A System for Calibrating Seepage Meters Used to Measure Flow Between Ground Water and Surface Water

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U.S. Department of the Interior
U.S. Geological Survey

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Cover photo by Donald Rosenberry: seepage meters in Shingobee Lake, Northern Minnesota.

Contents

Figures

Tables

Conversion Factors

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
millimeter (mm)	0.03937	inch (in)
Area		
square meter (m^2)	10.76	square foot (ft^2)
square centimeter (cm^2)	0.1550	square inch (in^2)
square centimeter (cm^2)	0.001076	square foot (ft^2)
Volume		
liter (L)	0.2642	gallon (gal)
liter (L)	1.057	quart (qt)
liter (L)	61.02	cubic inch (in^3)
milliliter (mL)	0.06102	cubic inches (in^3)
cubic meter (m^3)	264.2	gallon (gal)
cubic meter (m^3)	35.31	cubic foot (ft^3)
Flow rate		
milliliter per minute (ml/min)	0.06102	cubic inch per minute (in^3/min)
centimeter per day (cm/d)	0.0328	foot per day (ft/d)
Pressure		
kilopascal (kPa)	0.1450	pound per square inch (psi)
kilopascal (kPa)	0.009869	atmosphere, standard (atm)
kilopascal (kPa)	0.3346	feet of water (at 39 degrees F)
kilopascal (kPa)	0.01	bar

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F=(1.8×°C)+32

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C=(°F-32)/1.8

A System for Calibrating Seepage Meters Used to Measure Flow Between Ground Water and Surface Water

By Donald O. Rosenberry and Michael A. Menheer

Abstract

A system has been developed for generating controlled rates of seepage across the sediment-water interface representing flow between ground water and surface water. The seepage-control system facilitates calibration and testing of seepage measurement devices commonly called seepage meters. Two slightly different seepage-control systems were evaluated. Both designs make use of a 1.5-m-diameter by 1.5-m-tall polyethylene flux tank partially filled with sand that overlies a pipe manifold and diffuser plate to provide a uniform flux of water through the sand. The flux tank is filled with water to maintain a water depth above the sand bed of about 0.6 m. Flow is generated by routing water through tubing that connects an adjustable-height reservoir to the base of the flux tank, through the diffuser plate and sand, and across the sediment-water interface. Seepage rate is controlled by maintaining a constant water depth in the reservoir while routing flow between the reservoir and the flux tank. The rate of flow is controlled by adjusting the height of the reservoir with a manually operated fork lift. Flow from ground water to surface water (inflow) occurs when the water surface of the reservoir is higher than the water surface of the flux tank. Flow from surface water to ground water (outflow) occurs when the water surface of the reservoir is lower than the water surface of the flux tank. Flow rates as large as ±55 centimeters per day were generated by adjusting the reservoir to the extremes of the operable range of the fork lift.

Water in the reservoir is maintained at a nearly constant depth by pumping return flow between the reservoir and flux tanks based on output from a submersible pressure transducer placed in the reservoir. A datalogger switches the pump on and off at appropriate intervals to maintain a nearly constant water depth inside the reservoir, which maintains a virtually constant hydraulic gradient between the reservoir and flux tanks. The datalogger also records flow, in units of volume per time, as measured by an in-line flowmeter positioned between the base of the flux tank and the reservoir. Seepage flux in units of distance per time is determined by dividing the flowmeter output by the surface area at the sediment-water interface in the flux tank.

Spatial heterogeneity in seepage was evident in both flux tanks in spite of attempts to minimize heterogeneity during tank construction. Medium sand was used in both flux tanks and care was taken to homogenize the sand during and after filling of the tanks. Time was provided for release or dissolution of trapped air, and water was circulated to remove fine-grained sediments prior to system use. In spite of these precautions, seepage measured with five to six small 20.25-cm-diameter seepage meters varied by about a factor of two. Use of larger diameter seepage meters, which cover a larger percentage of the sediment surface of the flux tanks, greatly minimized measured seepage heterogeneity.

The seepage-control system was used to demonstrate that seepage-meter efficiency is sensitive to the type of seepage-meter bag and that bag-measured seepage rate is sensitive to the duration of the seepage-meter measurement only during very short measurement times.

The in-line flowmeter used with this system is incapable of measuring seepage rates below about 7 centimeters per day. Smaller seepage rates can be measured manually. The seepage-control system also can be modified for measuring slower seepage rates with the use of two flowmeters and a slightly different water-routing system, or a fluid-metering pump can be used to control flow through the flux tank instead of an adjustable-height reservoir.

Introduction

The recognition that ground water and surface water are connected and should be considered by water-resource scientists and managers as one resource (Winter and others, 1998) has led to increased interest in quantifying seepage between ground water and surface water. Seepage meters commonly are used to determine flow across the sediment-water interface and are one of the few methods available that provide a direct measurement of this exchange. These devices have been in use since the 1940s and 1950s when considerable effort was directed toward quantifying water loss from irrigation canals (Israelson and Reeve, 1944; Warnick, 1951; Robinson and Rohwer, 1952). However, more recent versions are smaller, easier to deploy, and inexpensive, making them a viable option for many water-resource studies.

The "half-barrel" seepage meter (Lee, 1977) has changed little since its inception in the mid 1970s (fig. 1). Originally consisting of the cut-off end of a steel storage drum to which a 4-liter plastic bag was attached, the device has been modified for use in a variety of environments, including near-shore (Lee and Cherry, 1978), deep-water (Boyle, 1994), and high-energy environments where a seepage meter would need to resist substantial wave- or current-generated forces (Cherkauer and McBride, 1988). Various sizes and types of chambers have been used, including coffee cans (Asbury, 1990), inverted plastic trash cans, lids from desiccation chambers (Duff and others, 1999), and galvanized stock tanks (Landon and others, 2001; Rosenberry and Morin, 2004). Considerable discussion also has been raised regarding the appropriate sizes and types of collection bags (for example Erickson, 1981; Shaw and Prepas, 1989; Cable and others, 1997; Isiorho and Meyer, 1999; Murdoch and Kelly, 2003).

All seepage meters under represent the natural flux of water across the sediment-water interface. This is due to the cumulative resistance to flow caused by routing water through the seepage cylinder, through the bag-connection plumbing, and into or out of the bag. Early devices used small-diameter glass, metal, or plastic tubes driven through rubber stoppers to connect the bag to the seepage cylinder. Substantial resistance to flow, or inefficiency, was generated when higher rates of seepage caused water to flow rapidly through these small-diameter tubes (Fellows and Brezonik, 1980; Rosenberry and Morin, 2004). Seepage-meter correction factors have been determined for various seepage-meter designs by comparing seepage rates generated in a seepage-flux tank with seepage rates from seepage meters installed in the calibration tanks. Reported values have ranged from 1.05 to 1.74 (table 1). This inefficiency has declined over time with improvements in seepage-meter design.

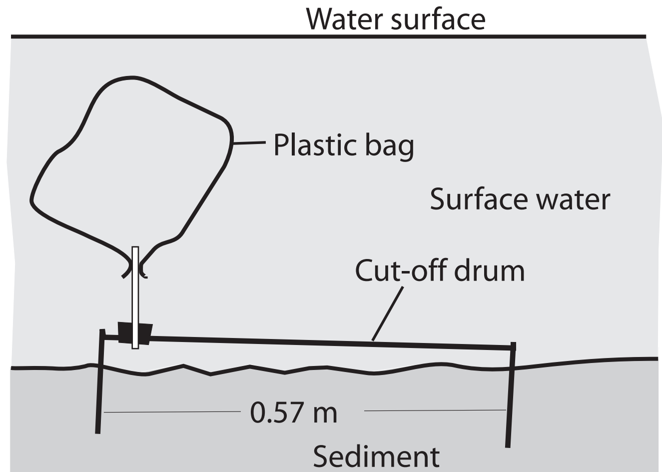


Figure 1. Half-barrel seepage meter (from Lee (1977)).

Many investigators now use larger-diameter bag-connection tubing to increase the efficiency of the seepage meter (Harvey and others, 2000; Rosenberry and Morin, 2004; Rosenberry, 2005). In addition, several types of automated seepage meters now exist that do not require the use of a seepage bag (Krupa and others, 1998; Paulsen and others, 2001; Taniguchi and Iwakawa, 2001; Tryon and others, 2001; Sholkovitz and others, 2003; Menheer, 2004; Rosenberry and Morin, 2004). Despite these improvements, inefficiencies remain that need to be quantified.

Table 1 Reported correction factors to adjust seepage-meter flow rates to actual rates.

Citation	Correction factor
(Erickson, 1981)	1.43 (flow from ground water to surface water)
(Erickson, 1981)	1.74 (flow from surface water to ground water)
(Cherkauer and McBride, 1988)	1.6
(Dorrance, 1989)	1.61
(Asbury, 1990)	1.11
(Belanger and Montgomery, 1992)	1.3
(Murdoch and Kelly, 2003)	1.25
(Rosenberry, 2005)	1.05

