Earth-Science Reviews 204 (2020) 103167

Contents lists available at ScienceDirect

Earth-Science Reviews

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

History and evolution of seepage meters for quantifying flow between groundwater and surface water: Part 1 – Freshwater settings

Donald O. Rosenberry[a,*], Carlos Duque[b], David R. Lee[c,d]

[a] U.S. Geological Survey, Lakewood, CO, USA
[b] WATEC, Department of Geoscience, Aarhus University, Aarhus, Denmark
[c] Canadian Nuclear Laboratories, Deep River, ON, Canada
[d] Department of Earth and Environmental Sciences, University of Waterloo, ON, Canada

ARTICLE INFO

Keywords:
Seepage
Seepage meter
Groundwater-surface-water exchange
Sediment-water interface

ABSTRACT

More than 75 years after its introduction, the seepage meter remains the only device for directly quantifying exchange across the sediment-water interface between groundwater and surface water. This device, first presented in the literature in the 1940s, has been in a state of near-constant improvement and design change, necessitating a review of the history and evolution of the device and a description of current best-measurement practices. Part 1 of this two-part review documents the evolution of seepage meters deployed in freshwater settings, including a listing of suggestions for best-measurement and deployment practices. Part 2 covers the same scope for seepage meters deployed in marine settings. Traditional seepage meters isolate a portion of the sediment bed; seepage commonly is determined by routing the volume of flow across that isolated interface to or from a submerged measurement bag over a known time interval. The time-integrated volume is then divided by the bed area covered by the meter to obtain a seepage flux expressed in distance per time. Both the instrument and the measurement are deceptively simple, leading some early users to question the viability of the measurement. Numerous sources of error have been identified and addressed over the decades, resulting in large improvements in measurement consistency and accuracy. Duration of each measurement depends on the seepage rate and can vary from minutes to days, leading to the erroneous and yet common assumption that seepage is relatively stable over time. Designs that replace the measurement bag with a flowmeter eliminate bag-related errors and provide much finer temporal resolution. Resulting data indicate seepage is highly variable in many settings and responds to numerous sub-daily processes, including evapotranspiration, rainfall, seiches and waves. Combining direct measurements from seepage meters with other measurements, such as vertical hydraulic gradients and vertical temperature profiles, provides far better understanding of the processes that control exchange between groundwater and surface water.

1. Introduction

The need to quantify exchange between groundwater and surface water has grown remarkably in response to increased exploitation of both groundwater and surface-water resources. Fortunately, so has the selection of tools and methods for quantifying this exchange (e.g., Rosenberry and LaBaugh, 2008). However, although it has been more than 75 years since a seepage meter was first presented in the literature (Israelson and Reeve, 1944), and more than 45 years since the “half-barrel” seepage meter was introduced (Lee, 1972; Lee, 1977), seepage meters remain the only device that provides a direct measure of the exchange of water across the sediment-water interface. The basic design and principles of operation are virtually unchanged since its inception, but numerous modifications and improvements in understanding of flow across the sediment-water interface have made the instrument more efficient, reliable, and suitable for installation and operation in a broader range of locations and applications. Here, we summarize the evolution in design and implementation, and the resulting improvements in understanding of measurements and data quality stemming from this device, in two parts; the first is limited to freshwater settings and the second is focused on the rapidly growing study of what is commonly referred to as submarine groundwater discharge. We also list best-measurement practices based on authors' experiences and the latest recommendations from the literature.

---

* Corresponding author.
E-mail address: rosenber@usgs.gov (D.O. Rosenberry).

https://doi.org/10.1016/j.earscirev.2020.103167
Received 18 October 2019; Received in revised form 30 January 2020; Accepted 13 March 2020

1.1. Basic operation

A seepage meter consists of two basic components; an open-ended cylinder that isolates a known area of the sediment bed, and a device or system that quantifies the volume of water that flows across the sediment-water interface bounded by the seepage cylinder. For the vast majority of seepage-meter designs, any water that crosses the sediment-water interface contained within the seepage cylinder is routed to or from a flexible seepage-collection bag that expands or contracts in response to net upward or downward flow, respectively. Net upward flow will increase the volume of water contained in the seepage-collection bag and net downward flow will reduce water volume inside the bag. The change in volume integrated over the duration of time that the bag is connected to the seepage cylinder is the volumetric seepage rate expressed as volume per time. That value, when divided by the bed area covered by the seepage cylinder, is seepage flux in volume per area per time, commonly presented as distance per time. This is not the same as, but is sometimes confused with, average linear velocity in porous-media flow, which is related to sediment porosity and also expressed in distance per time.

Although very simple, both conceptually and functionally, this device has proven suitable for quantifying seepage in a wide range of settings, including both shallow and deep lakes, wetlands, streams, rivers, estuaries, and coastal and deep-water marine settings. As described in detail below, substantial care is needed to reduce and eliminate sources of measurement error. The seepage bag, in particular, has been the source of numerous errors and operational complexities that have been discovered and addressed over several decades. Some investigators have replaced the seepage-collection bag with different types of flowmeters or with dye-dilution systems, all of which are discussed in the History section.

1.2. Summary of the literature

Prior to about 1995, almost all studies that made use of seepage meters in freshwater settings were conducted in lakes, with a few situated in wetlands. The emphasis has shifted considerably toward fluvial systems since then because of the rise in interest in what became known as hyporheic processes (e.g., Findlay, 1995; Harvey and Bencala, 1993; Stanford and Ward, 1993), and the associated need to quantify exchanges between groundwater, hyporheic water, and surface water. Of the 117 papers surveyed for this synthesis, 54% were conducted in lakes or wetlands, 39% in fluvial settings, and 8% in laboratory settings (Fig. 1A). If this same analysis is made based on literature published prior to 1995, the percentages are 84, 8, and 8, respectively.

Seepage meters were first introduced in North America and were used primarily in canals and lakes. Therefore, the seepage-meter literature also has been heavily concentrated in North America, with 83% of studies conducted in Canada and USA followed by 9% conducted in Europe (Fig. 1B). Usage in Europe is increasing more recently, however, with 19% of the studies since 2005 conducted in Europe.

Most seepage-meter studies (69% of those surveyed for this review) combine the use of seepage meters with other methods for quantifying exchange between groundwater and surface water. The Darcy approach, which determines seepage from locally measured hydraulic gradient and hydraulic conductivity, was combined with seepage meters in 45% of the studies. Eighteen percent used seepage meters and either a water-budget or water- and chemical-budget approach (Fig. 1C). The use of alternate methods also has increased over time. For example, since 2005, 54% of all seepage-meter studies conducted in fresh water also used the Darcy approach.

A substantial majority (63%) of seepage-meter studies conducted in freshwater settings are published in hydrology oriented literature, with only 18% published in limnology journals (Fig. 1D). This substantial bias toward the hydrology focused literature likely reflects the need to quantify groundwater-surface-water exchange from a watershed-scale perspective as well as a surface-water-budget perspective. For seepage-meter studies conducted in marine settings, nearly half are published in oceanographic literature (Duque et al., this issue, Fig. 1D).

2. History

Perhaps the first description of a mechanism that routed water from the sediment bed to a collection device was from a small island in the Mediterranean Sea off the coast of what is now Syria. Francis Kohout (1966) quoted Strabo, a Roman geographer who lived at the time of Christ, who described a method to collect drinking water during times of war. The device consisted of an inverted lead funnel placed on the bed and connected to a hose made from leather to convey freshwater from a submerged spring to boatmen who supplied drinking water to the nearby city. The first devices designed to quantify seepage flow had a surprisingly similar design.

2.1. Leaky canals – 1940-1960

The first mention of seepage meters in the scientific literature was associated with measurement of conveyance loss during transmission of water through canals, both lined and unlined (e.g., Israelson and Reeve, 1944; Rasmussen and Lauritzen, 1953; Robinson and Rohwer, 1952; Warnick, 1951). Most early designs consisted of metal bell housings connected via piping or tubing to a manometer that related hydraulic head inside of the seepage cylinder with canal stage. Using principles similar to that of a constant-head or falling-head permeameter, plots of head or change in head relative to equilibrium head and time were made, from which seepage was determined (e.g., Bouwer, 1962; Bouwer and Rice, 1963). Some of these early designs incorporated a submerged seepage bag filled with a known volume or weight of water (Fig. 2). A study conducted over multiple years during the early 1950s compared the head-decline design, termed the SCS meter, with a seepage-bag design, termed the USBR meter (SCS and USBR were abbreviations for Soil Conservation Service and U.S. Bureau of Reclamation). The authors recommended the seepage-bag design due to its simplicity of operation (Robison and Rowher, 1959).

2.2. Further study and extension to other settings – 1960s

Several improvements to the understanding of processes that control seepage occurred during the 1960s. Many of the seepage devices for use in canals extended from the canal bed to above the water surface, potentially creating a large disturbance to flow in the canal as well as altering the seepage being measured. Tests conducted with electric-analog models indicated that alterations of flow adjacent to the meter had no substantial net effect on measured seepage unless seepage was very small (Bouwer et al., 1962).

Advancements related to measurements of leakage from canals were extended to reservoirs, where water losses due to leakage needed to be determined. A seepage meter designed for this purpose may have been the first to apply the principle of timed measurement of concentration of an applied tracer to determine seepage rates (Zuber, 1970).

Thus far, seepage meters were designed to measure downward flow from surface water to ground water. However, the need for quantifying localized exchange between groundwater and surface water also pertained to wetlands and small ponds, where it was found that gradients and associated seepage directions could frequently reverse in response to alternating recharge and evapotranspiration (Williams, 1968). Piezometer nests installed in and near a small wetland in Saskatchewan also demonstrated potentials for flow both to and from the wetland, depending on the season (Meyboom, 1966). Seepage meters were needed that could measure flow across the sediment-water interface in both directions.

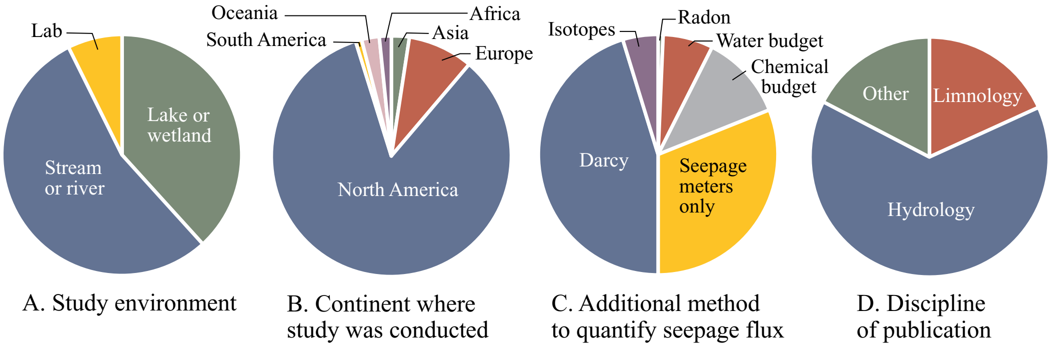

Fig. 1. (A) Setting in which seepage-meter study was conducted; (B) Continent on which study was conducted; (C) Method used to quantify seepage in addition to seepage meters (if no other method was used, the category is termed "Seepage meters only"); (D) Type of publication in which seepage-meter results were presented. (Data summarized from: Ala-aho et al., 2013; Alexander and Caissie, 2003; Anderson et al., 2014; Attanayake and Waller, 1988; Belanger and Kirkner, 1994; Belanger and Mikutel, 1985; Belanger et al., 1985; Belanger and Montgomery, 1992; Blanchfield and Ridgway, 1996; Bouwer, 1962; Bouwer and Rice, 1963; Boyle, 1994; Briggs et al., 2014; Briggs et al., 2013; Brock et al., 1982; Brodie et al., 2009; Bruckner et al., 1989; Brusch and Nilsson, 1993; Cey et al., 1998; Cherkauer and McBride, 1988; Cherkauer and McKereghan, 1991; Cherkauer and Zager, 1989; Choi and Harvey, 2000; Connor and Belanger, 1981; Cullmann et al., 2006; Dimova et al., 2013; Downing and Peterka, 1978; Duff et al., 1999; Dumouchelle, 2001; Essaid et al., 2006; Essaid et al., 2008; Fellows and Brezonik, 1980; Frape and Patterson, 1981; Frederiksen et al., 2018; Fritz et al., 2009; Fryar et al., 2000; Gardner, 2005; Gilmore et al., 2016a; Hagerthey and Kerfoot, 1998; Harvey et al., 2004; Hatch et al., 2010; Hotchkiss et al., 2001; Isiorho et al., 1996; Isiorho and Matisoff, 1990; Isiorho and Meyer, 1999; Jensen and Engesgaard, 2011; John and Lock, 1977; Jones et al., 2016; Kaleris, 1998; Keery et al., 2007; Kennedy et al., 2010; Kidmose et al., 2011; Kidmose et al., 2013; Kikuchi et al., 2012; Knights et al., 2017; Krabbenhoft and Anderson, 1986; Krabbenhoft et al., 1990; Krupa et al., 1998; LaBaugh and Winter, 1984; Landon et al., 2001; Langhoff et al., 2001; Langhoff et al., 2006; Lee, 1977; Lee and Cherry, 1978; Lee et al., 1980; Lesack, 1995; Libelo and MacIntyre, 1994; Lien, 2006; Lillie and Barko, 1990; Linderfelt and Turner, 2001; Lodge et al., 1989; Loeb and Hackley, 1988; Lowry et al., 2007; McCobb et al., 2009; Meigs and Bahr, 1995; Menheer, 2004; Metge et al., 2007; Mitchell et al., 1988; Mortimer et al., 1999; Murdoch and Kelly, 2003; Naranjo et al., 2019; Oxtobee and Novakowski, 2002; Ridgway and Blanchfield, 1998; Robison and Rowher, 1959; Rosenberry, 2000; Rosenberry, 2005; Rosenberry, 2008; Rosenberry et al., 2016a; Rosenberry et al., 2016b; Rosenberry et al., 2012; Rosenberry and Morin, 2004; Rosenberry and Pitlick, 2009a; Rosenberry and Pitlick, 2009b; Rosenberry et al., 2013; Rosenberry et al., 2000; Rosenberry et al., 2010; Schafran and Driscoll, 1993; Schneider et al., 2005; Schuster et al., 2003; Sebestyen and Schneider, 2001; Sebestyen and Schneider, 2004; Sebok et al., 2013; Shaw and Prepas, 1989; Shaw and Prepas, 1990b; Shaw et al., 1990; Simpkins, 2006; Solder et al., 2016; Taniguchi and Fukuo, 1993; Taniguchi and Fukuo, 1996; Toran et al., 2010; Toran et al., 2015; Ulrich et al., 2015; Welch et al., 1989; Woessner and Sullivan, 1984; Wojnar et al., 2013; Wroblicky et al., 1998; Zamora, 2007.)

