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Observing temporal patterns of vertical flux through streambed sediments using time-series analysis of temperature records

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SUMMARY

Rates of water exchange between surface water and groundwater (SW–GW) can be highly variable over time due to temporal changes in streambed hydraulic conductivity, storm events, and oscillation of stage due to natural and regulated river flow. There are few effective field methods available to make continuous measurements of SW–GW exchange rates with the temporal resolution required in many field applications. Here, controlled laboratory experiments were used to explore the accuracy of analytical solutions to the one-dimensional heat transport model for capturing temporal variability of flux through porous media from propagation of a periodic temperature signal to depth. Column experiments were used to generate one-dimensional flow of water and heat through saturated sand with a quasi-sinusoidal temperature oscillation at the upstream boundary. Measured flux rates through the column were compared to modeled flux rates derived using the computer model VFLUX and the amplitude ratio between filtered temperature records from two depths in the column. Imposed temporal changes in water flux through the column were designed to replicate observed patterns of flux in the field, derived using the same methodology. Field observations of temporal changes in flux were made over multiple days during a large-scale storm event and diurnally during seasonal baseflow recession. Temporal changes in flux that occur gradually over days, sub-daily, and instantaneously in time can be accurately measured using the one-dimensional heat transport model, although those temporal changes may be slightly smoothed over time. Filtering methods effectively isolate the time-variable amplitude and phase of the periodic temperature signal, effectively eliminating artificial temporal flux patterns otherwise imposed by perturbations of the temperature signal, which result from typical weather patterns during field investigations. Although previous studies have indicated that sub-cycle information from the heat transport model is not reliable, this laboratory experiment shows that the sub-cycle information is real and sub-cycle changes in flux can be observed using heat transport modeling. One-dimensional heat transport modeling provides an easy-to-implement, cost effective, reliable field tool for making continuous observations of SW–GW exchange through time, which may be particularly useful for monitoring exchange rates during storms and other conditions that create temporal change in hydraulic gradient across the streambed interface or change in streambed hydraulic conductivity.

1. Introduction

Rates of water exchange between surface water and groundwater (SW–GW) influence physical hydrological processes (Winter et al., 1998), stream biogeochemistry (Hayashi and Rosenberry, 2002) and the ecology of streams and near-stream environments (Hancock et al., 2005). Rates of SW–GW exchange are highly variable in time (e.g. Briggs et al., 2012; Fritz and Arntzen, 2007; Wroblicky et al., 1998) and space (e.g. Cardenas et al., 2004; Conant, 2004; Fanelli and Lautz, 2008), making such fluxes difficult to quantify, particularly while maintaining the high spatial and/or temporal resolution required in many field applications (Kalbus et al., 2006; Sophocleous, 2002). SW–GW exchange rates can fluctuate seasonally, daily or even sub-daily due to clogging of streambed sediments over time (e.g. Rosenberry and Pitlick, 2009; Kasahara and Hill, 2006), changes in gradient across the streambed interface during storm events (e.g. Argerich et al., 2011), oscillation of stage due to natural regimes and regulated river flow (e.g. Fritz and Arntzen, 2007), and diurnal fluctuations in hydraulic conductivity of bed sediments due to large daily temperature swings (e.g. Constantz et al., 1994). Despite interest in capturing these temporal patterns using automated field methods, few methods are available for long-term observation of SW–GW exchange that maintain the fine temporal resolution of measurement required to observe seasonal, daily and even sub-daily fluctuations in SW–GW exchange rates.

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Recent advances in heat tracing have provided an opportunity to improve the temporal scale and resolution of automated observation of SW–GW exchange (Anderson, 2005; Constantz, 2008; Stonestrom and Constantz, 2004), but validation and testing of these methods is required to understand limits of measurement resolution and temporal resolution. Of particular interest in this study is the application of one-dimensional heat transport modeling of paired records of temperature over time in the subsurface to infer rates of SW–GW exchange (e.g. Hatch et al., 2006; Keery et al., 2007). Over the past several years, several notable advances have been made in the application of one-dimensional heat transport modeling of SW–GW exchange, and examples of field applications are numerous (e.g. Anderson et al., 2010; Fanelli and Lautz, 2008; Lautz et al., 2010). Development of comprehensive computer codes have facilitated the ease with which large numbers of temperature time series records can be interpreted over multiple sites and multiple depths (Gordon et al., 2012; Swanson and Cardenas, 2010). Application of the one-dimensional heat transport model to high-resolution temperature time series data sets collected using distributed temperature sensing (DTS) has made it possible to map spatial changes in vertical flux with depth (Vogt et al., 2010), and automated computational methods have facilitated the more flexible interpretation of such high-resolution DTS temperature records to characterize fine-scale changes in flux with depth across multiple sites (Briggs et al., 2012; Gordon et al., 2012).

