water is significant for shallow streams and it consists of two contributions: conduction from bed to stream and net solar radiation entering bed. It is computed by the following expression:

$$\Phi_{bed} = \frac{\kappa_b}{0.5\delta_b}\left(T_b - T_w\right) - (1 - A_b)(1 - \beta)\exp\left[-\eta(D - 0.6)\right]\Phi_{ns} \tag{11}$$

where κ_b is the thermal conductivity of the streambed bed material, δ_b is the effective bed thickness used for hear conduction computation, T_w is the water temperature, T_b is the effective stream bed temperature which is updated each time step by $T_b = T_b^{\;old} - \dfrac{\Phi_{bed}\Delta t}{\rho_b c_b \delta_b}$ with ρ_b and c_b the density and specific heat of the bed materials and Δt is the time step for simulation, A_b is albedo of bed material, β is fraction of solar radiation absorbed in the top 0.6m of surface water, η is extinction coefficient in water [1/m], and D is water depth [m].

Numerical Method

A detailed presentation of the numerical method is omitted here. Basically, the flow equations are solved with the finite volume method that guarantees the mass conservation locally and globally. An implicit time marching scheme is used with the arbitrarily shaped unstructured mesh methodology of Lai (2003). A detailed presentation of the numerical method for the flow hydraulics may be found in Lai (2008). The temperature equation is discretized and solved similar to the momentum equation.

Test and Verification with Cases Having Analytical Solutions

The following three test cases solve the unsteady 1D temperature equation:

$$\frac{\partial T}{\partial t}+\frac{\partial UT}{\partial x}=k(T_{eq}-T) \tag{12}$$

The purpose is to test and verify the implementation and solution of the unsteady temperature equation within SRH-2D. The above equation has the following exact solution:

$$T(t,x)=T_0(t-\tau)e^{-\kappa\tau}+T_{avg}(1-e^{-\kappa\tau})+\kappa T_\Delta \frac{\cos[\omega(t-\tau)]}{\omega^2+\kappa^2}\left[\omega e^{-\kappa\tau}-\omega\cos(\omega\tau)+\kappa\sin(\omega\tau)\right]$$
$$+\kappa T_\Delta \frac{\sin[\omega(t-\tau)]}{\omega^2+\kappa^2}\left[-\kappa e^{-\kappa\tau}+\kappa\cos(\omega\tau)+\omega\sin(\omega\tau)\right] \tag{13}$$

In the above, $T_0(t)$ is boundary condition at x=0, κ is a first-order rate constant which is a function of meteorological parameters and water depth, $T_{eq} = T_\Delta \sin\left(\frac{2\pi t}{P_\Delta}\right) + T_{avg}$ is water temperature, $\tau = x/U$, and $\omega = \frac{2\pi}{P_\Delta}$.

The first case has the following parameters: a constant flow velocity of U=1.0 mile/day, a zero equilibrium temperature $T_{eq} = 0$, and a constant coefficient k=0.2/day. A 100 mile straight channel is assumed for SRH-2D modeling. The mesh has 100 mesh cells in the flow direction and 2 cells in the lateral. Initially temperature is 20 Celsius everywhere and the temperature at $x = 0$ is held at 20 Celsius all the time. Simulation is carried out for 50 days with a time step of one hour. The temperature at $x = 100$ miles is compared in Figure 1 between the model solution and the exact solution. A good agreement is obtained for this simple case.

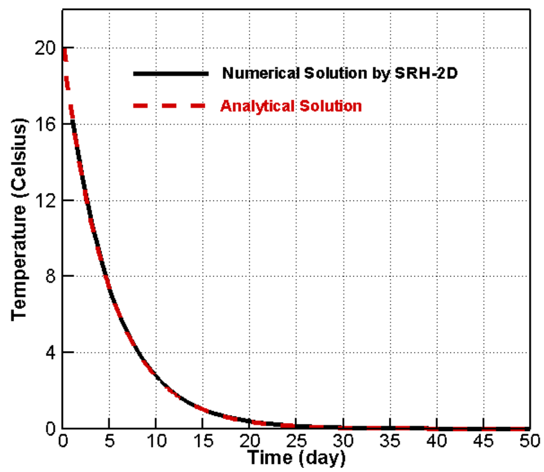

Figure 1. Comparison of temperature at 100-mile location between model and analytical solution for case 1.

