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A 3D analysis algorithm to improve interpretation of heat pulse sensor results for the determination of small-scale flow directions and velocities in the hyporheic zone

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ABSTRACT

The hyporheic zone is strongly influenced by the adjacent surface water and groundwater systems. It is subject to hydraulic head and pressure fluctuations at different space and time scales, causing dynamic and heterogeneous flow patterns. These patterns are crucial for many biogeochemical processes in the shallow sediment and need to be considered in investigations of this hydraulically dynamic and biogeochemical active interface. For this purpose a device employing heat as an artificial tracer and a data analysis routine were developed. The method aims at measuring hyporheic flow direction and velocity in three dimensions at a scale of a few centimeters. A short heat pulse is injected into the sediment by a point source and its propagation is detected by up to 24 temperature sensors arranged cylindrically around the heater. The resulting breakthrough curves are analyzed using an analytical solution of the heat transport equation. The device was tested in two laboratory flow-through tanks with defined flow velocities and directions. Using different flow situations and sensor arrays the sensitivity of the method was evaluated. After operational reliability was demonstrated in the laboratory, its applicability in the field was tested in the hyporheic zone of a low gradient stream with sandy streambed in NE-Germany. Median and maximum flow velocity in the hyporheic zone at the site were determined as 0.9×10^{-4} and 2.1×10^{-4} m s^{-1} respectively. Horizontal flow components were found to be spatially very heterogeneous, while vertical flow component appear to be predominantly driven by the streambed morphology.

1. Introduction

The saturated transition zone (hyporheic zone) between surface and groundwater bodies is a hydraulically and biogeochemical dynamic system with important functions affecting exchange of water, nutrients and heat (White, 1990; Bencala, 2000), nutrient cycling, attenuation of contaminants (Grimm and Fischer, 1984; Findlay et al., 1993; Pinay et al., 2009), habitat and refugia (Brunke and Gonser, 1997; Stubbington et al., 2009) and the general functioning of linked surface water–groundwater ecosystems (Boulton et al., 1998; Krause et al., in preparation). Exchange processes at this interface are governed by hydrologic processes that operate at a range of different scales (Poole et al., 2004; Vollmer, 2005; Fleckenstein et al., 2010). At larger scales (e.g. catchment) hydraulic conditions in the river and the underlying alluvial aquifer as well as geologic controls govern exchange patterns and may result in infiltrating surface water (losing reaches) or exfiltrating groundwater (gaining reaches) at different times (Woessner, 2000; Stonestrom and Constantz, 2004; Fleckenstein et al. 2006; Cardenas, 2009; Nützmann and Lewandowski, 2009). The structure and morphology of the river channel may result in inter-meander exchange pathways (Woessner, 2000; Cardenas et al., 2004; Boano et al., 2006) or local flow cells in the stream bed caused by topographic variations (e.g. step pool sequences, stream bed riffles, woody debris, etc.) (Sophocleous, 2002; Gooseff et al., 2006; Wondzell, 2006; Mutz et al., 2007). These processes superimpose each other in the hyporheic zone, resulting in complex and heterogeneous flow patterns in the streambed (e.g. Kaser et al., 2009; Rosenberry and Pitlick, 2009; Krause et al., in preparation).

Being able to characterize and quantify these patterns is of great importance in efforts to better understand biogeochemical processes in the hyporheic zone and to assess its potential to attenuate contaminants. Identifying the spatial extent and arrangement of

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gaining and losing reaches (vertical exchange flux), reaches of parallel flow (long horizontal flow path in the hyporheic zone) and reaches of alternating exchange between surface water body and hyporheic zone (short flow paths, frequent reversals in flow direction on a spatial and temporal scale) is of particular interest as the different water exchange regimes determine supply and residence time of oxygen and nutrients and thus, are crucial for biogeochemical turnover rates (Boulton et al., 1998).

To characterize surface water–groundwater exchange processes heat is a commonly used tracer. In several studies, heat has been used as a natural tracer to localize water exchange zones (Selker et al., 2006) and to quantify vertical flow with a one-dimensional (1D) solution of the heat transport equation (Stonestrom and Constantz, 2003, 2004; Schmidt et al., 2006; Anibas et al., 2009; Schornberg et al., 2010). Furthermore, different methods employing heat pulse injection techniques were applied to measure groundwater flow velocity (Melville et al., 1985; Ballard, 1996; Ballard et al., 1996; Alden and Munster, 1997), soil water flux (Kawanishi, 1983; Ren et al., 2000; Yang and Jones, 2009; Kamai et al., 2010) and also hyporheic flow (Greswell, 2005; Greswell et al., 2008, 2009) two-dimensionally (2D). Few studies, however, have utilized heat as a tracer of hyporheic flow in three dimensions. In the laboratory a three-dimensional (3D) setup was developed by Lewandowski et al. (2011) to measure flow in the hyporheic zone with a rough estimation of flow direction and flow velocity. The scale range of several centimeters covered by this device was chosen in accordance to the resolution of biogeochemical sampling methods like gel probes (Davison et al., 1991), dialysis samplers (Hesslein, 1976; Lewandowski et al., 2002) and multi-level samplers (Duff et al.,1998; Anneser et al., 2008).

