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Seepage velocities derived from thermal records using wavelet analysis

Milan Onderka [a,c], Stefan Banzhaf [b,*], Traugott Scheytt [b,1], Andreas Krein [c]

[a] Institute of Hydrology, Slovak Academy of Sciences, Račianska 75, Bratislava 823 00, Slovakia
[b] Technische Universität Berlin, Department of Applied Geosciences, Hydrogeology Research Group, Ernst-Reuter-Platz 1, 10587 Berlin, Germany
[c] Centre de Recherche Public – Gabriel Lippmann, Department of Environment and Agro-Biotechnologies (EVA), rue du Brill 41, 4422 Belvaux, Luxembourg

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SUMMARY

The main objective of this study was to determine if wavelet analysis can be used as a band-pass filter for non-stationary time series of temperature records. It was demonstrated that this new processing technique is efficient in calculating seepage velocities by using a virtual experiment and field data measured in the Mess Stream, Grand Duchy of Luxembourg, Europe. Temperature time series were measured continuously over a 2-year period in the streambed sediments. The seepage velocity was derived from the one-dimensional analytical solution of Stallman. However, the ubiquitous property of the temperature signal is that it is non-stationary, i.e. the frequency component of the signal becomes a function of time. Instead of applying traditional filtering techniques based on the Fourier transform, we introduce the continuous wavelet transform (CWT) as a band-pass filter to extract the daily component from raw temperature data. For the analysed time series, the estimated seepage velocities based on the amplitude ratio were always negative and within the range of −0.7 to −2.5 m d^{-1}, indicating gaining conditions prevailing in the Mess Stream. The uncertainty associated with the seepage velocities was calculated by the Monte Carlo analysis allowing several physical parameters of the model to vary over pre-defined intervals with normal distribution. Auxiliary hydraulic measurements in the stream and in the riverbank confirm the dominance of gaining stream conditions. However, the seepage rates based on the thermal records were much higher than the calculated Darcy velocities. This study demonstrates the applicability of continuous wavelet transform as an alternative method to Fourier transform for the analysis of non-stationary temperature time series.

1. Introduction

For more than 100 years researchers have used heat as a natural tracer for surface water and groundwater interaction (Slichter, 1905). This cost-effective method was frequently used to detect exchange between these two compartments, and recent advancements have made temperature an accurate tracer to assess hyporheic exchange in streams (Anderson, 2005). The term hyporheic zone was introduced by Orghidan (1959) and describes the area below and adjacent to a stream where groundwater and surface water mix. It has been recognised that this zone is of great importance regarding composition and quality of surface water as well as subsurface fauna (Hancock et al., 2005; Sophocleous, 2002; Triska et al., 1993).

Beginning with the simple description of temperature differences, researchers proposed methods for the calculation of water flow velocities and seepage rates based on temperature measurements. The best-known and hence most popular mathematical solution is the one-dimensional heat transport equation of Stallman (1965). The basis for these calculations of water fluxes is the fluctuation of the temperature signal on different time scales (e.g. diurnal, seasonal). Diurnal oscillations of the temperature signal are widely used to asses vertical flow rates of water fluxes in the streambed (Hatch et al., 2006; Keery et al., 2007; Silliman et al., 1995). The propagation of seasonal signals is studied to document exchange of surface water and groundwater on a larger timescale (Anibas et al., 2011; Molina-Giraldo et al., 2011). One advantage of using temperature as a groundwater tracer is that fluxes can be detected in a temporal and spatial distribution. Temperature measurements in streams using fibre-optic cables were recently introduced to hydrological sciences to detect gaining and losing reaches along the streambed (Briggs et al., 2012; Vogt et al., 2010).

The main issue when calculating seepage fluxes based on fluctuating temperature signals is to extract the daily component from raw temperature time series containing different frequencies (diurnal, seasonal, instrument noise, etc.). Among the various tools in time–frequency analysis, Fourier transform is the most commonly used (Hatch et al., 2006; Keery et al., 2007). The Fourier

* Corresponding author. Tel.: +49 (0)30 314 72921; fax: +49 (0)30 314 25674.
E-mail addresses: onderka@uh.savba.sk (M. Onderka), s.banzhaf@tu-berlin.de (S. Banzhaf), traugott.scheytt@tu-berlin.de (T. Scheytt), krein@lippmann.lu (A. Krein).
[1] Tel.: +49 (0)30 314 72921; fax: +49 (0)30 314 25674.

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transform is useful to analyse the frequency signature over the entire time domain (defined by the length of the time series), but it cannot capture the frequency response with respect to time (Salerno and Tartari, 2009). In addition, it requires that the data under investigation are stationary. However, the ubiquitous property of environmental signals is that they are commonly non-stationary, i.e. the magnitude of the signal at a particular frequency varies with time. Wavelet analysis can be seen as a natural extension to spectral and Fourier analysis. While its application to hydrology is relatively recent, the potential for wavelet analysis is quite broad. Pidlisecky and Knight (2011) used wavelet analysis to derive infiltration velocities in a pond based on resistivity measurements. A study by Henderson et al. (2009) applied wavelet transform to analyse fibre-optic temperature data. Wavelet analysis has also been used for hydrograph recession analysis (Sujono et al., 2004), river flow forecasting (Adamowski, 2008), and to analyse the rainfall–runoff processes on various temporal scales (Liu et al., 2011). Another new approach to analyse non-stationary - temperature time series is the dynamic harmonic regression that was recently introduced by Gordon et al. (2012).

