Revista SUG Nº18, 10 – 19 (publicado 11/2013)
Sociedad Uruguaya de Geología

STREAM WATER TEMPERATURE SIMULATION MODELS: A REVIEW

Stella, J.M.

Department of Civil and Environmental Engineering, University of Connecticut, USA
juan.stella@yahoo.com

ABSTRACT

Maximum and minimum daily temperatures can affect fish habitat, therefore, the prediction of temperature changes is needed to assess the impacts of potential watershed management decisions related with fish habitat, especially during low-flow periods. Prediction of temperature changes due to the variation in streamflow, groundwater flow and location along the stream, as well as anthropogenic changes, is frequently needed to assess the impacts of potential management decisions related with fish life in the stream. Although average daily temperatures are helpful, many times the diurnal changes are critical, including the maximum and minimum temperatures, creating the necessity to simulate temperatures along a stream. A number of existing models have been developed to predict stream temperatures, some of these are statistically based to predict average stream temperature based on parameters such as average air temperature of a corresponding interval of time. Other dynamic models such as physically-base, require extensive data inputs and calibration, and most were developed for large river systems to assess management alternatives such as reservoir release impacts.

Keywords: streams, theory, simulation, mass-energy balance

RESUMEN

Las temperaturas máxima y mínima diarias del agua pueden afectar el hábitat de los peces en un rio, por lo cual, la predicción de los cambios en la temperatura del agua puede ser necesaria para valorar los impactos que puedan tener potenciales decisiones en la de gestión de una cuenca relacionado con hábitat de los peces, especialmente durante períodos de bajos caudales. La predicción de cambios de temperatura debido a la variación en el caudal superficial, flujo de aguas subterráneas y su ubicación a lo largo del rio, así como cambios antropogenicos, son necesarios con frecuencia para valorar los impactos que las decisiones relacionadas con la gestión de la cuenca tienen con la vida de los peces en el rio. Aunque el promedio de las temperaturas diarias del agua en un rio son útiles, muchas veces los cambios diurnos en la temperatura son críticos, especialmente las temperaturas máximas y mínimas, creando la necesidad de una simulación de temperaturas del agua a lo largo del rio. Varios modelos existentes han sido desarrollados para predecir temperaturas del agua en un rio, algunos de estos son basados en bases estadísticas para predecir el promedio temperatura del agua en el rio en un intervalo de tiempo. Otros modelos dinámicos de base física requieren extensos ingresos de datos y su posterior calibración, La

mayoría de los modelos han sido desarrollados para grandes cauces para poder valorar alternativas a la gestión de una cuenca tales como el impacto que pueda tener la liberación agua en un embalse.
Palabras claves: Ríos, teoría, simulación, balance masa-energía

INTRODUCTION

Stream temperature prediction models are generally of two types: physically-based/ energy balance models and empirical models. A number of statistical models have been developed over the past two decades to predict stream temperatures from air temperatures, including those by Stefan & Preud'homme (1993), Mohseni et al. (1998), Caissie et al. (2001) and Nelson & Palmer (2007). Each of these models attempts to use an average daily, weekly or monthly air temperature to predict the stream temperature for the same interval, although sometimes with a lag.

Stefan & Preud'homme (1993) analyzed 11 streams in Minnesota using both daily and weekly intervals and found an average 2.7 and 2.1 degree C difference in predicted versus observed temperature for daily and weekly intervals, respectively. Small streams had low standard deviations between simulated and observed than large streams, and there was some time lag in maximum air versus stream temperatures. Mohseni et al. (1998) estimated weekly stream temperatures using a four parameter, non-linear regression function of air temperature for different seasons to account for heat storage at 584 gauging stations in the U.S. The overall coefficient of determination was "greater than 0.7 for the study" (Mohseni et al. 1998).

From an environmental point of view, the maximum daily stream water temperature is important to fish life. Caissie et al. (2001) modeled maximum daily stream water temperatures using a stochastic model based on the autocorrelation function of the water temperature time series to link the air and water temperatures in Catamaran Brook, in New Brunswick. They used Fourier and sine functions, and their combinations, in developing the long-term annual variation. A logistic regression approach was used for prediction (Caissie et al. 2001). Nelson & Palmer (2007) in an attempt to assess potential impacts of climate change on stream temperatures, developed empirical relationships to complement a simple model of in-stream temperature. They included the impact on water temperature of increased watershed imperviousness, destruction of the riparian vegetation, and increased siltation (Nelson & Palmer 2007).

