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Integrating seepage heterogeneity with the use of ganged seepage meters

Donald O. Rosenberry[*]
U.S. Geological Survey, MS 413, Bldg. 53, DFC, Lakewood, CO 80225

Abstract

The usefulness of standard half-barrel seepage meters for measurement of fluxes between groundwater, and surface water is limited by the small bed area that each measurement represents and the relatively large associated labor costs. Standard half-barrel cylinders were ganged together to allow one measurement of the summed seepage through all of the meters, reducing labor cost and increasing the representative area of measurement. Comparisons of ganged versus individual-meter measurements at two lakes, under both inseepage and outseepage conditions, indicate little loss of efficiency resulting from routing seepage water through the ganging system. Differences between summed and ganged seepage rates were not significant for all but the fastest rates of seepage. At flow rates greater than about 250 mL min^{-1}, ganged values were as low as 80% of summed values. Ganged-meter head losses also were calculated to determine their significance relative to hydraulic-head gradients measured at the field sites. The calculated reduction in hydraulic gradient beneath the seepage meters was significant only for the largest measured seepage rates. A calibration tank was used to determine single-meter and ganged-meter efficiencies compared to known seepage rates. Single-cylinder seepage meters required an average correction factor of 1.05 to convert measured to actual values, whereas the ganged measurements made in the tank required a larger correction factor of 1.14. Although manual measurements were used in these tests, the concept of ganging seepage cylinders also would be useful when used in conjunction with automated flowmeters.

Seepage meters are one of the few devices capable of making direct measurements of water flux across the sediment-water interface. As interest in quantifying exchanges between groundwater and surface water has grown, so has interest in using seepage meters to make these measurements. Several government agencies developed early versions in the 1940s and 1950s, primarily for use in irrigation canals (Reeve and Jensen 1949; Warnick 1951; Robinson and Rohwer 1952; Rasmussen and Lauritzen 1953; Robinson and Rohwer 1959), but they typically were large and/or expensive and difficult to employ. Since the advent of the "Lee-type" or "half-barrel" seepage meter (Lee 1977), this device has been widely used for measuring seepage fluxes in lakes (Connor and Belanger 1981; Erickson 1981; Woessner and Sullivan 1984; Loeb and Hackley 1988; Welch et al. 1989; Isiorho and Matisoff 1990; Lesack 1995; Rosenberry 2000; Sebestyen and Schneider 2001), wetlands (Choi and Harvey 2000), estuaries (Lee 1977; Zimmerman et al. 1985; Yelverton and Hackney 1986; Simmons Jr. 1992; Land and Paull 2001; Linderfelt and Turner 2001), and near-shore ocean margins (Cable et al. 1997; Shinn et al. 2002; Taniguchi 2002; Chanton et al. 2003; Michael et al. 2003). The device also has been used in river settings where currents were small (Connor and Belanger 1981; McBride 1987; Belanger and Walker 1990; Duff et al. 1999; Fryar et al. 2000).

Several problems are inherent with use of this device, many of which have been discussed extensively in the literature (Shaw and Prepas 1989; Asbury 1990; Belanger and Montgomery 1992; Cable et al. 1997; Isiorho and Meyer 1999; Schincariol and McNeil 2002; Shinn et al. 2002). Among these are problems associated with very slow rates of seepage and with measurement scale. Very low seepage rates require substantial time for making a measurement. An individual measurement can take one to several days if the seepage rate is small. While this problem is largely one of nuisance, problems resulting from measurement scale are more vexing. Seepage meters typically integrate flux velocity over an area of approximately 0.25 m^2 or less, whereas most researchers and watershed managers are more interested in seepage processes on the scale of hundreds to thousands of

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[*] E-mail: rosenber@usgs.gov