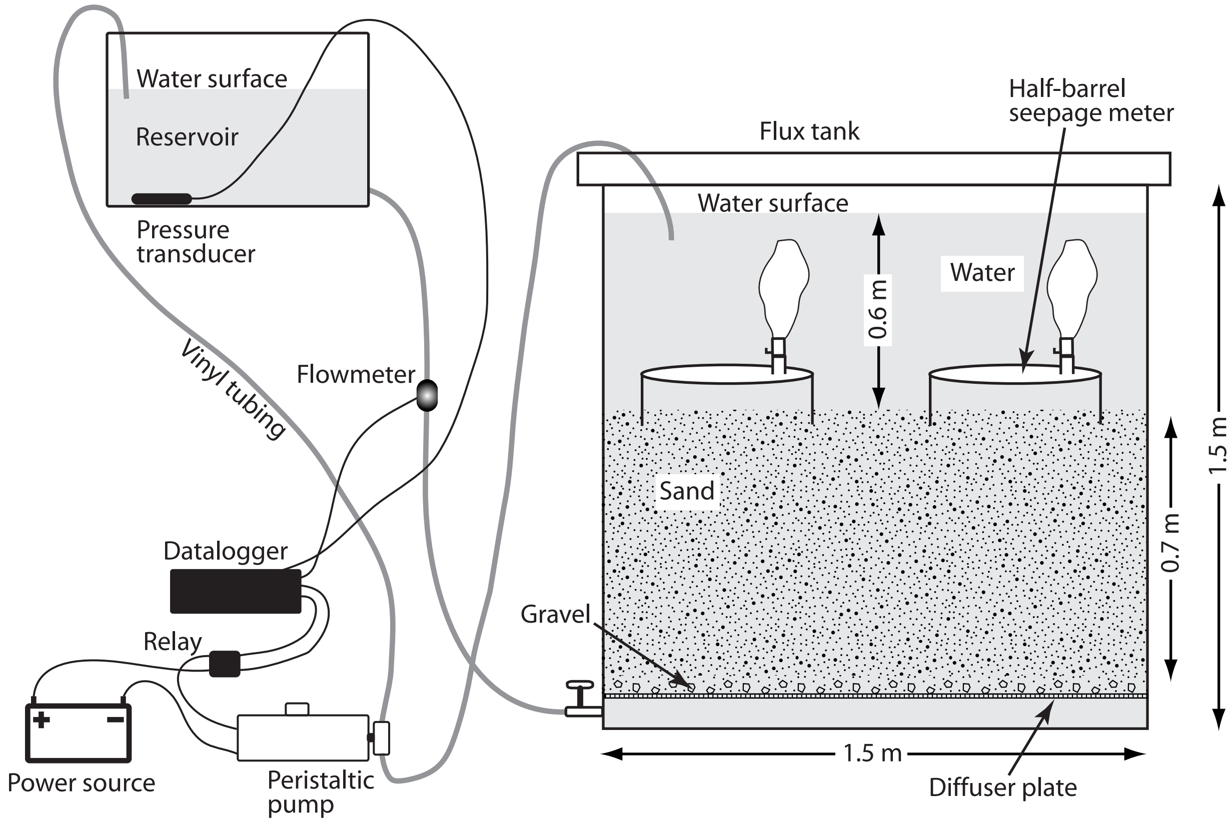


Figure 2. Major components of seepage-flux calibration system.

Determining the efficiency of existing and future seepage-meter designs requires the ability to generate a range of known seepage fluxes across a sediment-water interface. Several reports have described devices for generating controlled rates of seepage (Lee, 1977; Erickson, 1981; McBride, 1987; Shaw and Prepas, 1989; Asbury, 1990; Belanger and Montgomery, 1992). Most of these devices were only briefly described or were built for testing a specific design of seepage meter. A detailed description of a seepage-meter calibration system would facilitate the building and testing of various designs of seepage meters.

Purpose and scope

This report describes the design and construction of a seepage-control system built for the purpose of determining the efficiency of seepage meters that measure the flux of water across the sediment-water interface. Calibration of seepage meters with this system allows the determination of a correction factor that compensates for measurement inefficiencies. The seepage-meter correction factor converts seepage flux measured in the field to actual seepage flux. The seepage-control system provides precise control of water flow across the sediment-water interface, representing flow either from ground water to surface water or from surface water to ground water. The circular flux tank is large enough to allow installation of several typically sized seepage meters or one relatively large seepage meter.

The seepage-control system also was used to determine the effects of variations in seepage-meter design and operation on measured seepage rates. Examples of tests that can be done in this controlled environment include determination of seepage-meter bag-connection time, and bag type, on measured seepage rates relative to known seepage rates.

System components and overview of operation for calibrating seepage meters

The seepage-control system consists of a large flux tank, in which seepage across the sediment-water interface

Figure 3. Plastic tank used as the flux chamber. Drywall buckets (19-liter (5-gallon)) shown for scale.

is generated, and a smaller, adjustable-height reservoir (fig. 2). The polyethylene flux tank is 1.5 m in diameter and 1.5 m tall. Water is routed through flexible plastic (vinyl) tubing from an adjacent, much smaller reservoir to the base of the flux tank, through a diffuser plate and an overlying 0.7-m-thick bed of sand, and across the sediment-water interface to standing water in the tank that is approximately 0.6 m deep. Thicknesses of sand and water were selected to maximize sand thickness while still allowing an adequate water depth to fully submerge a variety of seepage meter types and sizes.

The flow rate and direction of flow across the sediment-water interface is controlled by adjusting the height of the reservoir relative to the water surface in the flux tank. If the water surface in the reservoir is higher than the water surface in the flux tank, flow from ground water to surface water, referred to here as inflow, will occur in the flux tank. If the water surface in the reservoir is lower than the water surface in the flux tank, flow from surface water to ground water, referred to here as outflow, will occur in the flux tank. At any given reservoir height, constant water depth in the reservoir and, therefore, constant flow between the reservoir and the seepage tank, is maintained with the use of a submersible pressure transducer that measures the depth of water in the reservoir. A datalogger records output from the pressure transducer and is programmed to control a peristaltic pump that pumps water between the flux tank and the reservoir. The datalogger turns the pump on and off at appropriate intervals to maintain a nearly constant water depth inside the reservoir. This ensures a virtually constant head difference that drives flow between the reservoir and the flux tank and, therefore, through the sand bed and across the sediment-water interface inside the flux tank.

Flux tank construction

Two slightly different versions of the flux tank are reported here; they are referred to as tank 1 and tank 2. In many cases, identical components are used. However, where components vary, both versions are described to provide additional information regarding options for construction and operation.

A 1.5-m-diameter by 1.5-m-tall (5 ft by 5 ft) polyethelyne tank with a capacity of 2,840 L (750 gallons) was selected for both flux tanks (fig. 3). Tank walls were 9.5 millimeters (mm) thick. The tank diameter is large enough to allow installation of four standard half-barrel seepage chambers.

Diffuser plates used for the two flux tanks were slightly different. A 13-mm-thick polyvinyl chloride (PVC) plate was used for tank 1 (fig. 4A). Because a PVC plate wider than 1.2 m (4 feet) could not be obtained, two pieces were welded together and then cut to create a 1.5-m-diameter circular plate. Holes 1.6 mm in diameter were drilled in a grid pattern to

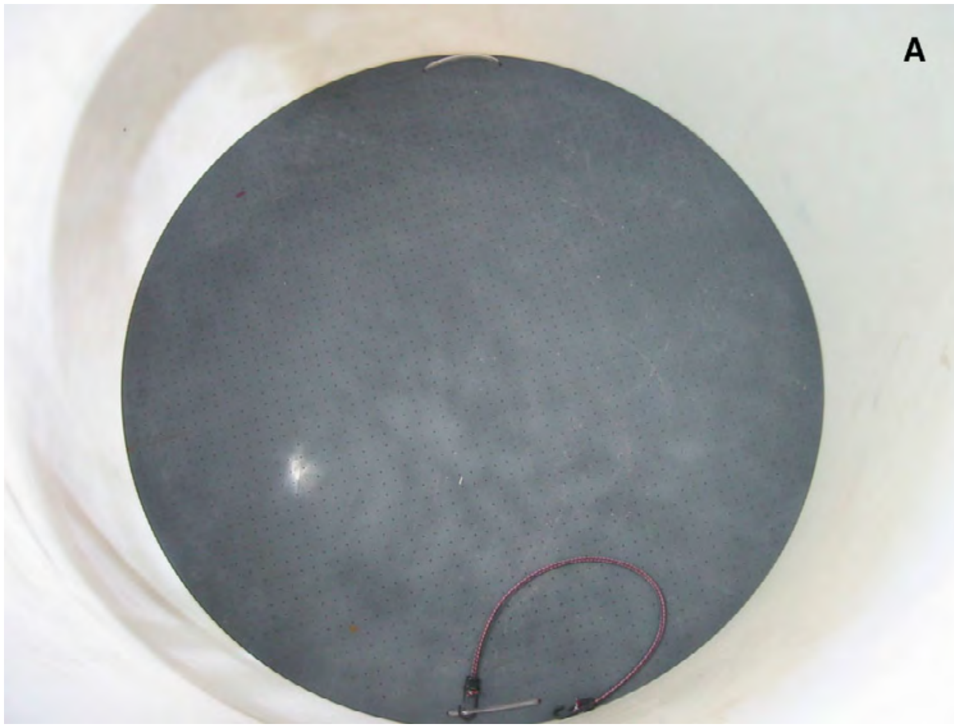
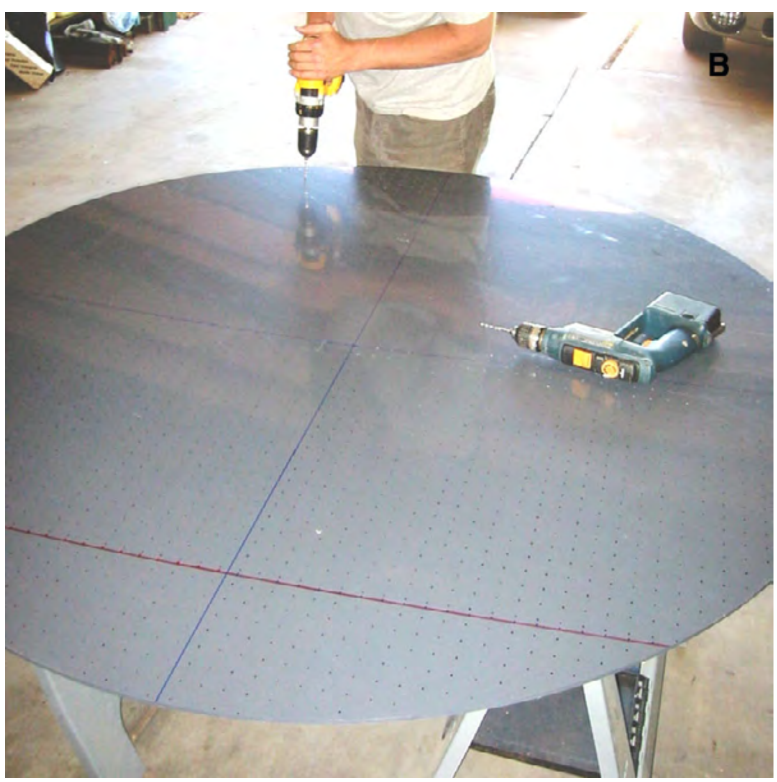


Figure 4. (A) Diffuser plate shown installed in tank 1. (B) Drilling 3.2-mm-diameter holes in diffuser plate for tank 2.



