Journal of Hydrology 495 (2013) 238–251

Contents lists available at SciVerse ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Integrated flow and temperature modeling at the catchment scale

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ARTICLE INFO

Article history:
Received 29 March 2012
Received in revised form 18 April 2013
Accepted 22 April 2013
Available online 6 May 2013
This manuscript was handled by Peter K. Kitanidis, Editor-in-Chief, with the assistance of Hongbin Zhan, Associate Editor

Keywords:
Stream temperature
Integrated surface water–groundwater modeling
Idaho
Silver Creek

SUMMARY

Changes in natural stream temperature levels can be detrimental to the health of aquatic ecosystems. Water use and land management directly affect the distribution of diffuse heat sources and thermal loads to streams, while riparian vegetation and geomorphology play a critical role in how thermal loads are buffered. In many areas, groundwater flow is a significant contribution to river flow, particularly during low flows and therefore has a strong influence on stream temperature levels and dynamics. However, previous stream temperature models do not properly simulate how surface water–groundwater dynamics affect stream temperature. A coupled surface water–groundwater and temperature model has therefore been developed to quantify the impacts of land management and water use on stream flow and temperatures. The model is applied to the simulation of stream temperature levels in a spring-fed stream, the Silver Creek Basin in Idaho, where stream temperature affects the populations of fish and other aquatic organisms. The model calibration highlights the importance of spatially distributed flow dynamics in the catchment to accurately predict stream temperatures. The results also show the value of including temperature data in an integrated flow model calibration because temperature data provide additional constraints on the flow sources and volumes. Simulations show that a reduction of 10% in the groundwater flow to the Silver Creek Basin can cause average and maximum temperature increases in Silver Creek over 0.3 °C and 1.5 °C, respectively. In spring-fed systems like Silver Creek, it is clearly not feasible to separate river habitat restoration from upstream catchment and groundwater management.

1. Introduction

Watershed management to optimize the health of the freshwater biotic community is becoming increasingly recognized as a necessary concept for achieving sustainability (Haper et al., 2008). Ecohydrology is a relatively new discipline within water management, which studies the functional interrelations between hydrology and biota at the catchment scale (Zalewski, 2000). Thus, the development of integrated ecohydrologic tools that can effectively relate the physical environment to measures of ecological status, and be applied at the catchment scale, is one of the most important challenges for the water resources community.

Temperature is a critical factor in defining the distribution of stream ecosystems and in determining the metabolic rates of organisms and their ability to interact with other species (Allan and Castillo, 2007). High stream temperatures can cause impaired growth and increased predation rates in certain aquatic species (Roth et al., 2010). Moreover, water temperature is the most important factor in fish reproduction (Fujimoto et al., 2008). Temperature serves as an indicator of water quality and ecosystem status, particularly fish habitat suitability. Therefore, the accurate simulation of stream water temperature in a catchment is an important goal in the context of ecohydrology.

Previous modeling work on heat loads in rivers was motivated by the impact of thermal loads from power plants (Butz et al., 1974; Jackman and Yotsukura, 1977; Kinzelbach, 1981; Poulin and Hubert, 1982). However, in many catchments heat loads to streams are dominated by diffuse sources rather than point sources. Thermal loads from diffuse sources may come from urban or agriculture runoff, and can be influenced by changes in natural drainage patterns and geomorphology, as well as changes in water use, land use, and vegetation. This study is focused on the impact of diffuse heat loads rather than heat point sources.

Stream temperature variations can be influenced by watershed management, such as surface and groundwater use, land use and vegetation management; often these catchment parameters are interrelated (Boyd and Kasper, 2003). Solar radiation is the most important source of heat to rivers during most of the year (Beschta, 1997; Boyd and Kasper, 2003). Removal of vegetation can significantly increase stream temperatures by increasing incoming radiation (Roth et al., 2010) as well as accelerate bank erosion, which can widen the stream channel. Increasing surface area and decreasing channel depth due to sediment accumulation, change river morphology, an important factor that affects stream temperatures (Klein et al., 2007). Water depth and flow volume influence the

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http://dx.doi.org/10.1016/j.jhydrol.2013.04.039

thermal inertia of the water body, which affects the amplitude of diurnal variations and the time lag to reach equilibrium temperature (Gu et al., 1998; Webb et al., 2003). The surface area of the stream affects the amount of heat exchange with the atmosphere and the time it takes to change the temperature of the water, given a certain heat flux (Larson and Larson, 1996). In addition, the surface area or the width of the channel affects the fraction of shade from stream bank vegetation or topography that covers a stream segment (Chen et al., 1998).

The flow regime in a channel has a direct impact on the thermal response of the stream. Several studies have quantified the relationship between flow and temperature (Shanley and Peters, 1988; Sinokrot and Gulliver, 2000; Webb et al., 2003). Sinokrot and Gulliver (2000) showed that increases in flow lead to a reduction in the amplitude of the diurnal temperature variation and critically high temperatures are more frequently exceeded under lower flows. Additionally, it is important to evaluate not only the amount of flow, but also the flow source. In rivers where a significant portion of the flow comes from groundwater, decreases in water table can cause temperature changes, especially in low flow periods. Conversely, areas that receive large amounts of runoff from higher temperature sources, such as surface drains, can contribute to high thermal loads downstream.

