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Quantification of bank filtration in restored and channelized sections of a losing stream reach using time series of natural tracers determined by point and distributed sensors

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INTRODUCTION

Hyporheic exchange has been identified as important for the ecological status of rivers and the quality of groundwater. In the hyporheic zone transformations of nutrients (Triska et al., 1993) and pollutants occur. For the assessment of groundwater quality in the vicinity of losing rivers, it is of particular importance to know the quantity of exchange fluxes between river and groundwater. Especially in Switzerland where 40% of the drinking water originates from pumping wells close to regulated rivers (BUWAL, 2004), travel times and mixing ratios of the pumped groundwater, which is a mixture of freshly infiltrated river water and old alluvial groundwater, are crucial parameters. In recent years many river restoration projects have been conducted at Swiss rivers connected to gravel aquifers. To increase habitat diversity common changes in riverbed morphology are e.g. widening of the riverbed or small meanders. The modified riverbed morphology may increase the variability and potentially the magnitude of hyporheic exchange processes, and may also affect the associated alluvial aquifer system. In terms of ecological habitat diversity an enhanced interaction between river and groundwater is an intended amendment of the system, but in the vicinity of riparian pumping wells river restoration measures are critical. Groundwater management in such contexts requires special methods for quantifying the exchange of water and solute mass between surface and subsurface water bodies. In this paper, we present a method for quantification of time-variable riverbed seepage rates by means of high-resolution profiles of distributed temperature data. Moreover, travel-time distributions of observation wells and a pumping well in a restored and channelized river section of River Thur in North-East Switzerland are determined through the use of nonparametric deconvolution technique (Cirpka et al., 2007) of EC time series.

TEST SITE

We study bank filtration at a test site in northeast Switzerland at an adjoining channelized and restored section of the peri-alpine losing River Thur, which is part of the RECORD Project (Assessment and Modeling of Coupled Ecological and Hydrological Dynamics in the Restored Corridor of a River (Restored Corridor Dynamics)). Due to its alpine to peri-alpine catchment (1750 km^2) and the absence of a lake or artificial reservoir discharge of River Thur exhibits strong fluctuations (low discharge: 3 m^3/s; mean discharge: 20–50 m^3/s; peaks up to 1000 m^3/s; Federal Office for the Environment, http://www.bafu.admin.ch/publikationen/01005). In the central Thur valley (altitude ~ 400 m a.s.l.), the river was channelized in the 1890s as a flood-protection measure. In response to large flooding events, restoration projects were realized since 1993, with the aim to improve flood protection and the ecological status of the river and the riparian zone. At our test site, the riverbed consists of gravel and river water is infiltrating through out the whole year into groundwater. The productive aquifer is about 5 - 6 m thick and consists of Pleistocene glacio-fluvial sandy gravels with an avarage hydraulic conductivity of 3.4×10^{-3}m/s.

METHODS

A wide range of methods exist to estimate water flux between surface water and groundwater. The exchange processes between both water bodies vary both in time and space (Woessner, 2000). Therefore, a spatial distribution and high temporal resolution of measurements is necessary to understand the exchange dynamics in a river corridor. Due to advances in sensor technique and data loggers, time-series analysis of natural tracers like temperature and EC has been shown to be useful in obtaining seepage rates and travel times of young groundwater in losing streams (Cirpka et al., 2007; Vogt et al., 2010).

Fiber-optic high-resolution streambed temperature profiling

The vertical and lateral temperature distribution in a riverbed is a function of boundary conditions, heat conduction and advection (Anderson, 2005). Therefore, streambed temperature profiles have been used to identify losing and gaining reaches of rivers (Constantz, 2008) and to quantify seepage rates (Keery et al., 2007). Time series obtained at several depths contain information on both effective advection and conduction in the sediment. To obtain high-resolution temperature profiles of the streambed over time we use DTS, which is based on the temperature dependence of Raman scattering. Light from a laser pulse is scattered along an optical fiber of up to several km length, which is the sensor of the DTS system. By sampling the back-scattered light with high temporal resolution, the temperature along the fiber can be measured with high accuracy (0.1 K) and spatial resolution (1 m) for 10 min measurement intervals. We wrapped an optical fiber around a 2 m long piezometer tube and measured the temperature distribution along the fiber (Figure 1). Due to the wrapping, we obtained a vertical resolution of approximately 5 mm. We analyzed the temperature time series by means of dynamic harmonic regression as presented by Keery et al. (2007), who calculated the amplitude and phase angle of diurnal temperature oscillations as continuous, auto-correlated time variables. From the travel time, which is a converted phase angle, and amplitude attenuation of the diurnal time signal, we estimated the apparent velocity and diffusivity of temperature propagation for each 5 mm depth interval, which then can be used to quantify time variable infiltration rates (Vogt et al., 2010).