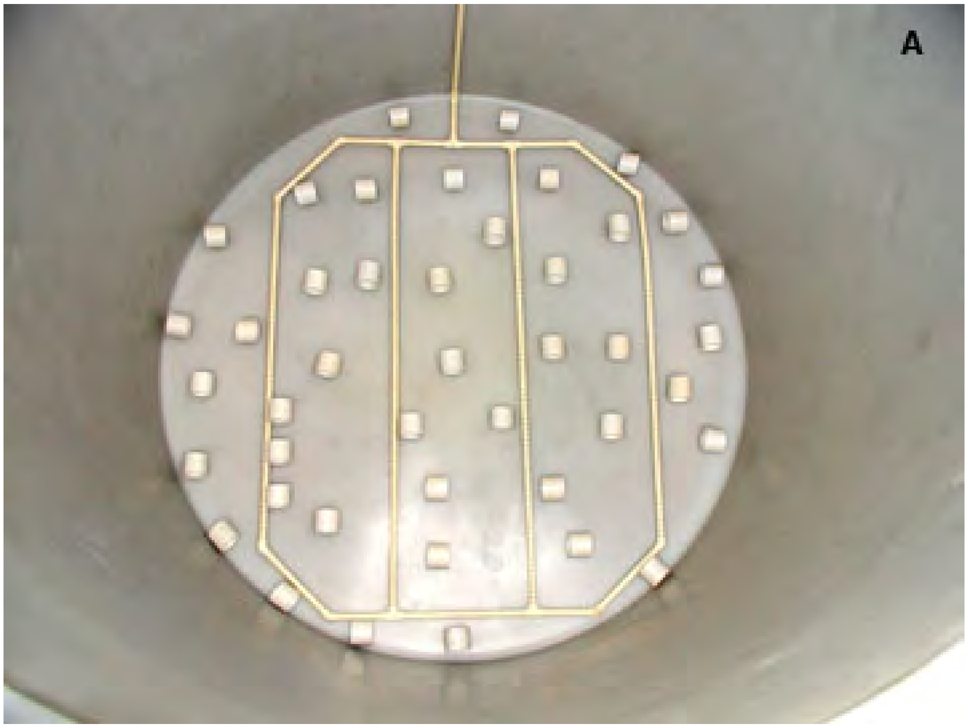
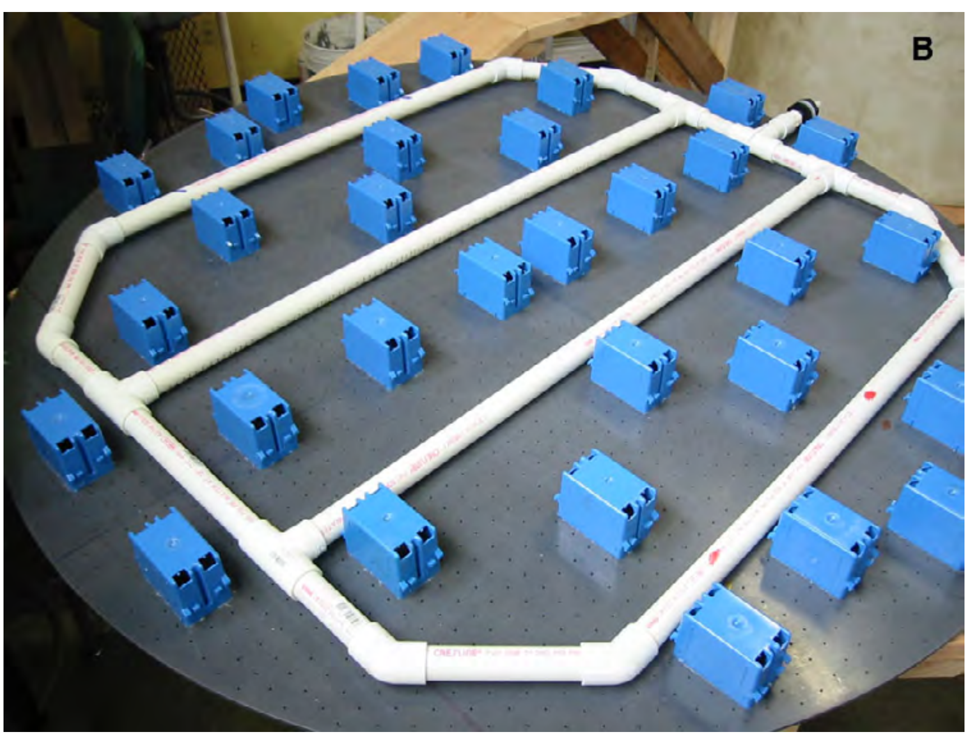


Figure 5. (A) PVC couplings used as supports for tank 1 diffuser plate. (B) Plastic electrical outlet boxes used as supports for tank 2 diffuser plate. Water-distribution plumbing shown on both A and B.



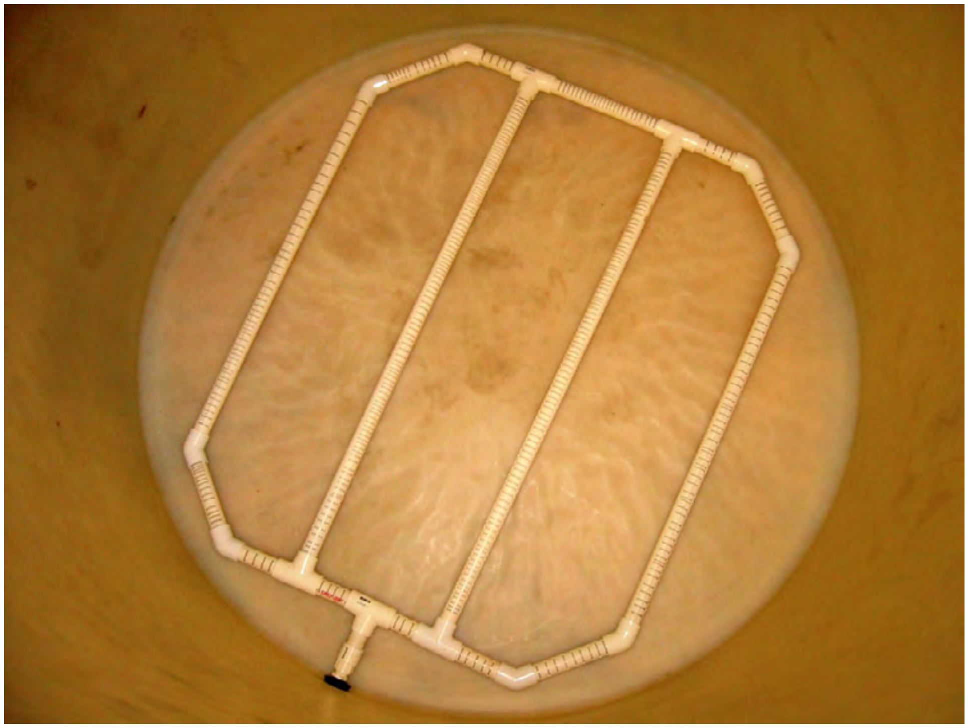


Figure 6. Slotted water-distribution manifold positioned in the bottom of tank 2 and attached to bulkhead fitting.

create a uniform distribution of water throughout the plate. For tank 2, a 6.5-mm-thick PVC plate was cut in a circle so it would just fit inside the seepage tank; the sheet was wide enough so as to not require welding. A grid of 3.2-mm-diameter holes was drilled in the PVC plate to allow even distribution of water flow across the plate (fig. 4B). For tank 1, PVC couplings were used to support the plate and the weight of sand that rests on top of the plate (fig. 5A). For tank 2, plastic electrical outlet boxes were used to support the PVC plate (fig. 5B). Both options are strong and inexpensive. Support pieces were glued in place with silicone sealant so that they blocked a minimum number of drilled holes in the tank 1 diffuser plate. For tank 2, the knock-out pieces in the electrical-outlet boxes were removed and boxes positioned so that no holes were blocked in the diffuser plate.

Water is distributed through a manifold of slotted PVC pipes beneath the diffuser plate. For tank 1, water was routed over the top of the tank and down the inside wall to the manifold system, eliminating the need to drill any holes in the tank. For tank 2, the manifold was connected to a bulkhead fitting installed in a 31.75-mm-diameter (1.25-in-diameter) hole drilled in the side of the tank near the base (fig. 6). For both tanks, the diffuser plate was carefully lowered into place and then silicone caulk was used to seal the edge of the plate to the side of the tank to prevent any preferential flow around the edge of the diffuser plate.

A geotextile fabric consisting of nylon monofilament with 300-micron openings and 44 percent open space was cut to fit, placed over the PVC diffuser, and covered with gravel. The textile fabric and gravel were intended to ensure that holes in the diffuser plate did not become clogged with fine-grained sediment. A 60-mm-thick layer of fine gravel with a median diameter of 4 mm was placed in tank 1. An 80-mm-thick layer of medium gravel with a median diameter of 11 mm was placed over the geotextile fabric in tank 2. Sand from an aggregate supplier was placed on top of the gravel. Medium sand of 0.75-mm median diameter was used in tank 1. Medium sand with a median diameter of 0.52 mm was used in tank 2. Both tanks were filled with tap water. Fresh water was pumped through the sand for several hours to wash out fines and organic debris. Once the initial flushing was finished, the reservoir was connected to the flux tank and water was circulated through the sand for several more hours. No seepage measurements were made for at least a week to allow any trapped gas to escape from the sand. During this time, water was circulated through the sand several times to aid in the removal of trapped gas.