2.3. *"Half-barrel" seepage meter – 1970s*

Limnologists and aquatic ecologists needed to quantify exchange across the sediment-water interface in lakes, in part because groundwater discharge to some lakes could be a substantially larger component of a lake water budget than precipitation (e.g., Mann and McBride, 1972; Schumann, 1973). Analytical modeling (McBride and Pfannkuch, 1975) and physical measurements (Lee, 1972) indicated that exchange likely was greatest in the shallow near-shore margins of lakes, requiring an instrument that could be deployed in shallow water. David Lee, a graduate student at the University of North Dakota, was cited in McBride and Pfannkuch (1975) as having made hundreds of measurements with a seepage meter capable of measuring seepage in water as shallow as about 10 cm deep (Lee, 1972).

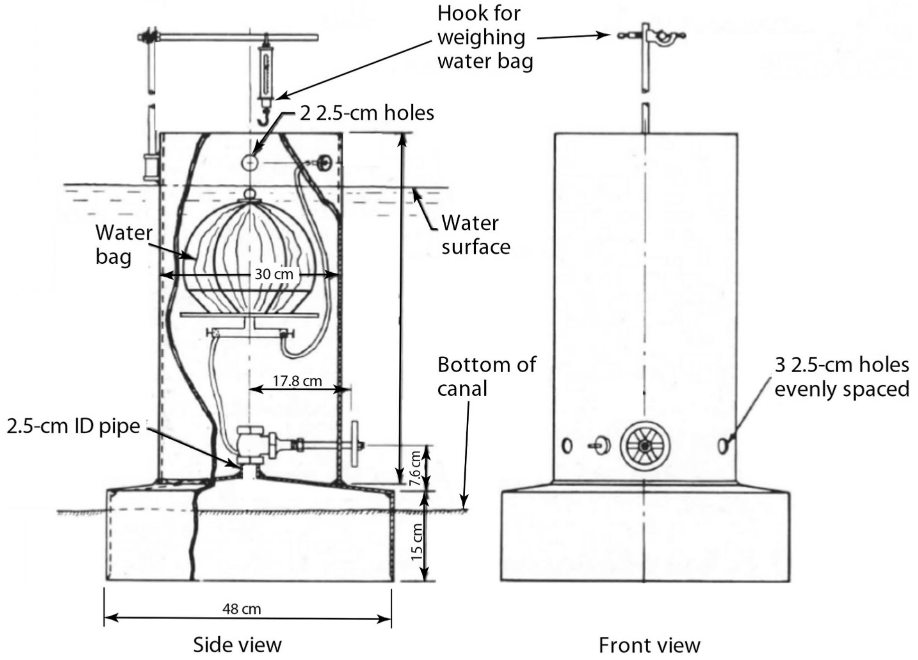

Fig. 2. Seepage meter designed for use in irrigation canals that makes use of a seepage bag measured by weight at the beginning and end of each measurement period (modified from Israelson and Reeve, 1944).

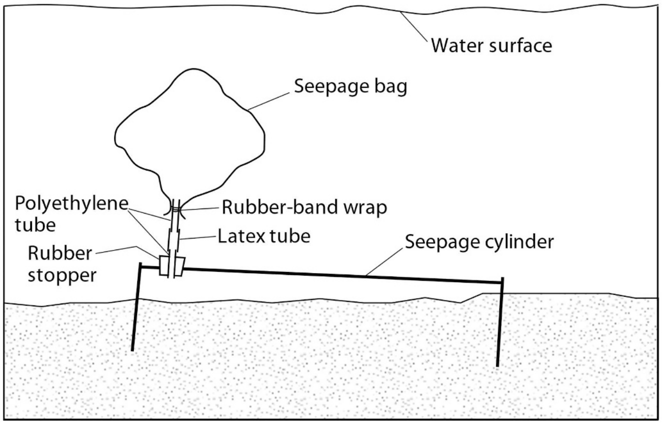

Fig. 3. Lee-type seepage meter (modified from Lee, 1977).

Lee's seepage meter (Fig. 3) consisted of the cut-off end of a standard 208-L (55-gal) steel storage drum that, when installed, would cover 0.258 m^2 of a sediment bed. Either end could be used, allowing two seepage cylinders to be created from one drum. Although no mention was made of the appropriate length of the cut-off end of the drum, a subsequent paper (Lee and Cherry, 1978) indicated a distance of 15 cm. Therefore, the commonly used "half barrel" descriptor is misleading because only about 30 cm of the 88-cm length of a 208-L drum is used.

A 4-L heat-sealed plastic bag was attached to a 6.4-mm-ID polyethylene tube with a rubber band. An identical short piece of polyethylene tube was pushed through a rubber stopper. Both tubes were connected with a slightly larger-diameter piece of flexible latex tubing. Lee (1972) started his measurements with the bag empty so he could analyze the collected water for concentrations of nutrients or other dissolved chemicals. He subsequently indicated that measurements of downward seepage could be made if the plastic bag was first filled with a known amount of water prior to bag attachment (Lee, 1977). Whether flow was upward or downward, seepage flux (q) was determined by:

$$q = (\Delta V/\Delta t)/A \tag{1}$$

where ΔV is the change in volume of water contained in the seepage bag, Δt is the duration that the bag was attached to the seepage cylinder, and A is the area of the bed covered by the seepage cylinder. Lee and most subsequent practitioners considered upward seepage as positive and downward seepage as negative. Seepage flux velocities ranging from 0.01 to nearly 2.6 μm/s (0.09–22.5 cm/d) were measured at several locations in both fresh and saline settings (Table in Lee, 1977).

The first modification of this basic design (Fig. 4, Lee and Cherry, 1978) allowed measurements in water less than 10 cm deep while also allowing any gas released from the sediment to be vented to the atmosphere.

The Lee and Cherry paper also was the first to present measurements of seepage in shallow streams provided surface-water velocities were less than 0.2 m/s. Practical application of this device was demonstrated in a comprehensive study of movement of a salt tracer applied from a line of shallow injection wells located 1 m from the shoreline of a sandy lakebed (Lee et al., 1980). This was the first mention of the efficacy of combining direct measurements of seepage, and adjacent measurement of vertical hydraulic gradient using a shallow piezometer, to calculate in-situ vertical hydraulic conductivity in a natural setting.

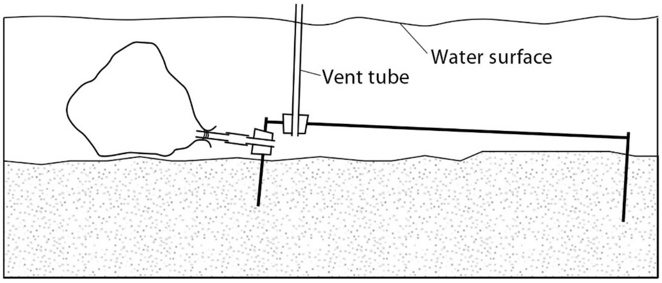

Fig. 4. Seepage meter modified for use in shallow water (modified from Lee and Cherry, 1978).

2.4. Early adoption of the Lee-type seepage meter – 1980s

Lee's meter received considerable and rapid interest beginning in the latter half of the 1970s, both because of a growing need to quantify transport of nutrients to lakes (e.g., Downing and Peterka, 1978; Fellows and Brezonik, 1981; Jaquet, 1976; John and Lock, 1977; Lee and Hynes, 1978; Schindler, 1974; Schindler et al., 1976), and because of a concordant increased interest in the distribution and variability of that exchange (Anderson and Munter, 1981; Downing and Peterka, 1978; Fellows and Brezonik, 1980; John and Lock, 1977; McBride and Pfannkuch, 1975; Winter, 1976; Winter, 1978).

Although most studies implemented seepage meters virtually identical to Lee's design, a few modifications made measurements either easier or more robust. A cut-off length of 20 cm, slightly larger than Lee's design, was the seepage-cylinder height reported in most studies. Some (i.e., Lewis, 1987; Zimmerman et al., 1985) used smaller-diameter seepage cylinders because they were easier to install. Ball valves (Lock and John, 1978) or pinch clamps (Fellows and Brezonik, 1980) were added to seepage bags to eliminate inadvertent water flow during bag attachment and removal. Several studies (Asbury, 1990; Fellows and Brezonik, 1980) also determined that larger-diameter tubing and hardware resulted in better meter efficiency, resulting in the measured value being closer to the true seepage rate. Some users of the device also suggested that the practice of analyzing chemistry of the water collected in a seepage bag was not a good indication of the chemistry of pore water or of groundwater discharging to the surface (i.e., Belanger and Mikutel, 1985; Frape and Patterson, 1981). Others indicated that pre-filling the bag with a known volume of approximately 1000 ml reduced measurement errors (Blanchfield and Ridgway, 1996; Erickson, 1981; Shaw and Prepas, 1989). This was attributed to the relaxed state of a bag being approximately half full. Bags nearly empty or full would induce flow to or from the bag that was unrelated to flow across the sediment-water interface.

2.5. Additional refinements and accuracy improvements – 1990s–2000s

Publications during the 1990s continued to tout the capabilities of the seepage meter, but some studies also pointed out limitations and new sources of error. A paper titled "Seepage meter errors" (Belanger and Montgomery, 1992) indicated that the standard deviation for repeated measurements at a single installation could be less than 5% and the standard deviation of multiple meters installed and operated at the same location was less than 20%. They devised a seepage-meter calibration tank to determine meter efficiency, defined as measured flow divided by true flow, and generated a correction factor to adjust for reductions in measured seepage due to flow and bag resistance. They determined that the standard Lee-type seepage meter measured only about 77% of actual seepage. Perhaps most notably, they reported substantial and consistent heterogeneity in flow through their seepage tank that was designed to create homogeneous flow. This corroborated the large heterogeneity that had been reported in the literature attributed to geology (e.g., Krabbenhoft and Anderson, 1986), or even when seepage meters were simply installed close to one another (Asbury, 1990; Belanger and Walker, 1990; Shaw and Prepas, 1990a; Woessner and Sullivan, 1984), which further supported the growing evidence that numerous meters were required to extrapolate data to a broader area. Local-scale spatial variability would continue to be a disturbing characteristic of seepage measurements during ensuing decades (e.g., Genereux et al., 2008; Lowry et al., 2007; Rosenberry et al., 2016a; Sebok et al., 2013), including corresponding measurements of vertical hydraulic gradient, in part because of the difficulty in resolving very small differences in head (Kennedy et al., 2007; Rosenberry and LaBaugh, 2008).

Researchers began to move beyond the near-shore margins of lakes. Cherkauer and McBride (1988) designed a meter suitable for deployment from large watercraft in the Great Lakes. They poured a concrete ring inside a portion of the seepage cylinder to add weight and stability to counteract lateral forces from large waves, and they remotely activated a valve from the surface that could start and stop flow to a seepage bag. Because of its built-in neck, Cherkauer and McBride (1988) used an intravenous fluid solution (IV) bag commonly used in hospitals. Tests indicated an efficiency of only 59–66%, likely due to the increased thickness and decreased flexibility of the IV bag. Boyle (1994) took a different approach and designed a meter that could be installed in deep water with a bag that was suspended near the water surface but beyond the effects of most waves. Boyle's device also included a weight to ensure that the seepage cylinder would be well seated in the sediment bed. The seepage bag was situated inside an inverted plastic pail that included a float to suspend the bag directly over the seepage cylinder. A snorkeler would dive to 1.5–2 m depth to deploy and retrieve the seepage bag. A similar design allowed the bag to float on the water surface for easier retrieval (Dorrance, 1989), although wave effects likely made measurements less robust.

