WATER TEMPERATURE AND HEAT EXCHANGE DYNAMICS IN THE STREAMS

Peter Halaj, Denisa Halajová, Viliam Bárek

Faculty of Horticulture and Landscape Engineering, Slovak University of Agriculture in Nitra, Hospodarska 7, SK-94976 Nitra, Slovakia

Abstract

Functionality of aquatic biota reaches optimal state within the certain range of the water temperatures. The water temperature is a critical determinant of the abundance and diversity of biota in the stream. It influences growth, survival, distribution, and reproduction processes of aquatic species. Better understanding of the processes connected to stream temperature regime, thermal energy exchange at the interface between the water and the atmosphere has become recently part of debates on climate change impacts. The article is focused on analysis of key aspects which mainly affect thermal regime and heat exchange dynamics in stream and summarize the tools for prediction of negative impact of thermal load. The authors describe possibilities for reducing the impact with goal to keep good ecological quality of the streams.

Key words: *water temperature, heat exchange dynamics, water temperature modelling, Stream water temperature-reduction practices*

INTRODUCTION

Human impact on rivers represents complex process that leads to various negative consequences (Fazekašová et al., 2014; Horák et al., 2013). These symptoms include changes in the diversity of river and floodplain landscapes (Čimo et al., 2011). A climate change impact also manifested in degradation of river water quality and cause increase of invasive plants and animal species and the disappearance of many native plants and animal species (Semancová et al, 2014). Temperature of water in rivers represents important factor with economic and ecological significance which affecting various physical, biological and chemical characteristics of surface water. It represents a key parameter influencing stream ecology and determines overall health of aquatic ecosystems (Coutant, 1999) . Extreme changes in water temperature may cause behavioral and physiological responses in aquatic biota and permanent increases in stream temperatures can influence the habitat suitability for native species (Holtby 1988). Water temperature increase often lead to fish abundance and diversity changes, dissolved oxygen depletion, occurence of neophyte-dominated macrophyte and rapid increase of algal bloom (Charlton, 2011; Hussner and Lösch, 2005). Therefore knowledge of the key factors enable to predict the stream temperature regime and estimate the thermal load impact on riverine system (Hester and Doyle, 2011).

1. FACTORS INFLUENCING WATER TEMPERATURE

Factors influencing temperature of water in river can be classified into four main groups: geomorphology of river bed, discharge parameters, streambed features and atmospheric conditions Atmospheric conditions belong among the key factor which is responsible for the heat exchange processes that take place at the water surface, including changes in phase (Caissie, 2006; Horák et al., 2011; Igaz et al., 2011). Another important factors represent topography and geographical settings because they affect microclimate conditions. Stream flow characteristics mainly influence the heating capacity (volume of water) and cooling through mixing processes (velocity and flow state) (figure 1). The daily maximum temperatures in a stream are strongly influenced by removal of riparian vegetation because of diurnal patterns of solar short-wave heat flux (Adams and Sullivan, 1989).

2. HEAT EXCHANGE PROCESSES IN STREAMS

The relations among factors that influence water temperature in stream are complex (figure 1). The process of stream heating can be describe as exchanges of energy at the air-water interface and at the streambed-water interface (figure 2) where. Solar radiation is the main input source of the energy budget in terms of heat gain (Caissie 2006; Čimo et al., 2012).