The size of the reservoir is not critical to the design of this seepage-calibration system. A 58-cm-diameter cut-off end of a plastic storage drum was used as reservoir 1. For reservoir 2, a 57-cm-diameter cut-off end of a plastic storage drum was used, the same type that was used to build cylinders for standard half-barrel seepage meters. A 0-69 kilopascal (kPa) (0-10 pounds per square inch (psi)) submersible pressure transducer was used to measure the water level inside reservoir 1. A 0-34.5 kPa (0-5 psi) submersible pressure transducer was

Figure 7. (A) Pneumatic foot-pump-operated fork lift used to adjust reservoir for tank 1. (B) Hand-crank fork lift used to adjust reservoir for tank 2.

Figure 8. In-line paddlewheel flowmeter.

used to measure the water level inside reservoir 2. The datalogger to which the pressure transducer was connected was programmed to allow a 1.5-mm change in water level before the peristaltic pump was turned on to route water to or from the surface water in the flux tank and reset the stage in the reservoir. This process maintained a nearly constant hydraulic-head difference between the reservoir and the flux tank during the entire time the reservoir was set at a specific height relative to the flux tank. Any range in reservoir stage could be programmed, but a 1.5-mm range was determined to be a good compromise between accuracy and frequency of operation of the peristaltic pump. For a less sensitive pressure transducer (for example, a 0-103 kPa range), this level of accuracy likely would not be possible. The pump was connected to a power source through a relay that was controlled by the datalogger (fig. 2). For flux tank 1, the relay switched direct current (DC) power to a peristaltic pump. For flux tank 2, an alternating-current (AC)-control relay was used to switch AC power to a peristaltic pump.

The height of the reservoir relative to the water surface of the flux tank was controlled with a manually operated fork lift. For tank 1, a foot-pump-operated hydraulic fork lift provided a range of heights for the water surface of the reservoir of about +1.7 to –1.1 m relative to the constant stage that was maintained in the flux tank (fig. 7A). For tank 2, a hand-crank fork lift provided a range in reservoir-stage height from +1.1 to -1.3 m relative to the water level in the flux tank (fig. 7B). For both tanks, additional height for generating larger positive gradients (seepage from the sand in the tank to surface water) could be attained by placing the reservoir on top of a container placed on the fork lift.

Operation of the seepage-control system

When flow from ground water to surface water (inflow) was generated by positioning the reservoir’s water surface higher than that in the flux tank, the directional control switch on the peristaltic pump was set to pump surface water from the flux tank to the reservoir. The pumped water re-supplied loss due to gravity flow from the reservoir to the flux tank. When flow from surface water to ground water (outflow) was generated by setting the reservoir’s water surface lower than that in the flux tank, the toggle switch on the peristaltic pump was set to pump water from the reservoir to surface water in the flux tank.

For both inflow and outflow, rate of flow between the reservoir and the seepage tank was monitored with a paddlewheel-type in-line flowmeter (fig. 8). The paddlewheel, which spins at a rate proportional to the velocity of water flowing through the meter orifice, sends an electrical pulse to the datalogger for each revolution. The datalogger sums the pulses over each 10-second time increment, and a multiplier and offset are used to convert pulses per 10 seconds to flow velocity. The flowmeter was capable of measuring flow rates ranging from 110 to 2,600 milliliters per minute (mL/min). This translated to seepage fluxes in the flux tank ranging from 8.7 to 205 centimeters per day (cm/d) (obtained by converting pulses to flow in milliliters per minute, and then multiplying by 1,440 minutes per day and dividing by the surface area of the calibration tank (18,242 cm^2). The actual upper limit of flow in the flux tank is determined by the maximum head difference that can be generated by the fork lift. For the hydraulic fork lift used with tank 1, the practical limits in seepage flow ranged from -50 to +50 cm/d. For the hand-crank fork lift used with tank 2, the limits ranged from -55 to +55 cm/d. Seepage rates are much larger if the flowmeter, and its asso-

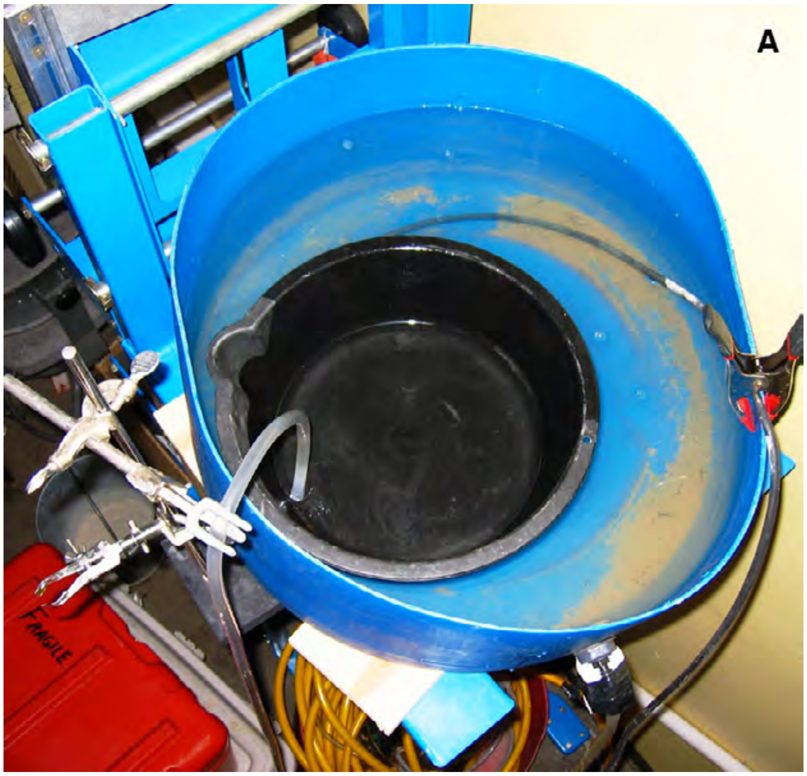


Figure 9. Floating pan used to check volumetric rate of flow from tank to reservoir. (A) Floating pan in reservoir measuring flow from ground water to surface water; (B) floating pan in seepage tank measuring flow from surface water to ground water.

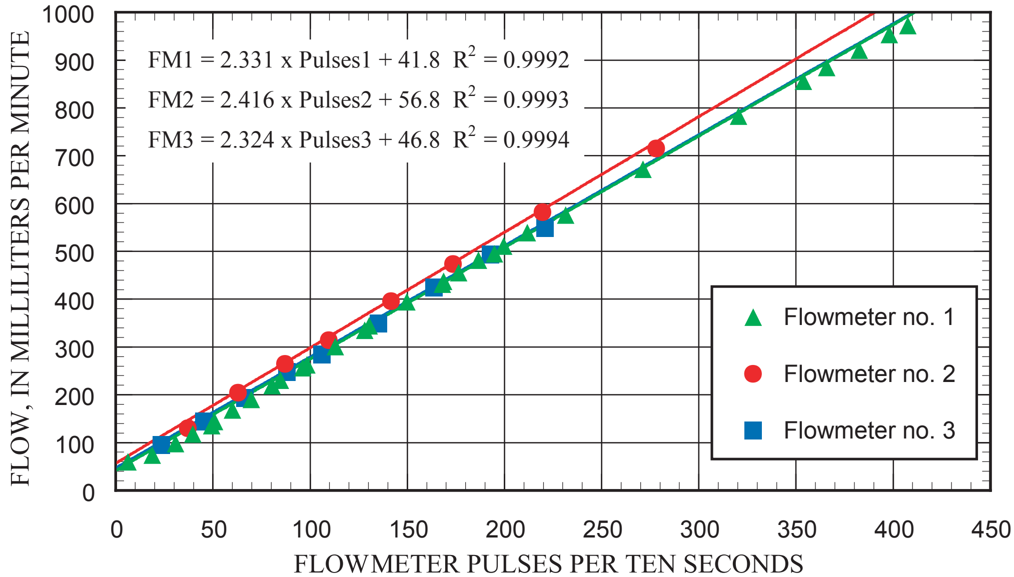


Figure 10. Linear regression relations between flowmeter pulses and flow from the reservoir to the tank for three flowmeters. [FM1, FM2, FM3; flow, in ml/min, indicated by flowmeter no. 1, 2, 3 respectively]

ciated resistance to flow, is removed. For example, without an in-line flowmeter, a seepage rate of 240 cm/d was generated in tank 1 with the water level in the reservoir only 39 cm higher than the surface water in the seepage tank.

Although the manufacturer of the in-line flowmeter supplied information for converting flowmeter pulses to a volumetric flow (for example, flow in milliliters per minute), greater accuracy could be obtained by individually calibrating each flowmeter used in the study to a separately measured, known rate of flow. Therefore, flow rates also were measured by routing water into a plastic pan floated in the tank that received return flow supplied by the peristaltic pump. Because water levels in both tanks were held virtually constant (level in the smaller-diameter reservoir was allowed to change by only 1.5 mm), time-averaged return flow must equal gravity-driven flow from one tank to the other. If inflow seepage was generated, the pan was floated in the reservoir (fig. 9A). If outflow seepage was generated, the pan was floated in the flux tank (fig. 9B). In both cases, time and volume were recorded while water was routed into the floating pan. After several pump cycles, the pan was removed, the volume of water in the pan was measured, and the volume per time was the time-averaged flow rate for a particular reservoir height that was held constant during the flow measurement. If water is routed to the floating pan for several pump cycles, and the pan measurement is always conducted so that the timed interval starts and stops just after the pump turns off, the measurement is quite accurate. Averages of flowmeter pulses summed over 10-second intervals were plotted in relation to volume of water collected in the floating pan for three flowmeters (fig. 10). Linear-regression relations show that two of the three flowmeters provided very similar data. Data from flowmeter number 2 indicated a slightly different multiplier and offset. The zero intercepts for the three flowmeter plots shown in figure 10 indicate that they are capable of measuring flow smaller than the manufacturer-stated minimum flow rate of 110 mL/min. However, at pulse rates slower than about 1.5/sec (about 80-90 mL/min, depending on the flowmeter), the paddlewheel in the flowmeter occasionally stops turning and the output goes to zero.