To date, limitations of the one-dimensional heat transport model have been primarily explored by using the analytical solution (Hatch et al., 2006; Keery et al., 2007) to derive known flux rates from temperature time series generated by fully-distributed, numerical models of heat and water transport through the subsurface (e.g. Cardenas, 2010; Lautz, 2010; Shanafield et al., 2011; Ferguson and Bense, 2011; Schornberg et al., 2010; Soto-Lopez et al., 2011). Differences between known flux rates through numerical water and heat transport models and those quantified by analysis of the model-generated temperature time series have revealed errors caused by deployment of temperature sensors, including sensor spacing uncertainty, thermal skin effects (i.e. lagged thermal response within a well pipe due to thermal buffering), temperature sensor accuracy, and discretization of the temperature time series (i.e. temporal resolution) (Cardenas, 2010; Shanafield et al., 2011; Soto-Lopez et al., 2011). Such comparisons have also quantified errors associated with thermal parameter uncertainty, such as assumed values of thermal diffusivity (Shanafield et al., 2011), and errors associated with violation of the model assumptions, such as non-vertical flow and non-sinusoidal temperature oscillations at the upstream boundary (Lautz, 2010). Despite these known limitations, the outcome of these modeling studies has generally been that one-dimensional heat transport modeling is an accurate and reliable method of deriving rates of SW–GW exchange.

Although modeling studies have thoroughly explored many of the theoretical limitations of the one-dimensional heat transport model, field-based comparisons between heat transport modeling results and independent measurements of SW–GW exchange are very few in number. In a few field-based studies, flux rate time series derived from heat transport modeling have been compared to paired measurements of hydraulic gradient across the streambed interface, with general agreement in flow direction between the two observations (Lautz et al., 2010; Rau et al., 2010). In these studies, streambed hydraulic conductivity has been derived by normalizing the heat transport modeling flux results to observed hydraulic gradients and, as such, the heat transport modeling results were not field-validated. Two field studies presented in the literature compare SW–GW exchange rates derived from the one-dimensional heat transport model with direct measurements of flux across the streambed interface, showing mean values over time were in general agreement (Briggs et al., 2012; Jensen and Engesgaard, 2011). To date, only one example of a controlled laboratory verification of the heat transport model exists in the literature (Munz et al., 2011). In that study, the primary objective was to evaluate potential for error from various temperature probe designs, but the authors also explored model sensitivity to thermal parameter uncertainty and thermal dispersivity.

Although previous studies have evaluated the effectiveness of the one-dimensional heat transport model under a variety of field and modeling conditions, no studies have addressed to what extent the model results accurately capture temporal changes in flux observed over a variety of time scales. Temporal changes in flux have been reported in a number of field studies where the one-dimensional heat transport model has been used (Briggs et al., 2012; Hatch et al., 2006; Jensen and Engesgaard, 2011; Keery et al., 2007; Vogt et al., 2010), and in some cases, mechanistic explanations for these temporal patterns are given (Briggs et al., 2012; Keery et al., 2007). But, in most studies those temporal patterns are largely ignored or regarded as an artifact of model uncertainty (Vogt et al., 2010) and authors have cautioned that temporal changes observed over short time scales are unreliable (Keery et al., 2007). The observed temporal patterns are questionable because such temporal changes in flux represent a violation of the model assumptions. The analytical solution to the one-dimensional heat transport model assumes steady-state conditions with respect to the magnitude of water flux (Stallman, 1965; Keery et al., 2007). In practicality, the model is applied under transient flux conditions in the field and even termed a transient model (Jensen and Engesgaard, 2011; Rau et al., 2010), but the solution for any single point in time is based on an assumption that flux is unchanging; computations are done for a series of independent steady-state models that are strung together to create a time-series of apparent flux. Conventional wisdom has been that the shortest reliable time step of such sequential steady-state modeling is one day (or one temperature oscillation cycle) (Keery et al., 2007), but this assumption has not been tested, nor is it based on any physical principle. Rather, the convention is driven by the practical methods typically used to derive the amplitude and phase of temperature signals, which make use of reference points on the temperature time series, such as the daily maxima or minima, that can only be isolated daily (Hatch et al., 2006; Lautz, 2010; Munz et al., 2011; Rau et al., 2010). With new signal processing tools, such as Dynamic Harmonic Regression (Taylor et al., 2007; Young et al., 1999), the changing amplitude and phase of temperature time series can be derived sub-daily, but the question remains as to what time interval the one-dimensional heat transport model can be applied accurately.

The objective of this study was to explore the accuracy of the one-dimensional heat transport model in a controlled, one-dimensional flow system with an imposed quasi-sinusoidal temperature oscillation at the upstream end of the flow system. In particular, this study was used to explore the effectiveness of the one-dimensional heat transport model for capturing temporal variability of flux, including instantaneous changes in flux, gradual changes in flux over time, and oscillations of flux over very short time periods. Experiments were also used to explore the degree to which perturbations of the temperature oscillation signal, such as those that would be introduced by changing weather in field studies, introduce apparent temporal changes in flux that do not reflect actual changes over time.

2. Methods

2.1. Experimental set-up

Sand column experiments were used to generate one-dimensional flow of water and heat through a porous medium with