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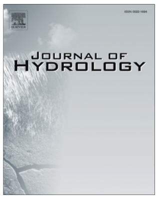

Numerical verification of hyporheic zone depth estimation using streambed temperature

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SUMMARY

The hyporheic zone is the active region of groundwater and surface water mixing, and consequently, through which the contaminants released to surface water are transferred to groundwater. Because of the high energy demand and expense associated with the remediation of contaminated groundwater, it has become a matter of primary concern to find an efficient and cost-effective way to restore the contaminated groundwater. Therefore delineating the hyporheic zone is of vital importance for the prevention and management of groundwater contamination. This paper proposes a method to estimate the depth of the hyporheic zone using heat transfer analysis for a streambed. In order to assess the adequacy of the proposed method, the sensitivity of the results of heat transfer analyses to the hyporheic flux was evaluated. Due to the high sensitivity to the hyporheic zone depth, the heat transfer analysis was determined to be appropriate to delineate the hyporheic zone depth. The depth estimated from the heat transfer analysis was comparable with that from a conventional tracer test. The proposed method has an advantage over existing methods of determining the hyporheic zone depth due to the fact that it only requires field temperature measurements.

1. Introduction

Stream water and groundwater can affect each other by sharing a hyporheic zone to degrade or improve the water quality (Findlay, 1995; Brunke and Gonse, 1997; Greenberg et al., 2002; Conant, 2004; Soulsby et al., 2005). The hyporheic zone is the area where mixing and exchange of surface and groundwater occurs, and often exhibits large chemical and hydraulic gradients (Smith, 2004; Kim et al., 2009). For the remediation of contaminated groundwater, natural attenuation by controlling environmental factors has recently received much attention (Fustec et al., 1991; Harman et al., 1996; Mengis et al., 1999; Babiker et al., 2004; Beller et al., 2004; Wakida and Lerner, 2005; Shomar et al., 2008; Hyun et al., 2011; Kim et al., 2013).

Due to the widespread contamination of surface water, overloading groundwater with organic matter and nutritive substances is a frequent occurrence (Schiff et al., 1990; Boyer et al., 2000; Sebestyen et al., 2008). It takes a lot of energy and enormous cost to remediate contaminated groundwater (Hynes, 1960; Johnson et al., 1997; Townsend et al., 1997; Parker et al., 2000), and thus, attention is being placed on measures for the efficient and cost-effective restoration of contaminated groundwater. Due to the complexity and diversity of the underground medium, the remediation of groundwater is very inefficient both in terms of economy and efficacy. Therefore a fundamental and logical assessment of the problem at hand was required.

Existing methods to estimate the mixing zone of surface water and groundwater include the installation of seepage meters (Taniguchi and Fukou, 1993; Langhoff et al., 2001; Murdoch and Kelly, 2003; Rosenberry and Morin, 2004; Rosenberry, 2008) or piezometers (Carver, 2001; Surridge et al., 2005; Hatch et al., 2006; Kim et al., 2009, 2013), gauging differential discharge (Lowry et al., 2007; Essaid et al., 2008), and trace injection tests (Bencala et al., 1990; Castro and Hornberger, 1991; Triska et al., 1993; Hoehn and Cirpka, 2006). With regard to the seepage meter installation, errors can be introduced by improper installation/deployment (Rosenberry and Pitlick, 2009). The piezometer installation requires intensive labor and has a limitation of point measurement (Hatch et al., 2006; Rosenberry et al., 2012). Differential discharge gauging is also labor-intensive and difficult when flows are low or turbulent. Lastly, tracer injection tests cannot distinguish subsurface flow from loss and may be affected by tracer adsorption (Constantz et al., 2003; Isiorho et al., 2005; Ruehl et al., 2006;

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Chen et al., 2007; Kim et al., 2013). Nevertheless, the tracer injection tests are widely used for hyporheic zone delineation (Triska et al., 1993).

Compared with such physical methods, which require higher cost, or chemical methods which inject further chemicals, usually causing a secondary contamination, estimating the depth of the contaminated region based on temperature change of the mixing zone of groundwater and surface water should be much more cost-effective (Stonestrom and Constantz, 2003; Anderson, 2005; Keery et al., 2007). Having focused on the fact that the temperature of a streambed is influenced by the hyporheic flux, we propose a method for estimating the depth of the hyporheic zone based on the analysis of heat transfer through the streambed (Lapham, 1989; Constantz et al., 1994; Constantz and Thomas, 1996; Taniguchi et al., 2003; Stonestrom and Constantz, 2004; Constantz, 2008; Hyun et al., 2011; Kim et al., 2011). The heat transfer analysis includes the heat transfer mode of conduction, advection and dispersion (Stallman, 1963; Silliman and Booth, 1993; Anderson, 2005; Constantz, 2008).

The main concept of the method is that the calculated temperature distribution which shows the best fit to the measured temperature distribution is determined from the heat transfer analysis by changing the hyporheic flux. The procedure obviously has an advantage over the previous methods of estimating the mixing zone because the proposed method simply requires the measurement of the temperature distribution in the field, as a single parameter upon which determinations are directly made.