Investigations involving seepage meters also became more numerous in marine settings (e.g., Bokuniewicz, 1980), where additional processes related to tides, waves, and mixing of variable-density water further complicated exchanges between surface and sub-surface water. The evolution in understanding and advances in measuring what became known as submarine groundwater discharge is covered in Duque et al. (part 2).

2.5.1. Seepage-bag issues

The seepage bag continued to be a source of error and frustration. Some investigators used bags with built-in necks to facilitate attachment of the bag to tubing, such as a hospital IV bag (Cherkauer and McBride, 1988), a condom (Fellows and Brezonik, 1980; Isiorho and Meyer, 1999), and in the subsequent decade hydration bags (Brodie et al., 2009), 4 L wine bags (Brodie et al., 2009), a camping-shower bag (Zamora, 2007), and a urine-collection bag (Zamora, 2007). Subsequent studies indicated that elastic bags, and particularly those with small workable volume such as condoms, introduced considerable error in seepage-meter measurements (Harvey and Lee, 2000; Murdoch and Kelly, 2003; Schincariol and McNeil, 2002) and should not be used.

In response to reports that an empty seepage bag introduced a large measurement error (Blanchfield and Ridgway, 1996; Shaw and Prepas, 1989), several subsequent papers explored the causes and solutions. Asbury (1990) indicated that bag efficiency for measurements of downward seepage decreased substantially once bag volume was reduced to about 500 ml. He determined that, as the bag was shrinking, the internal surfaces of the bag were coming into contact, reducing ready flow within the bag. Murdoch and Kelly (2003) later provided a thorough analysis of the variable degree and direction of error that seepage bags create. Seepage bags that are near empty can either create flow into the bag as they self-inflate to a relaxed partially full position, or they can resist flow into or out of the bag where plastic is adhered to plastic, as Asbury (1990) found. Folds in the bag can also isolate parts of the bag and increase resistance to bag inflation or deflation. As bags approach fullness, increased pressure is required to continue filling the bag, resulting in an undermeasurement of seepage. Murdoch and Kelly (2003) concluded that these errors can be minimized if bags are operated in the mid-range of fullness (discussed further).

2.5.2. Introduction of automated devices

Even after reducing bag-related errors, integrating each seepage measurement over the duration of bag attachment precluded determination of shorter-term temporal variability in seepage, leading to the common misconception that seepage, although highly spatially variable, was relatively constant over time. Some studies did report substantial temporal variability (e.g., Schneider et al., 2005; Sebestyen and Schneider, 2001), but even those measurements integrated temporal variability over the duration of each bag attachment. Fortunately, eliminating the seepage bag entirely became a viable new option. Taniguchi and Fukuo (1993) designed a heat-pulse flowmeter to record seepage. They obtained 5-min temporal resolution by pulsing a heat source for 2 s every 5 min and recording the resulting temperature signal at 5, 10, and 15 cm downstream from the heat source. Multiple points of temperature measurement allowed good resolution of the arrival time of peak temperature over a greater range of seepage rates. Using a 0.5-m-diameter seepage cylinder, they could measure seepage rates from 1.7 to 43.2 cm/d. That range could be increased by using seepage cylinders of different diameters. The authors demonstrated the value of this new capability by relating temporal variability in seepage in Lake Biwa, the largest lake in Japan, with lake seiche (Taniguchi and Fukuo, 1996). The device was later modified to use a continuous heat source rather than a pulsed heat source (Taniguchi et al., 2003). Another more elaborate heat-pulse seepage meter was developed in Florida to quantify both water and chemical fluxes across the sediment-water interface (Krupa et al., 1998). Termed the “Krupaseep,” the device included a translucent seepage cylinder to allow light to reach the bed and reduce anoxia beneath the meter. It also included several water-quality sensors installed inside and also outside of the cylinder, and a water-collection port for pulling water samples for chemical analysis. A third automated seepage meter was developed during the late 1990s that used an acoustic-velocity sensor in lieu of a seepage bag (Paulsen, 2000; Paulsen et al., 2001). This ultrasonic seepage meter was sampled at a frequency of 4 s and could measure seepage over a range of about 1–200 cm/d.

2.6. Further refinements – 2000–2010

Many of the errors and inefficiencies related to installation and operation of seepage meters were addressed and minimized by the turn of the century, but concerns related to seepage-meter bags, use in flowing water, and spatial and temporal heterogeneity led to additional improvements. Improvements during the first decade of the 21st century were particularly numerous.

2.6.1. Addressing velocity head

Starting as early as 1994 (Libelo and MacIntyre, 1994; Schneider, 1994), investigators began to report problems with making seepage measurements in flowing water. Studies conducted in controlled-flume and natural settings indicated seepage meters installed in flowing water would record much larger values for upward flow across the sediment-water interface than when surface-water currents were not present (Libelo and MacIntyre, 1994). The authors indicated that placing the seepage bag inside a shelter largely eliminated the current-related errors. Even measurements made in relatively quiescent lakes were potentially suspect. Sebestyen and Schneider (2001) found that disconnected and open seepage bags placed directly adjacent to identically filled bags attached to a seepage cylinder also recorded substantial changes in bag volume over time.

A thorough study on the effects of current velocity (Murdoch and Kelly, 2003) indicated that head in the collection bag would be reduced by the velocity-head component of total head:

$$h_{bag} = h_{tot} - u^2/2g \tag{2}$$

where h_{bag} is head inside the seepage bag where velocity is zero (m),

h_{tot} is total head in the stream (m),
u is current velocity (m/s),
and g is acceleration of gravity (m/s^2).

Murdoch and Kelly concluded that velocity head likely increased their seepage measurements by 5–10% at the relatively slow current velocity of 0.35 cm/s. However, currents likely also deformed the bag, creating erratic and unknown bag effects. Therefore, they recommended placing the bag inside a shelter that would remove velocity-head effects and eliminate any current-induced erratic bag deformations.

Velocity head related to seepage-meter measurements in marine settings also was discussed in several papers beginning with the disturbing title, "Seepage meters and Bernoulli's revenge," by Shinn et al. (2002). Presented in greater detail in Duque et al. (this issue), the consensus based on several ensuing publications was that the overall effect of fluid velocity was minor provided that the seepage bag was protected from currents.

Additional testing in a laboratory setting indicated the velocity-head effect related to flow deflected around a seepage cylinder was not substantial at surface-water velocities as large as 0.4 m/s (Rosenberry, 2008). As current velocity increased, variability in measured seepage increased slightly but there was no bias in the seepage data at seepage rates ranging from +20 cm/d to −20 cm/d. The consensus was that substantial changes in pressure head are created as water is forced to flow around the seepage cylinder, but the net effect is minimal. Eddies at the upstream and downstream sides of the seepage cylinder create low-velocity high-pressure areas. At the same time, accelerated flow around the sides of the cylinder create high-velocity low-pressure areas, the effects of which offset the eddy-induced low-velocity high-pressure areas. Tests conducted in a river with medium sand to fine gravel indicated that a standard cut-off-drum cylinder provided data similar to that from a much more streamlined cone-shaped cylinder unless sediment scour occurred (Rosenberry, 2008). Once the bed adjacent to the cylinder was scoured, upward seepage began to increase because sediment removed from the bed allowed water to more easily flow beneath the bottom edge of the cylinder and into the cylinder and seepage bag. The low-profile, conical cylinder reduced the deflection of flow in the river and the associated scour of the bed (Rosenberry, 2008).

Use, and also the placement, of a bag shelter was shown to be vitally important in fluvial settings, especially as surface-water velocity increased (Rosenberry, 2008). Extreme care was needed for placement of the seepage-bag shelter to ensure that total head at the seepage bag was the same as total head at the seepage cylinder. Because total head decreases in the direction of streamflow, placing a seepage bag downstream of the seepage cylinder results in a larger total head at the seepage cylinder than at the seepage bag, which induces flow from the cylinder to the bag. For surface-water currents close to 0.1 m/s, moving the seepage shelter and bag 3 m downstream of the seepage cylinder increased seepage by about 20%. However, where current velocity was increased to 0.65 m/s, moving the seepage shelter and bag 3 m downstream increased measured seepage 4-fold (Rosenberry, 2008).

2.6.2. Continuing bag improvements

Seepage-meter bags continued to evolve, with more and better determinations regarding their effect on seepage-meter efficiency. Murdoch and Kelly (2003) measured hydraulic head with a manometer to determine the pressure required as two types of seepage bags were slowly filled with a peristaltic pump. One bag was made from thick plastic and designed to be durable and robust, and the other was made of thin, pliable plastic. The thick-walled bag showed highly variable resistance as kinks in the bag were encountered and then overcome with increased bag fullness. Very large resistance at the beginning of many of the tests was attributed to adhesion caused by the sides of the bag sticking together. Neither of these features were evident in the data for filling of the thin-walled bags. Resistance increased greatly as the thick-walled bag approached 73% fullness and as the thin-walled bag approached 86% fullness. Although the thin-walled bag did not show the highly variable resistance during early stages of fullness, the authors recommended that all seepage-meter measurements start with some initial volume of water contained in the bag and end before the bag resistance begins to increase (Murdoch and Kelly, 2003).

Measurement of the volume of water contained in the seepage bag evolved as well. Most studies used a graduated cylinder with an observer accuracy of about +/− 5 ml. With the advent of inexpensive and accurate electronic scales with digital readout, measuring the change in combined mass of the bag, bag-attachment hardware, and water contained in the bag, became a much more accurate option (Rosenberry et al., 2008). However, because of difficulty with taring the instrument, the method did not work well on floating watercraft or on windy days. Substituting mass for volume was more complex in brackish or marine settings where water density was not virtually 1 g/ml.

Seepage-meter efficiency continued to improve with better bag-attachment methods, use of thin-walled bags, and larger-diameter connecting hardware. Even when connection hoses several m long were used between the seepage cylinder and the bag, meter efficiencies averaging 0.93 were achieved (Rosenberry, 2005). Tests, conducted in a 1.5-m-diameter sand tank designed to create controlled and known seepage rates (Rosenberry and Menheer, 2006), evaluated several seepage-bag designs and reported bag efficiencies slightly greater than 1 for the same 3.5-L bags used in the Murdoch and Kelly study (2003). Values greater than 1 were attributed to spatial heterogeneity within the tank even though great care was taken to create homogeneous conditions, a problem also reported earlier for a seepage tank in Florida (Belanger and Montgomery, 1992). Additional tests indicated that longer bag-connection times provided results that were likely more accurate than short bag-connection times. A seepage meter with a nearly identical 4-L seepage bag had an efficiency greater than 1 for seepage measurements made over 1-min time at seepage rates close to 20 cm/d. However, when measurements were made over longer periods, ranging from 5 to 30 min, with changes in volume contained in the bag ranging from 190 to 1200 ml, meter efficiency was between 0.93 and 0.99 and averaged 0.96. Similar tests conducted for a solar-shower bag and an IV-drip bag indicated bag efficiencies of 0.53 and 0.88, respectively (Rosenberry and Menheer, 2006).

2.6.3. Additional meter designs

Improvements to seepage meters continued to appear in the literature. Connecting multiple seepage cylinders (ganged seepage meter) to a single seepage bag served to better integrate spatial heterogeneity, allowed bag placement to be more convenient for making accurate measurements, and shortened bag-connection time (Rosenberry, 2005). Another design included a switch on the seepage bag that turned on a pump to evacuate water from the bag and then begin another measurement (Walthall and Reay, 1993).

2.6.4. Further refinement of bagless "automated" seepage meters

More devices were developed to replace the seepage bag with an alternate method of quantifying volumetric change over time, which eliminated the numerous bag-related sources of error mentioned previously. Most of these devices produced a signal that could be logged at specified time intervals by a datalogger, hence the commonly used descriptor, "automated." The "piezoseep" measured vertical head gradient in lieu of seepage flux (Kelly and Murdoch, 2003; Murdoch and Kelly, 2003). The device was essentially a seepage cylinder with a piezometer extending through the center of the cylinder with a screened interval about 10–15 cm beneath the sediment-water interface. Following installation, a range of known seepage rates was induced with a pump pulling water from inside the seepage cylinder and the corresponding difference in head between the piezometer and the surface water contained within the seepage cylinder was recorded. Once a locally determined relation between "seepage" and difference in head was established, the difference in head was used as a surrogate for seepage and monitored with a differential pressure transducer. An added benefit was that vertical hydraulic conductivity was determined in the process.