The spatial distribution of temperature along a river can be an indicator of the spatial variability in stream habitat conditions. River restoration efforts often focus on improving the bank vegetation and the geomorphology of the river, but river habitat conditions are also influenced by the catchment hydrology (Wissmar and Beschta, 1998). For example, changes in land use or water management (such as channelization, artificial ponding, and water diversions) can directly affect the thermal regime of a tributary, which can in turn deliver a high thermal load to the main stream. The simulation of water temperature in an integrated surface–groundwater hydrologic system makes it possible to assess the distribution of thermal loads in a catchment, which is a key step in understanding the impact of land use management on stream ecology.

Numerous types of stream temperature models have been developed over the past few decades; these can be broadly classified as regression, stochastic, and deterministic models (Cassie, 2006). Deterministic models have an advantage in that they can be applied at multiple scales (Cassie, 2006), but most importantly, they can be applied to evaluate management scenarios. For example, a regression model is only valid if the management boundary conditions are unchanged and therefore they cannot be used to simulate the effects of different management strategies.

Several deterministic models that couple stream hydrodynamics to heat transport have been developed in recent decades (Sinokrot and Stephan, 1993; Kim and Chapra, 1997; Younus et al., 2000; Boyd and Kasper, 2003). These models solve the one-dimensional Saint Venant equations for flow and the advection–dispersion equation for heat transport. An important source/sink term in these stream temperature models is the atmospheric heat exchange. Some models also include the sediment heat flux by conduction. However, most of the applications of these models have been limited to the stream scale and include groundwater flow represented as a fixed lateral inflow in one direction. Heat exchange by groundwater advection can be more important than conduction, if groundwater fluxes are large enough (Constantz, 2008). Moreover, Bogan et al. (2003) suggest that groundwater inflows can explain deviations in the relationship between stream temperature and stream equilibrium temperature with the atmosphere. Thus, a potentially important component of the heat balance for some river systems is neglected by such stream temperature models.

In many regions, groundwater flow controls the hydrologic regime of a river and thus, linking the temperature model to integrated surface water–groundwater models becomes important. An integrated model can simulate the dynamic two-way exchange (gains and losses) between surface water and groundwater so that the spatial variability and dynamics of stream hydrology can be better represented. Moreover, an integrated model can quantify the impact of surface and groundwater abstraction in a catchment more explicitly and thus directly and dynamically link the changes in management practices to stream temperature changes. Finally, a valuable aspect of linking a temperature model to an integrated catchment-scale surface water–groundwater model is the strong relationship between the volume and source of flow and temperature. This means that temperature data provide strong constraints on the flow sources and volumes and thus decrease model uncertainty.

In this study, we dynamically couple an integrated surface water–groundwater model to a surface water heat transport model. The flow model simulates 3-dimensional and spatially distributed hydrological processes and it dynamically exchanges flows between surface water and groundwater. The temperature model includes the atmospheric heat balance terms and surface water–groundwater heat exchange flux by both conduction and advection. Although the model has the capability of simulating groundwater temperature we assume a uniform groundwater temperature for the case study presented, primarily due to a lack of sufficient calibration data to parameterize a heat transport model for the groundwater compartment. This modeling approach provides a complete description of the processes that affect stream temperature and can be used to evaluate stream temperature impacts of climate change, land use, and water use changes at the catchment scale.

The capabilities of the modeling approach are illustrated using the Silver Creek case study. The Silver Creek system is a high-profile aquatic ecosystem, located in Idaho, USA. Ecosystem services (e.g., fishing, bird-watching, canoeing, water quality conservation, water supply, wetland buffer areas, etc.) in Silver Creek are highly dependent on surface water–groundwater dynamics. The Silver Creek Preserve managed by The Nature Conservancy hosts over 8000 visitors a year from every US state and 33 countries. Economic studies have shown that the Preserve contributes over 3 million US dollars to the local economy each year. The impact of surface and groundwater use in the catchment can be observed in the Silver Creek flow and temperature, which have affected the populations of fish and other aquatic organisms in this ecosystem. For example, fish kills in 1992 coincided with drought period and high temperatures (Wetzstein et al., 2000). This problem is exacerbated by increased water use. Thus, catchment managers are looking for solutions to achieve ecosystem sustainability.

2. Methodology

In this section, a description of the flow model components followed by the temperature model components is presented. The general modeling chart (Fig. 1) shows the hydrologic processes included in the model. The dashed gray line delineates the compartments that exchange both flow and heat in either one or two directions. The specific model inputs and data used for the case study and model calibration approach are described in Sections 3 and 4.

2.1. Flow modeling

The MIKE SHE code was chosen for this study because it has been widely used for integrated surface water–groundwater