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Research papers

Heat tracer test in a riparian zone: Laboratory experiments and numerical modelling

Jie Ren[a,b,*], Xiuping Wang[a], Zhenzhong Shen[b], Jian Zhao[b], Jie Yang[a], Ming Ye[c], Yinjun Zhou[d], Zhenhua Wang[e]

[a] State Key Laboratory of Eco-hydraulics in Northwest Arid Region of China, Xi'an University of Technology, Xi'an 710048, Shaanxi, China
[b] State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University, Nanjing 210098, Jiangsu, China
[c] Department of Earth, Ocean, and Atmospheric Science, Florida State University, Tallahassee 32306, FL, USA
[d] Changjiang River Scientific Research Institute, Wuhan 430010, Hu Bei, China
[e] College of Water & Architectural Engineering, Shihezi University, Shihezi City 832000, Xinjiang, China

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ABSTRACT

The use of water temperature as a tracer has been widely utilized for characterizing the dynamics of water flow and heat transport in riparian zones. By using experimental approaches, we investigated the effects of water temperature, hydraulic head, and heat radiation on water flow and thermal dynamics in riparian zones through sand tank experiments, which simulate the dynamics of water flow and heat transport in riparian zones. Water of low temperature was pumped into the sand tank, and changes of temperature at different locations of the sand tank were measured. Temperature data was examined for three different water temperatures (4.0 °C, 6.0 °C, and 9.5 °C), two different hydraulic heads (25 cm and 45 cm), and two different radiation temperatures (no radiation and 22 °C). The thermal dynamic variation pattern in different types of water temperatures, hydraulic heads, and radiation combinations, was also analyzed using a HYDRUS-2D model. The temperature sensors, located near the inlet infiltration boundary, required a shorter time to reach the steady state, because the temperature declined more rapidly near the inlet. The effect of lateral inflow on the temperature gradient was obvious. The temperature gradient in the horizontal direction gradually decreased, and the vertical temperature gradient gradually increased. In the initial stage of infiltration, the temperature gradient in the horizontal direction was larger than the temperature gradient in the vertical direction, however, as time goes on, the temperature gradient in the vertical direction was larger than the temperature gradient in the horizontal direction. In addition, the horizontal temperature gradient of the top sand layer was less affected by the water temperature. The closer the temperature observation point of the same horizontal section was to the infiltration boundary, the higher the rate of temperature difference changes. Comparison of the predicted and observed thermal dynamics variation of the 2-D sand tank shows good agreement, indicating that the major mechanism for water flow and thermal dynamics variation was hydraulic head. The sensitivity analysis results illustrate that the model was most sensitive to hydraulic head (H), followed by Van Genuchten parameter (α), permeability coefficient (K_s), water temperature (T), Van Genuchten parameter (n), residual moisture content (θ_r), and saturated moisture content (θ_s). The variation of each parameter was linear with the change of temperature field. Parameters which were positively related to the temperature field were T, α, θ_r and θ_s, which means the parameter value becomes larger as the temperature becomes larger, and vice versa. The parameters which were negatively related to the temperature field were H, K_s and n.

1. Introduction

Water temperature is one of the important factors that influences hydrologic and aquatic ecological environments. Large reservoirs are stratified with depth due to their capacity and slow flow rate. Water temperatures decrease with depth in large reservoirs and temperatures at the deepest layer remain constant all year. Release of low-temperature water from reservoirs can impact downstream aquatic environments. For example, the water temperature was low in discharges from reservoirs in spring and summer (Preece and Jones, 2002; Prats et al., 2010), and it was high in winter (Maheu et al., 2016). The low-temperature water from large reservoirs had an extremely important

* Corresponding author at: State Key Laboratory of Eco-hydraulics in Northwest Arid Region of China, Xi'an University of Technology, Xi'an 710048, Shaanxi, China.
E-mail address: renjie@xaut.edu.cn (J. Ren).

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impact on aquatic organisms and even aquatic ecosystems downstream of the dam.

Using groundwater temperature as a natural tracer, as opposed to using a chemical tracer, reduces negative impacts on the aquatic environment (Anderson, 2005; Constantz, 2008). In recent studies, water temperature as a natural tracer was used extensively to estimate heat exchange processes (Xie et al., 2015; Klepikova et al., 2016), groundwater discharges to surface waters (Duque et al., 2016), SW/GW interactions(Hyun et al., 2011; Naranjo and Turcotte, 2015; Munz et al., 2016; Schneidewind et al., 2016), and aquifer characteristics (Wildemeersch et al., 2014; Doro et al., 2015; Sakata, 2015; Colombani et al., 2015; Klepikova et al., 2016). Duque et al. (2010) studied the relations between rivers and the associated aquifers using groundwater temperature measurements, and general data on river discharge, and environmental and river temperatures. Sellwood et al. (2015) used in-well heat tracer tests to estimate borehole fluid flow rates and to evaluate the range of flow rates. Although the on-site thermal tracing test has yielded positive results, a more quantitative mechanism analysis is needed for the study of river ecology and solute exchange processes.