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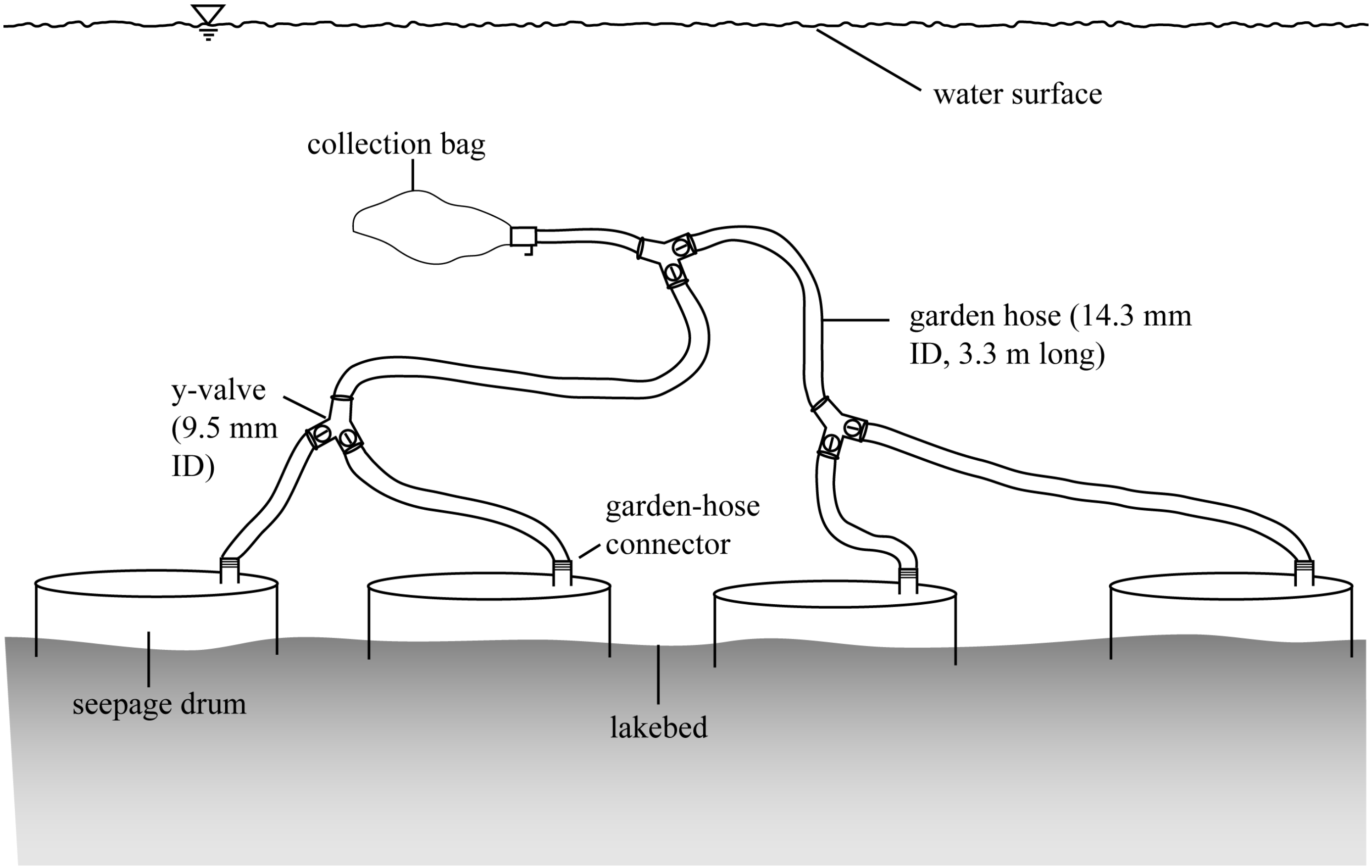

Fig. 1. Sketch of 4 seepage cylinders ganged together with standard garden hose and garden-hose Y connectors to one seepage collection bag.

m^2 or more. Some of the heterogeneity encountered when making measurements of seepage is process driven. Analytical and numerical modeling has shown that seepage should decrease with distance from shore (McBride and Pfannkuch 1975; Pfannkuch and Winter 1984; Winter and Pfannkuch 1984), and many field studies have corroborated this observation (Connor and Belanger 1981; Belanger and Walker 1990; Rosenberry 1990; Schafran and Driscoll 1993; Rosenberry 2000). However, numerous other studies also have shown that local-scale geologic heterogeneity often overwhelms the larger-scale topographically controlled seepage variability (Woessner and Sullivan 1984; Belanger and Mikutel 1985; Krabbenhoft and Anderson 1986; Cherkauer and Nader 1989; Belanger and Walker 1990). In such cases, it is difficult to scale seepage-meter measurements to shoreline-reach or lake- or wetland-wide interpretations without a large number of measurement locations.

Seepage meters would be much more useful if labor costs could be reduced, the scaling problem could be more conveniently addressed, and slow-flow measurements could be made more convenient. These issues can be addressed by connecting multiple seepage-meter cylinders to a single measurement bag (Fig. 1). In so doing, the seepage flux through all of the ganged seepage cylinders is summed in one bag, which increases the area represented by each measurement, integrates spatial heterogeneity over a larger area, and reduces the time required to collect a measurable change in volume of water contained in the bag.

A potential problem associated with this method is the combined frictional resistance of seepage flow routed through the seepage cylinder, tubing, Y fittings, valves, and any seepage-bag resistance. Frictional resistance is inherent in all seepage-meter designs to some extent and, although single-cylinder seepage meters do not contain hoses or Y fittings, they also are subject to head loss. A seepage-meter coefficient typically is used to convert measured seepage rates to true values. Coefficients in the literature range from 1.1 to 1.7 (Erickson 1981; Cherkauer and McBride 1988; Asbury 1990; Belanger and Montgomery 1992). Many of the less-efficient meter designs require larger coefficients, primarily because they use small-diameter tubing to connect the bag to the seepage cylinder. The use of large-diameter plumbing greatly reduces loss of efficiency, resulting in a smaller correction coefficient (e.g., Fellows and Brezonik 1980).