One example of the application of stochastic models is given by Lu & Piedrahita (1996) based on research in which they used stochastically generated weather parameters applied to aquaculture. Their model was similar to the model used by Sadeh (1986) to study the economic profitability of shrimp production in ponds and found that water temperature is a determinant of shrimp growth rate. The water temperature was determined from air temperature using a linear regression equation. However, statistical models are based on observations in specific situations and cannot, or at least should not, be applied beyond a limited range of observed values.

A more recent advancement in statistically based temperature models occurred when Geographical Information Systems (GIS) were introduced in water temperature models. The Geographical Information Systems-Stream Temperature model (GIS-STRTEMP) is a water temperature simulation model created for prediction of maximum stream temperature during the critical summer low-flow period in forested watersheds (Sridhar et al. 2004). The GIS-STRTEMP model was intended for estimation of worst case or maximum annual temperature, and is therefore applied on an event basis to low-flow conditions using maximum annual solar radiation and air temperature as input. For the research conducted in Cascades mountains, the low-flow conditions were defined as the 7-day 10-year low-flow (7Q10), which was estimated by a regional regression equation (Sridhar et al. 2004). This review is a summarization of the whole water temperature models applicable to the study of water temperature along a stream.

The physically-based to water temperature modeling approach requires mathematical expressions describing the physics of the major exchanges of both mass and energy in the system. The major drivers that control the rate of heat exchange are external to the stream. These forcing functions include precipitation, solar radiation, air temperature and topographic or canopy shade. These drivers, combined with the mass flow rate of the stream, determine the water temperature changes in a stream (Poole & Berman 2001).

Several physically-based temperature models have been developed and applied over the past 40 years. Larger rivers or releases associated with reservoir management were where the water temperature model started to be applied. Raphael (1962) successfully applied a technique for calculation of the thermal energy budget in the Central Valley to the Feather River, California and to several reservoirs on the Columbia River system. During the 1960's, the Water Resources Engineering (WRE) group applied the Water Temperature Simulation Model (WTSM) in the Central Valley of California (Orlob 1977). Starting in the 1970's, the United States Bureau of Reclamation (USBOR) started to apply the Reservoir Temperature Stratification (RTS) models to several mainstream reservoirs in the Sacramento River basin (Deas 2000). Rowell (1972) subsequently, conducted river temperature simulations on the Sacramento River upstream of Red Bluff, and then later (Rowell 1975) adapted the model to the Truckee River to identify minimum flows to maintain suitable water temperature for Lahontan Cutthroat Trout.

Subsequently, the Unites States Army Corps of Engineers - Hydrologic Engineering Center (USACE-HEC) created two multi-purpose water quality models capable of simulating water temperature over large portions of river streams. The HEC-5Q model components include water temperature, three conservative and three non-conservative constituents, dissolved oxygen and a phytoplankton option and has been applied to the Sacramento Valley reservoir system (Willey 1987) and the lower Yuba River (Salmon et al. 1992).

The model developed by Meyer & Orlob (1994), Water Quality for River-Reservoir Systems (WQRRS) is a comprehensive package that allows the simulation of the water quality in a reservoir, the hydraulics of a river, and the water quality of the river itself. A modified, commercial version of WQRRS was applied on the North Fork of the Stanislaus River (Meyer & Orlob 1994) to assess potential water temperature effects of proposed hydroelectric development. Orlob (1983) and Meyer & Orlob (1994) used WQRRS to investigate effects of climate change on water quality, including water temperature. Deas et al. (1997) applied WQRRS to simulate water temperature response for alternative operations for anatropous fish restoration in the Sacramento River downstream of Keswick Reservoir. Also Deas & Orlob (1998) applied WQRRS to Trinity Reservoir examining selective withdrawal and carryover storage issues for water temperature control in the Trinity River below Lewiston Dam.