Several other flowmeters were substituted for a seepage bag in addition to the previously mentioned heat-pulse and ultrasonic flowmeters. A subsequent heat-pulse meter used thermocouples instead of thermistors and had sensors on both sides of the heat source for recording bi-directional flow (Lien, 2006). However, temporal resolution was slightly reduced to about 13 min. Further improvements in electronics, along with local calibrations, allowed heat-pulse measurements of seepage as small as 0.29 cm/d, although temporal resolution was reduced to about 30 min (Zhu et al., 2015). Zhu et al. also noted the importance of calibrating heat-pulse meters based on expected ambient temperature for better accuracy. An off-the-shelf ultrasonic flowmeter was potted in epoxy to make it waterproof and was attached to an acrylic benthic-flux chamber to serve as a seepage meter (Menheer, 2004). The sensor worked well but required frequent zero-flow calibrations to adjust for sensor drift. Another device used an electromagnetic flowmeter originally designed for measuring vertical flow in boreholes in fractured rock (Rosenberry and Morin, 2004). That device had a very short temporal resolution of about 5 s and was used to demonstrate temporal seepage variability in response to thunderstorms, tides (Simonds et al., 2008), waves, rainfall, evapotranspiration, lake seiche, and upstream dam releases (Rosenberry et al., 2013). Several meters were developed based on dilution of dye or other chemicals released into the seepage cylinder. Details related to meters developed and deployed in a range of marine settings (Koopmans and Berg, 2011; Sholkovitz et al., 2003; Tryon et al., 2001) are discussed in Duque et al. (this issue). One automated system was designed for use in shallow freshwater streams and measured dilution of injected salt solution with a chloride-ion probe. Results compared favorably with data from bag-type and piezoseep meters (Craig, 2005).

2.7. Recent improvements, new devices, new methodologies

New measurement methods for quantifying groundwater-surface-water exchange continue to be developed and promoted and results commonly are compared with results from seepage meters. Several recent temperature-based methods show promise (e.g., Briggs et al., 2012b; Lewandowski et al., 2011; Vogt et al., 2010). A vertical-temperature-profiling method provided data from field installations that compared remarkably well with data from seepage meters for upward seepage rates ranging from 0.1 to nearly 300 cm/d (Rosenberry et al., 2016a). Fiber-optic distributed-temperature sensing also is now commonly used to identify areas of the sediment bed where upward seepage may be particularly fast (e.g., Briggs et al., 2012a; Sebok et al., 2013). Thermal-infrared imagery acquired from stationary, hand-held, or airborne platforms can serve the same purpose but only if temperature anomalies due to seepage extend to the water surface (e.g., Briggs et al., 2019; Hare et al., 2015). Combining a heat source with a fiber-optic cable, often referred to as active distributed-temperature sensing, shows promise for quantifying groundwater-surface-water exchange either on a vertical axis (Bakx et al., 2019; Briggs et al., 2016; Liu et al., 2013) or draped across a broad area of a sediment bed.

A relatively recent device that operates in a manner similar to that presented by Bouwer (1962) is called a tube seepage meter (Solder et al., 2016). The device consists of a 7-cm-diameter metal tube inserted into the sediment bed with the top of the tube extending above the water surface. With the bottom end of the tube inserted a known distance below the sediment-water interface, water level inside the tube will eventually indicate the head at the bottom of the tube. A hole in the side of the tube above the sediment-water interface is opened to allow the water level inside the tube to equal stream stage, the resulting zero-gradient value is recorded by an attached pressure transducer, the hole is then plugged, water is removed from inside the tube, and time-series data of head relative to zero-gradient head are recorded. The slope of the curve where head passes the zero-gradient point during recovery to equilibrium head is determined by.

$$q = (dh/dt)\,(a/A) \tag{3}$$

where a is the cross-sectional area of a small-diameter riser pipe that extends above the surface-water plane, and A is the diameter of the metal tube that penetrates the sediment. For downward seepage, water is added to start the measurement with head greater than zero-gradient head. The method assumes a constant surface-water stage during the period of measurement. In relatively coarse-grained sediment, a measurement can be made in about 5 min. In fine-grained sediments, the small-diameter riser pipe is not necessary ($a = A$) and the metal tube can extend above the water surface. Vertical hydraulic conductivity can also be determined with the device (Solder et al., 2016). The original Bouwer and Rice (1963) head-decline seepage meter was also modified for use in streams where sediments beneath the streambed are unsaturated (Wang et al., 2014), with a correction published a few years later to reduce error resulting from air compression within the manometer (Peng and Zhan, 2017).

One problem with the tube seepage meter is the very small area of the sediment bed (3.8×10^{-3} m^2) represented by the measurement. Solder (2014) created another device called the blanket seepage meter that addresses this problem. A Hypalon-rubber rectangle 0.75 m^2 in area is edged with overlapping metal flanges that extend about 5 cm into the sediment bed. Because the device is rectangular, multiple meters can be installed edge to edge to cover all or nearly all the cross-sectional distance of a stream. Seepage is determined based on dilution of a salt tracer injected into a mixing chamber connected to the outlet of the seepage blanket. Results from the device compared well with those from a Lee-type seepage meter but with a reduced meter efficiency (Solder, 2014).

A recently developed streambed point-velocity probe can also measure seepage via tracer injection but does not require a seepage cylinder. The device includes a shield to allow measurement of only the vertical component of upward or downward seepage in the uppermost 10 cm of the sediment bed (Cremeans and Devlin, 2017). Currently, the device is not suitable for seepage slower than about 50 cm/d.

An updated heat-pulse seepage meter that uses a single continuously heated thermistor greatly extends the low-flow measurement capability of automated devices (Skinner and Lambert, 2009). The device can measure seepage rates as small as 1 mm/d. The device can only measure unidirectional flow.

Another new seepage-meter design replaces the seepage bag with a cylinder floating at the water surface and connected to a seepage cylinder installed on the sediment bed (Lee et al., 2018). A tube extending from the seepage cylinder to the floating cylinder allows groundwater discharge to be routed to the floating cylinder. Water level inside the floating cylinder is maintained at a stage lower than surface-water stage and the point of entry of water flowing into the floating cylinder is maintained exactly at surface-water stage. The volume of groundwater discharge is determined each time the water collected in the floating cylinder is pumped out and measured (Lee et al., 2018). Only upward seepage can be measured.

3. Current understanding and best measurement design and practices

Many new devices and methods for quantifying exchange between groundwater and surface water have been created during the decades following the introduction of the simple, inexpensive, and effective Lee-type seepage meter (Lee, 1977). Because of near-constant improvements in the seepage meter and development of these other devices and measurement methods, much has been learned about the processes that control the exchange, the temporal and spatial heterogeneity of the exchange, and ways to minimize measurement error.

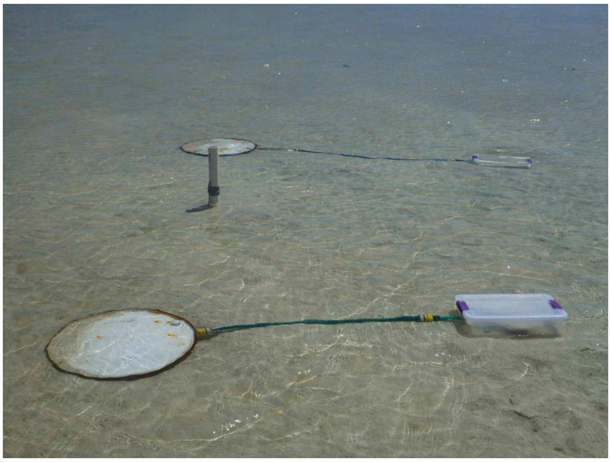

Fig. 5. Two seepage meters installed on either side of a piezometer with bag shelters positioned about 2 m from the seepage cylinder to eliminate current- and wave-related errors and minimize observer-induced measurement error.

Most investigators now recommend measuring vertical hydraulic gradient (i_v) at every location where seepage is measured (e.g., Kelly and Murdoch, 2003; Landon et al., 2001; Rosenberry et al., 2016a; Rosenberry and Hayashi, 2013). Measuring both parameters allows local-scale determination of vertical hydraulic conductivity,

$$K_v = q/i_v \tag{4}$$

a parameter that is scale-dependent, commonly required for models that simulate groundwater flow and groundwater-surface-water exchange, and is usually difficult to quantify. This simple rearranging of the Darcy equation to calculate K_v often does not work as well in fluvial settings, however, where flow beneath the sediment-water interface is not primarily vertical (Brookfield and Sudicky, 2013; Fanelli and Lautz, 2008; Käser et al., 2009; Rosenberry and Pitlick, 2009b) and yet i is determined along a vertical axis under the assumption of vertical flow. Even where flow is vertical, gradients at this scale can also be exceptionally small and difficult to measure.

For seepage-measurement devices that require a seepage bag, placing the bag inside a shelter is clearly one of the most important design improvements, whether working in fluvial, lacustrine, paludal, or estuarine settings. As mentioned earlier, measuring change in volume with a digital scale rather than a graduated cylinder improves accuracy in freshwater settings, but only when it is possible to reliably tare the scale.

Moving the seepage-collection bag away from the seepage cylinder (Fig. 5) also minimizes error by preventing pulses of water into the seepage cylinder caused by an observer stepping on the sediment bed when attaching or removing a seepage bag (Rosenberry and Morin, 2004). In fact, disturbance of the sediment bed should be avoided in general. A study at a small sand-bed lake documented substantial increase in measured seepage when the sediment bed was disturbed prior to making a measurement. Seepage following bed disturbance was at least double the undisturbed rates and increased nearly 8-fold at some locations compared to seepage measured prior to bed disturbance (Rosenberry et al., 2010).

Seepage is inherently heterogeneous, both spatially (Fig. 6) and temporally, and improved designs can better address that heterogeneity. Covering a larger portion of the sediment bed better integrates spatial heterogeneity, although ensuring a good seal between the seepage cylinder and sediment bed becomes more difficult as the circumference increases. Temporal variability was rarely mentioned during the first few decades of seepage-meter measurements. Early studies were focused where seepage rates were relatively slow, and measurements commonly were integrated over periods of a half to several days. Studies during ensuing decades included a greater percentage of locations where seepage rates were larger, several faster than 100 cm/d (Rosenberry et al., 2015), with much shorter durations for each measurement. Many of those seepage measurements were accomplished within several minutes to hours. No matter the duration, any temporal variability that may have occurred during each measurement was averaged over the time during which the bag was attached, contributing to the perception that temporal variability is minimal and of far less importance than spatial variability. As mentioned in Section 2.5.2, automated seepage meters can address this problem (Rosenberry et al., 2013), but most of these devices are still not widely used and few are commercially available.

Use of seepage meters in fluvial settings continues to grow, but the vagaries of placing a solid object in a flow field, potentially creating disturbance similar to that of a large boulder, remain a concern in swift-water settings. Although studies have been conducted that show reasonable and repeatable measurements can be made with seepage meters modified for use in flowing water (Rosenberry, 2008), some studies have also reported poor correlations between seepage and hydraulic gradients (Käser, 2010; Sickbert and Peterson, 2014; Woessner and Sullivan, 1984). Several studies have even indicated that measured seepage can be in the opposite direction of the associated measured hydraulic gradient (Angermann et al., 2012; Käser et al., 2009; Landon et al., 2001; Rosenberry et al., 2012; Rosenberry and Pitlick, 2009b). This has been attributed to differences in scales of measurements (Rosenberry and Pitlick, 2009b). A seepage meter measures flow across the sediment-water interface driven by gradients and flowpaths within a few cm of the interface, no matter the direction of flow, whereas a piezometer screened several tens of cm below the sediment-water

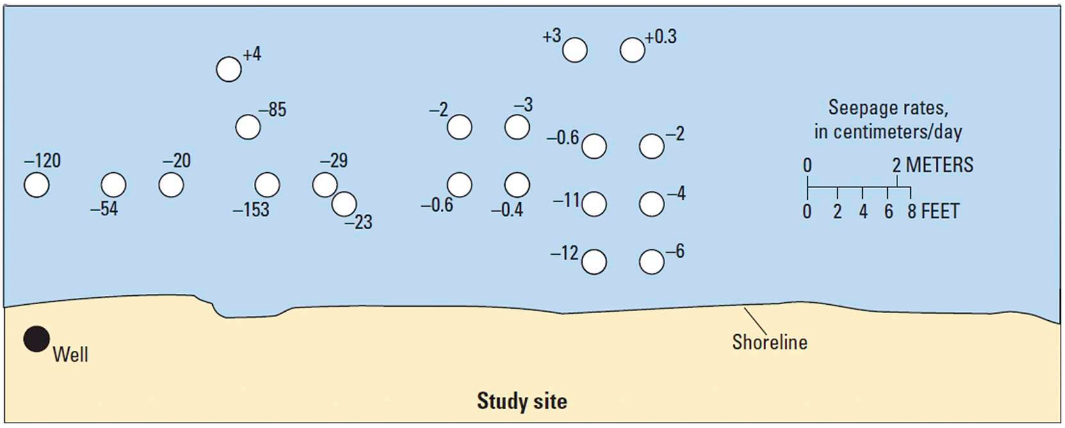

Fig. 6. Seepage measured in the near-shore margin of a small lake in New Hampshire, USA, showing a particularly extreme example of spatial heterogeneity, with values ranging from +4 to −153 cm/d over an 84 m^2 area. From LaBaugh and Rosenberry (2008).

interface provides the vertical component of hydraulic gradient in the underlying porous medium integrated over the distance from the well screen to the sediment bed, commonly on the order of 0.5 m. Given the complex, nested, and largely horizontal flow in the hyporheic zone (e.g., Lautz, 2010), all of which are driven primarily by local-scale bed topography, it is not surprising that interpreted exchanges based on the two methods may not always be in concordance. Although lakes and wetlands typically exhibit far less spatial and temporal complexity, seepage in these settings can also be driven by processes other than measured hydraulic gradients. Hydraulic effects from waves and currents, particularly in near-shore margins of larger lakes, can generate seepage rates and patterns greatly different from that determined from measured hydraulic gradients (e.g., Naranjo et al., 2019).

