The need to consider temporal variability when modelling exchange at the sediment–water interface

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Abstract Most conceptual or numerical models of flows and processes at the sediment–water interface assume steady-state conditions and do not consider temporal variability. The steady-state assumption is required because temporal variability, if quantified at all, is usually determined on a seasonal or inter-annual scale. In order to design models that can incorporate finer-scale temporal resolution we first need to measure variability at a finer scale. Automated seepage meters that can measure flow across the sediment–water interface with temporal resolution of seconds to minutes were used in a variety of settings to characterize seepage response to rainfall, wind, and evapotranspiration. Results indicate that instantaneous seepage fluxes can be much larger than values commonly reported in the literature, although seepage does not always respond to hydrological processes. Additional study is needed to understand the reasons for the wide range and types of responses to these hydrologic and atmospheric events.

Key words groundwater–surface–water exchange; seepage; temporal variability

INTRODUCTION

Research at the hyporheic ecotone involves an incredibly diverse range of disciplines. Scientists commonly interact at this interface to study processes relating to hydraulics, sediment transport, hydrology, geochemistry, and a variety of floral and faunal assemblages. Scaling understanding of these processes requires the coupling of models, each of which simulates only a portion of the range of complexity that exists at this setting. For example, improvements in understanding of the effects of surface-water hydraulics on exchange between groundwater and surface water have resulted from linking hydrodynamic models with groundwater flow models (Cardenas *et al.*, 2008; Cardenas, 2009). In spite of extensive and numerous investigations, spatial and temporal variability of groundwater–surface water interaction continues to confound understanding of processes and linkages. Because we are commonly more concerned with characterizing spatial variability, we usually make the assumption that temporal variability is much smaller or far less important, and assume that it is nil. However, physical conditions and hydrologic inputs change constantly and geochemical and biological processes respond to those changes with various lag times. This extensive complexity is often ignored, either with synoptic studies or presentation of time-averaged data. Quantifying and understanding temporal variability of physical conditions is the first step in linking these changes to geochemical and biological responses. Ultimately, in order to scale complexities of overlapping and lagging temporal variability, models will need to incorporate temporal variability rather than simply considering this setting at steady state.

Part of the problem regarding temporal variability is that we have thus far measured it over a limited range. We do a fair job of measuring variability on an inter-annual or seasonal scale, but quantifying temporal variability on scales of days or shorter is far less common. Quantifying variability of flow at the sediment–water interface, herein referred to as seepage, is a good example. Many of the methods at our disposal are indirect; for example, requiring measurement of hydraulic gradient and hydraulic conductivity in order to calculate seepage. Another common procedure is to use a natural or injected tracer to quantify flow along a groundwater flow path and infer the resulting exchange with surface water. Measurement of temporal or spatial variability in temperature at or beneath the streambed also is widely used to infer groundwater–surface water exchange (e.g. Keery *et al.*, 2007; Schmidt *et al.*, 2007; Schornberg *et al.*, 2010).

The seepage meter is one of the few instruments that provide direct measurement of exchange at the sediment–water interface (Fig. 1). This instrument is surprisingly simple in concept and implementation. An open-ended cylinder, typically the cut-off end of an industrial storage drum, is inserted into the sediment underlying a water body of interest. Seepage across the sediment–water interface isolated by the seepage cylinder is quantified by measuring the change in volume in a flexible bag that is attached to the cylinder. Although the basic design and implementation has changed very little since its inception in the mid-1970s (Lee, 1977), the instrument had been modified for use in a variety of settings, including streams and rivers (Rosenberry, 2008).

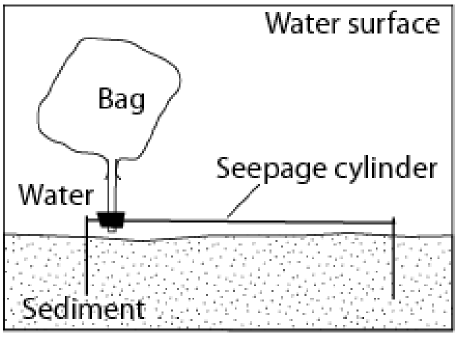

Fig. 1 "Lee (1977)-type" half-barrel seepage meter.

Fig. 2 Locations of study sites.

A seepage-meter measurement integrates temporal variability over the duration that the seepage bag is attached to the cylinder. Bag-attachment time depends primarily on the seepage rate; times commonly range from minutes to a day or more. Because the sensor is prone to operator error, investigators usually make multiple measurements and statistically summarize the results, extending the integration time to hours to days. Unless a study design dictates repeat measurements over the course of weeks or more, temporal variability is largely ignored for most studies that incorporate seepage meters.