The aim of this study is twofold: (i) to introduce the continuous wavelet transform (CWT), cross-wavelet spectra, and wavelet-phase difference as a tool for the extraction of diurnal temperature signals from time series of streambed temperatures measured at two depths; and (ii) to use the time lag and amplitude ratios calculated from the wavelet analysis to calculate seepage velocities. The method is demonstrated first on a virtual experiment and then using real temperature measurements conducted in an alluvial stream and its riverbank in the Grand Duchy of Luxembourg, Europe. Previous studies carried out at this field site (Banzhaf et al., 2011) are used to cross-check the results.

2. Materials and methods

2.1. Field site and installations

The practical application of wavelet analysis and seepage flux calculations based on temperature time series – which is described in Sections 2.2–2.4 – is demonstrated using field data, which was collected over a period of almost 2 years in a small brook and its riverbank in the Grand Duchy of Luxembourg. The field site is described in detail by Banzhaf et al. (2011) and investigated by other studies like Banzhaf et al. (2012), Meyer et al. (2011) and Pailler et al. (2009). For this study, data from two temperature sensors and surface water and groundwater levels in the riverbank of the Mess Stream (Fig. 1) were used. Surface water levels were measured with a stream gauge (ISCO 4120 flow logger, pressure probe) with a logging interval of 15 min (average values), and groundwater levels were measured with pressure probes (OTT Orphimedes and UIT CTD) with a logging interval of 30 min (individual values). Temperatures were measured with PT 100 sensors (Model 107 temperature probe, Campbell Scientific) with a logging interval of 30 min (individual values) next to the stream gauge with a spacing of 0.13 m. The total error (thermistors interchangeability, bridge resistor and applied linearisation) of the probe is <±0.3 °C over −25 to +50 °C.

The cross section of the field site in Fig. 1 displays three layers in the riverbank: the uppermost layer has a thickness of 0.4 m and consists of clayey fine sand and medium sand, below follows a layer with a thickness of 0.8 m which consists of clay, fine sand, and medium sand. The deepest layer consists of silty clay and fine sand. During the installation of the observation well a maximum thickness of 3.3 m was measured (not displayed in Fig. 1).

Water levels in the stream and the riverbank are dynamic. During the investigated period levels of surface water ranged from 0.13 to 2.44 m and groundwater levels (in a distance of 1.0 m from the bank) from 0.31 to 2.19 m; all values were levelled relative to the stream gauge zero. During high-water peaks, the riverbank is temporarily flooded and losing stream conditions are indicated by the hydraulic measurements (Fig. 1). However, under low-water conditions the Mess is a gaining stream with the piezometric surface located in the middle layer of the riverbank.

The mean discharge of the Mess was 261 L s^{-1} in the year 2008. In summer, multi-peaked flood waves are characteristic in the catchment. Especially thunderstorms produce runoff events characteristic of a steep gradient and a relatively short outlet. Precipitation events of very small intensities and amount are indicated by small discharge peaks, which result predominantly from the runoff from impervious surface areas. The long-lasting, low intensity winter precipitation events cause singular broad discharge maxima, which are primarily composed of laterally flowing soil water and groundwater (Meyer et al., 2011).

The hydraulic conductivity in the vicinity of the riverbank, which was calculated from measurements of well-water-level after pumping tests in the observation well, is 1.3×10^{-6} m s^{-1}. The aquifer is confined (Banzhaf et al., 2011).

2.2. Calculation of seepage rates

As the ambient temperature signal propagates into the aquifer, it is attenuated and shifted in time (Molina-Giraldo et al., 2011; Stallman, 1965). The degree of signal attenuation and its shift are determined by the fluid flow velocity, thermal properties of the sediment (or soil) matrix, and the frequency of the temperature signal (Stallman, 1965). Stream water temperature fluctuates on different time scales, with strong diurnal and seasonal fluctuations (Hoehn and Cirpka, 2006).

Suzuki (1960) was among the first who applied diurnal fluctuations in the form of a sinusoidal function as the upper boundary condition to the heat transport equation. He presented a method for estimating vertical fluxes of water from the amplitude ratios of temperature oscillations measured between two depths in a streambed sediment layer. Stallman (1965) refined the mathematical solution to the one-dimensional advection-convective problem. For the vertical movement of water in saturated sediments (Hatch et al., 2006), the upper boundary conditions are defined as a sinusoidal forcing:

$$T_w(t) = \sum_i A_i \cos\left(\frac{2\pi t}{P_i} - \varphi_i\right) \quad (1)$$

where $T_w(t)$ is water temperature above the streambed (°C) as a function of time t in s; A_i is the amplitude of temperature variation at the water–sediment boundary (°C); P_i is the period of temperature variations ($P = 1/f$; where f stands for frequency and P stands for period) and φ is the phase lag. With the upper boundary defined as a periodic fluctuation of temperature (Eq. (1)), the analytical solution according to Stallman (1965) and Goto et al. (2005) leads to Eq. (2). Assuming the existence of a vertical flow with a constant seepage velocity v_f (m d^{-1}) ($v_f > 0$ for a losing stream and $v_f < 0$ for a gaining stream), the thermal response of a sediment layer with depth z (m) to the upper boundary periodic forcing (Eq. (2)) is defined as:

$$T(t,z) = A\exp\left(\frac{vz}{2k_e} - \frac{z}{2k_e}\sqrt{\frac{\alpha_i + v^2}{2}}\right)\cos\left(\frac{2\pi t}{P_i} - \varphi_i - \frac{z}{2k_e}\sqrt{\frac{\alpha_i - v^2}{2}}\right) \quad (2)$$

where A (°C) is the amplitude of temperature variation at the water–sediment boundary; z is depth (m), v is the velocity of the thermal front (m s^{-1}); $k_e = \lambda/\rho c + \beta|v f|$ (m^2 d^{-1}) is the effective