The Box Exchange Transport Temperature and Ecology of Reservoirs (BETTER) model is a two-dimensional reservoir temperature and water quality model developed by the Tennessee Valley Authority. BETTER combines use of mathematic functions, geometry, meteorological conditions, and discharge in the reservoir to predict flow patterns water temperature and dissolved oxygen (TVA 1990). The USACE-HEC's CE-QUAL-R1 is used to study pre-impoundment and post-impoundment water quality problems and the effects of reservoir management operations on water quality. CE-QUAL-R1 also addresses problems of water quality associated with reservoir eutrophication, but requires substantial effort by a multidisciplinary staff to acquire data, create and debug the database, add site-specific factors to the computer code as necessary, and compute, plot, and analyze results (USGS 2005).

In the last twenty years, other water temperature simulation models have been developed and applied for more general uses. For example, the Enhanced Stream Water Quality Model (QUAL2E) was developed by EPA as a physically-based, stream water quality model that can simulate diurnal variations in water temperature among others things (EPA 2005). This model is steady-state flow, and is one-dimensional (longitudinal). QUAL2E was designed as a steady-state model for conventional pollutants in branching streams and well mixed lakes. The latest version of QUAL2E is called EPA and can be operated either as a steady-state or dynamic model and is intended for use as a water quality-planning tool (EPA 2005) and (Deas 2000).

The Stream Network Temperature model (SNTemp) was developed by the Soil Conservation Service and the U.S. Fish and Wildlife Service (Theurer 1984). This model is a steady-flow, physically-based, one-dimensional heat transport model that predicts the daily mean and maximum water temperatures as a function of stream distance and environmental heat flux. The net heat flux in SNTemp is calculated as the sum of heat that arrives and leaves from long-wave atmospheric radiation, direct short-wave solar radiation, convection, evaporation and streamside vegetation (shading).

In addition, the heat flux model incorporates groundwater inflow. The heat transport model is based on the dynamic temperature-steady flow equation and assumes that all input data, including meteorological and hydrological variables, can be represented by 24-hour averages. Typical applications include predicting the consequences watershed management on water temperatures, reservoir discharge or release water in water temperature changes, irrigation diversions, riparian shading alterations, channel modifications, or point source thermal loadings (USGS 2005). An example application of SNTemp is its use for evaluation of alternative project management scenarios for enhancement of fish populations as part of relicensing the Lake Chelan Hydroelectric Project by the Federal Energy Regulatory Commission (Payne et al. 2002).

The physically-based water temperature simulation model, SSTemp (Bartholow 2002), is a simplified version of SNTemp created by Theurer (1984). The SSTemp model assumes a one-dimensional, mixed system. It calculates a dynamic water temperature based on both external heat fluxes and transport of internal heat (Sansone & Lettenmaier 2001). The physical processes included in SSTemp include "convection, conduction, evaporation, as well as heat to or from the air (long wave radiation), direct solar radiation (short wave), and radiation back from the water" (Bartholow 2002). The first step in the model is the determination of the energy balance by the solar radiation, including how much is intercepted. The model then calculates the other fluxes to complete the energy balance. The water in the system is assumed to be completely mixed at a specific distance, i.e. there is no lateral or vertical temperature distribution across the stream channel. An average stream geometry is used for calculations unless there is a dam at the upstream end of the stream, and lateral inflow is uniformly apportioned throughout the segment length. The SSTemp model uses a 1-day time step and all inputs are given in terms of a daily value. The model does not allow either Manning's *n* or travel time to vary as a function of flow (Upper Chama River Report 2003). Details regarding an example application are available in the Upper Chama River Report (2003). The latest version of SSTemp (SSTemp 2.0) includes an uncertainty Monte Carlo analysis routine whereby input values are randomly selected from a range of values composing the input (Bartholow 2002).

Other water temperature models such as HSPF, Heat Source, CE-QUAL-W2, and QUAL2K can be applied in hourly time steps, but these models require a large number of variables and parameter calibration (EPA 2005) and (USEPA 2005). HSPF is included in BASINS a Decision Support System (DSS) and requires land use and climatic conditions along with the incorporation of a digital elevation model (USEPA 2005). Climatological data, such as solar radiation and precipitation, are usually obtained from the National Climatic Data Center (NCDC), which has an associated cost. This model requires the calibration of more than nine parameters for the simulation of water temperature alone (USEPA 2005). The Heat Source model, developed at Oregon State University (Boyd, 1996), requires inputs derived from spatial data sources and Thermal Infrared Radiometry (TRI) temperature data, and has a maximum time of simulation of 21 days (Boyd & Kasper 2004).