Manually operated meters have indicated temporal variability on the order of weeks to months in several studies. Seepage can vary in response to snowmelt and rainfall and seepage direction can reverse seasonally (Sebestyen & Schneider, 2001; Schneider *et al.*, 2005). On a much shorter time scale, seepage was shown to vary by the order of minutes to hours in a river where bed topography was evolving following a high-flow event (Rosenberry & Pitlick, 2009b).

Quantification of temporal variability at finer resolution is much better accomplished by connecting a flowmeter rather than a seepage bag to the seepage cylinder. Automated seepage meters have been used since the early 1990s when heat-pulse sensors, originally designed as sap-flow sensors for use in trees, were adopted for use with a seepage cylinder (Taniguchi & Fukuo, 1993). Several other flowmeter types have also since been developed, and most of these automated sensors have been used to quantify seepage response to tidal fluctuations in marine settings. Here we demonstrate the use of an electromagnetic seepage meter (Rosenberry & Morin, 2004) to quantify short-term temporal variability in a variety of freshwater settings (Fig. 2). We then discuss potential implications associated with this shorter-term temporal variability and suggest that conceptual and numerical models be constructed that can address temporal variability on this time scale.

SEEPAGE RESPONSE TO RAINFALL

Rainfall changes the hydraulic gradient in near-shore sediments when surface water stage responds to a different extent, or responds with a phase shift, compared to the response of the adjacent groundwater level. However, the extent and duration of the seepage response to rainfall are rarely documented. Measurements at several locations show a range of responses to small to moderate, locally measured rain events.

Seepage was fast at Mirror Lake, New Hampshire, USA, averaging –139 cm/d during the early morning hours of 18 July 2002 and prior to the onset of a thunderstorm that produced 16 mm of rain over a 1-hour period (Fig. 3(a)). Negative values indicate that seepage was from surface water to groundwater. Strong winds at the onset of the thunderstorm generated a seiche that lowered lake stage at the measurement location and reduced the hydraulic gradient between the lake and the hydraulic head in the groundwater beneath the lakebed. This resulted in a reduction in seepage of more than 20 cm/d that lasted only a few minutes until the lake seiche subsided. Lake stage rose about 0.7 cm during the next 10 minutes in response to 7.5 mm of rainfall, resulting in an increase in seepage of about 5 cm/d relative to pre-storm rates. Seepage gradually declined to pre-storm levels over the next 30 minutes as lake stage slowly rose, indicating that instantaneous lake-stage changes were being transmitted to changes in hydraulic head in the shallow lake sediments beneath the seepage meter. Resurgence in rainfall (6 mm of rain in about 5 minutes) caused lake stage to rise another 0.55 cm, causing seepage to increase by 7 cm/d. As the storm ended, seepage gradually decreased to a new, lower threshold of –131 cm/d, 8 cm/d slower than prior to the onset of the thunderstorm. Seepage rate in this sandy, highly permeable setting was strongly dependent on lake stage and hydraulic gradient in the sediment directly beneath the seepage meter.

Seepage was measured every 5 seconds at Ashumet Pond, Massachusetts, USA, and one-minute averages of seepage and lake stage were recorded over a 2-day period (Fig. 3(b)). Seepage was slower and in the opposite direction than at Mirror Lake and gradually decreased over the 2-day study period from about 53 to about 25 cm/d. Lake stage decreased by about 2 cm during the study period. Greater noise from both sensors indicates that windy periods existed each afternoon, generally beginning just before noon. About 4 mm of rain fell between 17:30 h and 21:30 h on 14 July. Lake stage rose about 1 mm at the onset of rainfall and then declined at a smaller rate during the rest of the rainfall event. Seepage response was delayed; seepage began to increase 2.5 hours after rainfall began and continued to increase until about 1.5 hours after rainfall stopped. Seepage increased from 48 to 55 cm/d, after which seepage decline resumed at a slightly smaller rate than prior to rainfall. This example indicates that rainfall was not sufficient to substantially change the lake stage but rain that fell on the near-shore margins evidently infiltrated rapidly to the water table and altered the local-scale hydraulic gradients near the shoreline and where the seepage meter was situated.