Lewandowski et al. (2011) showed the general applicability of the device and presented a first rough data analysis protocol. However, the data analysis routine presented by Lewandowski et al. (2011) has limitations and does not fully account for the 3-dimensionality of flow in the hyporheic sediments, which can lead to inaccuracies in estimates of flow direction and velocity. Hence the main goal of this study was to develop and test an improved 3D data analysis routine for a more accurate determination of flow direction and flow velocity. To keep the routine robust and simple enough for a fast analysis of the data obtained from the heat pulse sensor it relies on an analytical solution to the heat transport problem that was adapted to the specific requirements of a flexible 3D analysis. The derivation and development of the new routine will be presented in the methods section of this paper. To test the new data analysis routine and demonstrate improvements over the original analysis routine both routines are applied to data sets from laboratory experiments similar to those presented by Lewandowski et al. (2011). Field applicability of the overall methodology is demonstrated by an application of the routine to an extensive data set from field measurements at the River Schlaube (*in situ* measurements).

2. Materials and methods

2.1. Instrumental setup the original analysis routine

The principle of the heat pulse sensor described by Lewandowski et al. (2011) is that of a miniaturized tracer experiment using heat as an artificial tracer. A short heat pulse is emitted by a punctiform heater into the streambed sediment at a depth of 5–15 cm and moves through the porous medium by convective transport and heat conduction. Its propagation is detected by a three-dimensional array of up to 24 temperature sensors, arranged concentrically around the heat source on the surface of a virtual cylinder (Fig. 1). According to laboratory tests by Lewandowski et al. (2011), the adequate power for measurements at the scale of few centimeters is 12 W over 60 s, yielding an energy input of 0.72 kJ for each measurement. The resulting temperature at the heat source depends on the heat capacities and thermal conductivities of the water and the porous medium surrounding the heater as well as the subsurface flow velocity. The recorded temperature signal at the sensors, i.e. the temperature increase relative to ambient temperature ΔT, allows the user to draw inferences about flow through the porous medium. As described by Lewandowski et al. (2011) the presence of the measurement setup affects flow direction and flow velocity but we assume that the impact is minor, since the volume covered by the device is only 4.6% of the measurement volume. For more details on the device and the measuring procedure, the reader is referred to Lewandowski et al. (2011).

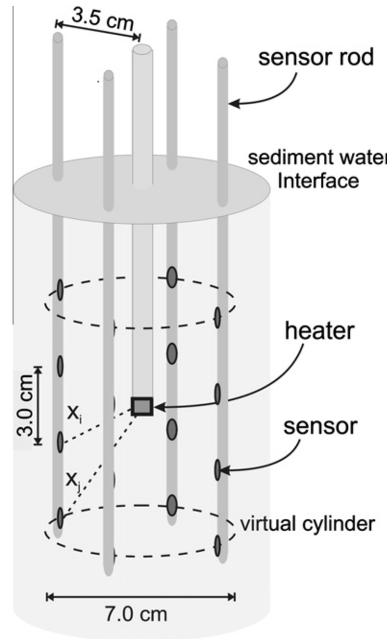

Fig. 1. Schematic diagram of the heat pulse sensor, consisting of four sensor rods with four temperature sensors each, arranged concentrically around the heater. The sensors are aligned cylindrically (diameter 7 cm) and the distances between heater and sensors are different ($x_i \neq x_j$).

The heat pulse sensor aims at the determination of flow direction on the one hand and a quantification of the flow velocity on the other hand. Lewandowski et al. (2011) described a method to estimate the flow direction based on the aforementioned instrumental setup by fitting a two-dimensional (2D) symmetric Gaussian distribution to the pattern of maximum temperatures on the surface of the virtual cylinder on which the temperature sensors are aligned. This estimate of flow direction is used to identify sensors closest to the flow vector. The flow velocity is calculated from breakthrough time of the temperature maximum t_{MAX} recorded at those sensors, the distance between sensors and heater x (Fig. 1) and an empirical retardation factor R of 1.8, which was calibrated with laboratory measurements under known flow conditions and a numerical model of the setup (Lewandowski et al., 2011). The determination of flow velocity according to the routine presented by Lewandowski et al. (2011) is based on the analysis of single curves and the range of information contained in the 3D setup of the device is not fully utilized.

2.2. Improved data analysis routine

Breakthrough curves at the different sensor positions under different flow velocities and directions differ in height, shape and