Influence of meteorological factors on modelling the thermal regime of a river

A Neagoe[1], E I Tică[1], K Ahmad-Rashid[2], F Popa[3] and B Popa[1]

[1]University Politehnica of Bucharest, Hydraulics, Hydraulic Machinery and Environmental Engineering Department, 313 Spl Independenţei, Bucharest, Romania
[2]University of Sulaimani, Kurdistan, Iraq
[3]University Valahia of Târgovişte, Aleea Sinaia Street, no. 13, Târgovişte, Dâmboviţa; ISPH Project Development, Calea Vitan 293, sector 3, Bucharest, Romania

E-mail: `bodan.popa@upb.ro`

Abstract. The aim of the paper is to determine whether the use of several parameters in a multi-linear regression equation can estimate the evolution of the water temperature. Thus, a simplified physical-based non-spatial model is designed for calculating the time variation of river water temperature. The water-to-air transfer function is constructed using the recorded environmental factors, instead the flow rate, respectively the depth of water in the riverbed, is assumed to be constant over the 31-days analysis period. A comparison between logistic relation, according to a classical proposed model and multiple linear regression with four parameters is done.

1. Introduction

The river water temperature, along with water quality parameters, is important to be known because it has a major influence on aquatic flora [1]. Although the literature abounds on this topic, the subject approach involves a compromise between the difficulty of collecting and processing an impressive amount of data used in the process-based river temperature modeling and the simplicity followed by the errors introduced by the statistical models.

Most of the time, some of the parameters of a complex physical model are unavailable from direct measurements (air humidity, nebulosity) or require additional calculations to be determined (incidental solar radiation).

Excluding the influence of the anthropic factor that can modify the river's thermal regime through pollution activities [2], the variation of the water temperature in the river is mainly influenced by weather conditions. In order to study the river thermal regime some deterministic models were developed [3-5]. A review of deterministic methods of estimating river water temperature with specification of programs written in various programming languages (Matlab, Fortran, C, C++) is done in [6].

It has been demonstrated that the main factor that influence the water temperature is the air temperature [7]. Where the vegetation / shading degree is not important in the area, simple forms of correlation between the two temperatures can be determined. There is a simple and quick tool for estimating the water temperature. In [8] is proposed a combination of methods based on nonlinear relationships between water temperature and air temperature viewed as temporal data series.

Very good results were obtained with a model based on Mosheni's logistical relationship [9].

Likewise, as in any other field, the artificial intelligence also contributed to the improvement of these methods [10].

Notation used in this paper:		
a	$-$	riparian or upland shading factor
c	$-$	air turbidity
C	$-$	cloud cover
c_p	$-$	the specific heat of the water ($4.19\cdot10^{-3}$ MJ/kg/^{0}C)
C_v	$-$	latent heat of water evaporation (cal/g)
E	$-$	evaporative rate (mm/day)
e_a	$-$	air water vapour pressure (mmHg)
e_s	$-$	saturated vapour pressure at the water temperature (mmHg)
H	$-$	water depth
H_c	$-$	convective heat transfer (MJ/m^2/day)
H_e	$-$	evaporative heat flux (MJ/m^2/day)
H_l	$-$	net long-wave radiation (MJ/m^2/day)
H_s	$-$	absorbed solar radiation (net short-wave radiation) (MJ/m^2/day)
H_{si}	$-$	incoming solar radiation (MJ/m^2/day)
H_t	$-$	the transfer function on air-water interface (MJ/m^2/day)
p_a	$-$	atmospheric pressure (760 mmHg)
R	$-$	solar radiation flux
t	$-$	time
T_a	$-$	air temperature
u_a	$-$	relative air humidity
w	$-$	wind velocity (m/s)
α_i	$-$	multi-linear regression coefficients
σ	$-$	Stefan-Boltzmann constant ($4.9\cdot10^{-9}$ MJ/m^2/K^4)
ρ	$-$	water density (kg/m^3)
ε	$-$	atmospheric emissivity

2. The deterministic model

The simplified non - spatial model for determining water temperature is based on the differential equation:

$$\frac{dT_w}{dt} = \frac{1}{\rho c_p H} H_t\left(t, R, T_a, u_a, c, w\right). \tag{1}$$

This model is used to generate values for the daily water temperature corresponding to some input values comprised of meteorological parameters. Since there are no measured values of the temperature, the values calculated in this way are still considered as "accurate".