Stability of flow

The method of controlling flow by varying the difference in head between the reservoir and the flux tank works well for large gradients that generate large rates of seepage. However, flow stability is decreased somewhat when smaller seepage rates are generated. The variability in seepage flux during a relatively small rate of flow is much larger than the variability in seepage flux during a relatively large rate of flow. In tank 1, for example, flow was maintained at an average rate of 26 cm/d for 1.5 hours and then decreased to an average rate of 7.5 cm/d for slightly longer than 2.5 hours (fig. 11A, B). During the faster flow test, the standard deviation was 0.06 but during the slower flow test the standard deviation increased to 0.14. In tank 2, flow was maintained at an average rate of 35.1 cm/d

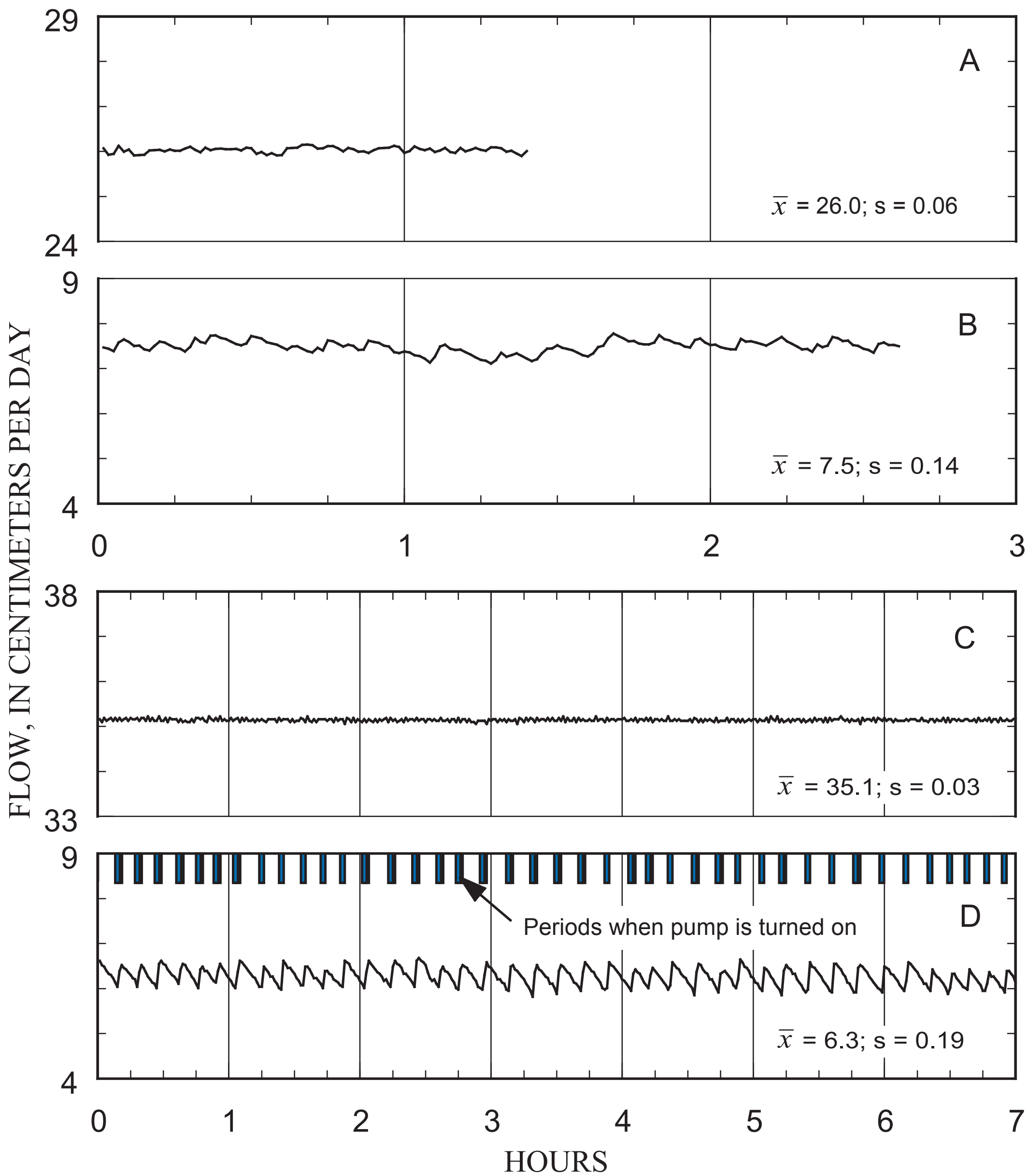


Figure 11. Variability in flow for relatively fast flow (A) and relatively slow flow (B) measured in tank 1, and relatively fast flow (C) and relatively slow flow (D) measured in tank 2. $\overline{x}$ = average; s = standard deviation.

for 7 hours, and then reduced to an average rate of 6.3 cm/d for 7 additional hours (fig. 11C, D). During the faster flow test, the standard deviation was only 0.03 cm/d, but during the slower flow test the standard deviation was 0.19 cm/d. The vertical bars in figure 11B indicate periods when the pump was turned on. It is evident that, as the pump cycled on and off, and as the head in the tank varied over a range of 1.5 mm during the slower flow test in tank 2, seepage varied cyclically over a range of 0.6 cm/d.

It is interesting to note that, during faster flow, the standard deviation in tank 1 is larger than in tank 2 but, during slower flow, the standard deviation in tank 1 is smaller than in tank 2. This is due to two factors: (1) use of a less accurate 0-69 kPa (0-10 psi) pressure transducer in reservoir 1 and (2) a smaller total resistance to flow between the reservoir and flux tank in seepage-system 2.

The less accurate pressure transducer in reservoir 1 did not maintain water level as precisely as the 0-34.5 kPa pressure transducer that was used in reservoir 2. Therefore, variability in seepage was less consistent in tank 1 (fig. 11A, B) than in tank 2 (fig. 11C, D).

Discounting the use of pressure transducers with different accuracy capabilities in the two reservoirs, flow variability should have been smaller because of the finer-grained sand in tank 2. A smaller hydraulic conductivity would have required a greater head difference to drive an equal amount of seepage in the two seepage tanks, and a 1.5-mm variability in that head difference would have represented a smaller percentage change in gradient and, therefore, a smaller variation in seepage per pump cycle. However, standard deviation in the tank-2 system was larger than in the tank-1 system, indicating that the total resistance to flow was smaller in the tank-2 system. This may be related to the use of larger diameter tubing and fittings in the tank-2 system. Standard deviation for the tank-2 slow flow example also may have been larger because the mean seepage flux in the slow flow example from tank 2 (fig. 11D) was slightly smaller than the mean seepage flux in the slow flow example from tank 1 (fig. 11B).

The larger variability of seepage flow in the test tanks during slow seepage rates is still quite small relative to the variability of seepage-meter flux indicated by replicate measurements in the flux tanks and relative to spatial variability

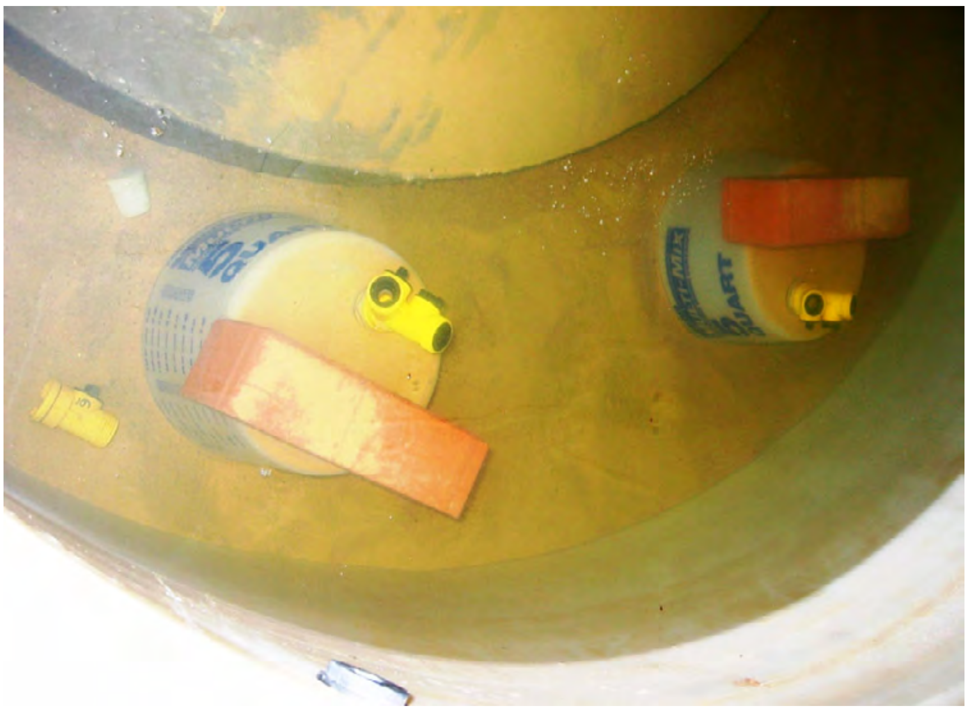


Figure 12. Paint-bucket seepage cylinders (20.25-cm-diameter) installed inside tank 2. Bricks resting on top of bucket are to counter buoyancy of the plastic. A silicone stopper and a hardware fitting are visible on the sand bed of the seepage tank. A large-diameter metal seepage cylinder is visible at the top of the photograph.

