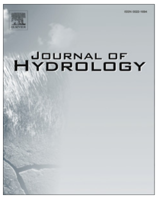
Journal of Hydrology 519 (2014) 3386–3399

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol



Non-stationary nonparametric inference of river-to-groundwater travel-time distributions

Zijie Liao[a], Karsten Osenbrück[b], Olaf A. Cirpka[a,*]

[a] University of Tübingen, Center for Applied Geoscience, Hölderlinstr. 12, 72074 Tübingen, Germany
[b] Water and Earth System Science (WESS) Competence Cluster, c/o University of Tübingen, Hölderlinstr. 12, 72074 Tübingen, Germany

ARTICLE INFO

Article history:
Received 9 May 2014
Received in revised form 22 August 2014
Accepted 29 September 2014
Available online 23 October 2014
This manuscript was handled by Peter K. Kitanidis, Editor-in-Chief, with the assistance of Jian Luo, Associate Editor

Keywords:
Travel-time distribution
Bank filtration
Non-stationarity
Nonparametric inference

SUMMARY

The travel-time distribution between rivers and groundwater observation points and the mixing of freshly infiltrated river water with groundwater of other origin is of high relevance in riverbank filtration. These characteristics usually are inferred from the analysis of natural-tracer time series, typically relying on a stationary input–output relationship. However, non-stationarity is a significant feature of the riparian zone causing time-varying river-to-groundwater transfer functions. We present a non-stationary extension of nonparametric deconvolution by performing stationary deconvolution with windowed time series, enforcing smoothness of the determined transfer function in time and travel time. The nonparametric approach facilitates the identification of unconventional features in travel-time distributions, such as broad peaks, and the sliding-window approach is an easy way to accommodate the method to dynamic changes of the system under consideration. By this, we obtain time-varying signal-recovery rates and travel-time distributions, from which we derive the mean travel time and the spread of the distribution as function of time. We apply our method to electric-conductivity data collected at River Thur, Switzerland, and adjacent piezometers. The non-stationary approach reproduces the groundwater observations significantly better than the stationary one, both in terms of overall metrics and in matching individual peaks. We compare characteristics of the transient transfer function to base flow which indicates shorter travel times at higher river stages.

1. Introduction

Bank filtration, in which river water infiltrates into the river banks and is extracted at some distance, plays a major role for water supply in many countries (e.g., Sontheimer, 1980; Kuehn and Mueller, 2000; Ray et al., 2002; Schubert, 2002). The water passage through the banks filters particles such as pathogenic bacteria (e.g., Weiss et al., 2005) and facilitates natural cycling of nutrients as well as removal of biodegradable contaminants (e.g., Doussan et al., 1997; Hoppe-Jones et al., 2010). Thus, bank filtration may partially replace technical water-purification systems. Its effectiveness highly depends on the travel time from the river to the well, which is often used as a proxy for the assessment of infiltrating river-water quality. In the regulations of several countries, inner protection zones for groundwater wells are defined by isochrones, e.g., in Germany by 50 days of travel time (DVGW, 1995) and in Switzerland by 10 days (BUWAL, 2004). Even though these protection zones regulate land use, the agencies recommend that infiltrating river water also exceeds the required travel time before being extracted. Thus, determining the travel times from rivers to observation and pumping wells is of vital importance in the management of river-fed groundwater resources.

The traditional technique of determining travel times is by tracer tests. In artificial-tracer experiments an easily detectable, conservative, and harmless compound, that is not yet present in the system, is injected into the stream and measured at all observation wells of interest (Leibundgut et al., 2009). These tests directly provide the volumetric fraction of river water in the well and the travel-time distribution. At larger rivers, however, very large tracer masses need to be injected, the largest fraction of which is not undergoing infiltration. Also, artificial-tracer tests yield only information about river-groundwater exchange at the time of the experiment.

As an alternative, natural tracers bearing a time signal have been analyzed. Besides concentrations of dissolved gases, such as radon (e.g., Hoehn and von Gunten, 1989), noble gases (e.g., Stute et al., 1997; Massmann et al., 2008), and chlorofluorocarbons (e.g., Beyerle et al., 1999; Darling et al., 2010), time series of

---

[*] Corresponding author.

E-mail addresses: liaozijie2007@gmail.com (Z. Liao), karsten.osenbrueck@uni-tuebingen.de (K. Osenbrück), olaf.cirpka@uni-tuebingen.de (O.A. Cirpka).

http://dx.doi.org/10.1016/j.jhydrol.2014.09.084
0022-1694/© 2014 Elsevier B.V. All rights reserved.

naturally fluctuating properties, such as water isotopes (e.g., Stichler et al., 1986; Hunt et al., 2005), temperature (e.g., Anderson, 2005), and specific electric conductivity (e.g., Cox et al., 2007; Cirpka et al., 2007) can be used to infer river-to-groundwater travel times. Specific advantages of using time series of physical properties are their low cost of detection and their continuous quality, which can be recorded over years. This becomes particularly important if high-frequency time series are required due to time-variant flow or boundary conditions, as is the case in most river systems. The dynamics might be caused by fluctuations of river and groundwater stages, changes in hydraulic conductivity of the river bed due to temperature variations and clogging of the river bed, as well as morphological changes of the river bed, to name the most important influences. In the present study, we will focus on non-stationary travel time distributions and therefore restrict the analysis to the interpretation of continuously measured fluctuating specific electrical conductivity.