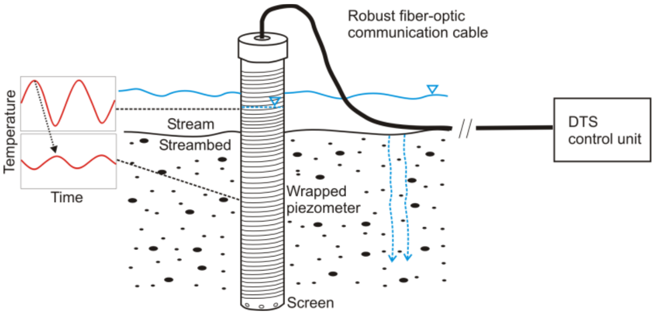

Figure 1. Schematic sketch of the fiber-optic high-resolution vertical temperature profiler.

Time-sries analysis of electrical conductivity

The river and selected observation wells at the channelized and restored river section were equipped with sensors with an integrated data logger for continuous measurements of hydraulic head, water temperature, and EC of water (DL/N 70, STS AG, Switzerland; error of single measurement: ±0.1% for head, ±0.25 K for temperature, and ±2 % for EC, according to manufacturer's manual). The measuring interval was set to 15 min. In the groundwater observation wells, the sensors were installed about 0.5–1.0 m below mean groundwater table. As the temperature signal is retarded compared to solute transport, we use EC data.

The River Thur shows strong fluctuations of EC. Diurnal, event related, and seasonal signals exist. During river bank filtration these signals are transported into the aquifer. The diurnal oscillations only propagate to wells close to the river. We analyze the diurnal EC oscillations by means of Dynamic Harmonic Regression as described above for temperature time series resulting in time variable travel times.

For travel times in the range of days to weeks we use non-parametric deconvolution. For a detailed description of nonparametric deconvolution of EC time series we refer to Cirpka et al. (2007). Due to dispersion and mixing, the EC signal is more and more damped with increasing travel time. Therefore, pumping wells or observation wells further away form the river show a strongly attenuated EC signal without diurnal oscillations. But characteristic event related EC fluctuations are still present and can be analyzed. In non-parametric deconvolution, we calculate a continuous transfer function which we interpret as travel time distribution between the river and the observation well. The river signal is the input and the groundwater signal the output signal. In contrast to parametric deconvolution, the transfer function in non-parametric deconvolution is free to adjust to the data. Hence, it is possible to detect multiple peaks. In order to achieve reasonable estimates, we use a geostatistical smoothness criterion and Lagrange multipliers to implement non-negativity.

RESULTS AND DISCUSSION

Streambed seepage rates

The high resolution of the fiber-optic vertical temperature profiler gives a detailed view of the diurnal variation of riverbed temperature over depth and time. The determination of time shift and amplitude attenuation for each depth interval was effective using dynamic harmonic regression. We estimate apparent seepage rates from the effective temperature velocities using literature values for thermal properties. Over the entire observation period shallow depths exhibit stronger apparent fluxes ($3.0 - 4.0 \times 10^{-5}$ m/s) than depths below 0.6 m ($1.5 - 2.5 \times 10^{-5}$ m/s). The estimated apparent seepage fluxes vary also over time (Figure 2).

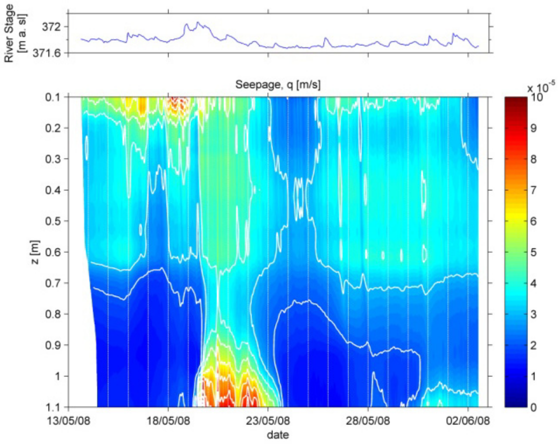

Figure 2. Estimated apparent seepage fluxes compared to the river stage. A: River stage of gauging station. B: Calculated vertical seepage fluxes. Contourlines: isolines of 1×10^{-5} m/s.