Current best practices, based on recommendations culled from the seepage-meter literature and authors' experience, are summarized in Table 1. In addition to listing best practices for all settings where flow across the sediment-water interface is assumed to be primarily vertical, a separate set of best practices is listed for hyporheic settings, where surface-water hydraulics are a factor and where the horizontal component of fluid flow through the sediment can dominate. A similar table for seepage-meter use in marine settings, where effects of waves and currents are generally much more substantial, is presented in Duque et al. (this issue). Many of the recommendations presented in that table would also apply for measurements made in the nearshore margins of large freshwater lakes.

Table 1
Best seepage-meter installation and operation practices based on suggestions from the literature and authors' experience.

Action	Pros	Cons
Lacustrine, paludal relatively low-energy setting		
Use a larger-diameter cylinder	Better integrates spatial heterogeneity. Larger area shortens measurement time.	Greater difficulty in ensuring a good seal between bottom edge of cylinder and sediment.
Use larger-diameter bag-connection hardware (> ~9 mm)	More efficient transmission of water to/from bag, particularly for faster seepage.	Hardware is slightly more expensive.
Insert cylinder at least 5 cm into bed	Less likely to have short-circuiting of flow beneath meter. Less likely to have bypass flow.	More difficult to install the deeper the installation.
Install/design cylinder so gas can be evacuated either continuously or manually between measurements	Reduces measurement error.	Added complexity.
Do not leave seepage cylinder in place for long periods (or use an “open-head” cylinder with a removable top (e.g., McCobb et al., 2009))	Removing cylinder between synoptic measurements allows sediment bed to evolve along with the surrounding uncovered bed.	Requires removal and re-installation of meter each time (or a lid-less cylinder can be installed with only the top removed and attached for each measurement.)
Connect bag hardware to the side of the cylinder	Allows operation in very shallow water.	Requires a means to vent gas from the top of the cylinder.
Use a short (~0.5 m to ~2 m) length of hose or large-diameter tubing to place the seepage bag away from seepage cylinder	Distances the observer from the seepage cylinder, eliminating the chance for creating artificial pressure and flow into the seepage cylinder.	Reduces meter efficiency, particularly for long reaches of hose or tubing. Hoses up to 10 m long are generally acceptable so long as they are relatively straight.
Make the bag-connection hose as straight as possible	Reduces loss of meter efficiency caused by angular momentum.	Connection hose may need to bend around obstructions on the bed.
Minimize the disturbance of the sediment bed within or adjacent to the seepage-cylinder installation	Seepage measurements are more representative of natural, undisturbed seepage.	Avoiding bed disturbance during installation can be quite difficult.
Place seepage bag inside a ventilated bag shelter	Greatly reduces errors caused by waves and currents on the seepage bag.	Adds complexity. Shelter needs to be well secured to the bed when waves become large.
Use a thin-walled bag, preferably one with a built-in neck	Bag is much more efficient and produces more consistent results.	Bag is more fragile and more susceptible to tears and rips.
Operate bag so it varies between 25 and 75% full	Minimizes opportunities for increased bag resistance and provides more consistent and accurate data.	Shortens the range of acceptable bag-connection time.
Use longer rather than shorter bag-connection times if possible	Minimizes any short-duration bag-related errors.	Fewer measurements – Requires either more field work or fewer data points.
Measure change in volume with a graduated cylinder	Device is simple, requires no batteries, and can be used on watercraft and on windy days.	Measurement precision is about +/− 5 ml for cylinders of 1000 ml capacity or greater. Bags need to be emptied with each measurement, which can be time consuming for larger bags.
Measure change in volume with a digital scale	Measurements are fast and accurate (~ +/− 1 ml). The entire bag and contained water can be weighed, precluding emptying of the bag for each measurement.	Devices are prone to failure if exposed to water, they require batteries, and scales cannot tare on unstable watercraft or in windy conditions.
Collect adjacent seepage-meter and piezometer data	Collecting both seepage and gradient data allows calculation of vertical hydraulic conductivity.	Installation and measurement of adjacent piezometer may compromise integrity of local sediment bed. Requires additional field work.
Be particularly mindful of meter efficiency in highly permeable sediments	Bypass flow can be substantially larger in permeable sediments; increased meter efficiency can offset that problem	Assumed meter efficiency and associated measured seepage rates can be greatly reduced in highly permeable sediments.
Use a flowmeter in lieu of seepage bag	Greatly improves temporal resolution and allows quantification of short-term temporal variability.	Greatly increases cost and complexity of the device.
Fluvial (hyporheic) setting		
Use low-profile, aerodynamic seepage cylinder	Reduces erosion of sediment adjacent to seepage cylinder.	May have to design and produce a suitable seepage cylinder.
Insert cylinder no more than 5–7 cm into sediment bed	Reduces the blocking of largely horizontal flowpaths, allowing more water to flow into or from the seepage cylinder.	May increase the chance of preferential flow beneath the bottom edge of the seepage cylinder.
Place bag shelter where surface-water stage is equal to that at the seepage cylinder	Eliminates bias in the measurement.	Not doing so can create large errors, particularly where surface-water gradient is large.
Place bag shelter away from fast currents	Increases accuracy by reducing the chance of current moving the bag shelter.	Long and/or curved hose between cylinder and bag shelter can reduce meter efficiency.
Use a flowmeter in lieu of seepage bag	Greatly improves temporal resolution and allows quantification of short-term temporal variability.	Greatly increases cost and complexity of the device.

4. Additional needs, future directions

Improvements in instrumentation and best-measurement practices undoubtedly will continue. Seepage meters have often been customized to suit the needs of a specific study objective or field conditions. Because the device is relatively simple and inexpensive to construct, improvements and additional modifications also are likely to continue. The device is also conceptually simple and easy to understand, making it a useful teaching tool (Lee in preparation).

Additional types of automated meters are needed that can resolve these very slow rates of flow with temporal resolutions commensurate with processes that drive seepage exchange. Current versions are orders of magnitude more expensive than manual meters, precluding their use in many studies. Future designs will hopefully be substantially less expensive, leading to wider adoption and use.

Longer deployments will allow better determination of temporal variability over weeks to months to seasons. However, isolating a portion of a sediment bed for long periods will result in that bed being static while the bed around it will continue to evolve in response to currents and waves and biology, making the measurements less representative. Ideally, meters would be developed that would allow the bed to be exposed to all external inputs during measurement and would not need to be isolated during a measurement. Until such a meter is devised, a good compromise is installing a seepage cylinder with a removable top (an “open-head” cylinder) that allows the top to be removed in between measurements and then reattached during each subsequent measurement period (McCobb and LeBlanc, 2011; McCobb et al., 2009).

Several previous devices could only quantify upward flow from groundwater to surface water. Automated meters have documented flow reversals on scales of seconds to days that occur in response to waves, seiches, passing watercraft, and other external forces (Rosenberry et al., 2013), clearly demonstrating the bias and unsuitability of meters that are uni-directional. These frequent reversals also can be important to biological and geochemical processes and additional work is needed to better quantify their occurrence, distribution, and implications.

Better characterization of spatial heterogeneity also is needed, including scaling point measurements to represent net seepage for entire bays or lakes or stream reaches. Further development of an active distributed-temperature-sensing system that can be draped across a substantial area of sediment-water interface shows great promise for addressing this issue that has plagued seepage meters from their inception.

Making the seepage chamber less hydraulically disruptive would greatly minimize the potential for errors related to flowing water and waves (e.g., Smith et al., 2009). Some studies have used conical or spherical cylinder shapes but those studies are few. The recent rapid advancement in injection-molding and 3-D-printing capabilities should result in greater use of streamlined designs, resulting in smaller data variance.

One best practice suggested by numerous authors is to use a combination of methods to quantify exchange (e.g., Brodie et al., 2007; Essaid et al., 2008; González-Pinzón et al., 2015; Hatch et al., 2010; Karan et al., 2013; Kennedy et al., 2010; Kidmose et al., 2011; Kidmose et al., 2013; Klos et al., 2015; Rosenberry et al., 2016b; Rosenberry et al., 2012; Sebok et al., 2013), including scaling these approaches to better address spatial heterogeneity (e.g., Gilmore et al., 2016b; Kikuchi et al., 2012; Simpkins, 2006). This multiple-methods approach is also promoted for marine settings (Burnett et al., 2006; Mulligan and Charette, 2006; Simonds et al., 2008) as presented in Duque et al. (Part 2, this issue) in greater detail. Doing so will continue to more rapidly advance the quantification and understanding of processes that control exchanges at the sediment-water interface of this single and connected groundwater and surface-water resource (Winter et al., 1998).

Acknowledgments

We thank Mary Anderson, previous editor of the journal *Ground Water*, for her persistence in requesting this long-overdue update of the modifications, improvements, and evolution of this useful tool for quantifying exchange between groundwater and surface water. We also thank Richard W. Sheibley and three anonymous reviewers for their constructive comments that improved the manuscript. This work was carried out as part of the activities of the Aarhus University Centre for Water Technology, WATEC. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

Ala-aho, P., Rossi, P.M., Kløve, B., 2013. Interaction of esker groundwater with headwater lakes and streams. J. Hydrol. 500, 144–156.

Alexander, M.D., Caissie, D., 2003. Variability and comparison of hyporheic water temperatures and seepage fluxes in a small Atlantic salmon stream. Groundwater 41 (1), 72–82.

Anderson, M.P., Munter, J.A., 1981. Seasonal reversals of groundwater flow around lakes and the relevance to stagnation points and lake budgets. Water Resour. Res. 17 (4), 1139–1150.

Anderson, R.B., Naftz, D.L., Day-Lewis, F.D., Henderson, R.D., Rosenberry, D.O., Stolp, B.J., Jewell, P., 2014. Quantity and quality of groundwater discharge in a hypersaline lake environment. J. Hydrol. 512, 177–194.

Angermann, L., Lewandowski, J., Fleckenstein, J.H., Nützmann, G., 2012. A 3D analysis algorithm to improve interpretation of heat pulse sensor results for the determination of small-scale flow directions and velocities in the hyporheic zone. J. Hydrol. 475, 1–11.

Asbury, C.E., 1990. The Role of Groundwater Seepage in Sediment Chemistry and Nutrient Budgets in Mirror Lake, New Hampshire. PhD Thesis. Cornell University, Ithaca 275 pp.

Attanayake, M.P., Waller, D.H., 1988. Use of seepage meters in a groundwater-lake interaction study in a fractured rock basin - a case study. Can. J. Civ. Eng. 15, 984–989.

Bakx, W., Doornenbal, P.J., van Weesep, R.J., Bense, V.F., Oude Essink, G.H.P., Bierkens, M.F.P., 2019. Determining the relation between groundwaer flow velocities and measured temperature differences using active heating-distributed temperature sensing. Water 11, 1619. https://doi.org/10.3390/w11081619.

Belanger, T.V., Kirkner, R.A., 1994. Groundwater/surface water interaction in a Florida augmentation lake. Lake Reserv. Manag. 8 (2), 165–174.

Belanger, T.V., Mikutel, D.F., 1985. On the use of seepage meters to estimate groundwater nutrient loading to lakes. Water Resour. Bull. 21 (2), 265–272.

Belanger, T.V., Montgomery, M.T., 1992. Seepage meter errors. Limnol. Oceanogr. 37 (8), 1787–1795.

Belanger, T.V., Walker, R.B., 1990. Ground water seepage in the Indian River Lagoon, Florida. In: American Water Resources Association Technical Publication Series TPS, 90-2, pp. 367–375.

Belanger, T.V., Mikutel, D.F., Churchill, P.A., 1985. Groundwater seepage nutrient loading in a Florida Lake. Water Res. 19 (6), 773–781.

Blanchfield, P.J., Ridgway, M.S., 1996. Use of seepage meters to measure groundwater flow at brook trout redds. Trans. Am. Fish. Soc. 125, 813–818.

Bokuniewicz, H., 1980. Groundwater seepage into Great South Bay, New York. Estuar. Coast. Mar. Sci. 10, 437–444.

Bouwer, H., 1962. Variable head technique for seepage meters. Trans. Am. Soc. Civ. Eng. 127 (3), 434–447.

Bouwer, H., Rice, R.C., 1963. Seepage meters in seepage and recharge studies. J. Irrig. Drain. Div. 89 (1), 17–42.

Bouwer, H., Myers, L.E., Rice, R.C., 1962. Effect of velocity on seepage and its measurement. J. Irrig. Drain. Div. 88 (3), 1–14.

Boyle, D.R., 1994. Design of a seepage meter for measuring groundwater fluxes in the nonlittoral zones of lakes – evaluation in a boreal forest lake. Limnol. Oceanogr. 39 (3), 670–681.

Briggs, M.A., Lautz, L.K., McKenzie, J.M., 2012a. A comparison of fibre-optic distributed temperature sensing to traditional methods of evaluating groundwater inflow to streams. Hydrol. Process. 26 (9), 1277–1290.

Briggs, M.A., Lautz, L.K., McKenzie, J.M., Gordon, R.P., Hare, D.K., 2012b. Using high-resolution distributed temperature sensing to quantify spatial and temporal variability in vertical hyporheic flux. Water Resour. Res. 48 (2) W02527.