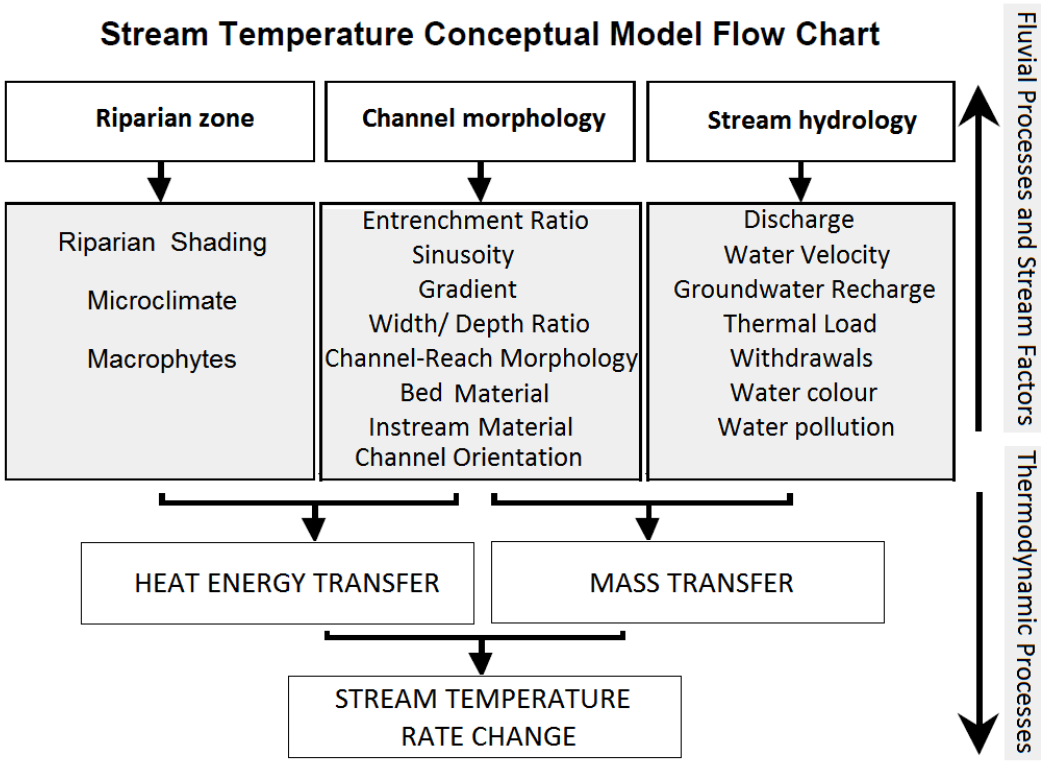


Figure 1: Conceptual model of factors affecting stream temperature (adopted after Cristea and Janisch, 2007)

Inputs of heat energy from solar radiation can be large compared to the losses associated with heat exchange. Therefore, most of the solar energy is stored in the stream, thereby causing an increase in water temperature in a downstream direction. Other factors which influence heat exchange process are: cloudiness, shading, solar angle, discharge, tributary contributions and groundwater contributions.

2.1 Short-wave solar radiation

Solar radiation is radiant (electromagnetic energy) from the sun. Short-wave solar radiation is contained in a wavelength range between 0.14 μm and about 4 μm. Short-wave solar radiation represent the major thermal input to an un-shaded water body during the day when the sky is clear.

2.2 Long-wave atmospheric radiation

The long-wave radiation from the atmosphere ranges in wavelength range from 4 μm to 120 μm. It depends mainly on air temperature and humidity and increases with both parametres increases. It is the major thermal input to a body of water at night and during warm cloudy days.

2.3 Long-wave back radiation from the water to the atmosphere

Heat energy is sent back to the atmosphere in form of long-wave back radiation in the wavelength range from about 4 μm to 120 μm. This radiation represents a major part of the heat loss from a water body.