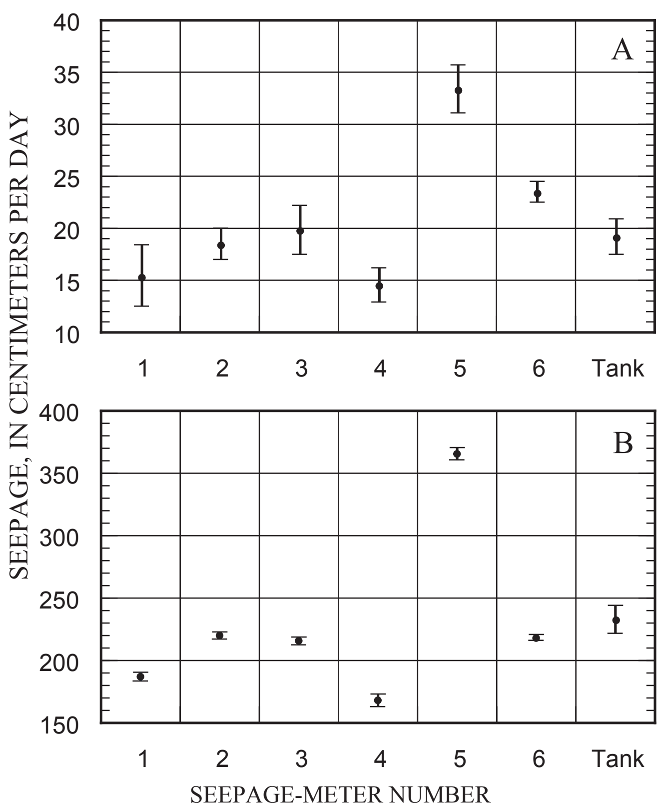


Figure 13. Spatial variability of seepage flux in tank 1 as measured by six 20.25-cm-diameter seepage meters at (A) a relatively slow seepage rate and (B) an order-of-magnitude faster seepage rate.

of seepage flux in the seepage tanks (discussed in the next section). For the purpose of calibrating seepage meters, the short-term seepage variability is not a considerable problem because seepage-meter measurements are conducted for longer durations during slow seepage rates, and any short-term seepage-flux variation is averaged over the duration of the seepage-meter measurements. Nevertheless, flow stability can be improved by reprogramming the datalogger to maintain water level in the reservoir within a range smaller than the 1.5-mm range used in this study.

Uniformity of flow through sand

Several studies have indicated that seepage measured by closely spaced seepage meters can vary substantially. Shaw and Prepas (1990) indicated that seepage in a lake varied by a factor of two or more between two seepage meters spaced only 1 meter apart. Rosenberry (2005) indicated that seepage can vary by an order of magnitude or more on a scale of several meters. In contrast to the natural environment, tests conducted in a seepage-meter calibration tank assume that the distribution of flow across the sediment-water interface is relatively uniform. However, seepage-meter measurements made in both flux tanks indicate that substantial spatial heterogeneity in seepage exists even in homogeneously distributed sand, indicating that several seepage meters should be distributed across the flux tank to average out the effects of heterogeneity during seepage-meter efficiency tests.

Small-diameter seepage meters were constructed from 20.25-cm-diameter plastic paint-mixing containers (fig. 12). These meters were spaced randomly across tank 1, and seepage through the meters was measured at a relatively slow flow and a very fast flow (fig. 13). Considerable spatial heterogeneity is indicated by the seepage-meter data. During the slow flow test, averages of three measurements made at each seepage meter ranged from 14.6 to 33.4 cm/d. Standard deviations ranged from 0.9 at meter 6 to 2.8 at meter 1. The average value for seepage measured at all six seepage meters was 20.9 cm/d, slightly larger than the 19.2 cm/d value indicated by the flowmeter connected to the flux tank (fig. 13A). When flow was increased by approximately an order of magnitude, the relative seepage rates were maintained while the difference in seepage rate from one location to another increased, also by about an order of magnitude (fig. 13B). The range of seepage indicated by the fast-flow seepage-meter measurements was much larger than during the slow flow tests, with averages of measurements made at each paint-bucket seepage meter ranging from 168 to 365 cm/d. The average of seepage rates determined at all six seepage meters was 229 cm/d, whereas seepage through the flux tank measured with the floating-pan method was 233 cm/d.

Seepage heterogeneity was shown to exist in tank 1 through random placement of seepage meters. Heterogeneity was tested in tank 2 by placing seepage meters evenly across the tank along three different axes while seepage was maintained at a constant rate of flow (fig. 14). Seepage rates along each axis, determined by averaging values from the five meters positioned along each axis, were 43.5, 43.8, and 44.3 cm/d. Average seepage rates at each seepage-meter location, based on three measurements at each seepage meter, ranged from 34.9 to 53.9 cm/d. Standard deviations of measurements made at each meter ranged from 0.3 to 10.2 cm/d. For each of the seepage-meter orientations, all meters were removed and repositioned in the tank, including seepage meter 3, which was positioned in the center of the tank each time. Even though that meter was moved only slightly from one installation to the next, the average value for seepage measured at that meter ranged from 34.9 to 41.2 cm/d. These data indicate that attempting to resolve seepage fluxes at resolutions finer than about 5 cm/d may be unwarranted.

Tests conducted in tank 1 by using two diameters of seepage meter indicate that problems with spatial heterogeneity in seepage are greatly minimized with use of a larger diameter seepage meter (fig. 15). The slow flow data from figure 13A

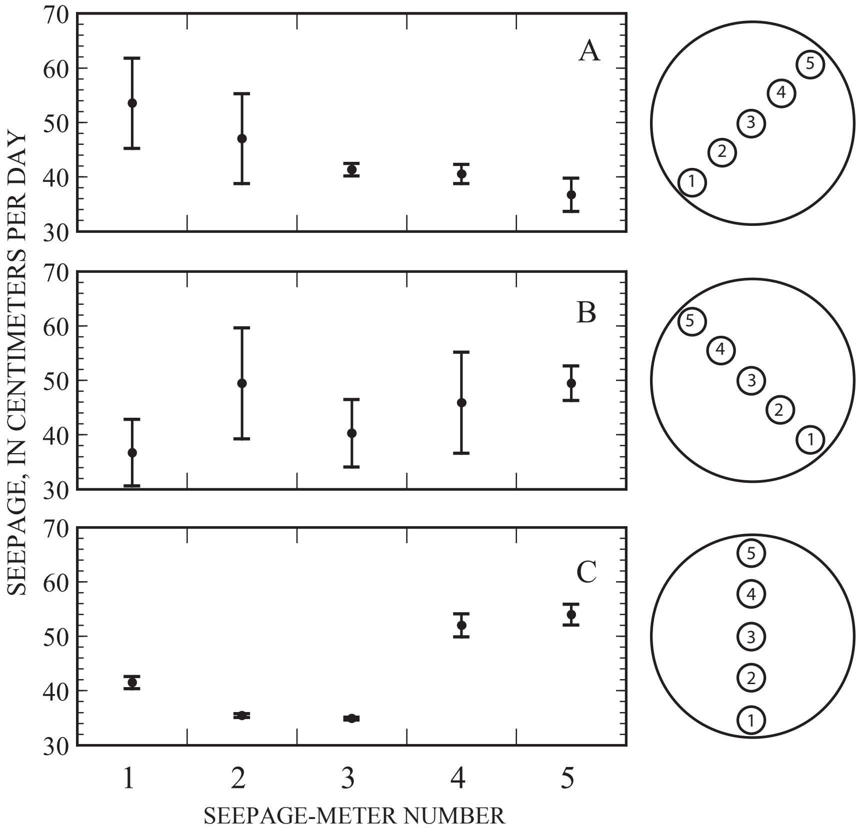


Figure 14. Seepage heterogeneity in tank 2 based on five seepage meters aligned along three axes (A-C). Diagrams indicate configuration of 20.25-cm-diameter seepage-meters for each axis.

showing large seepage heterogeneity are repeated in figure 15A. However, if the 20.25-cm-diameter paint-bucket seepage meters are replaced with 57-cm-diameter half-barrel seepage meters, much of the spatial heterogeneity is averaged out (fig. 15B). Average seepage rates are nearly the same when measured with the small (19.2 cm/d) or large (19.7 cm/d) seepage meters. However, the large range in seepage measured at individual small diameter seepage meters (18.8 cm/d range) was reduced considerably when measured with four larger diameter seepage meters (3.4 cm/d range).

Spatial heterogeneity in seepage seems to be inherent even in well sorted sand. In tank 2, the water was drained, the sand bed was stirred with shovel and rake, water was added to the tank, and the sand bed was stirred and raked again in an attempt to reduce the spatial heterogeneity in seepage. Heterogeneity was reduced substantially following stirring of the bed (fig. 16). Before stirring, average seepage rates varied from 16.1 to 38.0 cm/d for the five small diameter seepage meters, a range of 21.9 cm/d. After stirring, average seepage rates varied from 24.4 to 35.7 cm/d, a range of 11.3 cm/d.

Calibration examples

Numerous reports have discussed the type, size, and weight of seepage-meter bags. Bags have ranged in size from condoms (for example, Fellows and Brezonik, 1980; Schincariol and McNeil, 2002) to 15-L trash bags (Erickson, 1981). Murdoch and Kelly (2003) and Zamora (2006) suggested the

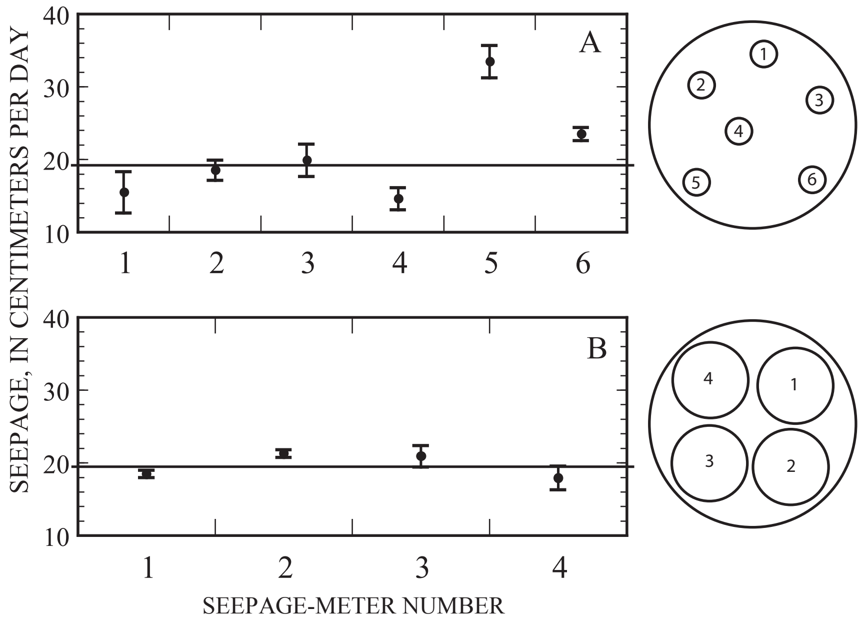


Figure 15. Seepage heterogeneity in tank 1 based on (A) random placement of six 20.25-cm-diameter seepage meters and (B) placement of four 57-cm-diameter seepage meters. Diagrams indicate seepage-meter configuration for each figure panel. Horizontal bars indicate median seepage rates.