Results from various combinations of ganged seepage meters installed in two separate lakes are presented and com-

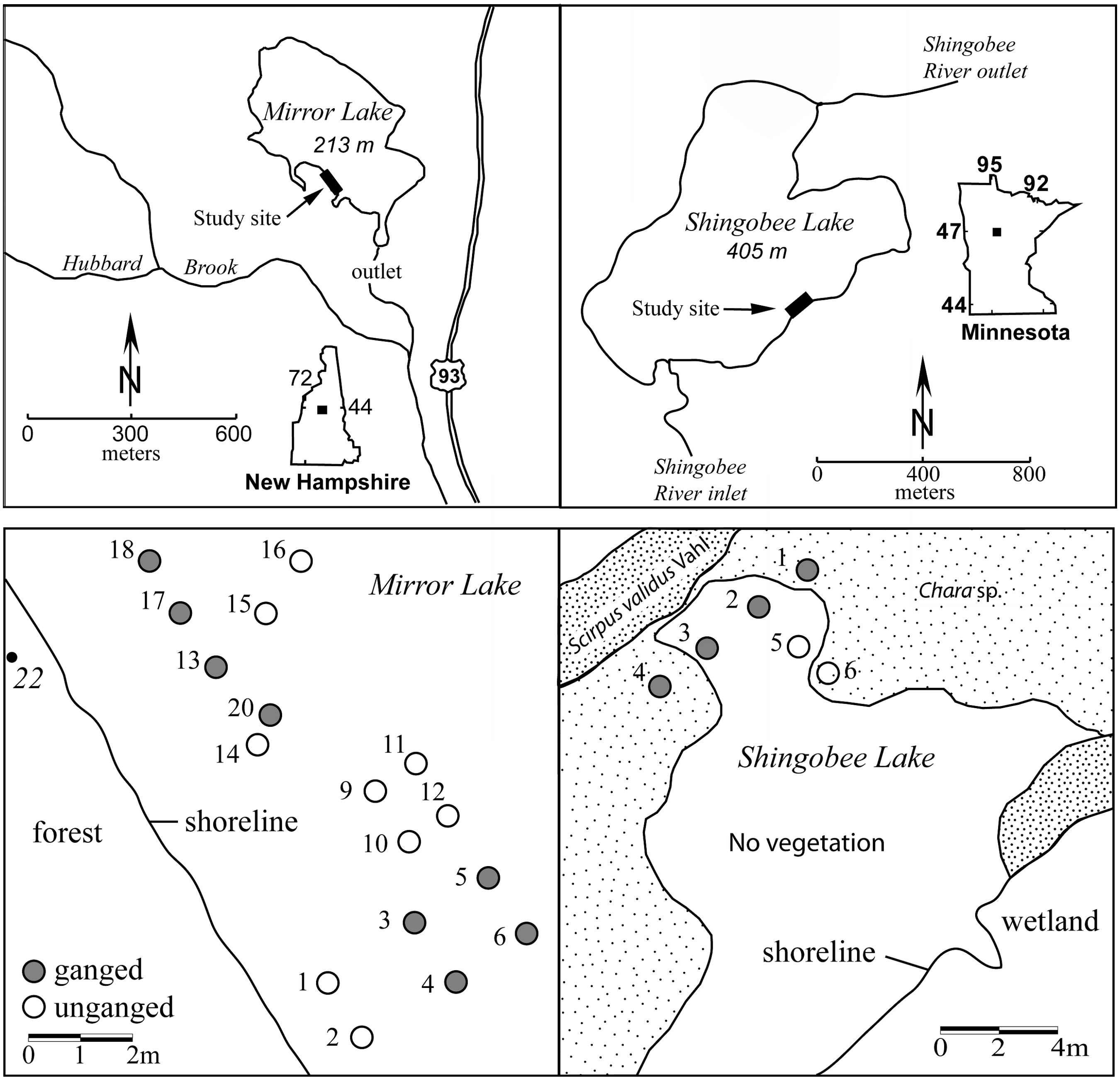

Fig. 2. Location of field sites in New Hampshire and Minnesota, USA, and positioning of seepage meters in the study lakes.

pared with summed values of measurements at individual seepage meters. At Shingobee Lake in north-central Minnesota (Fig. 2), water seeps from groundwater to the lake through fine-grained, flocculent, organic-rich sediments. Sediments were very soft and walking on the bed would greatly disturb the sediments at this site. Because water depth was shallow (40 to 58 cm depth), meters were installed and serviced from a canoe or small boat to minimize physical disturbance during measurement. At the study site in Mirror Lake in central New Hampshire, water seeps from the lake to groundwater through medium to coarse-grained sand. Meters were serviced while standing on the lakebed in water depths that ranged from 23 to 150 cm.

Frictional head loss associated with the ganging systems also is calculated using the Darcy-Weisbach method (Munson et al. 2001) with seepage rates that were measured at both lakes. Lastly, data are presented from a seepage-meter test tank where known and controlled seepage flux rates are compared with seepage fluxes through ganged meters installed in the test tank.

Fig. 3. Ganged seepage cylinders in Shingobee Lake, MN.

Materials and procedures

The Lee-type half-barrel seepage meter (Lee 1977) consists of a cylinder that covers a known area of the sediment-water interface connected to a variable volume chamber, typically a plastic bag. The cylinder described by Lee consists of the cut-off end of a 208-L (55-gallon) steel drum (0.8 mm wall thickness) that, when placed on the bed of a surface-water body, covers 0.255 m^2 of surface area. In this study, high-density polyethylene plastic drums of slightly smaller diameter (0.250 m^2, 2.2 mm wall thickness) were used because of reduced expense, the ease of cutting the drums, and the reduced potential for injury during meter handling and installation. A weight was required to counter the buoyancy force from the submerged plastic. A 4-L thin-walled plastic bag was bunched together at the bag opening and attached to a garden-hose shut-off valve. The bag was prefilled with a known volume of water, excess air was removed from inside the bag, and the valve was closed, making the bag ready for deployment. The bag and shut-off valve were threaded onto a male garden-hose connector attached to each seepage cylinder, and the valve was opened to begin the measurement period. The valve was closed at the end of the measurement period, and the volume remaining in the bag was measured. The change in volume per time attached to the meter constituted the volumetric seepage flux ($L^3 T^{-1}$). That value was divided by the area covered by the meter to obtain a seepage flux velocity ($L T^{-1}$). Seepage values are reported here as cm d^{-1} except when summed and ganged values are compared, where it is more appropriate to present results volumetrically; in such cases, units of mL min^{-1} are used.