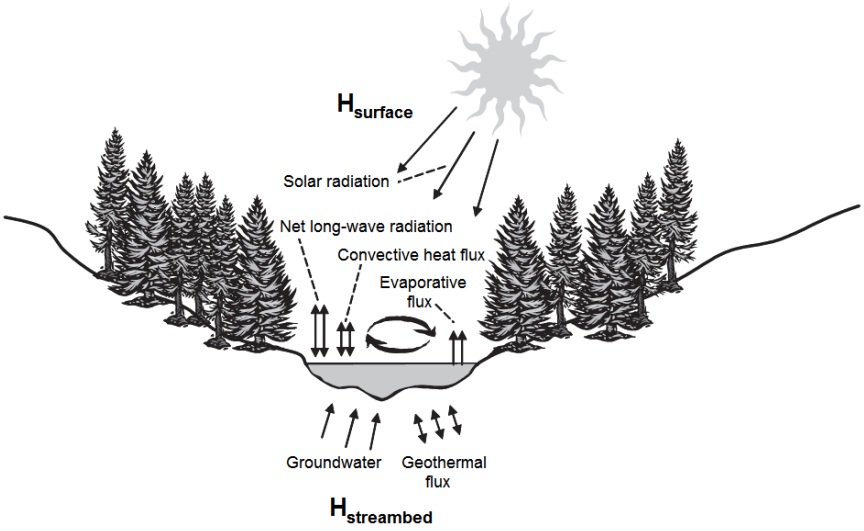


Figure 2: Scheme of heat exchange process in streams (adopted after Caissie, 2006)

2.4 Evaporation flux at the air-water interface

This form of heat flux is influenced mostly by the wind speed and the vapor pressure gradient between the water surface and air above the water.

2.5 Convection flux at the air-water interface

Convection flux at the air-water interface is driven by the temperature difference between water and air and by the wind speed. Heat is transferred in the direction of temperature gradient.

2.6 Bed conduction flux and hyporheic exchange

This component of the heat budget represents the heat exchange through conduction between the bed and the water body and the influence of hyporheic exchange. The bed conductance depends on size and conductance properties of the bed material. The heat transfer through conduction is proportionally to thermal differences between the substrate and water. Heat transfer between stream and the stream bed is an important factor of water temperature variation.

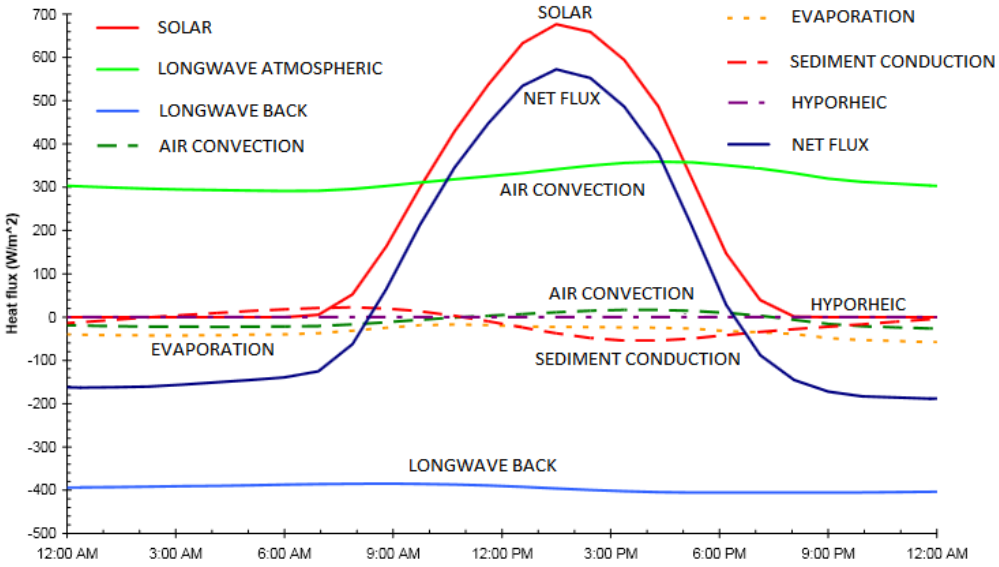


Figure 3: Estimated heat fluxes in a typical river during summer period (adopted after WDOE, 2007)