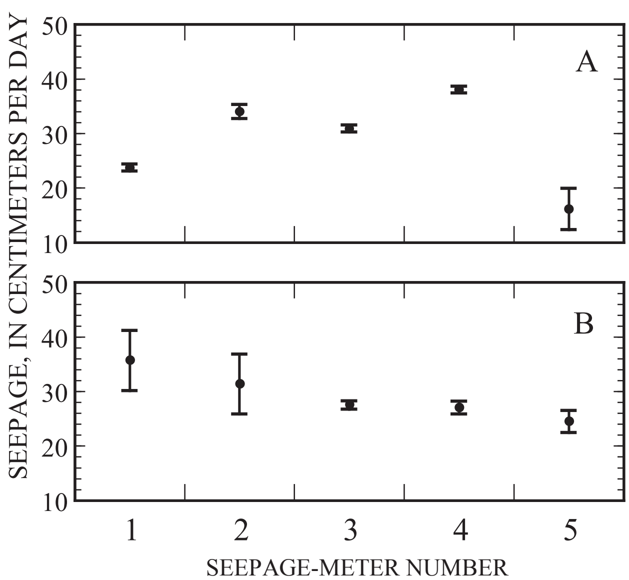


Figure 16. Seepage heterogeneity as indicated by five 20.25-cm-diameter seepage meters installed in tank 2 before (A) and after (B) draining, stirring, and refilling water in the tank, and restirring the sand bed in an attempt to reduce heterogeneity.

Table 2. Seepage-meter bag efficiency as determined by attaching selected bags to 57-cm-diameter seepage cylinders and comparing average seepage rate from seepage meters with average seepage flux in tank 2.

[n, number of observations; cm/d, centimeters per day; s, standard deviation; bag efficiency, bag seepage / tank seepage; bag correction factor, 1 / bag efficiency]

Bag type	n	Average bag seepage (cm/d)	s	Average tank seepage (cm/d)	Bag efficiency	Bag correction factor
4-L freezer storage bag	6	42.0	1.1	40.0	1.05	0.95
3.5-L shipping bag	6	43.0	1.1	39.8	1.08	0.93
9.4-L solar-shower bag	3	21.2	2.8	39.8	0.53	1.89
1.1-L IV-drip bag	3	35.1	0.4	39.7	0.88	1.14

Table 3. Seepage-meter efficiency related to bag-connection time, as determined by attaching 4-L freezer storage bags to seepage cylinders for a range of times and comparing mean seepage rate from seepage meters with mean seepage flux in tank.

[min, minutes; ml, milliliters; cm/d, centimeters per day; s, standard deviation; n, number of observations]

Bag-connection time (min)	Flow direction	Average change in volume (ml)	Average from seepage-meters (cm/d)	s	n	Average tank seepage (cm/d)	Meter efficiency
1	Inflow	43	24.1	3.8	6	22.5	1.07
5	Inflow	189	21.3	1.2	4	22.5	0.95
10	Inflow	378	21.4	1.2	4	22.5	0.95
30	Inflow	1,114	21.0	1.2	4	22.5	0.93
1	Outflow	-38	-21.5	1.4	8	-22.7	0.95
5	Outflow	-199	-22.5	1.4	4	-22.7	0.99
10	Outflow	-384	-21.7	0.9	4	-22.7	0.96
30	Outflow	-1,190	-21.7	1.5	4	-22.7	0.96

use of inflatable bags designed for protecting items during shipping. Four-L sandwich bags are perhaps the most common choice for a seepage-meter bag. Shaw and Prepas (1989) reported an anomalous influx of water during the first 30 minutes following bag installation. They suggested prefilling the bags with 1,000 mL of water to minimize this problem. Cable and others (1997) reported similar results.

These and other seepage-bag-related questions can be tested and evaluated with the seepage-control system. For example, the effects of various types and thicknesses of seepage-meter bags on seepage-meter efficiency can be tested. Averages of seepage flux through two 57-cm-diameter plastic half-barrel seepage cylinders, as measured with several different bag types, were compared with the flux-tank values (table 2). Seepage-meter efficiency was determined by dividing the average seepage-meter flux by the average flux-tank values. Table 2 shows that the relatively thick plastic used to construct a solar-shower bag results in small seepage-meter efficiency compared to the other bags. The intravenous (IV)-drip bag also is less efficient than the first two bags listed in the table. Conversely, efficiency values greater than 1 are problematic and indicate that the seepage meter overmeasured seepage rate. Efficiency values greater than 1 likely are the result of an insufficient bag-measurement time, an insufficient number of measurements to average out measurement errors, or the seepage cylinders being positioned over an area of preferential flow relative to the tank-averaged flow. More thorough study would be required to determine a robust efficiency value for a given combination of seepage cylinder and seepage bag. Such an analysis was conducted in tank 1, where seepage measured with 4-L freezer-storage bags connected to plastic half-barrel seepage chambers achieved an efficiency of 0.95 (Rosenberry, 2005). Murdoch and Kelly (2003) determined an efficiency of 0.80 when they used the 3.5-L shipping bags listed in table 2. Their smaller system efficiency relative to that reported here may have been due in part to the efficiency of their bag-connection hardware.

Bag-connection time may have been a factor in the comparisons made in table 2. An anomalously large influx may have occurred if the bag was not connected for a sufficiently long time (Shaw and Prepas, 1989). Most plastic bags have a “memory effect” that results in exertion of slight pressure by the bag until it fills or empties to a relaxed, neutral position determined by the bag manufacturing process. Error caused by this process can be minimized either by pre-filling the bag with an amount of water that allows the bag to be near its relaxed state, or by making a seepage measurement over a longer time period, which averages the erroneous short-term seepage flux with a long period of non-bag-affected seepage flux. It is difficult to determine precisely what the best initial bag volume should be. Shaw and Prepas (1989) indicated that an anomalous influx of water occurred when 3.5-L bags were pre-filled with 1,000 or even 2,000 ml of water, but the bags lost water when pre-filled with 3,000 ml. Bag-connection time often is shortened to allow a greater number of measurements in a given time period, perhaps compromising the accuracy of the shorter bag-connection times.

The seepage calibration tank provides an opportunity to test the influence of bag-connection time. Seepage-meter measurements were made at moderate seepage rates of +22.5 cm/d (inflow) and -22.5 cm/d (outflow) by using a plastic half-barrel cylinder and 4-L freezer storage bags that were pre-filled with about 1,000 mL of water for inflow and about 1,700 mL of water for outflow (table 3). If an insufficient bag-connection time results in anomalous flow into a bag that is unrelated to seepage flux, then bag-measured seepage rates should be erroneously large for flow from ground water to surface water. Conversely, bag-measured seepage rates should be erroneously small for flow from surface water to ground water. This appears to be the case for bag-connection times of only one minute (table 3). However, for all other measurements there appears to be no relation between bag-connection time and bag-measured seepage rate, suggesting that an initial volume of about 1,000 to 1,700 mL leads to minimal bag-related error.

Additional modifications

Reducing spatial heterogeneity in seepage

As noted earlier, considerable spatial heterogeneity in seepage was observed in both flux tanks (tank 1 and tank 2). This heterogeneity appears to be inherent in all seepage measurements and at all scales. A smaller flux tank could be used so that the seepage meter being tested would cover nearly all of the surface area of the flux tank, in which case any spatial heterogeneity in seepage flux would be averaged over the area covered by the seepage meter. However, this would either preclude testing of other sizes of seepage cylinder or would require flux tanks to be sized to fit a particular size of seepage cylinder. Perhaps a better solution, as mentioned earlier, is to install enough seepage meters to cover most of the surface area of the flux tank.

Simulating slow seepage rates

The seepage-control systems described in this report were designed to provide a means for testing and calibrating seepage meters for use in lakes, estuaries and wetlands. The systems can adequately generate medium to large seepage fluxes relative to what has been observed in natural settings, but the inexpensive paddlewheel-type flowmeter that was used in this study cannot measure tank fluxes smaller than about 7 cm/d. As seepage rates become smaller, the paddlewheel inside the flowmeter intermittently stops turning until the seepage rate is reduced to the point at which the paddlewheel stops turning

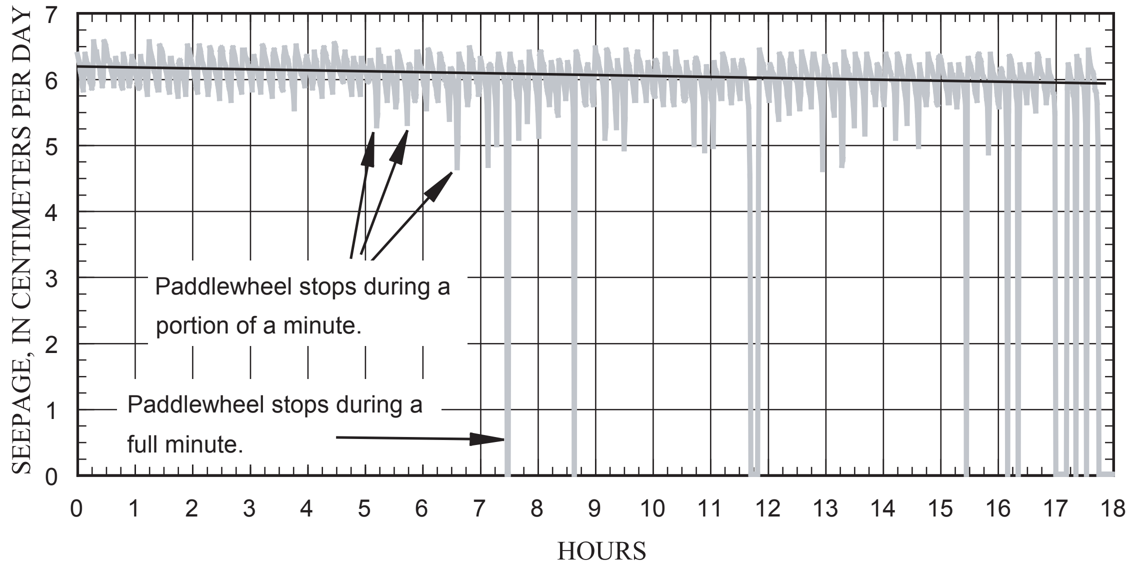


Figure 17. Paddlewheel flowmeter output showing flowmeter dropout at minimum threshold of measurable flow, in centimeters per day. Solid line shows decrease in mean tank-averaged seepage flux from 6.2 to 5.8.

