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Fluctuations of electrical conductivity as a natural tracer for bank filtration in a losing stream

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ABSTRACT

A key parameter used in the assessment of bank filtration is the travel time of the infiltrated river water during the passage through groundwater. We analyze time series of electrical conductivity (EC) in the river and adjacent groundwater observation wells to investigate travel times of young hyporheic groundwater in adjoining channelized and restored sections of River Thur in North-East Switzerland. To quantify mixing ratios and mean residence times we perform cross-correlation analysis and non-parametric deconvolution of the EC time series. Measurements of radon-222 in the groundwater samples validate the calculated residence times. A simple relationship between travel time and distance to the river has not been observed. Therefore, we speculate that the lateral position and depth of the thalweg as well as the type of bank stabilization might control the infiltration processes in losing rivers. Diurnal oscillations of EC observed in the river and in nearby observation wells facilitate analyzing the temporal variation of infiltration. The diurnal oscillations are particularly pronounced in low flow situations, while the overall EC signal is dominated by individual high-flow events. Differences in travel times derived from diurnal and overall EC signals thus reflect different infiltration regimes.

1. Introduction

In order to achieve a “good ecological status” as required by the European Water Framework Directive [14], river management has changed in the last decades from river regulation by channelization to restoration. River restoration actions aim to increase the diversity of habitats in a restored corridor of the river by increasing the hydromorphological variability. Typical measures include the removal of bank armoring, the elimination of overbanks, and the establishment of gravel bars, islands and meanders similar to those found in a natural state.

The impact of river corridor restoration on water quality is currently under debate. Most papers focus on the effects of river restoration on hyporheic exchange, which is said to increase the self-cleaning capacity of the river [8,21], to create thermal refugia for aquatic biota [1], and hotspots of biogeochemical processing [28,30]. Common local-scale alterations of stream flow that enhance hyporheic exchange are in-stream geomorphic structures such as gravel bars, steps, pools, and log dams [25]. At a regional scale, preferential flow through paleochannels [36], channel sinuosity [7,42], and secondary channels [40] influence the interaction with the hyporheic zone. Hence, river restoration projects aim to increase the exchange between river and subsurface by widening of the riverbed, re-meandering stream reaches, constructing gravel bars, or by side-arm reconnections [3,24]. Conversely, concerns have been raised that these measures may facilitate early breakthrough in pumping wells adjacent to revitalized rivers [20], which may lead to contamination of drinking water, e.g., by bacteria. As a consequence, Swiss legislation prohibits river revitalization in the inner protection zone of drinking water wells, defined by a minimum residence time of 10 days [5]. A considerable part of Swiss pumping wells are close to losing rivers, so that a large fraction of the extracted water consists of freshly infiltrated river water, characterized by groundwater residence times of a few days. Therefore, the knowledge of the spatial and temporal variation of travel times is crucial for determining the effects of river restoration activities on riparian wells for drinking water supply and to counteract threatening effects.

For a comprehensive review of methods to assess surface water–groundwater interaction, we refer to Kalbus et al [23]. In the following, we will review common methods to determine travel times in river–groundwater systems. Since this paper deals with river water infiltration into the aquifer, methods for quantification of groundwater discharge into a river will not be discussed. The traditional technique to determine the travel time from a river to a well is to add a pulse of a conservative tracer, such as a fluorescent dye, into the river and observe the breakthrough curve in the well [12,26,29]. The fraction of freshly infiltrated water in the extracted water and the travel time distribution can be determined from the breakthrough curve. In large rivers, this method requires large amounts of tracer and determines the flow parameters only for the hydraulic conditions during the test period. Environmental and natural tracers are another option to determine residence times. Travel times up

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to two weeks can be estimated from radon-222 concentrations [18], but hold only for the hydraulic conditions during sampling. Travel times in the range of several years can be determined by the tritium–helium-method or analysis of anthropogenic trace gases like chlorofluorocarbons and sulfur hexafluoride [4]. That is, there is a substantial gap in the range of travel times determined by measuring dissolved gases; and there is a need of analyzing continuous signals in order to obtain information on river–groundwater exchange under changing hydrological conditions.

Water level, water temperature and electrical conductivity (EC) of water are easy to measure, robust, physical parameters. Modern sensors and data loggers facilitate straight-forward data collection over time. The most common natural tracer used in studies of river–groundwater exchange is temperatre. Recently, Anderson [2] and Constantz [10] have reviewed the use of temperature in this context. Temperature fluctuations in a river and the adjacent aquifer are typically analyzed by a 1-D analytical solution of the convective–conductive heat transport equation for arbitrary temperature signals of the infiltrating river water [34], by cross-correlation methods [19,33], or by spectral analysis of the convective–conductive heat transport equation[17,27,38]. However, temperature is a suboptimal tracer. In comparison to conservative solute transport, heat transport is retarded depending on the porosity and thermal properties of the sediments [2], which may be difficult to determine in the field. Moreover, the seasonal temperature signal is not a unique indicator of river water infiltration [19]. Cox et al. [11] showed that the combination of intermittent EC and temperature data improves the determination of river–groundwater interaction. Fluctuations of EC in the river, in contrast to temperature, may be more characteristic and do not undergo retardation when propagated into the hyporheic zone and aquifer [9,33,37].