The U.S. Army Corps of Engineer's two-dimensional quality model (CE-QUAL-W2) was supported by the United States Environmental Protection Agency (EPA) for the purpose of predicting water quality associated with storm runoff (Cole & Wells 2002). A computational grid is needed for the CE-QUAL-W2 model to create a finite difference representation of the water body. A fine grid resolution is necessary to produce highly accurate results with this model which increases necessary data collection efforts and processing time compared to low-resolution grids. Furthermore, CE-QUAL-W2 requires the input of bathymetric data (Cole & Wells 2002). Hanna et al. (1999) applied this model to investigate the effect of a temperature control device on a reservoir's thermal regimen.

Brown's equation for water temperature has been widely used in forestry, to predict water temperature at a point. This model assumes that the net change in energy stored is a function of the net thermal radiation flux, conductive, convective and advective fluxes, and that the advective inflow and groundwater inflow are negligible (Sansone & Lettenmaier 2001). The Brown's model applied by Robillard et al.(1982) in the Fernow Experimental watershed Parsons, West Virginia, shows that the model has its application for stream sections smaller than 700 m in length. For this model the measurement of average streamflow width, wetted surface and streamflow surface for summer water temperature calculation. Also the discharge should be representative of the mean discharge through the wetted stream, and vegetative shading topography should be determined as accurately as possible. Also this model does not consider inflowing groundwater (Robillard et al.1982).

Only two studies have been conducted using water temperature simulation models for the study of water temperatures in small streamflows under low-flow conditions. One is the RTS model that was applied to the Truckee River, California (Rowell 1975), but with a monthly time step (Deas 2000). The other one is the SSTemp model that uses a daily time step which has been applied in the Upper Chama River, New Mexico (Upper Chama River Report 2003).

DISCUSSION

Each of the models described have limitations such as the large number of parameters and inputs necessary for their application to small rivers or to their ease of use, so there is still a need for an easily-applied model for small rivers under shallow-flow conditions during low-flow summer discharges, especially to assess diurnal effects. The best model is one that maintains accuracy but yet is simple in its approach and application. Dooge (1986), in his article "Looking for hydrology laws", raised two important questions: "Is hydrology now an established science?" and "Is hydrology practice now firmly based on scientific principles?" Klemes (1986) opinion was that, "at the present stage of hydrologic sciences, hydrologic modeling is most credible when it does not pretend to be too sophisticated and all inclusive, and remains confined to those simple situations whose physics is relatively well understood."

Although tools such as Geographic Information Systems and hydrologic simulation models have improved the capacity to measure and quantify landscape and hydrologic processes, there are limitations in knowing the exact value of some parameters related to stream temperature. Therefore, it is difficult to address stream temperature in all of its complexity (Boyd & Kasper 2004). Dooge suggested, regarding the importance of the scale, that success first be obtained on systems which correspond to the category of simple mechanism, and the linkage of macro parameters with micro parameters remains a daunting problem (Dooge 1986).

Bacteria, chemistry, algae growth and fish life are directly related with water temperature in the river. The possible daily fluctuations in water temperature produce changes in the behavioral and physiological aspects of aquatic organism, such that habitat becomes unsuitable for native species (Poole & Berman 2001). The data compiled by Hoogenhout & Amesz (1965) link the variation of photoautotrophic unicellular algae grow with the temperature in fresh water marine systems. In their research, John & Rose (2004) found a linear relationship between fecal coliform, enterococci, RNA coliphage, Cryptosporidium and temperature and total dissolved solids (TDS). Also the modified form of the Van't Hoff- Arrhenius relationship (Tchobanoglous & Schroeder 1987) shows a power relationship between the biochemical oxygen demand (BOD) and temperature. Smale & Rabeni (1995) showed a strong correlation between the frequency distribution of species tolerance and critical maximum temperatures.

The water temperature simulation (WTS) model coupled two components, water balance and energy balance, using STELLA® software. The model was developed in modules for the different sectors with parameters entered as inputs (Stella 2007).