Briggs, M.A., Voytek, E.B., Day-Lewis, F.D., Rosenberry, D.O., Lane, J.W., 2013. Understanding water column and streambed thermal refugia for endangered mussels in the Delaware River. Environ. Sci. Technol. 47 (20), 11423–11431.

Briggs, M.A., Lautz, L.K., Buckley, S.F., Lane, J.W., 2014. Practical limitations on the use of diurnal temperature signals to quantify groundwater upwelling. J. Hydrol. 519 (Part B), 1739–1751.

Briggs, M.A., Buckley, S.F., Bagtzoglou, A.C., Werkema, D.D., Lane Jr., J.W., 2016. Actively heated high-resolution fiber-optic-distributed temperature sensing to quantify streambed flow dynamics in zones of strong groundwater upwelling. Water Resour. Res. 52 (7), 5179–5194.

Briggs, M.A., Dawson, C.B., Holmquist-Johnson, C.L., Williams, K.H., Lane, J.W., 2019. Efficient hydrogeological characterization of remote stream corridors using drones.

Hydrol. Process. 33 (2), 316–319.

Brock, T.D., Lee, D.R., Janes, D., Winek, D., 1982. Groundwater seepage as a nutrient source to a drainage lake: Lake Mendota, Wisconsin. Water Res. 16, 1255–1263.

Brodie, R., Sundaram, B., Tottenham, R., Hostetler, S., Ransley, T., 2007. An overview of Tools for Assessing Groundwater-Surface Water Connectivity. Bureau of Rural Sciences, Canberra.

Brodie, R.S., Baskaran, S., Ransley, T., Spring, J., 2009. Seepage meter: progressing a simple method of directly measuring water flow between surface water and groundwater systems. Aust. J. Earth Sci. 56 (1), 3–11.

Brookfield, A., Sudicky, E., 2013. Implications of hyporheic flow on temperature-based estimates of groundwater/surface water interactions. J. Hydrol. Eng. 18 (10), 1250–1261.

Bruckner, A.E., Hornberger, G.M., Mills, A.L., 1989. Field measurement and associated controlling factors for ground water seepage in a piedmont impoundment. Hydrol. Process. 3 (3), 223–235.

Brusch, W., Nilsson, B., 1993. Nitrate transformation and water movement in a wetland area. Hydrobiologia 251, 103–111.

Burnett, W.C., Aggarwal, P.K., Aureli, A., Bokuniewicz, H., Cable, J.E., Charette, M.A., Kontar, E., Krupa, S., Kulkarni, K.M., Loveless, A., Moore, W.S., Oberdorfer, J.A., Oliveira, J., Ozyurt, N., Povinec, P., Privitera, A.M.G., Rajar, R., Ramessur, R.T., Scholten, J., Stieglitz, T., Taniguchi, M., Turner, J.V., 2006. Quantifying submarine groundwater discharge in the coastal zone via multiple methods. Sci. Total Environ. 367, 498–543.

Cey, E.E., Rudolph, D.L., Parkin, G.W., Aravena, R., 1998. Quantifying groundwater discharge to a small perennial stream in southern Ontario, Canada. J. Hydrol. 210 (1–4), 21–37.

Cherkauer, D.A., McBride, J.M., 1988. A remotely operated seepage meter for use in large lakes and rivers. Groundwater 26 (2), 165–171.

Cherkauer, D.S., McKereghan, P.F., 1991. Ground-water discharge to lakes: focusing on embayments. Groundwater 29 (1), 72–80.

Cherkauer, D.S., Zager, J.P., 1989. Groundwater interaction with a kettle-hole lake: relation of observations to digital simulations. J. Hydrol. 109, 167–184.

Choi, J., Harvey, J.W., 2000. Quantifying time-varying ground-water discharge and recharge in wetlands of the northern Florida Everglades. Wetlands 20 (3), 500–511.

Connor, J.N., Belanger, T.V., 1981. Ground water seepage in Lake Washington and the Upper St. Johns River Basin, Florida. Water Resour. Bull. 17 (5), 799–805.

Craig, A.L., 2005. Evaluation of Spatial and Temporal Variation of Groundwater Discharge to Streams. MS Thesis. Clemson University, Clemson, SC 117 pp.

Cremeans, M.M., Devlin, J.F., 2017. Validation of a new device to quantify groundwater-surface water exchange. J. Contam. Hydrol. 206, 75–80.

Cullmann, J., Junk, W.J., Weber, G., Schmitz, G.H., 2006. The impact of seepage influx on cation content of a Central Amazonian floodplain lake. J. Hydrol. 328 (1–2), 297–305.

Dimova, N.T., Burnett, W.C., Chanton, J.P., Corbett, J.E., 2013. Application of radon-222 to investigate groundwater discharge into small shallow lakes. J. Hydrol. 486, 112–122.

Dorrance, D.W., 1989. Streaming potential and seepage meter studies at Upper Lake Mary near Flagstaff, Arizona. M.S. Thesis. University of Arizona, Tucson 182 pp.

Downing, J.A., Peterka, J.J., 1978. Relationship of rainfall and lake groundwater seepage. Limnol. Oceanogr. 23 (4), 821–825.

Duff, J.H., Toner, B., Jackman, A.P., Avanzino, R.J., Triska, F.J., 1999. Determination of groundwater discharge into a sand and gravel bottom river: a comparison of chloride dilution and seepage meter techniques. Verh. Int. Ver. Theor. Angew. Limnol. 27, 1–6.

Dumouchelle, D.H., 2001. Evaluation of Ground-Water/Surface-Water Relations, Chapman Creek, West-Central Ohio, by Means of Multiple Methods. 01-4202. U.S. Geological Survey, Denver.

Erickson, D.R., 1981. A Study of Littoral Groundwater Seepage at Williams Lake, Minnesota Using Seepage Meters and Wells. M.S. Thesis. University of Minnesota, Minneapolis 135 pp.

Essaid, H.I., Wilson, J.T., Baker, N.T., 2006. Spatial and Temporal Variability in Streambed Fluxes, Leary Weber Ditch, Indiana, Third Federal Interagency Hydrologic Modeling Conference. Joint Federal Interagency Conference, Reno, NV. pp. 8.

Essaid, H.I., Zamora, C.M., McCarthy, K.A., Vogel, J.R., Wilson, J.T., 2008. Using heat to characterize streambed water flux variability in four stream reaches. J. Environ. Qual. 37, 1010–1023.

Fanelli, R.M., Lautz, L.K., 2008. Patterns of water, heat, and solute flux through streambeds around small dams. Groundwater 46 (5), 671–687.

Fellows, C.R., Brezonik, P.L., 1980. Seepage flow into Florida lakes. Water Resour. Bull. 16 (4), 635–641.

Fellows, C.R., Brezonik, P.L., 1981. Fertilizer flux into two Florida lakes via seepage. J. Environ. Qual. 10 (2), 174–177.

Findlay, S., 1995. Importance of surface-subsurface exchange in stream ecosystems: the hyporheic zone. Limnol. Oceanogr. 41 (1), 159–164.

Frape, S.K., Patterson, R.J., 1981. Chemistry of interstitial water and bottom sediments as indicators of seepage patterns in Perch Lake, Chalk River, Ontario. Limnol. Oceanogr. 26 (3), 500–517.

Frederiksen, R.R., Christensen, S., Rasmussen, K.R., 2018. Estimating groundwater discharge to a lowland alluvial stream using methods at point-, reach-, and catchment-scale. J. Hydrol. 564, 836–845.

Fritz, B.G., Mendoza, D.P., Gilmore, T.J., 2009. Development of an electronic seepage chamber for extended use in a river. Groundwater 47 (1), 136–140.

Fryar, A.E., Wallin, E.J., Brown, D.L., 2000. Spatial and temporal variability in seepage between a contaminated aquifer and tributaries to the Ohio River. Ground Water Monit. Remediat. 20 (3), 129–146.

Gardner, L.R., 2005. Role of geomorphic and hydraulic parameters in governing pore water seepage from salt marsh sediments. Water Resour. Res. 41, W07010. https://doi.org/10.1029/2004WR003671.

Genereux, D.P., Leahy, S., Mitasova, H., Kennedy, C.D., Corbett, D.R., 2008. Spatial and temporal variability of streambed hydraulic conductivity in West Bear Creek, North Carolina, USA. J. Hydrol. 358, 332–353.

Gilmore, T.E., Genereux, D.P., Solomon, D.K., Solder, J.E., 2016a. Groundwater transit time distribution and mean from streambed sampling in an agricultural coastal plain watershed, North Carolina, USA. Water Resour. Res. 52 (3), 2025–2044.

Gilmore, T.E., Genereux, D.P., Solomon, D.K., Solder, J.E., Kimball, B.A., Mitasova, H., Birgand, F., 2016b. Quantifying the fate of agricultural nitrogen in an unconfined aquifer: Stream-based observations at three measurement scales. Water Resour. Res. 52 (3), 1961–1983.

González-Pinzón, R., Ward, A.S., Hatch, C.E., Wlostowski, A.N., Singha, K., Gooseff, M.N., Haggerty, R., Harvey, J.W., Cirpka, O.A., Brock, J.T., 2015. A field comparison of multiple techniques to quantify groundwater–surface-water interactions. Freshw. Sci. 34 (1), 139–160.

Hagerthey, S.E., Kerfoot, W.C., 1998. Groundwater flow influences the biomass and nutrient ratios of epibenthic algae in a north temperate seepage lake. Limnol. Oceanogr. 43 (6), 1227–1242.

Hare, D.K., Briggs, M.A., Rosenberry, D.O., Boutt, D.F., Lane, J.W., 2015. A comparison of thermal infrared to fiber-optic distributed temperature sensing for evaluation of groundwater discharge to surface water. J. Hydrol. 530, 153–166.

Harvey, J.W., Bencala, K.E., 1993. The effect of streambed topography on surface-subsurface water exchange in mountain catchments. Water Resour. Res. 29 (1), 89–98.

Harvey, F.E., Lee, D.R., 2000. Discussion of "The effects of bag type and meter size on seepage meter measurements" by S.A. Isiorho and J.H. Meyer. Groundwater 38 (3), 326–327.

Harvey, J.W., Krupa, S.L., Krest, J.M., 2004. Ground water recharge and discharge in the Central Everglades. Groundwater 42 (7), 1090–1102.

Hatch, C.E., Fischer, A.T., Ruehl, C.R., Stemler, G., 2010. Spatial and temporal variations in streambed hydraulic conductivity quantified with time-series thermal methods. J. Hydrol. 389, 276–288.

Hotchkiss, R.H., Wingert, C.B., Kelly, W.E., 2001. Determining irrigation canal seepage with electrical resistivity. J. Irrig. Drain. Eng. 127 (1), 20–26.

Isiorho, S.A., Matisoff, G., 1990. Groundwater recharge from Lake Chad. Limnol. Oceanogr. 35 (4), 931–938.

Isiorho, S.A., Meyer, J.H., 1999. The effects of bag type and meter size on seepage meter measurements. Groundwater 37 (3), 411–413.

Isiorho, S.A., Beeching, F.M., Stewart, P.M., Whitman, R.L., 1996. Seepage measurements from Long Lake, Indiana Dunes National Lakeshore. Environ. Geol. 28 (2), 99–105.

Israelson, O.W., Reeve, R.C., 1944. Canal Lining Experiments in the Delta Area, Utah. 313. Utah Agricultural Experimental Station.

Jaquet, N.G., 1976. Ground-water and surface-water relationships in the glacial province of northern Wisconsin – Snake Lake. Groundwater 14 (2), 194–199.

Jensen, J.K., Engesgaard, P., 2011. Nonuniform groundwater discharge across a streambed: heat as a tracer. Vadose Zone J. 10 (1), 98–109.

John, P.H., Lock, M.A., 1977. The spatial distribution of groundwater discharge into the littoral zone of a New Zealand lake. J. Hydrol. 33, 391–395.

Jones, P.M., Trost, J.J., Diekoff, A.L., Rosenberry, D.O., White, E.A., Erickson, M.L., Morel, D.L., Heck, J.M., 2016. Statistical Analysis of Lake Levels and Field Study of Groundwater and Surface-Water Exchanges in the Northeast Twin Cities Metropolitan Area, Minnesota, 2002 through 2015. 2016-5139-A. U.S. Geological Survey, Reston.

Kaleris, V., 1998. Quantifying the exchange rate between groundwater and small streams. J. Hydraul. Res. 36 (6), 913–932.

Karan, S., Engesgaard, P., Looms, M.C., Laier, T., Kazmierczak, J., 2013. Groundwater flow and mixing in a wetland–stream system: Field study and numerical modeling. J. Hydrol. 488, 73–83.

Käser, D.H., 2010. Hyporheic Exchange Along Pool-riffle Sequences. PhD Thesis. Lancaster University, Lancaster 195 pp.

Käser, D.H., Binley, A., Heathwaite, A.L., Krause, S., 2009. Spatio-temporal variations of hyporheic flow in a riffle-step-pool sequence. Hydrol. Process. 23, 2138–2149.

Keery, J., Binley, A., Crook, N., Smith, J.W.N., 2007. Temporal and spatial variability of groundwater–surface water fluxes: development and application of an analytical method using temperature time series. J. Hydrol. 336, 1–16.