Test case 2 has the following parameters: a constant flow velocity of U=1.0 mile/day, a zero equilibrium temperature $T_{eq} = 0$, and k=0.0. A 100-mile straight channel is assumed. The initial temperature is zero everywhere but the temperature at $x = 0$ is changing with time according to $T(x=0) = 10 + 10\sin\left(\frac{2\pi t}{P}\right)$ with the period P = 20 days. The same mesh is used as case 1. The computed temperature at $x = 40$ miles is compared with the exact solution in Figure 2. The computed temperature remains at zero until about day 35. Theoretically, the temperature wave reaches the location at day 40. The discrepancy is due to the numerical diffusion caused by discretization error as zero diffusion is assumed in the analytical Solution.

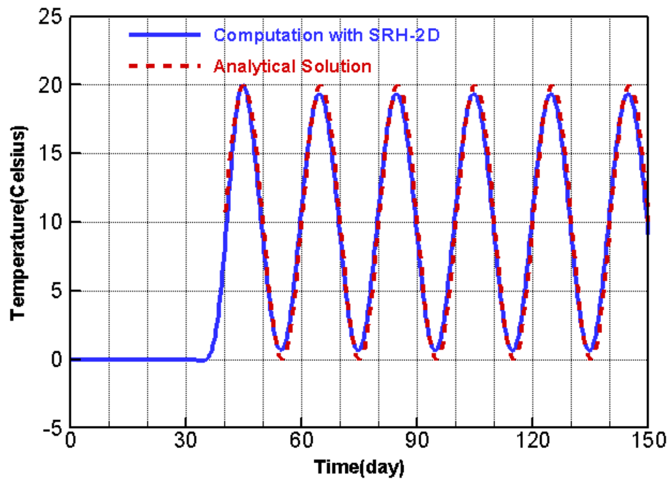

Figure 2. Comparison of simulated temperature and the exact solution at a location of 40 miles for case 2.

Test case 3 has the following parameters: a constant flow velocity of U=1.0 mile/day, $T_\Delta = 10$, $T_{avg} = 15$, $P_\Delta = 360$, and a constant coefficient k = 0.2/day. A 100-mile straight channel is assumed for SRH-2D modeling. The mesh has 100 or 300 mesh cells in the flow direction and 2 cells in the lateral. Initially temperature is 11.51 Celsius everywhere and the temperature at $x = 0$ is $T_0(t) = 10\sin(\frac{2\pi t}{10}) + 10$. Simulation is carried out for 150 days with a time step of 6 minutes. The temperature at $x = 4.5\ miles$ is compared in Figure 3 between the model solution and the exact solution. A good agreement is obtained.

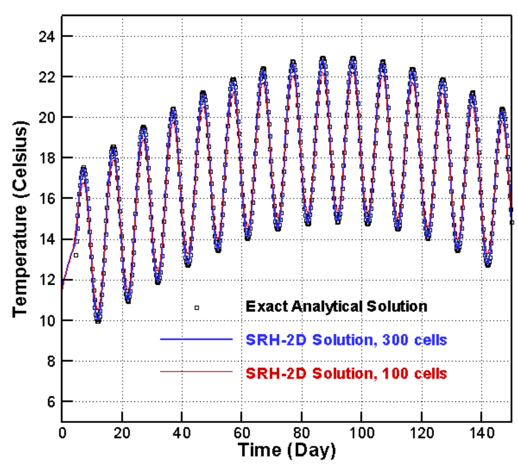

Figure 3. Comparison of simulated temperature and exact solution at channel mile 4.5 for case 3.

Temperature Modeling for the KcKay Dam Tailwater

The SRH-2D temperature model used a river reach downstream of the KcKay Dam for model verification and application. A reach along the McKay Creek and the first 2.57 miles of the Umatilla River has been studied by Bender (2001) with the 1D temperature model ADYN/RQUAL.

<u>*Case Description:*</u> McKay Dam and Reservoir are located on McKay Creek about 6 miles south of Pendleton, northeast Oregon. Downstream of the dam, the McKay Creek flows into the middle Umatilla River (at about RM 52). The Umatilla River drains into the Columbia River at about Columbia River Mile 289. The 2.57-mile reach of the Umatilla River from the confluence of the Umatilla River and the McKay Creek to the Reith Bridge could be managed to provide a water temperature to benefit the fishery. In particular, the flat slope and pools within the first mile of the Umatilla River downstream of the confluence with McKay Creek provides potential habitat for fish.

Cross-sectional channel survey downstream of the McKay Creek was conducted in March and November 2000 by Reclamation staff. The U.S. Army Corp of Engineers (Walla Walla District Office) provided sparse cross-section data of the Umatilla River collected in 1950. Around 64 cross-sections were assembled by Bender (2001) to carry out the temperature study for a 9-mile reach from McKay Dam to downstream of the Reith Bridge on the Umatilla River. The same cross sectional data are used to construct a 2D model for SRH-2D modeling in this study.