The most profound way of analyzing tracer time series in a bank-filtration system would be by calibrating a mechanistic, spatially explicit coupled river-groundwater flow-and-transport model (e.g., Malaguerra et al., 2013). This is often not possible, because the exact river bathymetry, distribution of hydraulic subsurface parameters, and boundary conditions are not known. Under such conditions, the target of tracer-data analysis is restricted to identifying a linear input–output relationship between the measured time series in the river (input) and the observation or pumping well (output).

Many approaches of linear input–output relationships can be casted as convolution models, in which the input signal is convoluted with the transfer function to obtain the output signal. If average values of the signals differ, an additional systematic offset may be needed. The transfer function is also denoted impulse-response function or Green's function. Its integral is the signal-recovery rate, and the normalized transfer function (integrating to unity) is the travel-time distribution.

An easy approach of identifying a single characteristic transfer time between the two time series is by cross-correlation, in which the time shift with the highest correlation coefficient is interpreted as the effective travel time (e.g., Sheets et al., 2002). In order to account for smoothing of the input signal by the transfer process, the input signal may be filtered before cross-correlation, and the optimal combination of filter width and time shift is sought for (e.g., Vogt et al., 2009). Together with the linear-regression coefficients obtained for the optimal combination of filter width and time shift, the results of this analysis may be interpreted as parametric travel-time distribution amended by a recovery rate and a systematic offset in the time series.

A simple and parsimonious approach of inferring a non-negative transfer function is by assuming a non-negative distribution, such as the log-normal, gamma, or inverse Gaussian distribution, which is fully described by a few shape parameters, and fitting these parameters (e.g., Luo et al., 2006; Maloszewski and Zuber, 1993). Fitting one-dimensional transport models with constant coefficients would also fall into this category (for a comprehensive overview of 1-D transport solutions see Toride et al., 1993), but the one-dimensional interpretation of data resulting from complex three-dimensional transport may lead to a misguided assignment of physical properties to the system under investigation.

Even when parametric travel-time distributions without direct relationship to a specific one-dimensional transport problem are chosen as transfer functions, the inferred solutions are restricted to predefined shapes. Multi-modal distributions, or distributions allowing broad peaks and long tails are mostly not tested. However, the complexity of riverbed morphology and sediments could facilitate such transfer functions. To overcome this difficulty, our workgroup has developed non-parametric methods of estimating non-negative, smooth transfer functions and applied them to bank-filtration problems (Cirpka et al., 2007; Vogt et al., 2010), stream-to-stream tracer tests (Payn et al., 2008), and the identification of hyporheic travel-time distributions (Liao and Cirpka, 2011; Liao et al., 2013). Recently, McCallum et al. (2014b) suggested a similar method in which the smoothness regularization of Cirpka et al. (2007) has been replaced by applying the singular-value-decomposition based pseudo-inverse in the solution of the resulting close-to-singular system of linear equations.

All approaches discussed above are based on the assumption of stationarity. That is, the response of the system to a unit-pulse input signal is assumed to be always identical. This is in contrast to riparian systems being dynamic. As a consequence, the transfer functions inferred by stationary methods reflect a weighted time average of the true dynamic system behavior at best.

The problem of non-stationarity occurs in various applications of time-series analysis. Many methods of handling non-stationarity are extensions of stationary approaches. A way of circumventing non-stationarity is by applying a sliding window to the time series, resulting in smaller sections of the data, which are then analyzed by a suitable stationary method. The overall scheme is non-stationary because the stationary analysis is repeated for each window, so that the inferred parameters can change with the sliding of the window. Small window sizes allow for stronger non-stationarity, and applying overlapping windows leads to smoother transitions of the inferred parameters. Boker et al. (2002) combined cross-correlation and the sliding-window method to obtain the dynamic properties of a system from associated time series.

In a similar way, Schmidt et al. (2012) proposed an extension of the dynamic-time-warping method (Dürrenmatt et al., 2013; Berndt and Clifford, 1994), where variations in the time lag between time series of electrical conductivity were derived from an optimal (warping) path within the correlation matrix.

All these dynamic methods have improved the understanding of river-groundwater systems in terms of the mean travel time, but dynamic non-parametric deconvolution, which considers both the potential unconventional shape of the transfer function and the non-stationary property of the river-to-groundwater system, has not yet been conducted.

In the present work, we propose a non-stationary extension of the nonparametric deconvolution method of Cirpka et al. (2007) to determine travel-time distributions between rivers and observation wells. Non-stationarity is achieved by applying the sliding-window technique with local stationarity for the windowed input-to-output relationship. We choose short overlapping windows and penalize rapid changes in the determined transfer function, yielding a continuously and smoothly changing travel-time distribution. Like in the approach of Cirpka et al. (2007), we do not predefine the functional shape of the travel-time distribution but require smoothness for regularization. To the best of our knowledge, this is the first time that dynamic, nonparametric travel-time distributions are determined from continuous tracer time series.

We apply our method to a more than one-year long time series of electric conductivity (EC) collected at River Thur, Switzerland, and adjacent observation wells. This field site has been intensively explored in the past years (Cirpka et al., 2007; Coscia et al., 2011; Schneider et al., 2011 among others). From the time-dependent transfer functions estimated by the method, we infer the recovery rate, the mean travel time, and the spread of the travel-time distribution from the river to the piezometers as function of time and analyze their potential relationships with river stage.