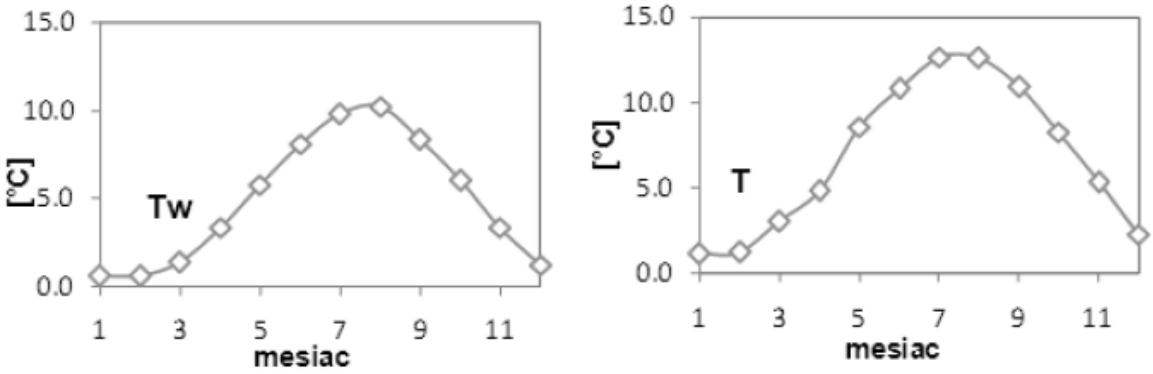


Figure 4: Comparision of input data (longterm mean month air temperature) and results (longterm mean month water temperature in river) of water quality model for the Bela River in Slovakia in period 1991-2010 (Martincova et al., 2012)

3. FACTORS OF HEAT EXCHANGE PROCESSES IN STREAMS

Changes in stream temperatures will reflect the change in air temperature, although often at a reduced amplitude (*figure 4*). The main source of hourly fluctuations in water temperature during the day is solar radiation (WDOE, 2007). The daily maximum temperatures in a stream are strongly influenced by removal of riparian vegetation because of diurnal patterns of solar short-wave heat flux (Adams and Sullivan, 1989).The complete heat budget of a stream largly depends on characteristics of mass transfer process (dischrage, velocity of water with given temperature) in channel. Mass transfer relates to transport of flow volume downstream, instream mixing, inflow in tributaries or outflows from stream (diversions, bypass). The sensitivity and response of stream temperatures to factors driving the heat transport process have diferent been evaluated in TMDL analyses conducted by NCRWQCB (2000) using reach-scale temperature models with data representing specific site conditions.

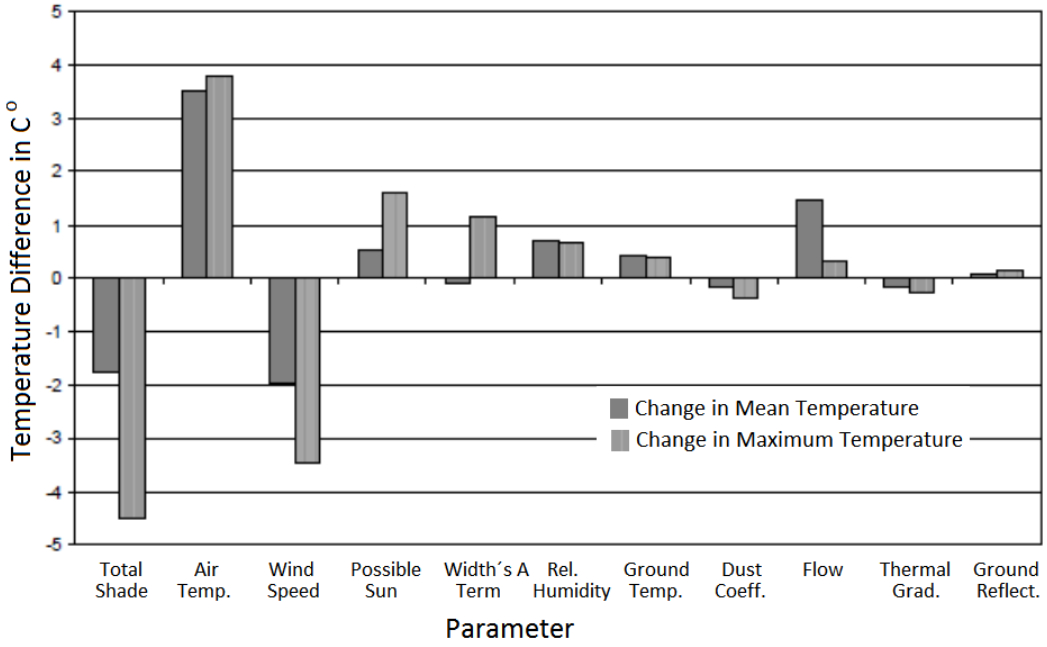


Figure 5: Sensitivity analysis of water temperature drivers in river (adopted after NCRWQCB,2000)