In the ganged configuration, standard garden hose of 14.3-mm inside diameter (ID) was submerged so that all air was evacuated from the hose, and then connected to each seepage cylinder. The lengths of garden hose were joined with Y connectors (Fig. 1) that are readily available at most hardware stores. Each Y connector also contained two ball valves, which facilitated making measurements from various combinations of seepage cylinders. The minimum ID of these ball valves was 9.5 mm. An additional Y connector was attached to each seepage cylinder to allow either ganged measurements or the attachment of a seepage bag to individual cylinders. This was done for evaluation purposes only and would not be necessary for a standard ganged-seepage measurement. Hose lengths were 3 m or shorter to minimize frictional-head losses, although longer hose lengths also could be used if seepage cylinders are spaced across a larger area.

For each ganged installation, measurements were made at individual seepage cylinders followed by a separate ganged-cylinder measurement. This process was repeated three to six times to allow averaging of seepage measurements. Measurements were made during nearly calm conditions, eliminating the need for seepage-bag shelters. Piezometers were installed in the lakebed near each ganged-cylinder site to determine hydraulic gradients in the vicinity of the seepage measurements. Horizontal hydraulic conductivity beneath the lakebed was determined with single-well slug tests at Mirror Lake. Slug-test data collected by Kishel and Gerla (2002) were used for the Shingobee Lake site. Sediments were assumed to be isotropic near the sediment-water interface.

Assessment

Field results—Seepage from groundwater to Shingobee Lake was relatively slow to moderate. Average rates measured at individual seepage cylinders over a 2-d period ranged from 2.9 to 10.2 cm d^{-1}. Little spatial variability was detected at the Shingobee site at the scale tested (6-m distance from one end of the meter transect to the other). Meters were placed in an area where a groundwater spring was known to exist (Rosenberry et al. 2000) and where sediment temperature was much lower than lake water. Two of the ganged meters were placed in beds of *Chara* sp., and two were placed where the lakebed was devoid of vegetation (Fig. 3). Seepage rates were measurably greater at one of the *Chara* sites, but seepage rates were quite similar at the three other seepage cylinders (Table 1).

The summed seepage from individually measured meters compared quite closely with ganged seepage rates (Table 1, Fig. 4A). Several combinations of 2, 3, or 4 meters were ganged together. In five of six tests, the ganged value was slightly

Table 1. Seepage flows (mL min^{-1}) for individual meters, summed meters, and ganged meters measured at Shingobee Lake and Mirror Lake*

	Individual seepage meter				**Summed seepage**	**Ganged seepage**	**Ganged ÷ summed**	***t* test *P* value**
	S1	S2	S3	S4	S1-S4	S1-S4		
Mean	18	5.2	8.7	10.6	42.5	40.9	96%	0.475
s	3.23	0.85	0.49	2.66	3.72	3.81		
n	6	6	6	6	6	6		
	S1	S2	S3	S4	S1-S4	S1-S4		
Mean	18.1	6.2	9.1	9.4	42.8	41.1	96%	0.438
s	0.36	1.84	0.26	1.29	3.05	1.28		
n	3	3	3	3	3	3		
		S2	S3	S4	S2-S4	S2-S4		
Mean		5.2	8.7	10.6	24.5	21.9	90%	0.277
s		0.85	0.49	2.66	3.55	2.69		
n		6	6	6	6	3		
		S2	S3	S4	S2-S4	S2-S4		
Mean		6.5	9.1	9.8	25.4	26.7	105%	0.707
s		1.63	0.22	1.25	2.78	3.54		
n		4	4	4	4	2		
			S3	S4	S3-S4	S3-S4		
Mean			9.0	12.1	21.2	18.8	89%	0.772
s			0.49	2.66	2.97	1.77		
n			6	6	6	2		
			S3	S4	S3-S4	S3-S4		
Mean			9.1	9.7	18.8	17.7	94%	0.119
s			0.25	1.13	1.27	0.28		
n			5	5	5	2		
	M3	M4	M5	M6	M3-M6	M3-M6		
Mean	–19.8	–7.3	–1.4	–4.1	–32.5	–32.2	99%	0.762
s	0.35	0.90	0.25	1.01	1.59	0.84		
n	3	3	3	3	3	5		
	M13	M17	M18	M20	M13-M20	M13-M20		
Mean	–248.8	–34.3	–90.0	–51.3	–424.3	–337.5	80%	0.0003
s	18.87	4.35	11.66	2.50	15.95	9.57		
n	4	4	4	4	4	4		
			M13	M20	M13,M20	M13,M20		
Mean			–248.8	–51.3	–300.0	–260.0	87%	0.016
s			18.87	2.50	18.71	8.16		
n			4	4	4	4		
			M17	M18	M17,M18	M17,M18		
Mean			–35.7	–85.6	–121.3	–120.0	99%	0.864
s			4.35	8.17	8.25	10.00		
n			5	5	5	3		

*Meter numbers equate to numbered circles in Fig. 2 and are preceded by an S for Shingobee Lake and an M for Mirror Lake. Student *t* test *P* values (variances assumed unequal) indicate significance of differences between summed versus ganged values.
s = standard deviation; *n* = number of observations.

smaller than the summed value from individual meter measurements. However, for all cases, differences between summed and ganged values were not significant at the 0.05 confidence level.