Kelly, S.E., Murdoch, L.C., 2003. Measuring the hydraulic conductivity of shallow submerged sediments. Groundwater 41 (4), 431–439.

Kennedy, C.D., Genereux, D.P., Corbett, R., Mitasova, H., 2007. Design of a light-oil piezomanometer for measurement of hydraulic head differences and collection of groundwater samples. Water Resour. Res. 43, W09501. https://doi.org/10.1029/2007WR005904.

Kennedy, C.D., Murdoch, L.C., Genereux, D.P., Corbett, D.R., Stone, K., Pham, P., Mitasova, H., 2010. Comparison of Darcian flux calculations and seepage meter measurements in a sandy streambed in North Carolina, United States. Water Resour. Res. 46 (9). https://doi.org/10.1029/2009wr008342.

Kidmose, J., Engesgaard, P., Nilsson, B., Laier, T., Looms, M.C., 2011. Spatial distribution of seepage at a flow-through lake: Lake Hampen, Western Denmark. Vadose Zone J. 10 (1), 110–124.

Kidmose, J., Nilsson, B., Engesgaard, P., Frandsen, M., Karan, S., Landkildehus, F., Søndergaard, M., Jeppesen, E., 2013. Focused groundwater discharge of phosphorus to a eutrophic seepage lake (Lake Væng, Denmark): implications for lake ecological state and restoration. Hydrogeol. J. 21 (8), 1787–1802.

Kikuchi, C.P., Ferré, T.P.A., Welker, J.M., 2012. Spatially telescoping measurements for improved characterization of ground water-surface water interactions. J. Hydrol. 446–447, 1–12.

Klos, P.Z., Rosenberry, D.O., Nelson, G.R., 2015. Influence of hyporheic exchange, substrate distribution, and other physically-linked hydrogeomorphic characteristics on abundance of freshwater mussels. Ecohydrology 8, 1284–1291.

Knights, D., Parks, K.C., Sawyer, A.H., David, C.H., Browning, T.N., Danner, K.M., Wallace, C.D., 2017. Direct groundwater discharge and vulnerability to hidden nutrient loads along the Great Lakes coast of the United States. J. Hydrol. 554 (Supplement C), 331–341.

Kohout, F.A., 1966. Submarine Springs: A Neglected Phenomenon of Coastal Hydrology, Symposium on Hydrology and Water Resources Development. Central Treaty Organization, Ankara, Turkey, pp. 391–413.

Koopmans, D., Berg, P., 2011. An alternative to traditional seepage meters: dye displacement. Water Resour. Res. 47 (1), W01506.

Krabbenhoft, D.P., Anderson, M.P., 1986. Use of a numerical ground-water flow model for hypothesis testing. Groundwater 24, 49–55.

Krabbenhoft, D.P., Bowser, C.J., Anderson, M.P., Valley, J.W., 1990. Estimating groundwater exchange with lakes: 1. The stable isotope mass balance method. Water Resour. Res. 26 (10), 2445–2453.

Krupa, S.L., Belanger, T.V., Heck, H.H., Brock, J.T., Jones, B.J., 1998. Krupaseep – the next generation seepage meter. J. Coast. Res. 210–213 Special Issue no. 26.

LaBaugh, J.W., Rosenberry, D.O., 2008. Introduction and characteristics of flow. In: Rosenberry, D.O., LaBaugh, J.W. (Eds.), Field Techniques for Estimating Water Fluxes Between Surface Water and Ground Water U.S. Geological Survey Techniques and Methods 4-D2, Reston, VA, pp. 1–38.

LaBaugh, J.W., Winter, T.C., 1984. The impact of uncertainties in hydrologic measurement on phosphorus budgets and empirical models for two Colordo reservoirs. Limnol. Oceanogr. 29 (2), 322–339.

Landon, M.K., Rus, D.L., Harvey, F.E., 2001. Comparison of instream methods for measuring hydraulic conductivity in sandy streambeds. Groundwater 39 (6), 870–885.

Langhoff, J.H., Christensen, S., Rasmussen, K.R., 2001. Scale Dependent Hydraulic Variability of a Streambed on an Outwash Plain, Ground Water Conference. Maastricht, The Netherlands.

Langhoff, J.H., Rasmussen, K.R., Christensen, S., 2006. Quantification and regionalization of groundwater-surface water interaction along an alluvial stream. J. Hydrol. 320 (3–4), 342–358.

Lautz, L.K., 2010. Impacts of nonideal field conditions on vertical water velocity estimates from streambed temperature time series. Water Resour. Res. 46, W01509. https://doi.org/10.1029/2009WR007917.

Lee, D.R., 1972. Septic Tank Nutrients in Groundwater Entering Lake Sallie, Minnesota. MS Thesis. University of North Dakota 96 pp.

Lee, D.R., 1977. A device for measuring seepage flux in lakes and estuaries. Limnol. Oceanogr. 22 (1), 140–147.

Lee, D.R., 2020. Using Seepage Meters and Mini-Piezometers: Teaching and Related Anecdotes, The Groundwater Project eBooks. University of Guelph in preparation. gw.project.org.

Lee, D.R., Cherry, J.A., 1978. A field exercise on groundwater flow using seepage meters and mini-piezometers. J. Geol. Educ. 27, 6–20.

Lee, D.R., Hynes, H.B.N., 1978. Identification of groundwater discharge zones in a reach of Hillman Creek in southern Ontario. Water Pollut. Res. Can. 13, 121–133.

Lee, D.R., Cherry, J.A., Pickens, J.F., 1980. Groundwater transport of a salt tracer through a sandy lakebed. Limnol. Oceanogr. 25 (1), 45–61.

Lee, B.-J., Lee, J.-H., Kim, D.-H., 2018. An alternative approach to conventional seepage meters: Buoy-type seepage meter. Limnol. Oceanogr. Methods 16 (5), 299–308.

Lesack, L.F.W., 1995. Seepage exchange in an Amazon floodplain lake. Limnol. Oceanogr. 40 (3), 598–609.

Lewandowski, J., Angermann, L., Nützmann, G., Fleckenstein, J.H., 2011. A heat pulse technique for the determination of small-scale flow directions and flow velocities in the streambed of sand-bed streams. Hydrol. Process. 25, 3244–3255.

Lewis, J.B., 1987. Measurements of groundwater seepage flux onto a coral reef: spatial and temporal variations. Limnol. Oceanogr. 32, 1165–1169.

Libelo, E.L., MacIntyre, W.G., 1994. Effects of surface-water movement on seepage-meter measurements of flow through the sediment-water interface. Appl. Hydrogeol. 2 (4), 49–54.

Lien, B.K., 2006. Development and Demonstration of a Bidirectional Advective Flux Meter for Sediment-Water Interface. EPA/600/R-06/122. U.S. Environmental Protection Agency, Cincinnatti.

Lillie, R.A., Barko, J.W., 1990. Influence of sediment and groundwater on the distribution and biomass of Myriophyllum spicatum L. in Devil’s Lake, Wisconsin. J. Freshw. Ecol. 5 (4), 417–426.

Linderfelt, W.R., Turner, J.V., 2001. Interaction between shallow groundwater, saline surface water and nutrient discharge in a seasonal estuary: the Swan–Canning system. Hydrol. Process. 15, 2631–2653.

Liu, G., Knobbe, S., Butler, J.J., 2013. Resolving centimeter-scale flows in aquifers and their hydrostratigraphic controls. Geophys. Res. Lett. 40 (6), 1098–1103.

Lock, M.A., John, P.H., 1978. The measurement of groundwater discharge into a lake by direct method. Int. Rev. Gesamten Hydrobiol. 63 (2), 271–275.

Lodge, D.M., Krabbenhoft, D.P., Striegl, R.G., 1989. A positive relationship between groundwater velocity and submersed macrophyte biomass in Sparkling Lake, Wisconsin. Limnol. Oceanogr. 34 (1), 235–239.

Loeb, S.L., Hackley, S.H., 1988. The distribution of submerged macrophytes in Lake Tahoe, California and Nevada, and the possible influence of groundwater seepage. Verh. Int. Ver. Theor. Angew. Limnol. 23, 1927–1933.

Lowry, C.S., Walker, J.F., Hunt, R.J., Anderson, M.P., 2007. Identifying spatial variability of groundwater discharge in a wetland stream using a distributed temperature sensor. Water Resour. Res. 43 (10), W10408.

Mann, W.B., McBride, M.S., 1972. The hydrologic balance of Lake Sallie, Becker County, Minnesota. 800-D. U.S. Geological Survey, Washington DC.

McBride, M.S., Pfannkuch, H.O., 1975. The distribution of seepage within lakebeds. US Geol. Surv. J. Res. 3 (5), 505–512.

McCobb, T.D., LeBlanc, D.R., 2011. Water-quality data from shallow pond-bottom groundwater in the Fishermans Cove area of Ashumet Pond, Cape Cod, Massachusetts, 2001–2010. 588. U.S. Geological Survey.

McCobb, T.D., LeBlanc, D.R., Massey, A.J., 2009. Monitoring the removal of phosphate from ground water discharging through a pond-bottom permeable reactive barrier. Ground Water Monit. Remediat. 29 (2), 43–55.

Meigs, L.C., Bahr, J.M., 1995. Three-dimensional groundwater flow near narrow surface water bodies. Water Resour. Res. 31 (12), 3299–3307.

Menheer, M.A., 2004. Development of a Benthic-Flux Chamber for Measurement of Ground-Water Seepage and Water Sampling for Mercury Analysis at the Sediment-Water Interface. 2004–5298. U.S. Geological Survey, Reston, VA.

Metge, D.W., Harvey, R.W., Anders, R., Rosenberry, D.O., Seymour, D., Jasperse, J., 2007. Use of carboxylated microspheres to assess transport potential of *Cryptosporidium parvum* oocysts at the Russian River water supply facility, Sonoma County, California. Geomicrobiol J. 24, 231–245.

Meyboom, P., 1966. Unsteady groundwater flow near a willow ring in hummocky moraine. J. Hydrol. 4, 38–62.

Mitchell, D.F., Wagner, K.J., Asbury, C., 1988. Direct measurement of groundwater flow and quality as a lake management tool. Lake Reserv. Manag. 4 (1), 169–178.

Mortimer, R.J.G., Krom, M.D., Boyle, D.R., Nishri, A., 1999. Use of a high-resolution porewater gel profiler to measure groundwater fluxes at an underwater saline seepage site in Lake Kinneret, Israel. Limnol. Oceanogr. 44 (7), 1802–1809.

Mulligan, A.E., Charette, M.A., 2006. Intercomparison of submarine groundwater discharge estimates from a sandy unconfined aquifer. J. Hydrol. 327, 411–425.

Murdoch, L.C., Kelly, S.E., 2003. Factors affecting the performance of conventional seepage meters. Water Resour. Res. 39 (6). https://doi.org/10.1029/2002WR001347.

Naranjo, R.C., Niswonger, R.G., Smith, D., Rosenberry, D., Chandra, S., 2019. Linkages between hydrology and seasonal variations of nutrients and periphyton in a large oligotrophic subalpine lake. J. Hydrol. 568, 877–890.

Oxtobee, J.P.A., Novakowski, K., 2002. A field investigation of groundwater/surface water interaction in a fractured bedrock environment. J. Hydrol. 269, 169–193.

Paulsen, R., 2000. Defining groundwater outcrops in West Neck Bay, Shelter Island, New York using direct contact resistivity measurements and transient underflow measurements. In: Proceedings of the Ground-Water/Surface-Water Interactions Workshop. Environmental Protection Agency, Denver, Colorado, pp. 138–142.

Paulsen, R.J., Smith, C.F., O'Rourke, D., Wong, T., 2001. Development and evaluation of an ultrasonic ground water seepage meter. Groundwater 39 (6), 904–911.

Peng, X., Zhan, H., 2017. Air compressibility effect on Bouwer and Rice seepage meter. Groundwater 55 (6), 899–905.

Rasmussen, W., Lauritzen, C.W., 1953. Measuring seepage from irrigation canals. Agric. Eng. 34, 326–330.

Ridgway, M.S., Blanchfield, P.J., 1998. Brook trout spawning areas in lakes. Ecol. Freshw. Fish 7, 140–145.

Robinson, A.R., Rohwer, C., 1952. Study of Seepage Losses from Irrigation Channels. U.S. Department of Agriculture, Soil Conservation Service.

Robison, A.R., Rowher, C., 1959. Measuring Seepage from Irrigation Channels. 1203. U.S. Department of Agriculture.

Rosenberry, D.O., 2000. Unsaturated-zone wedge beneath a large, natural lake. Water Resour. Res. 36 (12), 3401–3409.

Rosenberry, D.O., 2005. Integrating seepage heterogeneity with the use of ganged seepage meters. Limnol. Oceanogr. Methods 3, 131–142.

Rosenberry, D.O., 2008. A seepage meter designed for use in flowing water. J. Hydrol. 359, 118–130.

Rosenberry, D.O., Hayashi, M., 2013. Assessing and measuring wetland hydrology. In: Anderson, J.T., Davis, C.A. (Eds.), Wetland Techniques Volume 1: Foundations. Springer, Dordrecht, pp. 87–225.