The model simulation starts from midnight July 27, 2000 and continues for 5 days. Temperature measurements at selected locations provide a comparison between model predictions and measured data. Continuous McKay Creek and Umatilla River temperature data were collected by the Umatilla tribes at the following four locations: Scheeler's Bridge (McKay RM 3.7), McKay School Bridge (McKay RM 1.9, Fish Barrier at the confluence (McKay RM 0.0), and Reith Bridge (Umatilla RM -2.57).

<u>*Mesh and Model Input Parameters:*</u> The simulation domain consists of about 6 miles of McKay Creek downstream of the McKay Dam and 3 miles of Umatilla River downstream of the confluence between McKay Creek and Umatilla River. The developed 2D mesh consists of 4,024 cells with both quadrilateral cells and triangular cells. The topography is interpolated from the cross sectional survey data.

Boundary conditions include water discharge and temperature downstream of the McKay Dam and upstream of the confluence in the Umatilla River. The hourly McKay Dam release discharge and temperature are used as upstream boundary conditions for the modeling period. The discharge downstream of the McKay Dam varies from 242 to 257 cfs and temperature ranges from 8.3 to 9.1 Celsius. The hourly flow, from 40 to 49 cfs, at Pendleton, Oregon is used as the upstream condition of the Umatilla River. The temperature, ranging from 24 to 27 Celsius, at the Umatilla River is based on a synoptic survey taken on July 28, 2000.

Initial conditions of the modeling used a steady state flow discharge of (257 cfs) at midnight of July 27, 2000. The initial temperature varies depending on the location of the cross section from 8.4C downstream of the McKay Dam to 23.0C at the Reith Bridge.

Hourly meteorological data, including cloud cover, air temperature, dewpoint temperature, air pressure and wind speed, are based on the national Weather Service (NWS) data from Pendleton, Oregon; and Agrimet solar radiation data are from Hermiston, Oregon (station HMRO).

Vegetation shade data includes the azimuth angle, tree height, tree distance to water edge at each cross section. They are delineated based on the aerial photo map.

Results and Discussion: Simulation is carried out from midnight of July 27, 2000 and lasts for five days. The simulated temperature is cross-sectionally averaged at five locations where measured temperature is available. Comparisons of the simulated and measured temperature are shown in Figure 4 to Figure 8 at measurement five locations.

It is seen that agreement is favorable for all locations with the maximum difference less than one degree Celsius. This comparison is encouraging as little effort is spent to locally calibrate the model to achieve a good match. Default values are used for most thermal processes and the few parameter values that are calibrated are constant for the entire reach modeled.

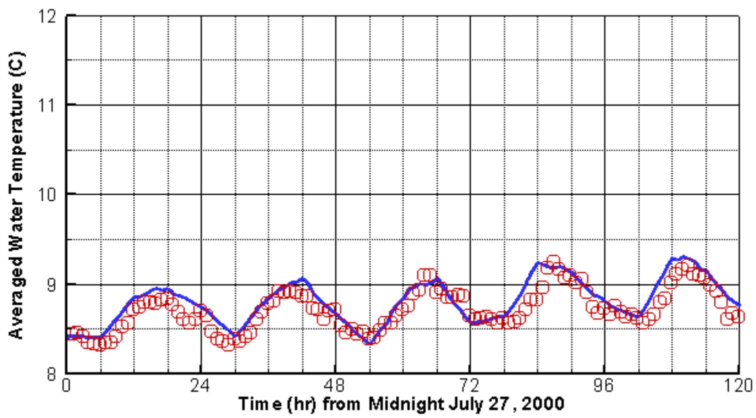

Figure 4. Comparison of temperature near McKay Dam (McKay RM 6.0) from July 28 through August 1, 2000; Solid Line: Simulated; Symbol: Measured

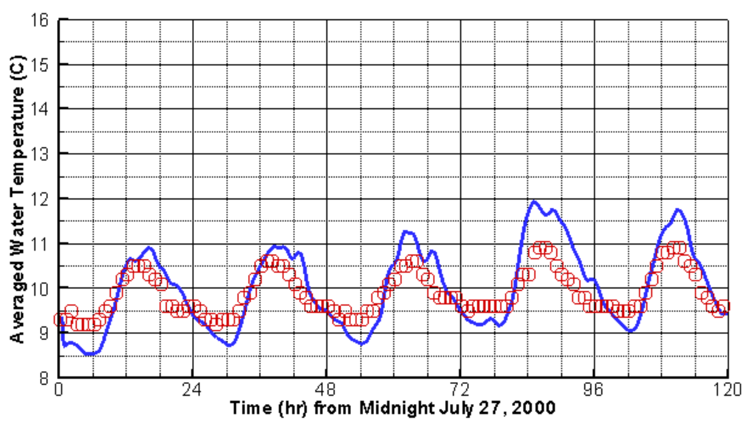

Figure 5. Comparison of temperature at Scheeler's (McKay RM 3.7) from July 28 through August 1, 2000; Solid Line: Simulated; Symbol: Measured