The total heat flux can be calculated by relation:

$$H_t = H_s + H_l + H_e + H_c. \tag{2}$$

The net short-wave radiation can be determined like the incoming minus reflected radiation at the surface of the water [11]:

$$H_s = 0.97\,H_{si}(1-a), \tag{3}$$

$$H_{si} = [0.355 + 0.68(1-c)]H_{cs}. \tag{4}$$

The upland shading factor depends on forest cover and topography and has values between 0 and 1 [12]:

$$a = 0.127\exp(-0.0005234\,H_{si}). \tag{5}$$

The net long-wave radiation can be calculated using the Stefan – Boltzmann relation [3]:

$$H_l = 0.97\sigma\left[\varepsilon(T_a + 273)^4 - (T_w + 273)^4\right]. \tag{6}$$

For the atmospheric emissivity [13], it was proposed the relation:

$$\varepsilon = \left(0.53 + 0.065\sqrt{e_a}\right)(1 + 0.4c). \tag{7}$$

The evaporative heat flux is given by [14]:

$$H_e = k\rho C_v E, \tag{8}$$

in which k is a transformation coefficient in desired measurement units, and the evaporation rate, E, is:

$$E = (a + b*w)\left[e_s - e_a\right]. \tag{9}$$

Coefficients for the evaporation rate can be determined depending on the analyzed location:

$$e_a = u_a e_s, \tag{10}$$

$$e_s = 6.11\exp\left(\frac{17.3\cdot T_a}{273.3 + T_a}\right). \tag{11}$$

For the convective heat transfer it can be used the Bowen ratio [15]:

$$H_c = RH_e, \tag{12}$$

$$R = 0.61\frac{p_a}{1000}\left|\frac{T_a - T_w}{e_s - e_a}\right|. \tag{13}$$

The data were taken from the meteo.blue.ro website, for October 2014, recorded at the Craiova meteorological station. For the respective area, the solar radiation flux was calculated and considered.

The temperature variation with depth, and degree of shading or morphology of the water course weren't taken in account. For simplicity, the flow rate, respectively, water depth in the riverbed was considered constant throughout the analysis.

3. Multi-linear regression model

A linear regression equation was determined to estimate the water temperature according to the four recorded sizes: nebulosity (c), wind velocity (w), air humidity (u_a) and air temperature (T_a) as:

$$T_w = \alpha_1 c + \alpha_2 w + \alpha_3 u_a + \alpha_4 T_a + \alpha_5, \tag{14}$$

in which coefficients α_i, $i = \overline{1,5}$ are determined by the smallest part method so that the values obtained with equation (8) are as close as possible to the values provided by the model based on equation (1).