Fluctuations of EC in rivers may have several causes. Turnover of carbon by aquatic biota in summer and impacts by sewage treatment plants may cause diurnal variations. Precipitation events in the catchment result in dilution of river water over several days. In alpine and pre-alpine catchments, snowmelt yields a decrease of the seasonal signal of EC in spring, whereas road salting in settlement areas results in an increase of EC in winter. Upon river water infiltration these signals are transported into the aquifer. The transport processes in groundwater cause a time shift and an attenuation of the river signal. Several methods exist for the assessment of travel time information from these signals: cross-correlation of the time series, calibration of an advective–dispersive model, parametric and non-parametric deconvolution, among others [9].

In this paper, we investigate travel times of young hyporheic groundwater in adjoining channelized and restored sections of the losing River Thur in North-East Switzerland using long-term time series of EC in the river and multiple observation wells. We analyze diurnal oscillations of EC observed in the river and nearby observation wells by means of dynamic harmonic regression [43] to obtain time shifts and amplitudes of the diurnal signal, which can be transferred to temporal variations of infiltration. For further analysis we remove the diurnal component determined by dynamic harmonic regression and the seasonal trend from the raw data and perform cross-correlation and non-parametric deconvolution of the time series to quantify mixing ratios and mean residence times. While cross-correlation yields a single optimal time shift value between the river and groundwater signals, we obtain the full distribution of travel times by non-parametric deconvolution. Measurements of radon-222 in groundwater samples are used as an independent test of the EC-based residence times.

2. Theory

2.1. Fluctuations of electrical conductivity

Diurnal fluctuations of physical and chemical parameters are typical for all streams. The interplay between photosynthesis, respiration, and gas-transfer results in diurnal variations of oxygen [32] and carbon dioxide [41] concentrations, which are also affected by diurnal temperature fluctuations [13]. The variations in dissolved carbon dioxide continuously change the equilibrium of inorganic carbon species involving precipitation and dissolution of calcium and magnesium carbonates, which results in fluctuations of total dissolved solids. This is a common feature in calcareous streams during low discharge [16]. As EC of water is a sum-parameter for the concentration of solute ions, the above mentioned processes influence EC. If diurnal changes of EC are in phase with variations in discharge, evapotranspiration may be the reason [6] or daily changes in the pattern of groundwater discharge to a gaining stream [39].

Diurnal fluctuations are superimposed by seasonal fluctuations reflecting seasonality of biogeochemical cycling, the hydrological regime, and anthropogenic impacts. For the perialpine River Thur, which is also analyzed in the present study, Cirpka et al. [9] attributed a distinct decrease of EC in late spring to snow melt in the upper catchment. In the catchment of this river, storm events lead to a rapid decrease in EC by 20-50% within hours indicating the dilution of groundwater–borne water by meteoric water with considerably lower EC. These signals can be followed in groundwater observation wells adjacent to the river [9,37].

2.2. Propagation of electrical-conductivity fluctuations into the aquifer

We assume that EC of water can be computed by linearly combining concentrations of dissolved ions, each of which is essentially undergoing the same advective–dispersive transport. Then, the transport of EC fluctuations from the river to observation points within the aquifer can be described by the advection–dispersion-reaction equation:

$$\frac{\partial \sigma'}{\partial t} + \mathbf{v}\cdot\nabla\sigma' - \nabla\cdot(\mathbf{D}\nabla\sigma') = r \tag{1}$$

in which $\sigma'(\mathbf{x},t)$ denotes the fluctuation of EC about a mean value, $\mathbf{x}$ is the vector of spatial coordinates, t is time, $\mathbf{v}$ is the effective velocity vector, $\mathbf{D}$ is the dispersion tensor, and the term r accounts for changes in electric conductivity by reactive processes such as precipitation/dissolution reactions.

In the following analysis, we will neglect fluctuations caused by reactions within the aquifer, i.e., $r\approx 0$. Also, without knowing the exact flow field, we may interpret observed EC fluctuations within the aquifer as if they were caused by one-dimensional transport, which mainly implies neglecting transverse dispersion:

$$\frac{\partial \sigma'}{\partial t} + v_a\frac{\partial \sigma'}{\partial s} - D_a\frac{\partial^2 \sigma'}{\partial s^2} = 0 \tag{2}$$

in which s is the longitudinal coordinate, and v_a and D_a are the apparent velocity and dispersion coefficient, respectively. The apparent coefficients are uniform coefficients determined by fitting 1-D analytical expressions to observed breakthrough curves of EC fluctuations that are caused by multi-dimensional transport in reality.

For the diurnal fluctuations, it is useful to consider a periodic boundary condition of EC in the river, $s = 0$:

$$\sigma'(s=0,t) = a_0 \times \cos\left(2\pi\left(t - t_0^{\max}\right)f\right) \tag{3}$$

in which a_0 is the amplitude of EC fluctuations in the river, f is the frequency (here one per day), and $t_0^{\max}$ is the time of maximum EC in the river.

To obtain a simple analytical expression in the 1-D apparent problem, we assume that the EC fluctuations vanish at the limit of an infinite distance:

$$\lim_{s\to\infty}\sigma'(s,t) = 0. \tag{4}$$