The example of sensitivity analysis results is presented in *figure 5* where is documented fact that air temperature is a stronger driver of water temperature. On other hand side shading, wind speed and groundwater inputs are the greatest modifiers of the relationship of air temperature to equilibrium temperature (Morrill et al. 2005).

4. STREAM TEMPERATURE MODELLING

Deas and Lowney (2000) divide mathematical models for stream and reservoir applications as physically based deterministics , empirical, or "mixed". The physically based deterministic models have governing equations for heat transport and fluid flow to simulate water temperature. They need to describe a geometry of the system, discharge and climatic conditions. An empirical models often use regression models between observed characteristics of the system. These models are however some limitations of the model use connected to situation when we need to simulate the system response for the other state of system than for standard conditions for which derived relationships have been elaborated. Most of the models use a mixture of empirical and physical based determinisic approaches. Modelling of heat transport through a river system represents the similar problem as modelling of pollution transport by water quality models. Although the equations and concepts are similar for both types of applications, water temperature modeling in rivers presents some unique challenges. Characteristics of thermal pollution may change along the stream, at tributaries, bifurcations, drains or other inflows and heat exchange exists along the entire course of the river (Deas and Lowney, 2000). In thermal pollution modelling two basic transport mechanisms may be distinguished in process of downstream transport. The prevalent form of thermal pollution transport with the main flow is termed advection. As the thermal pollution moves downstream it spreads in all directions due to diffusion and dispersion. The first publications connected to water temperature prediction were primarily focused on modelling of discharge temperatures from reservoirs and regulated water systems (Morse, 1970). The recent temperature models are offently a submodel of complex water quality models. They are more sophisticated and focused on the detailed impacts of increased water temperatures on aquatic ecosystems (Webb et al. 2008). In table 1 is presented water temperature model clasiffication with comparision of their advantages and disadvantages.

Table 1: Comparison of advantages and disadvantages of four different types of water temperature models (adopted after Benyahya et al., 2007)

Water temperature models	Advantages	Disadvantages
Deterministic model	Adapted to impact studies Quantification of Energy Components	Numerous input parameters Costly in development and application High data requirements
Equilibrium temperature model	Simple model Few input parameters Conceptual model Low data requirements	Semi-empirical Not well adapted to impact studies
Artificial neural network model	Simple in application Few input parameters No need to know the relationship between the input and output Low data requirements	No physical explanation of the underlying process Applied with caution outside the calibration range
Stochastic model	Simple application Low input requirement (usually only air temperature)	Not well adapted to environmental impact studies Based on statistics relations rather than the physical processes

5. STREAM TEMPERATURE-REDUCTION PRACTICES

The most efficient method to maintain low stream temperatures is to reduce heat loading from solar radiation, increasing the availability of cooler water by providing riparian shade (Tóth and Feriancová, 2014). The another type of measures represent modifying the operations of existing dams to recover many of the environmental and social benefits of healthy ecosystems. An increasing of flow from a reservoir during low flow periods has positive impact on water temperature regime in stream below the dam. The key measure for adaptation in catchment scale is connected to promotion of land management practices that increase natural rainfall retention within the catchment. This will help to reduce diffuse pollution of water, to store water in the catchment and will help to reduce both the peak and low flows. Arrington and Roa-Espinosa (2004) introduce two technical mesures for temperature-reduction practices. Rock crib designed as a bed of rocks that receives runoff from a developed area and support heat exchange between water and rocks cools heated runoff. The second measure represents thermal swaleas as a vegetated trench that receives runoff from a developed area and reduce heated runoff mainly by controlling the rate at which heated runoff is introduced into a stream. In Table 2. are presented examples of the basic measuresused in process of stream water temperature-reduction practices