It is obvious that the equation thus determined can be used to approximate a water temperature value for the month corresponding to the meteorological parameters used (in this case, for Oct. 2014).
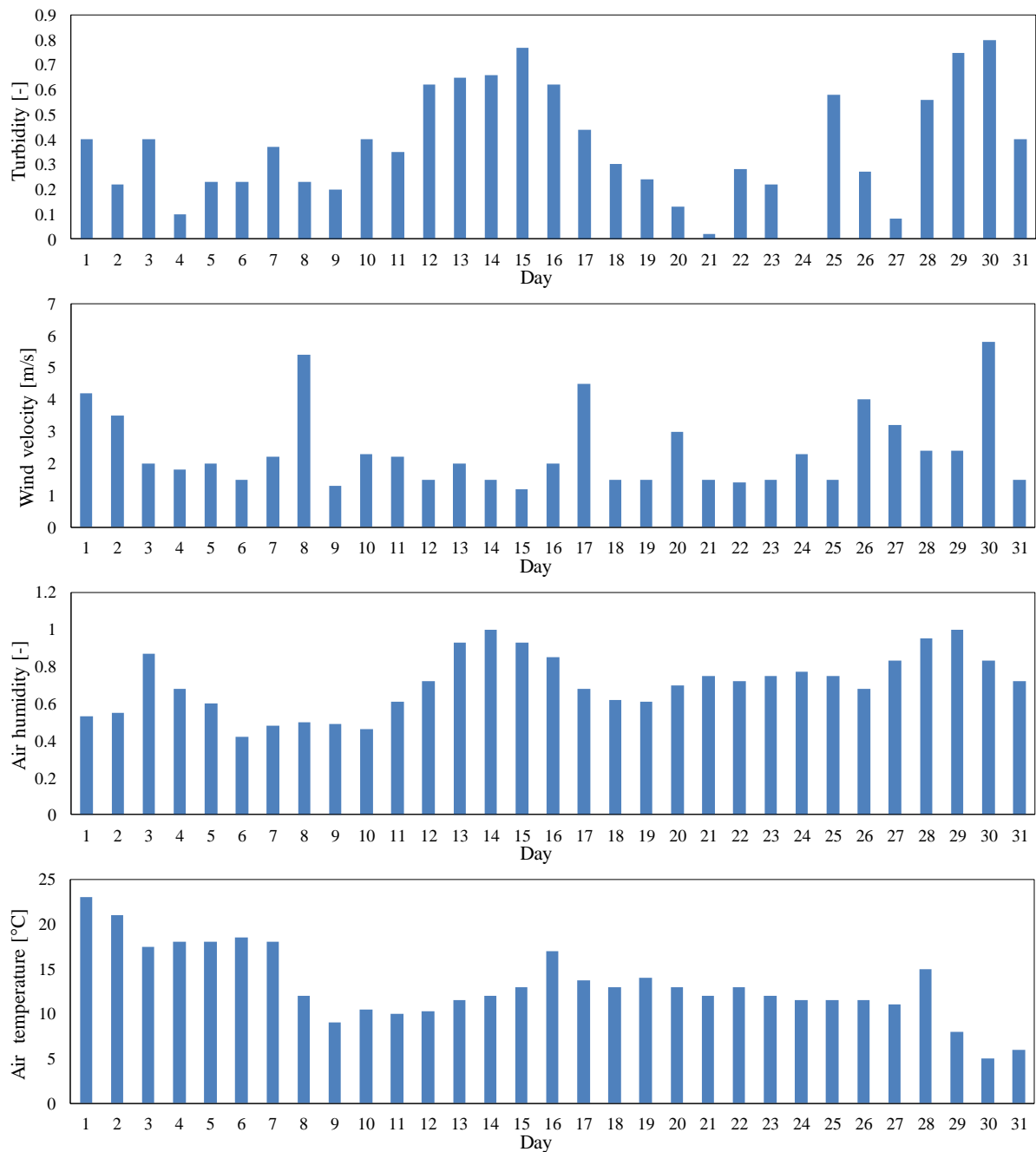
Mohseni in [9] proposed the following relation for water temperature variation:

$$T_w = \frac{\alpha}{1 + e^{\gamma(\beta - T_a)}} \quad , \tag{15}$$

in which coefficients α, β, γ are obtained using the Matlab curve fitting options.

4. Results

The available data for the 31-days analysis period, respectively: the turbidity, the wind speed, the air humidity, and the air temperature are shown in Figure 1.

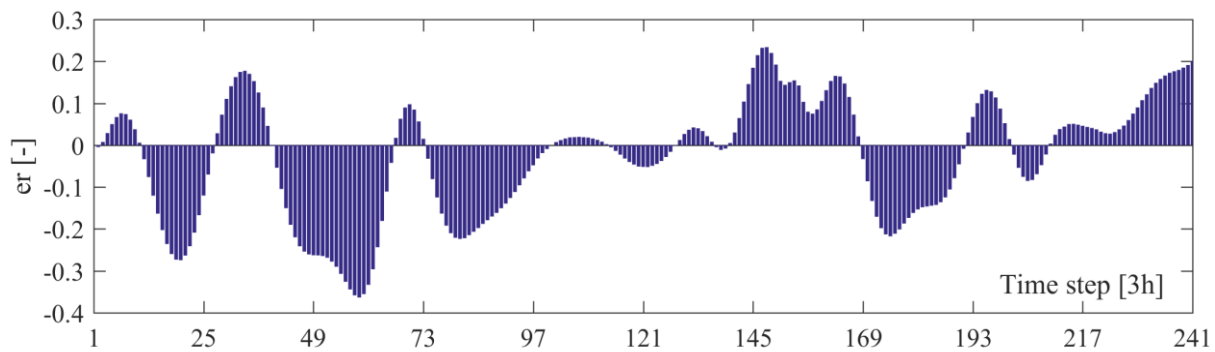**Figure 1.** Mean daily recorded input values in analytical model

The integration of the equation (1) was performed numerically using the second order Runge Kutta method using the initial condition for water temperature $T_{w0} = 22^0$C.

Since the transfer function is constructed using discretely recorded daily values, the need to evaluate this function in intermediate nodes led to an approximation calculation by interpolation using the Matlab spline function for 3-hours increments.