The present paper focuses on the assessment of the adequacy of the proposed method, which estimates the depth of the hyporheic zone by gathering field temperature and performing conduction–advection–dispersion analysis (CAD analysis). The adequacy is assessed by evaluating the difference between the real field temperature distribution over time and its corresponding values from CAD analyses. The sensitivity of the sum of squared differences (SSD) to the two factors of hyporheic flux, which are the hyporheic zone depth and the hyporheic flux magnitude, was evaluated. The SSDs for different hyporheic flux shapes are all proven to be more sensitive to the hyporheic zone depth than its magnitude. This result demonstrates the appropriateness of the proposed method. Lastly, field temperature data was collected and the hyporheic zone depth was estimated by CAD analyses, and then the result was compared with that from the conventional tracer test.

2. Materials and methods

2.1. Conventional method for estimating the hyporheic zone depth

Tracer test is one of the conventional methods for estimating the hyporheic zone depth (Triska et al., 1993; Bertin and Bourg, 1994; Harvey and Fuller, 1998; Hill and Lymburner, 1998). The commonly used equations to model one-dimensional transport in streams with groundwater exchange and storage are

$$\frac{\partial C}{\partial t} = -\frac{Q}{A}\frac{\partial C}{\partial x} + \frac{1}{A}\frac{\partial}{\partial x}\left(AD\frac{\partial C}{\partial x}\right) + \frac{q_L^{in}}{A}(C_L - C) + \alpha(C_s - C) - \lambda C \quad (1)$$

$$\frac{\partial C_s}{\partial t} = \alpha\frac{A}{A_s}(C - C_s) - \lambda_s C_s \quad (2)$$

where t = time (s), x = direction along the stream (m), C = concentrations in the stream (mg/L), C_s = concentrations in the storage zone (mg/L), C_L = concentration in the groundwater (mg/L), Q = in-stream volumetric flow rate (m^3/s), q_L^{in} = reach-averaged groundwater influx per meter of stream ($m^3/s/m$), D = longitudinal dispersion coefficient in the stream (m^2/s), A = stream area (m^2), A_s = storage zone cross-section area (m^2), α = storage-exchange coefficient (s^{-1}), λ = first order rate constant describing net uptake of a reactive solute by a biological process in stream flow (s^{-1}), λ_s = first order rate constant describing net uptake of a reactive solute by a geochemical process in the storage zone (s^{-1}).

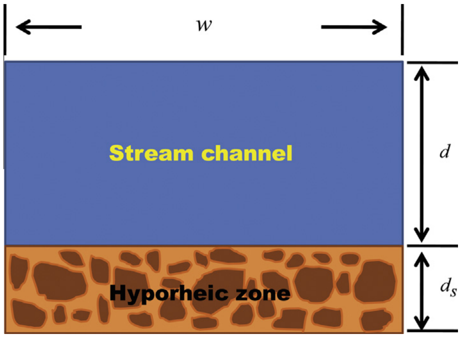

Fig. 1. Simple characterizations of the spatial dimension of the hyporheic zone.

A nonreactive solute tracer such as chloride is injected into a stream. The interaction of the stream water with groundwater is assumed to not exist because the water flux measured near the hyporheic zone is small and the distance between tracer injection point and chloride concentration monitoring point is short. Then with the assumptions made above, the equations are simplified as

$$\frac{\partial C}{\partial t} = -\frac{Q}{A}\frac{\partial C}{\partial x} + \frac{1}{A}\frac{\partial}{\partial x}\left(AD\frac{\partial C}{\partial x}\right) + \alpha(C_s - C) \quad (3)$$

$$\frac{\partial C_s}{\partial t} = \alpha\frac{A}{A_s}(C - C_s) \quad (4)$$

A rate constant α defines the rate at which stream water is exchanged for water in storage zones. According to Harvey et al. (1996), the parameters of the storage zone model in Eqs. (3) and (4) can be related to the hyporheic fluxes defined by

$$q_s = \alpha A \quad (5)$$

where q_s = storage-exchange flux, i.e., the average flux of water through storage zones per unit length of stream ($m^3/s/m$)

Mathematically, the storage-exchange flux is identical with the hyporheic-exchange flux, and the rate constant α is determined by using a measured storage-exchange flux. Storage-zone cross-sectional area A_s can be determined by solving Eqs. (3) and (4) simultaneously and comparing its results with that from the tracer test. Harvey and Wagner (2000) recommended a simple way in which the hyporheic zone depth d_s can be calculated from the storage-zone cross-sectional area A_s. As shown in Fig. 1, a stream channel in which the storage-zone cross-sectional area is considerably smaller than the cross-sectional area of the stream ($A_s < A$), and where stream width w is much greater than the stream depth ($w/d > 20$), the hyporheic zone depth is simply approximated by

$$d_s = \frac{A_s}{wn} \quad (6)$$

where d_s = hyporheic zone depth (m), w = stream width (m), n = channel sediment porosity (–).

2.2. Proposed method for estimating the hyporheic zone depth

This study arises from the fact that the temperature distribution of the streambed is influenced by the hyporheic flux, and intends to estimate the depth of the hyporheic zone. Hence, the temperature distribution of the streambed can be calculated by CAD analyses. The heat transfer in the streambed is described by the following differential equation of one-dimensional