Rainfall caused very little response in seepage at Shingobee Lake, Minnesota, USA, relative to other variability. No change in seepage during or following 13.5 mm of rainfall on 28 July is evident (Fig. 3(c)). An additional 8.6 mm of rain that fell during the afternoon of 30 July may have resulted in a brief increase in seepage. Upward seepage increased from 39.7 to 41.0 cm/d during the rain event, but the magnitude of that increase and subsequent decrease is well within the range in seepage that occurred during the rest of the measurement period.

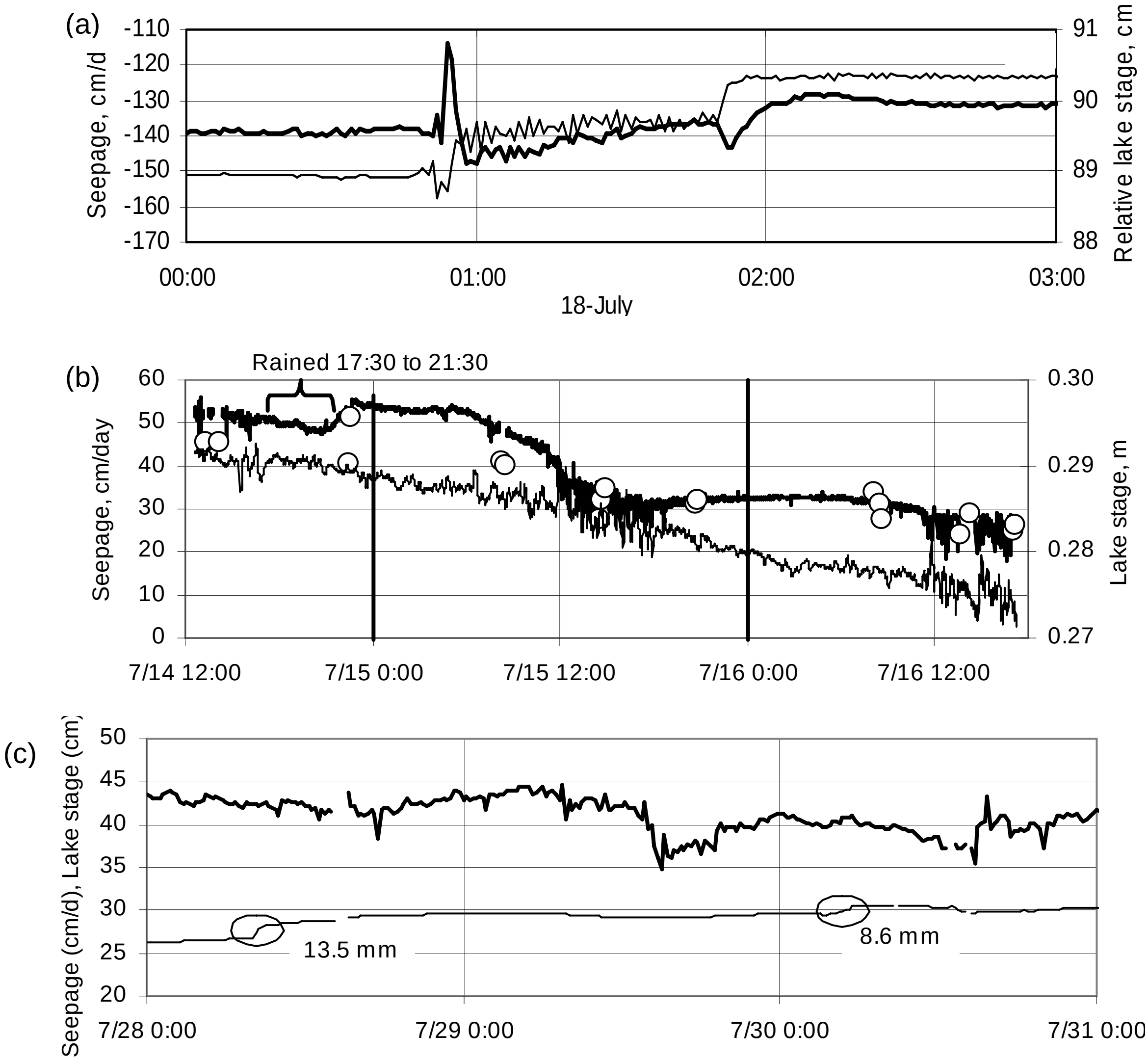

Fig. 3 Seepage (thick line) and relative lake stage (thin line) at 1-minute resolution at (a) Mirror Lake, NH, (b) Ashumet Pond, Massachusetts, and (c) Shingobee Lake, Minnesota. Circles in (b) indicate values from manual seepage measurements. Ovals and adjacent values in (c) indicate periods and amounts of rain.