In recent years, with the application of automated observation technology, as well as the progress of data processing technology, the effects of water temperature changes over time on the physical properties of river beds can be more accurately examined. For example, temperature time series methods were extensively used to calculate vertical water fluxes (Keery et al., 2007; Gordon et al., 2012), Darcy velocity (McCallum et al., 2012), and groundwater-surface water exchange (Irvine et al., 2015). Tonina et al. (2014) based on temperature time series of surface and streambed pore waters, monitored local changes in streambed surface elevations at a daily time scale. He found that time series analysis of paired in-stream and pore water temperatures can predict variations in streambed surface elevations at the daily time scale with a 20% accuracy. More recently, Wilson et al. (2016) presented a method that inverts thermal time series data to estimate the timing and depth of transient hydrodynamic exchange. They found that it was possible to identify the depth of flushing using shallow datasets, in which flushing extended below the deepest sensor. This finding was used to estimate the influence of streambed or riverbed sediments on groundwater surface water exchange fluxes (Irvine et al., 2015).

Several research efforts were designed to characterize groundwater discharge to surface waters and ground velocities by performing distributed temperature sensing (DTS). Among them, Mamer and Lowry (2013) represented the initial lab testing of a new combined method to assess the viability of using pairs of DTS time series profiles to quantify and locate zones of discrete groundwater discharge throughout an entire stream reach. Bakker et al. (2015) presented a new methodology for using a heat tracer test to determine groundwater velocities. It inserts fiber optic cables vertically into unconsolidated sedimentary aquifers without the need for boreholes, and to measure temperature along these cables using DTS. Hare et al. (2015) compared thermal infrared to fiber-optic distributed temperature sensing for locating discrete groundwater discharges to surface water.

The above studies show that many scholars have used water temperature as a tracer to study the river-related problems, but the evaluation of water temperature as a tracer to study water flow and thermal variation mechanisms in riparian zones is rarely reported. Somewhat later, Sawyer et al. (2009) monitored water-table elevation, temperature, and specific conductivity along a transect perpendicular to the Colorado River (Austin, Texas, USA), 15 km downstream of the Longhorn dam to evaluate the penetration distance and rates of dam-induced lateral hyporheic exchange paths. They found that wooded riparian zones can reduce stream temperatures, particularly in terms of maximum temperatures. Bowler et al. (2012) conducted a systematic review of the available evidence for the effects of wooded riparian zones on stream temperature to assess the effectiveness of this intervention. They used hydraulic and temperature data to calibrate the reliable conservative transport model as calibration constraints. Due to the interface between surface water and groundwater in riparian zones and the particularity of the hyporheic location and structure, its difficult to measure water flow and heat transport in riverbed hyporheic exchange processes. These exchange areas are an important manifestation of the complex edge effect of the riparian zone, which have important protection functions for rivers and groundwater. And it is becoming a hot topic for future research.

Riparian zones played the key role in the function of aquatic ecosystems which could affect the chemical, physical and biological processes. When low-temperature water from a reservoir is released, it infiltrates into the riparian zones, and mixes with natural groundwater allowing for heat exchange. Then, the low temperature water released from the reservoir forms the soil non-isothermal environment under the two-way radiation conditions which consists of the low temperature water layer in lower part and the upper natural temperature surface, and could cause the redistribution of temperature and moisture field inevitably. There were significant changes on riverbed sediment and riparian saturation-unsaturated zone heat state, and these differences could be characterized by groundwater activities. Soil moisture and temperature were the most important influencing factors of geochemical and ecological processes in the unsaturated zone (Halloran et al., 2016). The distribution and variation of soil temperature affects the physical and chemical properties of the soil and the biochemical cycle (Paul et al., 2004; Maurer and Bowling, 2014). Studies have shown that soil temperature changes directly affected the soil respiration rate (Contosta et al., 2016; Wang et al., 2016). Soil respiration was one of the main fluxes of the global carbon cycle and was an important determinant of ecosystem carbon balance (Riveros-Iregui et al., 2007), its strength was second only to primary productivity (Laganiere et al., 2012), and it was mainly composed of microbial decomposition of soil organic matter and root respiration (Curtin et al., 2012). Low-temperature water also had adverse effects on downstream cropland irrigation. Yang et al. (2012) concluded that the maximum impact scope of low-temperature water was 55 km and water temperature reached the minimum growth temperature of rice during April and June. The use of engineering or non-engineering measures to manage the reservoir discharge temperature regulation and to reduce the adverse effects of low-temperature water on the environment and ecology has become a major problem in the field.

Recent experimental studies have been concerned with the effect of hydraulic conductivity of silty clay under infiltration of low-temperature water (Ren et al., 2014), the purpose of this study was to develop a process, using the 2-D riparian zone test and to use this new test to evaluate water flow and thermal dynamics in riparian zones using the injection of a heat tracer test. In Section 2, we present a methodology for of laboratory experiments and the numerical modeling utilized in this study. In Section 3, we describe laboratory experimental procedures used to evaluate water flow and thermal dynamics in a sand tank. We also reconstructed a numerical model, using three sets of experiments to calibrate and verify. In addition, we used the sensitivity analysis method to analyze the parameters of the model.

2. Methodology

2.1. Laboratory experiments

Experiments were conducted in a sand tank with a precise heating/cooling control system (see Fig. 1). The total sand tank length is 80 cm. The working sediment-filled section is 60 cm in length, 20 cm wide, and 80 m in height. Water flow in the tank was horizontal (Fig. 1b). The inlet and outlet were furnished with perforated plates and gauze to ensure uniform flow across the entire cross-section without losing any sediment. The perforated plates device at the upstream end minimizes pulsing action and facilitates a smooth flow of water into the study section. The upstream reservoir has two overflow holes, 30 cm and