At Mirror Lake, seepage cylinders were ganged in two combinations of 4 meters and two combinations of two meters. Seepage from the lake to groundwater was much more spatially variable (Table 1, Fig. 4B and 4C) and some of the seepage rates were very large. Average seepage rates measured at individual seepage cylinders ranged from 0.8 to 140 cm d^{-1}. For the ganged combinations of seepage cylinders where seepage rates were relatively small, the differences between summed and

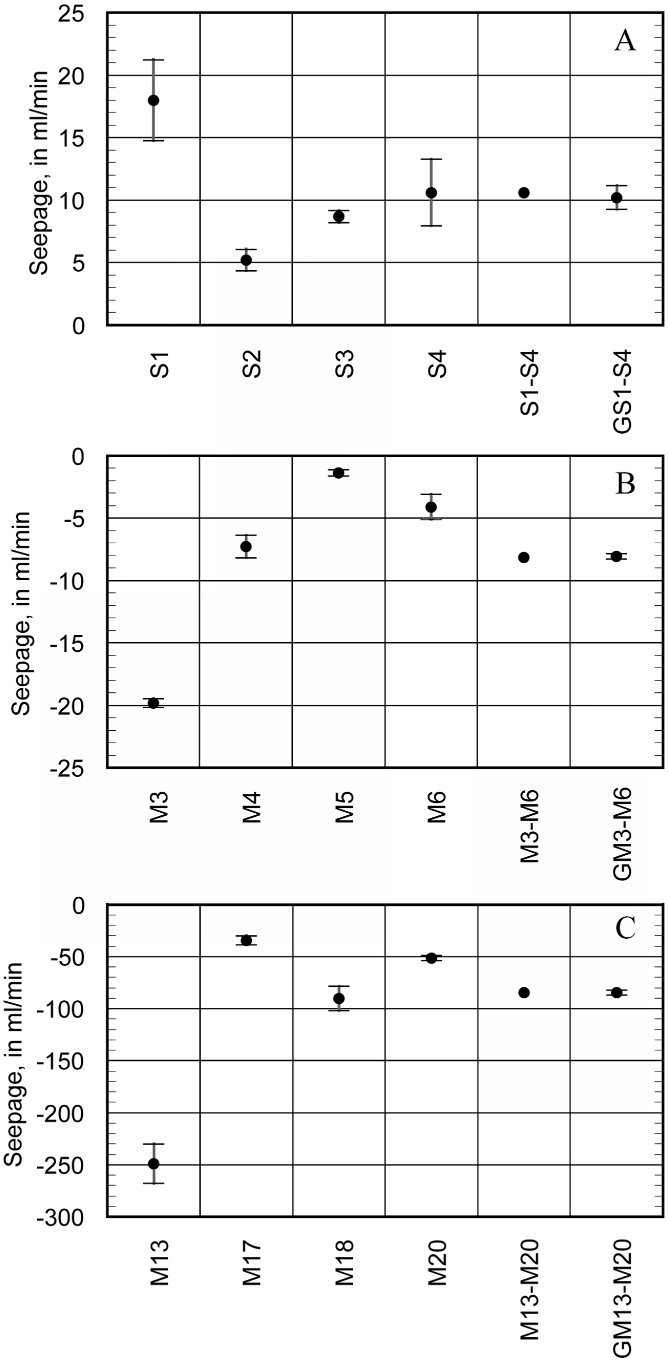

Fig. 4. Seepage rates at individual seepage meters, mean of seepage from 4 individual meters, and mean of ganged measurements divided by the number of seepage cylinders. Error bars represent 1 standard deviation from the mean. (A) Shingobee Lake meters 1 to 4, (B) Mirror Lake meters 3 to 6, (C) Mirror Lake meters 13, 17, 18, 20.

ganged values were not significant at the 0.05 probability level (Table 1). However, at the ganged combinations where seepage rates were much larger, differences between ganged and summed values were significant, indicating frictional losses became important at these largest flow velocities.

Little loss in seepage-meter efficiency resulting from ganging cylinders appears to occur at flow rates less than about 130 mL min^{-1} (Fig. 5). However, for flow rates of about 250 mL min^{-1} or greater, substantial head loss results in significantly diminished measured seepage rates. When meters M13, M17, M18, and M20 were ganged together, the mean flow rate was 87 mL min^{-1} less than the summed mean values from individual meter measurements (Fig. 5B, column h). When meters M13 and M20 were ganged together, the mean flow rate was 40 mL min^{-1} less than the summed mean values from individual meter measurements (Fig. 5B, column i). For these two comparisons, ganged measurements were 80% and 87%, respectively, of summed seepage values (Table 1). The greatest head loss occurred at the smallest restriction, which was the 9.5-mm ID valve. Flow velocities associated with seepage-meter measurements generally are very low. However, at the 9.5-mm valve to which the seepage bag is connected, flow velocity was 7 cm s^{-1} for a 300 mL min^{-1} flow rate and 10 cm s^{-1} for a 424 mL min^{-1} flow rate. Flow at these velocities still was well within the laminar-flow range, however.