SEEPAGE RESPONSE TO WAVES

An automated seepage meter was placed 1.5 m from the shoreline of Ashumet Pond to quantify discharge of groundwater contaminated with phosphorus (McCobb *et al.*, 2003; Rosenberry & Morin, 2004). Because discharge was focused near shore, the 1.5-m-diameter seepage cylinder was installed not fully submerged, but with a free-water surface inside of the seepage cylinder. The flowmeter was attached to the seepage cylinder below the water level and was scanned every second with averages calculated every 15 seconds. Seepage rates were exceptionally large and ranged from ±1500 cm/d (Fig. 4). Waves were small to moderate in response to a windspeed of 2–3 m/s and some of the noise and exceptionally large seepage measured by the flowmeter was the result of water flowing into and out of the seepage cylinder as wave pulses were transmitted to and from the water inside of the cylinder. The mean value of 150 seepage measurements recorded over a nearly 40-minute period was 22.9 cm/d. This compared very well with the average of 9 measurements made at 3 manually operated seepage meters located adjacent to the automated seepage meter, which was 27.9 cm/d.

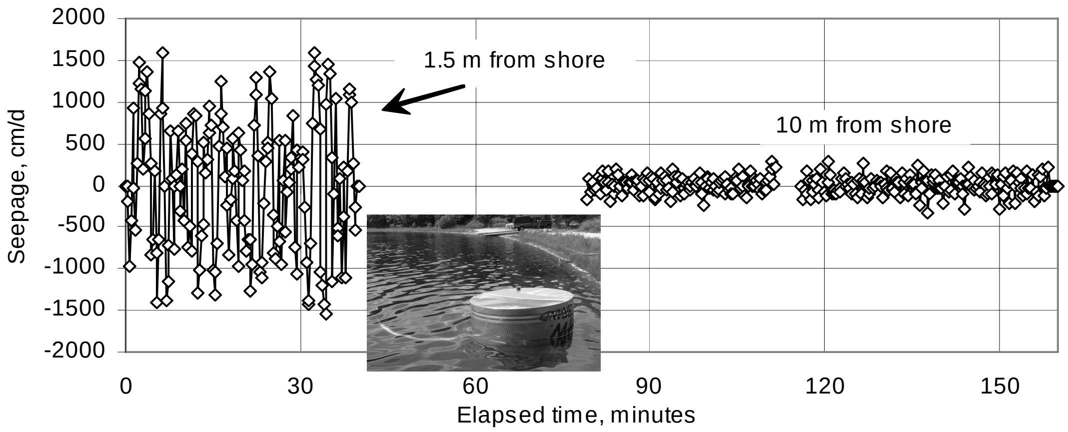

Fig. 4 Seepage every 15 seconds measured at Ashumet Pond, Massachusetts, with photo inset showing seepage cylinder 1.5 m from shore attached to an electromagnetic flowmeter.

The meter was subsequently moved to 10 m from shore, where it was fully submerged and operated in a normal manner. The average of 300 measurements that ranged from +293 to –342 cm/d was 4.3 cm/d. The average of 2 measurements from an adjacent manually operated seepage meter was 3.4 cm/d.

These data indicate that water routinely flows across the sediment–water interface in response to passing waves of unremarkable size. Some of the instantaneous seepage rates are very large and resulting flow within the porous media is likely turbulent much of the time. Because force associated with turbulent flow is proportional to the square of velocity, some wave-generated seepage is likely able to transport sediment. This has been documented for upward seepage in particular (Rosenberry & Pitlick, 2009a).

SEEPAGE RESPONSE TO EVAPOTRANSPIRATION

Seepage recorded at 1-minute resolution over a 10-day period at Shingobee Lake showed substantial diurnal variability (Fig. 5). Seepage varied over a range of 3–5 cm/d during most days. Maximum and minimum seepage values generally occurred between 04:15 h and 06:30 h and between 15:00 h and 19:00 h, respectively. This response is similar to water-level changes that commonly occur in shallow monitoring wells as a result of evapotranspiration. Therefore, at this site it appears that seepage responds much more substantially to evapotranspiration (Fig. 5) than to rainfall (Fig. 3(c)).