During falling river stage after a small event the highest infiltration occurred. The small temperature amplitudes during this time at a depth below 0.9 m may have distorted the estimate of seepage rates. While the temporal variation can easily be attributed to changing hydrological conditions, namely the difference between the river stage and the hydraulic head in groundwater at depth, the vertical variation is more complex. Vertical variability of hydraulic conductivity alone cannot explain vertical variation of the apparent vertical seepage flux, because we used a 1-D uniform expression for heat transport (Vogt et al., 2010). Thus, a variation of the vertical flux must be balanced by variations of horizontal flux components. Our findings represent only local exchange, but demonstrate that the presented method works. In future studies we thus plan to install a grid of fiber-optic temperature profilers to obtain a multi-dimensional image of the vertical and lateral seepage processes on a larger scale.

Travel times of young groundwater

Data evaluation and an automatic temperature compensation of the EC data guarantee that the fluctuations of EC do not reflect instrument instability or temperature effects, but changes in solute ion concentrations. The diurnal oscillations occur perennially under low discharge conditions. Like for the streambed temperature data, the determination of time shift (Figure 3) and amplitude attenuation of the diurnal EC oscillations was effective using dynamic harmonic regression and the time shift results show a temporal variability.

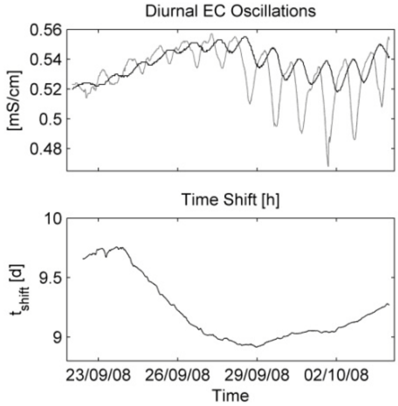

Figure 3. Diurnal oscillations of EC over a time period of approximately two weeks and the calculated time shift of the diurnal EC fluctuations. Gray line: river; black lines: observation well close to the river.

The event-related changes of EC are associated with a variation of discharge of the River Thur (Figure 4A). During peak flow, EC shows distinct minima. Figure 4B shows the travel time distribution for a pumping well in the channelized river section determined by non-parametric deconvolution of the EC time series. The secondary peak may possibly be explained by the existence of several flow paths from the river to the well with distinct travel times. We observed the shortest travel times in the restored river section, where observation wells are situated close to the river. In the channelized river section the travel times of the observation wells with the same distance of 5 – 20 m to the river are about three times longer. We attribute this fact to the differences in riverbed morphology, type of bank, and elevation of the overbanks. In particular, banks with gravel bars without steep slopes offer the river the possibility to create various flow paths with increasing water level due to a bigger area of infiltration.

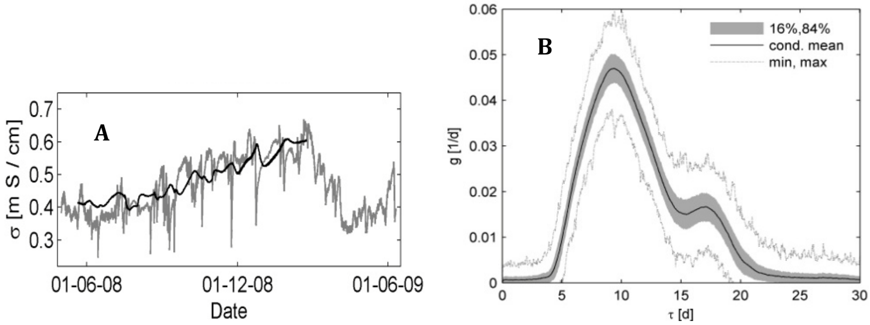

Figure 4. Data and result for a pumping well in the channelized river section. A: Time series of electrical conductivity. B: Travel-time distribution after non-parametric deconvolution.

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