The software uses a finite difference approach to solve the dynamic differential equations for the conservation of mass and energy that results from the icon-based model constructions. The boxes in are called "stocks" and are the storages of either mass or energy for a given reach of a river. The large arrows with valves represent "fluxes" of mass or energy into or out of the stock. The small thin arrows are "connectors" that indicate the dependence of one component another (Ford 2000). The water balance and energy balance sectors are coupled by the connectors of corresponding components. For example, latent heat (LH) is coupled with evaporation (Evap), while the internal energy influx is coupled to the mass-influx or discharge. Conservation of mass is automatically maintained by the STELLA® software based on the created diagram or "flowchart" (Stella 2007).

The water temperature simulation (WTS) model coupled two components, water balance and energy balance, using STELLA® software. The model was developed in modules for the different locations with parameters entered as inputs. The software uses a finite difference approach to solve the dynamic differential equations for the conservation of mass and energy that results from the icon-based model constructions. The dynamic model uses diagrams called "stocks" that are the storages of either mass or energy for a given reach of a river, large arrows with valves represent "fluxes" of mass or energy into or out of the stock and small thin arrows are "connectors" that indicate the dependence of one component another (Ford 2000). The water balance and energy balance between locations are coupled by the connectors of corresponding components. Conservation of mass is automatically maintained by the STELLA® software based on the created diagram or "flowchart". Tributary inflows can be added from measured tributary discharges. Similarly, lateral inflow (outflow) from (to) a ground water system can be added as a flux based on either measurement or a coupled ground water model. The development of the equations describing the mass and energy fluxes necessary to develop the mathematical model are in Stella (2007). WTS has two parameters: Daily evaporation is the total daily depth of evaporation that will hourly weighted by the observed hourly distribution of net solar radiation to predict hourly evaporation values and radiation intercepted, is the percent of radiation intercepted by all the filters between the atmosphere and the stream.

CONCLUSIONS

No stream water temperature model has been developed yet, that uses an hourly time step to simulate the water temperature in small stream under low-flow conditions typical of summer seasons in New England. Stella (2007) developed a simple, (two coefficients, six variables (meteorological inputs) and five boundary conditions) physically-based Water Temperature Simulation (WTS) model as a function of water and energy fluxes using a dynamic, coupled mass and energy balance approach to apply to low to moderate flows in small rivers such as the Fenton River using a time step of one hour. Table 1 summaries the number of coefficients, variables and boundary conditions used by selected existing models as well as a proposed model and shows an important difference in the number of parameters, variables and boundary conditions needed to simulate water temperature in streamflow.

TABLE 1: Water temperature model simulation, number of parameters and variables, boundary conditions and time step

Model	Parameters	Variables	Boundary conditions	Time step
HSPF[1]	9	8	3	Minutes
Heat Source[2]	11	5	7	Hourly
CE-QUAL-W2[3]	8	23	9	2 seconds
QUAL2K[4]	17	17	8	Hourly
WTS[5]	2	6	5	Hourly

[1] Basins-HSPF 2005
[2] Boyd & Kasper 2004
[3] Cole & Wells 2002
[4] EPA 2005
[5] Stella 2007

WTS and SSTemp are similar in concept, i.e. both models are physically-based models that apply thermodynamic equations to streamflow. However, several differences in approach exist between the models. One major difference is the time step: SSTemp was constructed to work on a daily time step but WTS use an hourly time step. Prediction of hourly values will allow assessment of diurnal effects including maximum and minimum temperature values which often are critical in ecological systems. Another difference is the approach used for physical attributes of the river channel. SSTemp uses a power function of width as a function of stream discharge, while WTS used a representative cross section, either an observed or "idealized" wetted cross section of the channel to represent the geometric shape of the river. The same meteorological and hydrological hourly inputs that are used for WTS can be used for SSTemp. It was assumed that the SSTemp can predict the average hourly water temperature. Another major difference between the, WTS and SSTemp is the number of parameters used to represent the incoming solar radiation and latent heat. WTS applies a simplified method using only two parameters. One is the radiation intercepted to represent all the filters between the atmosphere and the stream. The other parameter is the daily evaporation used to calculate the latent heat. SSTemp requires the amount of dust in the air, percent of possible sun (clouds) and geometric parameters such distance, height and density of the vegetation in both sides of the stream to represent the canopy along the river.