Table 2: Stream water temperature-reduction practices

Practice	Practice description	Goals
Riparian shading	Reestablishment of maximum riparian vegetation	Reduction of heat loading from solar radiation.
Low flow increasing	An increasing of flow from a reservoir during low flow periods	Increasing of depth and velocity of water Increase discharge of cooler water from outlet works of reservoirs

Hyporheic cooling	Removal of stream channel revetments, restoration of historical channels to	Increasing the interaction between surface and subsurface water Increasing of groundwater level
Land use management	Increasing of retention capacity of the catchment	Reduction of peak flows and low flows
Storm water management	Rock crib building Thermal swale building	Increasing the heat exchange between water and rocks that cools runoff water. Reduction of heated runoff by controlling the runoff rate into a stream.

CONCLUSION

Water temperature is one of the most important physical characteristics of aquatic systems.It represents important factor with economic and ecological significance and affecting various physical, biological and chemical characteristics of surface water. Changes in stream temperatures will mainly reflect the changes in air temperature. There exist other important factors responsible for the heat exchange process. Therefore knowledge of the key factors enable to predict the stream temperature regime and estimate the thermal load impact on riverine system. The important role in environmental impact studies over last decades have water temperature models which have been used for the studies and have proven useful in water resources planning and management.

ACKNOWLEDGEMENT

This paper was elaborated within the Research VEGA 1/0744/13 of the Ministry of Education, Science, Research and Sport of the Slovak Republic.

REFERENCES

Adams, T.N. , Sullivan, k. 1989. The physics of forest stream heating: a simple model. Timber, Fish, and Wildlife, Report No TFW-WQ 3-90-007. Washington State Department of Natural Resources, Olympia, WA.

Arrington, K., Roa-Espinosa, A. 2004. Protecting Cold Water Streams – GIS Tackles Thermal Loading in Urban Watersheds. Land Information Bulletin from the National Consortium for Rural Geospatial Innovations, Great Lakes, University of Wisconson- Madison. Available at www.ruralgis.org. Accessed 4/5/2015.

Benyahya,L., Caissie, D., St-Hilaire, A., Ouarda, T. B.M.J, Bernard Bobée, B. 2007. A Review of Statistical Water Temperature Models. In: Canadian Water Resources Journal / Revue canadienne des ressources hydriques. Vol. 32, Issue 3, pp. 179-192.

Caissie, D. 2006. The thermal regime of rivers: a review. In: Freshwater Biology, Vol. 51, pp. 1389–1406

Charlton, M.N. 2011. Oxygen depletion in Lake Erie: has there been any change? In: Journal canadien des sciences halieutiques, Vol. 37, pp.72–80.

Čimo, J., Horák, J., Maderková, L., Igaz, D. 2011. Trends of soil freezing on Danubian lowland. In: Journal of International Scientific Publications: Ecology & Safety, vol. 5, part. 1, pp 221-228. ISSN 1313-2563.

Čimo, J., Maderková, L., Horák, J., Igaz, D., Pásztorová, S. 2012.Measurement tolerance analysis of solar radiation. In: Journal of International Scientific Publications: Ecology & Safety, vol. 6, No. 1, pp 261-267. ISSN 1313-2563.

Coutant, C.C. 1999. Perspectives on Temperature in the Pacific Northwest's Fresh Waters. Environmental Sciences Division Publication 4849 (ORNL/TM-1999/44), Oak Ridge National Laboratory, Oak Ridge, TN, 108 pp.

Cristea, N. Pelletier, G. J. 2005. Wenatchee River temperature total maximum daily load study Washington State Dept. of Ecology, Environmental Assessment Program Olympia, WA 2005, 133 p.

Deas, M.L., Lowney, C.L. 2000. Water temperature modeling review. Prepared for the California Water Modeling Forum. Central Valley, CA. Available Online: http://cwemf.org/Pubs/BDMFTempReview.pdf . Accessed: 4/2015.