To determine the importance of inserting a disturbance / measurement error into a model input variable has artificially "altered" it, at a time, an input size with a random value comprised between 0 and not more than 1% of the maximum value of the corresponding unassigned variable.
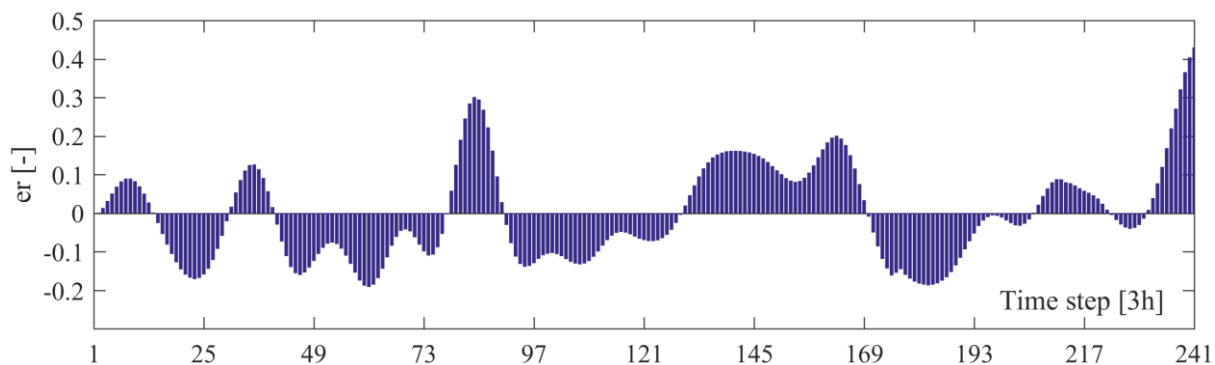
By running the program with a modified variable, it was obtained sets of results of the water temperature that were compared with the values considered "exact" obtained in the case of modeling with all the real input data (artificially unaltered).

From Figure 2 it can be observed that for the turbidity data were randomly disturbed with a maximum value of 0.089 (for this month the turbidity varied between a minimum value of $0 \div 0.82$) and a maximum error of 0.23% was recorded.
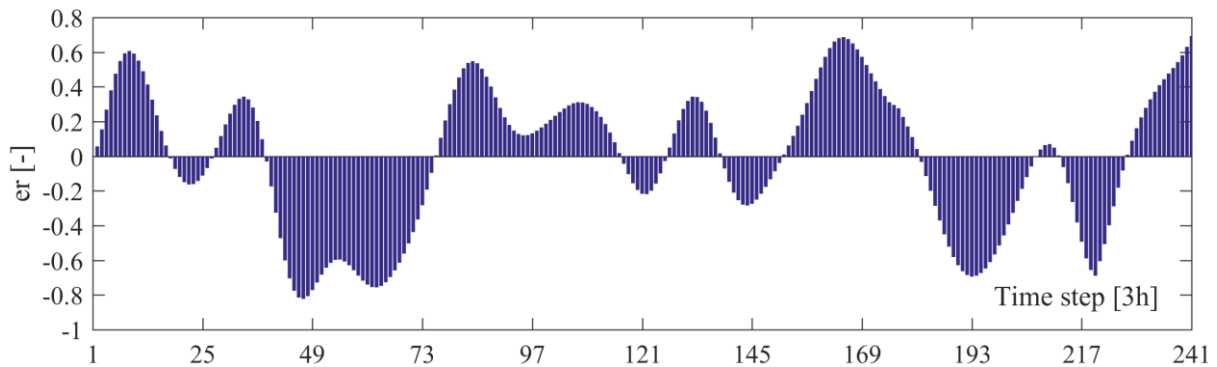