Loss of seepage-meter efficiency associated with ganging cylinders is primarily a function of fluid velocity and the resulting head loss associated with the ganging plumbing. For example, if flow is from groundwater to surface water, head loss from the ganging system increases the head in the seepage cylinder, resulting in a decreased head gradient in the underlying porous medium and a concomitant decrease in seepage rate according to Darcy's Law. If head loss is sufficiently large, some of the fluid that would normally flow across the sediment-water interface covered by the seepage cylinder will be diverted and cross the sediment-water interface beyond the area covered by the seepage cylinder. This process is shown in Fig. 6, where a high-efficiency meter is positioned next to a lower-efficiency meter. This diversion of flow around a low-efficiency meter also will occur where surface water flows to groundwater. Based on results from the two sites presented here, it appears that water was more readily diverted around the area covered by the seepage cylinders at the Shingobee Lake site than at the Mirror Lake site. When meters S3 and S4 were ganged, there was a measurable loss of seepage flux at relatively low seepage rates (Fig. 5A, columns e and f). However, when meters M17 and M18 were ganged together, the loss of seepage flux relative to unganged values was smaller than at Shingobee Lake even at seepage rates that were five times larger (Fig. 5C, column j).

Head loss associated with the plumbing connecting the seepage cylinders was calculated using the Darcy-Weisbach method (Munson et al. 2001). A system of four seepage cylinders ganged together with garden hose and Y connectors, as shown in Fig. 1, was simulated, and the largest measured velocities from each site were used in the calculations. All modeled garden-hose segments were 14.3 mm ID and 3.3 m long, and the ball valves contained in the Y connectors were assumed to

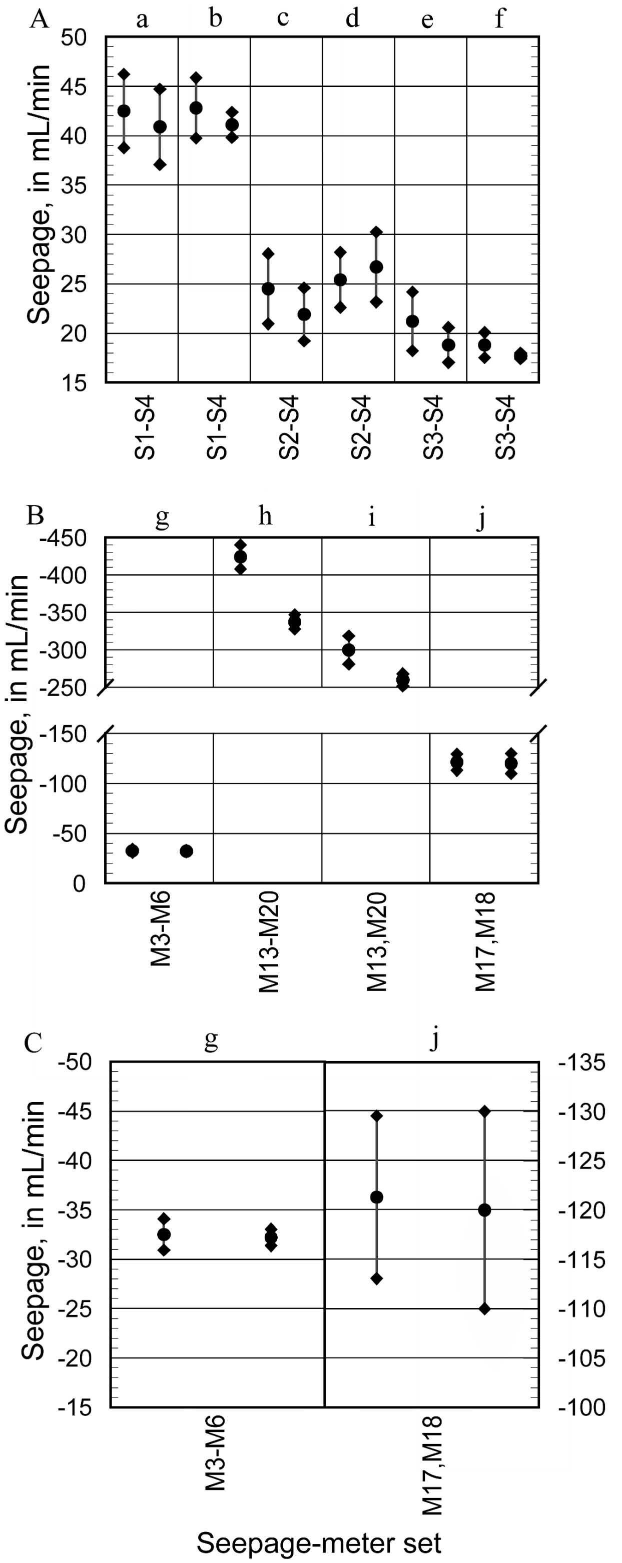

Fig. 5. Summed seepage versus ganged seepage. For each column, left-most value is sum of measurements made at individual seepage cylinders; right-most value is from bag attached to ganged cylinders. Error bars represent 1 standard deviation from the mean. (A) Ganged cylinders at Shingobee Lake, (B) ganged cylinders at Mirror Lake, (C) expanded scale for slow-seepage sites at Mirror Lake.