SEEPAGE RESPONSE TO BIOLOGY

Seepage measured near the shore of a small cove extending from the main channel of the Russian River, California, USA, averaged 0.3 cm/d over a 4-day period during late June (Fig. 6). Seepage did not respond to changes in river stage ranging over more than 15 cm. Seepage was stable at times but, in general, was noisy with short-term deviations as large as 8 cm/d. These deviations were the result of minnows that occasionally would swim into and remain inside of the 13-mm-diameter orifice through which seepage was measured. The presence of minnows would corrupt or alter the seepage rate.

This process was artificial in this case, due to the presence of a cylinder through which organisms could swim and seek refuge, but it also exists at the sediment–water interface and is called bioirrigation (Cable *et al.*, 2006; Meysman *et al.*, 2006; Lewandowski *et al.*, 2007). Burrowing worms, shrimp, and other filtering animals can generate seepage rates as large as 2.2 cm/d (Cable *et al.*, 2006), easily within the range of seepage rates commonly measured in marine and freshwater settings.

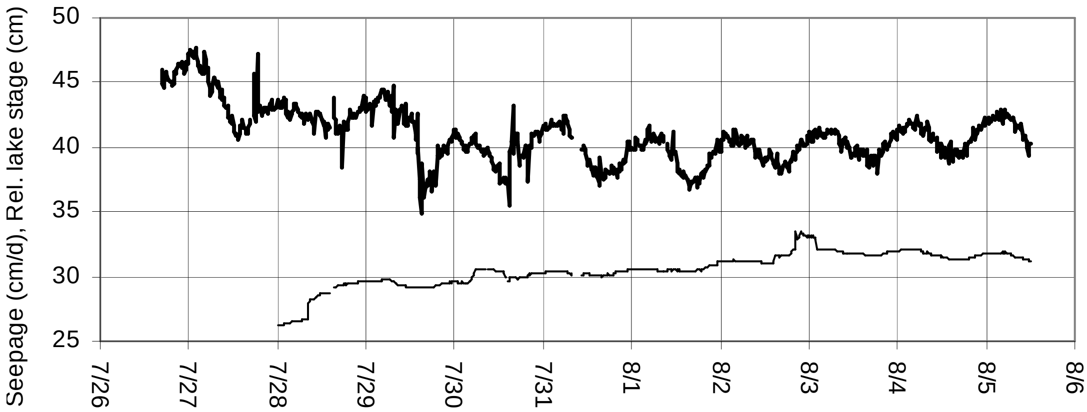

Fig. 5 Seepage (thick line) and relative lake stage (thin line) at Shingobee Lake, Minnesota.

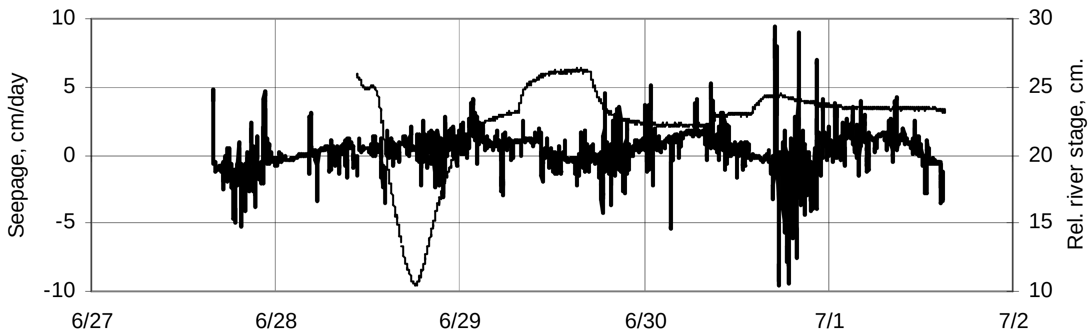

Fig. 6 Seepage (thick line) and relative river stage (thin line) at Russian River, California.

RELEVANCE OF TEMPORAL VARIABILITY

Much of the temporal variability demonstrated here will be relevant to physical, biological, and geochemical processes at the sediment–water interface. Water and chemical residence time, for example, is greatly dependent on seepage rate. Pore-water chemistry associated with mean discharge of groundwater to surface water likely would have greatly different characteristics compared to pore water in a setting where frequent reversals in seepage direction at the sediment–water interface occurred but the time-averaged value still indicated groundwater discharge. Variations in seepage rate and direction on time scales of seconds to minutes to hours first need to be measured, characterized, and understood before models can be generated or modified to incorporate this new level of complexity that thus far has largely gone unstudied.

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