Figure 2. Errors introduced using altered values for nebulosity

For wind speeds that were randomly disturbed with a maximum value of 0.54 m/s (this month the turbidity varied between a minimum value of $1 \div 6.03$ m/s), a maximum error of 0.42 % was recorded, Figure 3.
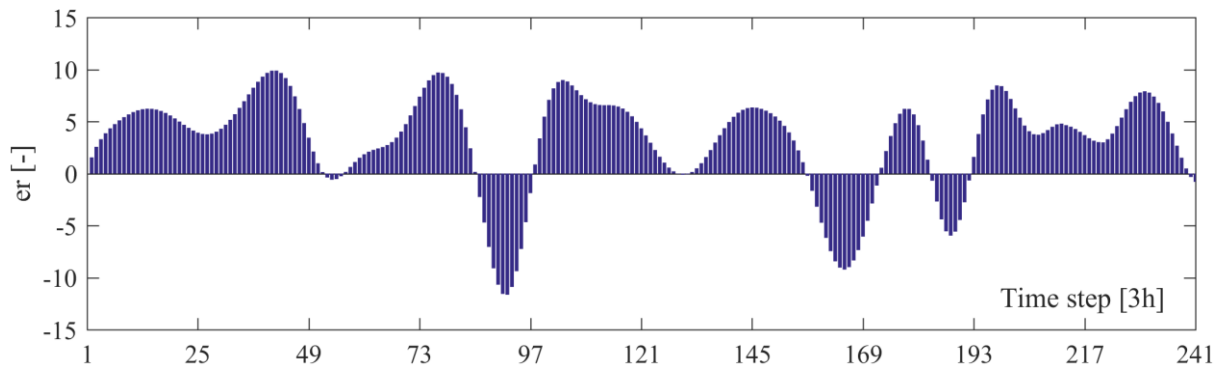

Figure 3. Errors introduced using altered values for wind speed

From Figure 4, it can be observed that for air humidity data that was randomly disturbed by a maximum value of 0.09 (for this month air humidity varied between a minimum of $0.4 \div 1$), a maximum percent error of 0.69 % was recorded.

Figure 4. Errors introduced using altered values for air humidity

For air temperature data that was randomly disturbed with a maximum value of 2.48 °C (this month it varied between 5 and 23.12 °C), a maximum percentage error of 9.89 % was recorded, Figure 5.

Figure 5. Errors introduced using altered values for air temperature

The model proposed calibration by Mohseni for the available values for the 31 days of October 2014, led to the determination of the coefficients: $\alpha = 52, \beta = 30.46, \gamma = 0.06739$, so the equation (15) becomes:
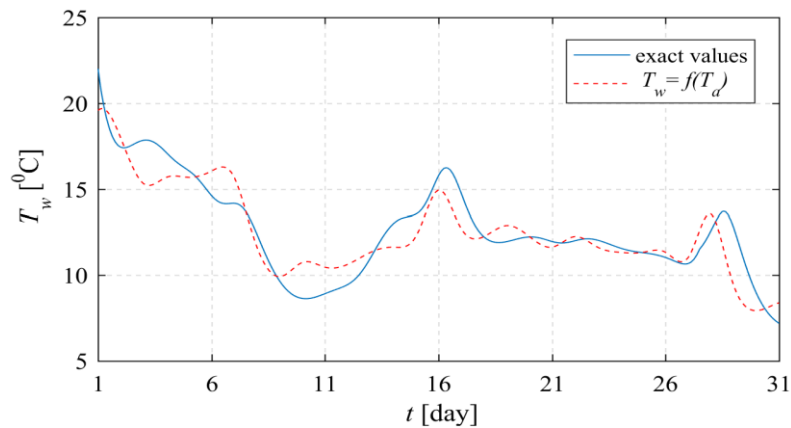
$$T_w = \frac{52}{1 + e^{0.06739(30.46 - T_a)}}. \tag{16}$$

Comparison of the values obtained with the logistic equation with one variable (Mohseni [9]) and the "accurate" values of the water temperature is shown in Figure 6. It can be observed a maximum deviation of about 2 ^{0}C between the two curves.

As for the multiple regression equation, coefficients were determined for this purpose so that the water temperature is obtained as a linear combination of nebulosity, wind speed, air humidity and air temperature, in the form:
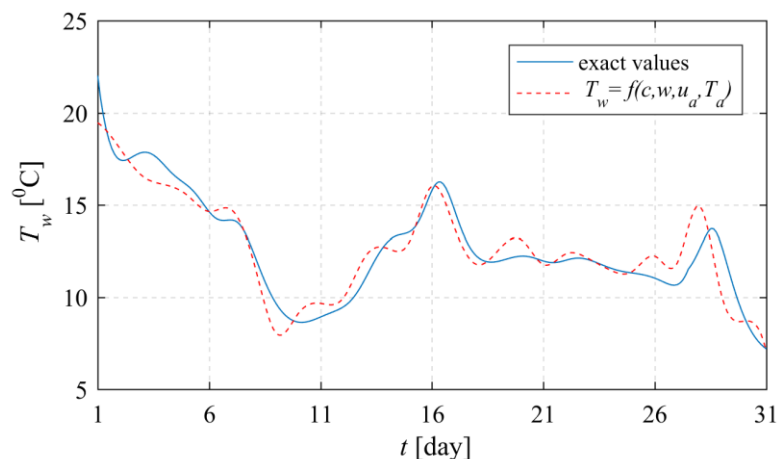
$$T_w = \frac{\alpha}{1 + e^{\gamma(\beta - T_a)}} , \tag{17}$$