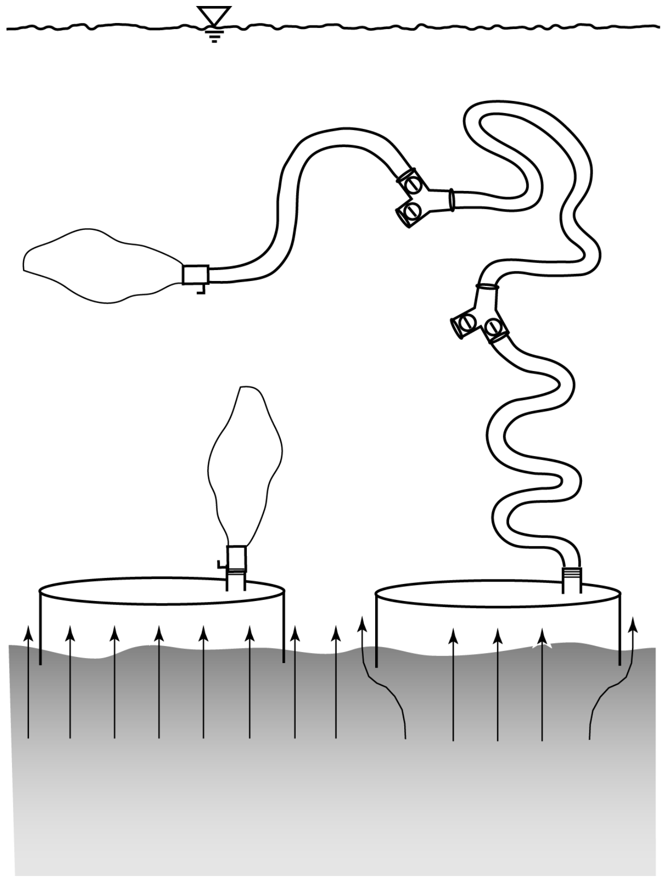

Fig. 6. Sketch showing deflection of groundwater flow lines and reduction in measured seepage flux resulting from excessive friction-head losses.

be of low efficiency to provide a conservative estimate of head loss. The Darcy-Weisbach equation can be stated as

$$H_l = f\frac{L}{D}\frac{V^2}{2g} \tag{1}$$

where H_l is pressure-head loss due to friction (L), f is Moody friction factor (dimensionless), L is pipe length over which H_l occurs (L), V is fluid velocity ($L\ T^{-1}$), D is pipe (garden hose) internal diameter (L), and g is acceleration due to gravity ($L\ T^{-2}$).

An equivalent length of garden hose was calculated to represent the head loss associated with the Y connectors that contained plastic ball valves. The equivalent length method is calculated as

$$L_{eq} = \frac{KD}{f} \tag{2}$$

where K is loss coefficient (unitless).

A conservative value of 2 was chosen for K for the ball valve (Munson et al. 2001). If fluid flow is laminar, the Moody friction factor is

$$f = \frac{64}{\mathrm{Re}} \tag{3}$$

where Re is Reynolds number = *VD*/kinematic viscosity (unitless).

All flow velocities through the garden hose and ball valves were well below the turbulent range based on calculated values for Re.

Head losses for all sections of garden hose and all ball valves were summed for each ganged-cylinder measurement. Calculated frictional head loss for the four-cylinder ganging combinations at Shingobee Lake ranged from 0.50 to 0.63 mm. Calculated frictional head losses were much larger for the fast-flowing M13-M17-M18-M20 ganging combination at Mirror Lake, ranging from 5.92 to 6.52 mm.

Head-loss calculations were quite sensitive to water temperature, especially for the fastest seepage rates. A temperature of 15°C was assumed for all calculations. Head loss would be significantly larger for colder temperatures and smaller for warmer temperatures. For example, for the M13-M17-M18-M20 ganged-meter measurement at Mirror Lake, where individual seepage flows from the ganged cylinders were 249, 34, 90, and 51 mL min^{-1} (Table 1), head loss increased by 29% at a temperature of 5°C and decreased by 17% at a temperature of 25°C. For the smaller seepage rates measured with the S1-S2-S3-S4 ganged-meter combination at Shingobee Lake, where individual flows from the ganged cylinders were 18.1, 6.2, 9.1, and 9.4 mL min^{-1} (Table 1), head loss increased by 11% at a temperature of 5°C and decreased by 6.5% at a temperature of 25°C.