BIBLIOGRAPHY

BARTHOLOW, J. (2002) **Stream Segment Temperature Model (SSTEMP) Version 2.0.** [internet], Colorado, U.S. Geological Survey. Disponible desde: <http://www. fort. usgs. gov/products/Publications/10016/10016.pdf> [Acceso 2de enero 2005].

BOYD, M. (1996) **Heat Source: stream temperature prediction**, Master Thesis, Departments of Bioresource Engineering and Civil Engineering, Oregon State University.

BOYD, M.; KASPER, B. (2004) **Analytical Methods for Dynamic Open Channel Heat and Mass Transfer**. [internet], Oregon, Oregon State University. Disponible desde: <http://www.heatsource.info.com> [Acceso 20 de diciembre 2005]

CAISSIE, D.; EL-JABI, N.; SATISH, M. (2001) Modelling of maximum daily water temperatures in a small stream using air temperatures. **Journal of Hydrology**, 251, p.14–28.

COLE T.; WELLS, S. (2002) CE-QUAL-W2: A **Two-Dimensional, Laterally Averaged, Hydrodynamic and Water Quality Model, Version 3.1**. U.S. Army Corps of Engineers, Washington, DC

DEAS, M.; MEYER, G.; LOWNEY, C.; ORLOB, G.; KING, I. (1997) **Sacramento River Temperature Modeling Project Report**. Center for Environmental and Water Resources Engineering University of California, Davis. Report (97-01).

DEAS, M.; ORLOB, G. (1998) **Shasta River Hydrodynamic and Water Temperature Modeling.** Project**.** Center for Environmental and Water Resources Engineering. Sacramento, California. Report (97-01).

DEAS, M. (2000) Water Temperature Modeling Review Central Valley. **Bay Delta Modeling Forum**. Sacramento, California.

DOOGE, J. (1986) Looking for hydrologic laws. **Water Resources Research,** 22(9), p. 468-588.

EPA (2005) **River and Stream Water Quality Model QUAL2K**. [internet], Environmental Protection Agency, Pennsylvania. Disponible desde:<http://www.epa.gov/ATHENS/wwqtsc/html/qual2k.html>[Acceso 10 de diciembre 2005].

HANNA, R.; SAITO, L.; BARTHOLOW, J.; SANDELIN. J. (1999) Results of Simulated Temperature Control Device Operations on In-Reservoir and Discharge Water Temperatures Using CE -QUAL-W2. **North American Lake Management Society,** 15(2), p.87-102.

HOOGENHOUT, H.; AMESZ, J. (1965). Growth rates of photosynthetic microorganisms in laboratory cultures. **Archiv für Mikrobiologie,** 50(1), p.10-25.

JOHN, D.; ROSE, J. (2004) Survival of fecal indicator bacteria, bacteriophage and protozoa in Florida's surface and ground waters. Potential Implications for Aquifer Storage and Reco. Final Report of the Fate of Microorganisms in Aquifers. **Southwest Florida Water Management District**. Michigan State University East Lansing, Michigan.

KLEMES, V. (1986) Dilettantism in hydrology: Transition or destiny. **Water Resources Research,** 22(9), p.177-188.

LU, Z.; PIEDRAHITA, R. (1998) **Modeling of temperature, dissolved oxygen, and fish growth rate in stratified ponds using stochastic input variables.** Pond Dynamics/Aquaculture CRSP. 16th Annual Technical Report, Oregon State University.

MEYER, G.; ORLOB, G. (1994) Impacts of Global Warming on the Quality of Surface Waters. **Department of Civil and Environmental Engineering, University of California at Davis**, Davis, CA

NELSON, K.; PALMER, M. (2007) Stream Temperature Surges Under Urbanization and Climate Change: Data, Models, and Responses. **Journal of the American Water Resources Association,** 43 (2), p. 440–452.

ORLOB, G. (1977) Mathematical modeling of surface water impoundments. **Resource Management Associate Inc.** California. U.S. Department. of the Interior. Project (T-0006), p.119.