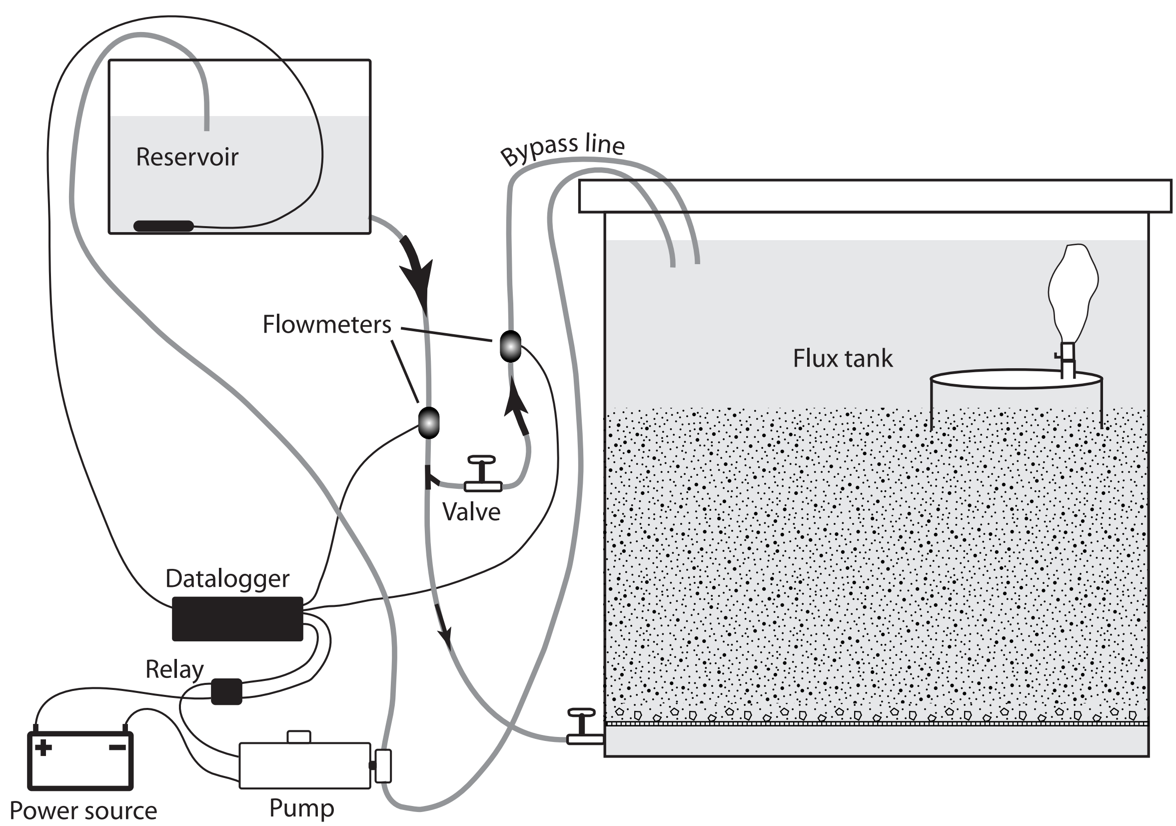


Figure 18. Seepage-flux calibration system modified for use with bypass flowmeter.

altogether (fig. 17). Therefore, calibration of seepage meters for seepage rates smaller than about 7 cm/d requires frequent floating-pan measurements to manually determine the seepage rate at a specific reservoir height.

Seepage rates smaller than the measurable threshold of the flowmeter can be generated with smaller differences in head between the seepage tank and the reservoir. A relation can be developed between difference in head and seepage flux by using the floating-pan method as a control. The relation also would depend on the diameter of tubing connecting the reservoir to the flux tank, and on the thickness and hydraulic conductivity of the sediment in the flux tank.

A second flowmeter could be added to a bypass line, as shown in figure 18, and a control valve adjusted so that flow through each flowmeter was well above the low-flow threshold. The difference between flows measured by the two flowmeters divided by the surface area of the sediment-water interface in the flux tank would be the seepage flux routed through the sand in the flux tank. Small rates of seepage could be generated with this modification. The floating-pan method would be necessary to assess the cumulative errors associated with differencing output from two flowmeters.

A peristaltic or other fluid-metering pump could be used to replace the head-dependent system used in this study to generate flow through the flux tank. Ideally the pump would be capable of operating for many hours while delivering water at a constant rate. If a precision-delivery, small-volume pump were used, the reservoir would not be necessary, although a floating-pan or other means for determining rate of flow would be a prudent addition to provide a check on the rate of flow delivered by the pump.

Summary

A seepage-control system has been developed to create a range of controlled flows of water across the sediment-water interface, representing flow between ground water and surface water, for the purpose of calibrating seepage meters of various designs. As currently configured, the system can simulate seepage rates ranging from about ±7 cm/d to ±55 cm/d. Two seepage-control systems using slightly different components were evaluated. Simple modifications will allow generation of both larger and smaller seepage rates if needed.

Both seepage-control systems include a flux tank, in which water is routed through a sand bed and across the sediment-water interface to surface water about 0.6 m deep, sufficiently deep to submerge most designs of seepage meter. The tanks used were 1.5 m in diameter, large enough to allow installation of four standard-size 57-cm-diameter half-barrel seepage cylinders. A diffuser plate separates the sand in each flux tank from a manifold system installed in the bottom of the tank that distributes water uniformly to the diffuser plate. A uniform grid of holes provides a uniform distribution of water to the base of the sand. A sheet of permeable geotextile fabric and a thin layer of gravel prevent the holes in the diffuser plate from becoming clogged.

Flexible vinyl tubing routes water between the base of the flux tank and a smaller reservoir, the height of which is adjusted to generate flow through the sand in the flux tank. Rate, as well as direction, of flow can be controlled by operating an adjustable-height fork lift to raise or lower the reservoir relative to the water surface in the flux tank. Water in the flux tank and reservoir is maintained at a virtually constant depth by routing return flow through vinyl tubing that extends from the surface water in the flux tank to the reservoir. Flow through the return-flow tubing is generated with an in-line peristaltic pump. The pump is turned on or off by a relay switch that is controlled by a datalogger. The datalogger controls the relay and pump based on output from a pressure transducer that rests on the bottom of the reservoir, and turns the pump on and off at appropriate intervals to maintain a nearly constant water depth inside the reservoir. For this study, water level in the reservoir fluctuated over a range of 1.5 mm.

Flow between the reservoir and flux tanks was measured with an in-line paddlewheel-type flowmeter. The datalogger was programmed to average the pulses generated by the flowmeter for each 10-second interval and then generate 1-minute averages of flow through the flowmeter in milliliters per minute. This volumetric rate of flow was converted to a flux velocity by dividing by the surface area of sediment-water interface in the flux tank to generate flux rates in centimeters per day. Although head difference was not allowed to fluctuate by more than 1.5 mm for any given reservoir height setting, allowing head difference to vary by 1.5 mm generated a measurable cyclical variation in seepage flux. This temporal variability in generated seepage flux was inconsequential, both because it was small compared to all but the smallest generated seepage fluxes, and also because the seepage-meter measurements integrated the variability over the time required for each measurement, which was inversely proportional to the seepage rate.

Spatial heterogeneity in seepage flux was surprisingly large in both flux tanks, in spite of attempts to minimize seepage heterogeneity during tank construction. Medium sand was installed in both flux tanks and care was taken to homogenize the sand during filling of the tanks. Sand was stirred during and after water was added to the tanks. Time was provided for release of any air that may have been trapped when water was added to the sand. Fine-grained sediments were flushed from the system prior to use of each flux tank. In spite of these precautions, spatial heterogeneity was considerable when small-diameter seepage chambers (20.25-cm-diameter paint-mixing containers) were used. Seepage rates varied by about a factor of two, although averages of measurements made at 5 or 6 small-diameter seepage meters were close to the flux-tank-integrated seepage rates. Use of larger-diameter seepage chambers greatly minimized the problem by averaging spatial heterogeneity in seepage flux over a larger area.

The seepage-control system was used to calibrate several seepage-meter designs and to test the inefficiency, or flow reduction, associated with use of different types of seepage-meter bag. Four seepage-meter bag types were tested in the flux tank. Bag efficiency was determined as the ratio of the average seepage rate measured by the bag to the seepage rate generated in the flux tank. Two of the bag types had very high efficiencies and two had low efficiencies. The influence of time of bag connection on measured seepage rates also was tested because previous investigators had determined that short bag-connection times resulted in anomalous measured seepage rates. Results of attaching seepage bags for durations ranging from 1 to 30 minutes indicated that anomalous seepage rates were measured only during the 1-minute bag-connection time.

Use of a reservoir and in-line flowmeter restricts the range of generated seepage fluxes. The upper end of the measurable range is limited by the vertical distance that the reservoir can be positioned relative to the water level in the flux tank. The lower end of the measurable range is limited by the capability of the paddlewheel flowmeter. Flow through the flowmeter was not sufficient to turn the paddlewheel when the flux velocity was less than about 7 cm/d. Greater seepage rates can be achieved by removing the in-line flowmeter and making manual measurements of return flow while maintaining near-constant water levels in both tanks. Smaller seepage rates also can be achieved by relying on manual check measurements of return flow to indicate seepage rate, differencing output from two flowmeters, or by using a low-volume, high-precision pump to accurately meter flow at slow flow rates.

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