Rosenberry, D.O., LaBaugh, J.W., 2008. Field Techniques for Estimating Water Fluxes Between Surface Water and Ground Water. 4-D2. U.S. Geological Survey, Denver.

Rosenberry, D.O., Menheer, M.A., 2006. A System for Calibrating Seepage Meters Used to Measure Flow Between Ground Water and Surface Water. 2006-5053. U.S. Geological Survey.

Rosenberry, D.O., Morin, R.H., 2004. Use of an electromagnetic seepage meter to investigate temporal variability in lake seepage. Groundwater 42 (1), 68–77.

Rosenberry, D.O., Pitlick, J., 2009a. Effects of sediment transport and seepage direction on hydraulic properties at the sediment-water interface of hyporheic settings. J. Hydrol. 373, 377–391.

Rosenberry, D.O., Pitlick, J., 2009b. Local-scale spatial and temporal variability of seepage and hydraulic conductivity in a shallow gravel-bed river. Hydrol. Process. 23, 3306–3318.

Rosenberry, D.O., Striegl, R.G., Hudson, D.C., 2000. Plants as indicators of focused ground water discharge to a northern Minnesota lake. Groundwater 38 (2), 296–303.

Rosenberry, D.O., LaBaugh, J.W., Hunt, R.J., 2008. Use of monitoring wells, portable piezometers, and seepage meters to quantify flow between surface water and ground water. In: Rosenberry, D.O., LaBaugh, J.W. (Eds.), Field Techniques for Estimating Water Fluxes Between Surface Water and Ground Water. U.S. Geological Survey Techniques and Methods 4-D2, Denver, pp. 39–70.

Rosenberry, D.O., Toran, L., Nyquist, J.E., 2010. Effect of surficial disturbance on exchange between groundwater and surface water in nearshore margins. Water Resour. Res. 46, W06518. https://doi.org/10.1029/2009WR008755.

Rosenberry, D.O., Klos, P.Z., Neal, A., 2012. In situ quantification of spatial and temporal variability of hyporheic exchange in static and mobile gravel-bed rivers. Hydrol. Process. 26 (4), 604–612.

Rosenberry, D.O., Sheibley, R.W., Cox, S.E., Simonds, F.W., Naftz, D.L., 2013. Temporal variability of exchange between groundwater and surface water based on high-frequency direct measurements of seepage at the sediment-water interface. Water

Resour. Res. 49 (5), 2975–2986.

Rosenberry, D.O., Lewandowski, J., Meinikmann, K., Nützmann, G., 2015. Groundwater – the disregarded component in lake water and nutrient budgets. Part 1: effects of groundwater on hydrology. Hydrol. Process. 29 (13), 2895–2921.

Rosenberry, D.O., Briggs, M.A., Delin, G., Hare, D.K., 2016a. Combined use of thermal methods and seepage meters to efficiently locate, quantify, and monitor focused groundwater discharge to a sand-bed stream. Water Resour. Res. 52 (6), 4486–4503.

Rosenberry, D.O., Briggs, M.A., Voytek, E.B., Lane, J.W., 2016b. Influence of groundwater on distribution of dwarf wedgemussels (*Alasmidonta heterodon*) in the upper reaches of the Delaware River, northeastern USA. Hydrol. Earth Syst. Sci. 20 (10), 4323–4339.

Schafran, G.C., Driscoll, C.T., 1993. Flow path-composition relationships for groundwater entering an acidic lake. Water Resour. Res. 29 (1), 145–154.

Schincariol, R.A., McNeil, J.D., 2002. Errors with small volume elastic seepage meter bags. Groundwater 40 (6), 649–651.

Schindler, D.W., 1974. Eutrophication and recovery in experimental lakes: implications for lake management. Science 184, 897–898.

Schindler, D.W., Newbury, R.W., Beaty, K.G., Campbell, P., 1976. Natural water and chemical budgets for a small precambrian lake basin in central Canada. J. Fish. Res. Board Can. 33, 2526–2543.

Schneider, R.L., 1994. Environmental Controls of Plant Species Diversity in Coastal Plain Pondshore Communities. PhD Thesis. Cornell University 268 pp.

Schneider, R.L., Negley, T.L., Wafer, C., 2005. Factors influencing groundwater seepage in a large, mesotrophic lake in New York. J. Hydrol. 310, 1–16.

Schumann, D., 1973. Annual variation of seepage of lakes in the moraine area of the German Democratic Republic, Hydrology of Lakes Symposium. In: Proceedings of the Helsinki Symposium, pp. 101–108 International Association of Hydrological Sciences, Helsinki.

Schuster, P.F., Reddy, M.M., LaBaugh, J.W., Parkhurst, R.S., Rosenberry, D.O., Winter, T.C., Antweiler, R.C., Dean, W.E., 2003. Characterization of lake water and ground water movement in the littoral zone of Williams Lake, a closed-basin lake in north central Minnesota. Hydrol. Process. 17, 823–838.

Sebestyen, S.D., Schneider, R.L., 2001. Dynamic temporal patterns of nearshore seepage flux in a headwater Adirondack lake. J. Hydrol. 247, 137–150.

Sebestyen, S.D., Schneider, R.L., 2004. Seepage patterns, pore water, and aquatic plants: hydrological and biogeochemical relationships in lakes. Biogeochemistry 68, 383–409.

Sebok, E., Duque, C., Kazmierczak, J., Engesgaard, P., Nilsson, B., Karan, S., Frandsen, M., 2013. High-resolution distributed temperature sensing to detect seasonal groundwater discharge into Lake Væng, Denmark. Water Resour. Res. 49 (9), 5355–5368.

Shaw, R.D., Prepas, E.E., 1989. Anomalous, short-term influx of water into seepage meters. Limnol. Oceanogr. 34 (7), 1343–1351.

Shaw, R.D., Prepas, E.E., 1990a. Groundwater-lake interactions: I. Accuracy of seepage meter estimates of lake seepage. J. Hydrol. 119, 105–120.

Shaw, R.D., Prepas, E.E., 1990b. Groundwater-lake interactions: II. Nearshore seepage patterns and the contribution of ground water to lakes in central Alberta. J. Hydrol. 119, 121–136.

Shaw, R.D., Shaw, J.F.H., Fricker, H., Prepas, E.E., 1990. An integrated approach to quantify groundwater transport of phosphorus to Narrow Lake, Alberta. Limnol. Oceanogr. 35 (4), 870–886.

Shinn, E.A., Reich, C.D., Hickey, T.D., 2002. Seepage meters and Bernoulli's Revenge. Estuaries 25 (1), 126–132.

Sholkovitz, E., Herbold, C., Charette, M., 2003. An automated dye-dilution based seepage meter for the time-series measurement of submarine groundwater discharge. Limnol. Oceanogr. Methods 1, 16–28.

Sickbert, T., Peterson, E.W., 2014. The effects of surface water velocity on hyporheic interchange. J. Water Resour. Prot. 6, 327–336.

Simonds, F.W., Swarzenski, P.W., Rosenberry, D.O., Reich, C.D., Paulson, A.J., 2008. Estimates of Nutrient Loading by Ground-Water Discharge into the Lynch Cove Area of Hood Canal, Washington. 2008-5078. U.S. Geological Survey, Reston, VA.

Simpkins, W.W., 2006. A multiscale investigation of ground water flow at Clear Lake, Iowa. Groundwater 44 (1), 35–46.

Skinner, A.J., Lambert, M.F., 2009. Evaluation of a warm-thermistor flow sensor for use in automatic seepage meters. IEEE Sensors J. 9 (9), 1058–1067.

Smith, A.J., Herne, D.E., Turner, J.V., 2009. Wave effects on submarine groundwater seepage measurement. Adv. Water Resour. 32, 820–833.

Solder, J.E.E., 2014. Quantifying Groundwater-Surface Water Exchange: Development and Testing of Shelby Tubes and Seepage Blankets as Discharge Measurment and Sample Collection Devices. MS Thesis. University of Utah 152 pp.

Solder, J.E., Gilmore, T.E., Genereux, D.P., Solomon, D.K., 2016. A tube seepage meter for in situ measurement of seepage rate and groundwater sampling. Groundwater 54 (4), 588–595.

Stanford, J.A., Ward, J.V., 1993. An ecosystem perspective of alluvial rivers: connectivity and the hyporheic corridor. J. N. Am. Benthol. Soc. 12 (1), 48–60.

Taniguchi, M., Fukuo, Y., 1993. Continuous measurements of ground-water seepage using an automatic seepage meter. Groundwater 34 (4), 675–679.

Taniguchi, M., Fukuo, Y., 1996. An effect of seiche on groundwater seepage rate into Lake Biwa, Japan. Water Resour. Res. 32 (2), 333–338.

Taniguchi, M., Burnett, W.C., Smith, C.F., Paulsen, R.J., O'Rourke, D., Krupa, S.L., Christoff, J.L., 2003. Spatial and temporal distributions of submarine groundwater discharge rates obtained from various types of seepage meters at a site in the northeastern Gulf of Mexico. Biogeochemistry 66, 35–53.

Toran, L., Johnson, M., Nyquist, J., Rosenberry, D., 2010. Delineating a road-salt plume in lakebed sediments using electrical resistivity, piezometers, and seepage meters at Mirror Lake, New Hampshire, U.S.A. Geophysics 75 (4), WA75–WA83.

Toran, L., Nyquist, J., Rosenberry, D., Gagliano, M., Mitchell, N., Mikochik, J., 2015. Geophysical and hydrologic studies of lake seepage variability. Groundwater 53 (6), 841–850.

Tryon, M., Brown, K., Dorman, L., Sauter, A., 2001. A new benthic aqueous flux meter for very low to moderate discharge rates. Deep-Sea Res. I Oceanogr. Res. Pap. 48, 2121–2146.

Ulrich, C., Hubbard, S.S., Florsheim, J., Rosenberry, D., Borglin, S., Trotta, M., Seymour, D., 2015. Riverbed clogging associated with a California riverbank filtration system: an assessment of mechanisms and monitoring approaches. J. Hydrol. 529 (Part 3), 1740–1753.

Vogt, T., Schneider, P., Hahn-Woernle, L., Cirpka, O.A., 2010. Estimation of seepage rates in a losing stream by means of fiber-optic high-resolution vertical temperature profiling. J. Hydrol. 380, 154–164.

Walthall, H.G., Reay, W.G., 1993. Groundwater-seepage meter. NASA Tech. Briefs 17 (12), 52.

Wang, W., Li, J., Wang, W., Chen, X., Cheng, D., Jia, J., 2014. Estimating streambed parameters for a disconnected river. Hydrol. Process. 28 (10), 3627–3641.

Warnick, C.C., 1951. Methods of Measuring Seepage Loss in Irrigation Canals. No. 8. University of Idaho Engineering Experiment Station.

Welch, S.J., Lee, D.R., Killey, R.W.D., 1989. A comparison of methods for estimating groundwater recharge from a lake, FOCUS conference on Eastern regional ground water issues, Kitchener, ON, Canada, Oct. 17-19, 1989. [Monograph] In: Proceedings of the FOCUS Conference On Eastern Regional Ground Water Issues, pp. 25–39 Natl. Water Well Assoc., Dublin, OH, United States (USA), Kitchener, ON, Canada.

Williams, R.E., 1968. Flow of ground water adjacent to small, closed basins in glacial till. Water Resour. Res. 4 (4), 777–784.

Winter, T.C., 1976. Numerical Simulation Analysis of The Interaction of Lakes and Ground Water. 1001. U.S. Geological Survey.

Winter, T.C., 1978. Numerical simulation of steady state three-dimensional groundwater flow near lakes. Water Resour. Res. 14 (2), 245–254.

Winter, T.C., Harvey, J.W., Franke, O.L., Alley, W.W., 1998. Ground Water and Surface wAter: A Single Resource. 1139. U.S. Geological Survey, Denver.

Woessner, W.W., Sullivan, K.E., 1984. Results of seepage meter and mini-piezometer study, Lake Mead, Nevada. Groundwater 22 (5), 561–568.

Wojnar, A.J., Mutiti, S., Levy, J., 2013. Assessment of geophysical surveys as a tool to estimate riverbed hydraulic conductivity. J. Hydrol. 482, 40–56.

Wroblicky, G.J., Campana, M.E., Vallett, H.M., Dahm, C.N., 1998. Seasonal variation in surface-subsurface water exchange and lateral hyporheic area of two stream-aquifer systems. Water Resour. Res. 34 (3), 317–328.

Zamora, C., 2007. Estimating Water Fluxes Across the Sediment-Water Interface in the Lower Merced River, California. 2007-5216. U.S. Geological Survey, Reston.

Zhu, T., Fu, D., Jenkinson, B., Jafvert, C., 2015. Calibration and application of an automated seepage meter for monitoring water flow across the sediment-water interface. Environ. Monit. Assess. 187 (4), 1–11.

Zimmerman, C.F., Montgomery, J.R., Carlson, P.R., 1985. Variability of dissolved reactive phosphate flux rates in nearshore estuarine sediments: effects of groundwater flow. Estuaries 8 (2B), 228–236.

Zuber, A., 1970. Method for determining leakage velocities through the bottom of reservoirs. Isot. Hydrol. 129 (48), 761–771 IAEA-SM.