ORLOB, G. (1983) One-Dimensional Models for Simulation of Water Quality in Lakes and Reservoirs. En: Wiley Interscience, **Mathematical Modeling of Water Quality in Lakes and Reservoirs**, New York.

PAYNE, T. (2002) Chelan River Stream Network Temperature Model. **Lake Chelan Hydroelectric Project.** FERC Project No. 637 Prepared for Public Utility District of Chelan County. Washington.

POOLE, G.; BERMAN, C. (2001) An ecological perspective on in-stream temperature: Natural heat dynamics and mechanisms of human-caused thermal degradation. **Environmental Management**, 27(6), p. 787-802.

RAPHAEL, J. (1962) Prediction of temperatures in rivers and reservoirs, **ASCE Journal of Power Division,** 88 (PO2), p.157-181.

ROBILLARD, P.; WALTER, M.; BRUCKNER, L. (1982) Planning guide for evaluating agricultural nonpoint source water quality controls. **Environmental Research Laboratory**. Georgia. p.733.

ROWELL, J. (1972) **Reservoir and Stream Predictions in the Upper Sacramento River Basin**, Doctor Thesis, Department of Geography, California State University.

ROWELL, J. (1975) Truckee River Temperature Prediction Study. **U.S. Bureau of Reclamation,** California

SADEH, A. (1986) Uncertain Consideration Resulting from Temperature Variation on Growth of Penaeus Stylirostris in Ponds. **Sea Grant College Program**, Texas A & M University, Texas.

SALMON, M.; BREITENBACH, M.; STEINER. D. (1992) **Report on Water Temperature Modeling on the Yuba River**. Bookman-Edmonston Engineering, Inc., Sacramento, California.

SANSONE, A.; LETTENMAIER, D. (2001) A GIS-Based Temperature Model for the prediction of maximum stream temperatures in the cascade Mountain Region. **Water Resources Series**. Technical Report 168. Seattle, Washington.

SMALE, M.; RABENI, C. (1995) Hypoxia and Hyperthermia tolerance of headwater stream fishes, **Transactions of American Fisheries Society**, 124, p. 698-710.

Sridhar, V.; Sansone, A.; Lamarche, J.; Dubin, T.; Lettenmaier. D. (2004) Prediction of streamflow temperature in forested watershed. **Journal of American Water Resources Association**, 40(1), p. 97-213.

STEFAN, H.; PREUD'HOMME. E. (1993) Stream temperature estimation from air temperature. **Water Resources Research** , 29 (1), p. 27-45.

STELLA, J. (2007) **Modeling temperature, recession curves and event response for two third-order eastern Connecticut streams**, Doctor Thesis, Department of Natural Resources and Management Engineering, Universidad of Connecticut.

TCHOBANOGLOUS, G.; SCHROEDER, E. (1987) **Water Quality.Addison**, Massachusetts, Wesley Publishing Company.

TENNESSEE VALLEY AUTHORITY (TVA) (1990) BETTER: A two -dimensional reservoir water quality model, technical reference manual and user's guide. **Water Resources Research Laboratory**, Report WR28-2-590-152. Knoxville, Tennessee.

THEURER, F.; VOOS, K.; MILLER, W. (1984) Instream water temperature model. **Western Energy and Land Use Team, Division of Biological Services, Research and Development**. Fish and Wildlife Service, U.S. Department of the Interior, Washington D.C.

WILLEY, R. (1987) Water Quality Modeling of Reservoir System Operations Using HEC-5 (No. HEC-24). **Hydrologic Engineering Center**, Davis, California.

UPPER CHAMA RIVER REPORT (2003) **New Mexico Environment Department** [internet]. New Mexico, Surface Water Quality Bureau. Disponible desde: <http://www.nmenv.state.nm.us/swqb/Chama> [Acceso 5 de diciembre 2005].

U.S. ENVIRONMENTAL PROTECTION AGENCY (USEPA) (2005) **BASINS-HSPF Version 3.1, User's Manual**. EPA-823-B-01-001, Washington, D.C.

USGS (2005) **United States Geological Survey** [internet], Virginia, Water Quality Models. Disponible desde:<http://smig.usgs.gov/SMIC/SMIC.html> [Acceso 12 de diciembre 2005].