$$T_w = -1.7609 - 1.2269\,c + 0.4023\,w + 5.9492\,u_a + 0.7337\,T_a.$$

Figure 6. Values obtained with the logistic equation with one variable (Mohseni) and the "accurate" values of the water temperature

A comparison between the values obtained with the multi-linear regression equation and the "exact" values of the water temperature is shown in Figure 7.

Figure 7. Multiple-linear regression and "accurate" values of the water temperature

In this case between the two curves the deviations are much smaller.

5. Conclusions

Small perturbations on input parameters of the deterministic model can influence the output that is the river water temperature. The turbidity and wind velocity seem to have the less importance in the water temperature influence.

The analysis shows that air temperature is the dominant factor in the modeling of the thermal regime of water from the river, which has made it possible in many of the regression models to use only this one independent variable.

If all four parameters (turbidity, velocity, air humidity, and air temperature) are considered, the regression relation found is close to the values determined by the deterministic model in which the input data are the real ones.

From the comparison between multiple linear regression and the model proposed by Mohseni in [9] it follows that the use of multiple inputs in a linear model can provide satisfactory results.

References

[1]   Caissie D 2006 The thermal regime of rivers: a review, *Freshwater Biology* **51**(8) 1389-1406

[2]   Holtby L B 1988 Effects of logging on stream temperatures in Carnation Creek, British Columbia, and associated impacts on the coho salmon (Oncorhynchus kisutch), *Canadian Journal of Fisheries and Aquatic Sciences* **45**(3) 502-515

[3]   Caissie D, Satish M G and El-Jabi N 2007 Predicting water temperatures using a deterministic model: Application on Miramichi River catchments (New Brunswick, Canada)*, Journal of Hydrology* **336**(3-4) 303-315

[4]   Morin G and Couillard D 1990 Predicting river temperatures with a hydrological model, *Encyclopedia of Fluid Mechanic, Surface and Groundwater Flow Phenomena* **10** 171-209

[5]   Sinokrot B A and Gulliver J S 2000 In-stream flow impact on river water temperatures, *Journal of Hydraulic Research* **38**(5) 339-349

[6]   Dugdale S J, Hannah D M and Malcolm I A 2017 River temperature modelling: A review of process-based approaches and future directions, *Earth-Science Reviews* **175** 97-113

[7]   Mohseni O and Stefan H G 1999 Stream temperatures/air temperature relationship: a physical interpretation, *Journal of Hydrology* **218**(3) 128-141

[8]   Kamarianakis Y, Ayuso S V, Rodríguez E C and Velasco M T 2016 Water temperature forecasting for Spanish rivers by means of nonlinear mixed models, *Journal of Hydrology: Regional Studies* **5** 226-243

[9]   Sahoo G B, Schladow S G and Reuter J E 2009 Forecasting stream water temperature using regression analysis, artificial neural network, and chaotic non-linear dynamic models, *Journal of Hydrology* **378**(3-4) 325-342

[10]   Dingman S L 1993 *Physical Hydrology*, Macmillan College Publishing Company, New York

[11]   Koberg G E 1964 *Methods to Compute Long-Wave Radiation From the atmosphere and Reflected Solar Radiation From a Water Surface*, Geological Survey, United States Government printing office, Washington

[12]   Croley T E 1989 Verifiable Evaporation Modeling in the Laurentian Great Lakes, *Water Resources Research* **25**(5) 781-792

[13]   Bowie G L, Mills W B and Porcella D B 1985 *Rates, constants, and kinetics formulations in surface water quality modeling*, Second Edition, Environmental Protection Agency, USA

[14]   Bowen I S 1926 The ratio of heat losses by conduction and by evaporation from any water surface, *Physical Review* **27** 779-787

[15]   Mohseni O, Stefan H G and Erickson T R 1998 A nonlinear regression model for weekly stream temperatures, *Water Resources Research* **34**(10) 2685-2692