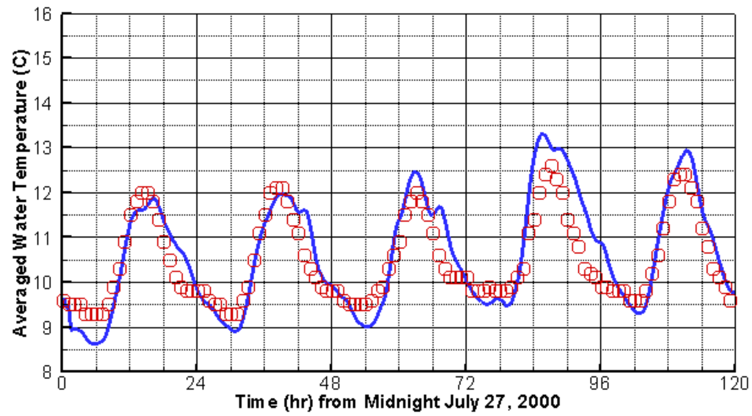

Figure 6. Comparison of temperature at School (McKay RM 1.9) from July 28 through August 1, 2000; Solid Line: Simulated; Symbol: Measured

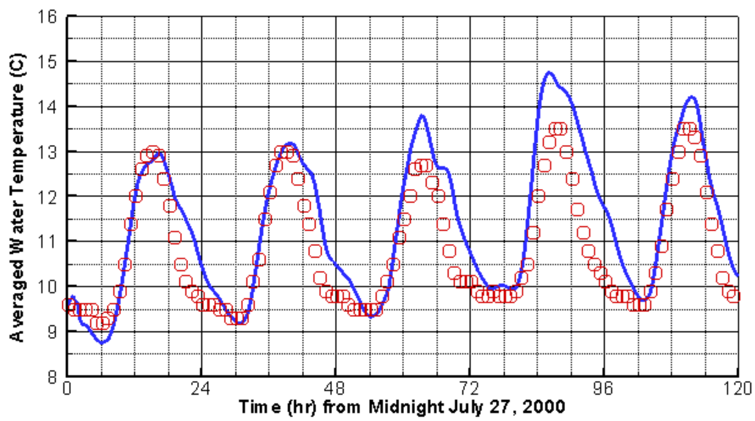

Figure 7. Comparison of temperature at Fish Barrier (McKay RM 0.01) from July 28 through August 1, 2000; Solid Line: Simulated; Symbol: Measured

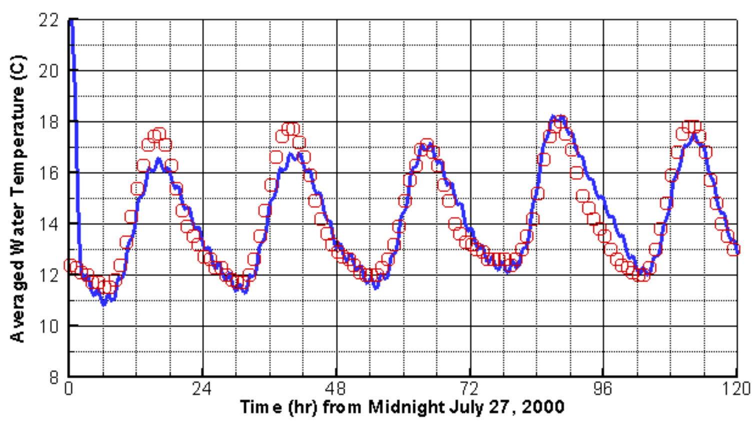

Figure 8. Comparison of temperature at Reith Bridge (RM -2.57) from July 28 through August 1, 2000; Solid Line: Simulated; Symbol: Measured

Concluding Remarks

A 2D depth-averaged temperature module is developed and incorporated into the existing SRH-2D model to simulate both flow hydraulics and diurnal temperature change. Such a model would be useful for habitat modeling, particularly for cases where spatial features such as agricultural returns, gravel pits, groundwater upwelling, side channel activation, and streamside vegetation are present.

Only development, testing, and a verification study are reported. The model is shown to reproduce the cases with exact solutions accurately; the model also matches a 9-mile reach downstream of the McKay Creek Dam in Northeast Oregon. Comparison between the model and the measurement is encouraging. The next step for development will collect lateral measured data on the San Joaquin River to compare against simulated data.

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