Fazekašová, D., Huttmanová, E., Fazekaš, J. 2014. Time and Spatial Variability of Physical and Chemical soil Parameters in Conditions of the Sustainable Soil Use in Carpatian region Management 2014. In: International conference Management 2014. pp 421-424. ISBN 978-80-8165-052-9.

Hester, E. T., Doyle, M.W. 2011. Human Impacts to River Temperature and Their Effects on Biological Processes: A Quantitative Synthesis. In: Journal of the American Water Resources Association (JAWRA), Vol. 47, No. 3, pp. 571-587.

Holtby, L. B. 1988. Effects of logging on stream temperatures in Carnation Creek, British Columbia, and associated impacts on the coho salmon (Oncorhynchus kisutch). In: Canadian Journal of Fisheries and Aquatic Sciences, Vol. 45, pp. 502–515.

Horák, J., Igaz, D., Kondrlová, E., Čimo, J., Žembery, J., Candráková, E. 2013. Effect of conventional tillage and reduced tillage on N2O emission from a loamy soil under spring barley. In: Water resources. Forest, marine and ocean ecosystems, pp. 533-543, ISBN 978-619-7105-02-5.

Horák, J., Igaz, D., Šinka, K., Kondrlová, E., Štekauerová, V. Čimo, J. 2011. Estimates of nitrous oxide (N2O) emission from arable soils in the selected region of Slovakia using a process-based agro-ecosystem model. In: Journal of International Scientific Publications: Ecology & Safety, Vol. 5, part. 1, pp 229-240, 2011. ISSN 1313-2563.

Hussner, A. , Lösch, R. 2005. Alien aquatic plants in a thermally abnormal river and their assembly to neophyte-dominated macrophyte stands (River Erft, Northrhine-Westphalia). In: Limnologica,Vol. 35, pp. 18-30.

Igaz, D., Čimo, J., Horák, J. 2010. Hodnotenie výskytu sucha v podmienkach Podunajskej pahorkatiny. In Acta hydrologica slovaca, 2010, roč. 11, č. 2, pp 375-381. ISSN 1335-6291

Igaz, D., Horák, J., Kondrlova, E., Čimo, J. 2011. Digestate influence after biogas production on soil parameters. In: Journal of International Scientific Publications: Ecology & Safety., vol. 5, part. 1, pp. 213-220. ISSN 1313-2563

Martincová, M., Pekárová, P.,Miklánek, P. Milan Onderka, M., Mrafková, L. 2012. Modelovanie vybraných ukazovateľov kvality vody Belej v období 1991-2010. In: Acta Hydrologica Slovaca, Vol. 13, No. 1, pp. 142–152.

Morrill, J., R. Bales, R, Conklin, M. 2005. Estimating stream temperature from air temperature: Implications for future water quality, In: J. Environ. Eng., Vol.131, No.1, pp. 139–146.

Morse, W.L., 1970. Stream Temperature Prediction Model. In: Water Resources Research Vol: 6, pp. 290–302.

North Coast Regional Water Quality Control Board (NCRWQCB), 2000. Navarro River watershed technical support document for the total maximum daily load for sediment and technical support document for the total maximum daily load for temperature. December 2002.

Semancová, P., Fazekašová, D., Kotorová, D., Michaeli, E., Solár, V. 2014. The biological activity of soil ecosystems in the locality of dry polder Besa. In: 14th international multidisciplinary scientific geoconference SGEM 2014. Volume II, Forest ecosystems, marine and ecosystems, pp. 259-266.

Tóth, A., Feriancová, Ľ. 2014. Analysis Tools for Green Infrastructure in Urban Areas and Open Land'. In: M. Raček, ed. 2014. Plants in Urban Areas and Landscape. Nitra: Slovak University of Agriculture, pp 148-151.

WDOE. 2007. Walla Walla waters hed temperature total maximum daily load. Publication No. 07-10-030. Olympia, Washington. p. 110.

Webb, B.W., David M. Hannah, D.M., Moore, R.D., Brown, L.E., Nobilis, F. 2008. Recent advances in stream and river temperature research. In: Hydrol. Process., Vol. 22, pp. 902– 918.