Reduction in measured seepage rate in response to meter inefficiency depends on heterogeneity, hydraulic conductivity, and anisotropy of the sediments, in addition to alterations in the head gradient. At Mirror Lake, the measured hydraulic-head gradient was small (0.02), and the hydraulic conductivity was relatively large for lakebed sediments (3.3×10^{-2} cm s^{-1}). Hydraulic gradient was measured over a 0.5-m vertical distance; the measured difference in hydraulic head between water level inside the piezometer and the lake surface was 0.01 m. The approximately 6 mm of calculated head loss at the highest flow rates measured at Mirror Lake should cause a 60% change in hydraulic gradient and a similar change in measured seepage flux. As indicated in Table 1, the average reduction of the ganged seepage flux relative to the summed seepage fluxes at the largest seepage rates was 20%, indicating that local-scale heterogeneity or anisotropy of the porous medium was influencing the distribution of and change in hydraulic gradient induced by the presence of the seepage cylinders. At Shingobee Lake, the hydraulic-head gradient was much larger (0.5) and hydraulic conductivity was much smaller (1.3×10^{-4} cm s^{-1}) (Kishel and Gerla 2002) than at Mirror Lake. Seepage rates and the associated ganged-plumbing-related head losses were much smaller than at Mirror Lake. The small calculated frictional head losses (0.50 to 0.63 mm) changed the measured difference in hydraulic head by less than 1%. Based on the largest flow rates measured at the Shingobee Lake site, ganged seepage rates were reduced by 4% compared to summed seepage rates. Comparisons of head-loss calculations point out that altered head gradients resulting from ganging meters did not explain all of the observed difference in seepage between summed and ganged field measurements. Darcy-Weisbach calculations also may have underestimated head loss because they ignored losses associated with curves in garden hose and losses that occur where flows converge at the Y connectors.

Laboratory results—The actual seepage rate at a field site cannot be known unless the efficiency of the seepage meter used to measure seepage flux is known. A 1.5 m diameter × 1.5 m high seepage test tank was partially filled with medium-grain sand through which water was routed at known and controlled rates to simulate seepage across the sediment-water interface. The sand bed above a porous water-distribution plate was about 80 cm thick and water above the sand bed was about 60 cm deep. The tank was large enough to allow installation of four half-barrel seepage cylinders. Seepage bags identical to those used at the field sites were connected directly to the cylinders to provide individual-cylinder seepage rates. Cylinders also were ganged together using the same diameter garden hose and the same number of Y connectors as were used at field installations. Controlled rates of seepage were varied from 5 to 37 cm d^{-1} during the calibration tests. Both inflow and outflow conditions were simulated. Known seepage fluxes through the seepage tank were compared with values obtained from bags connected to the single-cylinder or ganged cylinders.

Seepage rates measured by single-cylinder seepage meters were surprisingly similar to the known tank fluxes. Ratios of measured to known fluxes, based on 26 comparisons for each meter over an 8-fold range in seepage flux, varied from 0.84 to 1.05 (Fig. 7). This small variation is due in part to heterogeneity in the permeability of the medium-grained sand placed in the test tank. When seepage fluxes from all four meters were averaged for each of 26 tests, the mean ratio of measured to known seepage flux was 0.95. This indicates that the standard half-barrel seepage meter, as configured with the thin-walled plastic bag and garden-hose connector hardware, has a correction factor of 1.05. Previously reported meter correction factors are 1.74 (Erickson 1981), 1.6 (Cherkauer and McBride 1988), 1.3 (Belanger and Montgomery 1992), 1.25 (Murdoch and Kelly 2003), and 1.11 (Asbury 1990). The smaller correction factor indicates a greater efficiency for the meters used in this study, which likely is due primarily to the use of larger-diameter hardware to connect the bag to the seepage cylinder. Harvey et al. (2000) also recommended the use of large-diameter bag-connection hardware to reduce errors in seepage-meter measurements.

Ganged measurements from the calibration tank averaged 93% of summed measurements, the same ratio as the average of ganged/summed values from the Mirror Lake and Shingobee Lake field sites. The ganged-meter efficiency averaged 0.88 (Fig. 7), indicating a ganged-meter correction factor of 1.14. The ratio of measured to known seepage rate did not change appreciably over the range of seepage rates generated in the

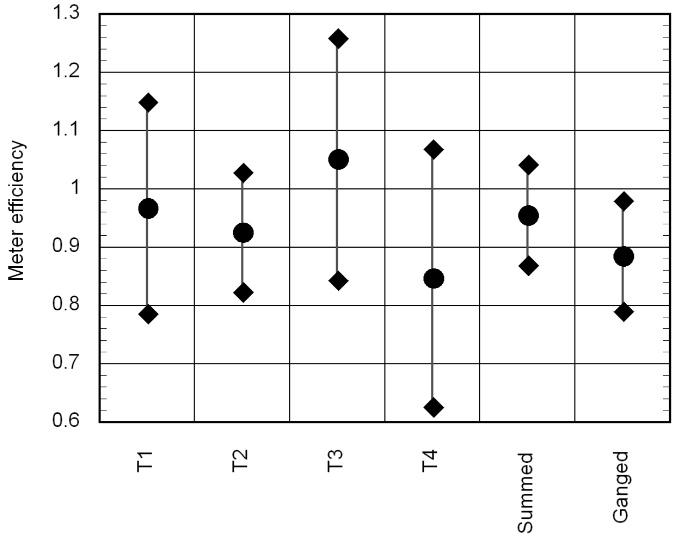

Fig. 7. Efficiency (ratio of measured to known seepage rates determined in laboratory tank) of individually measured seepage cylinders ($n = 26$), the summed volumetric values of all four individually measured seepage cylinders divided by the sum of the surface area covered by all four meters ($n = 26$), and measurements made through the ganged plumbing ($n = 31$). Error bars are 1 standard deviation from the mean.

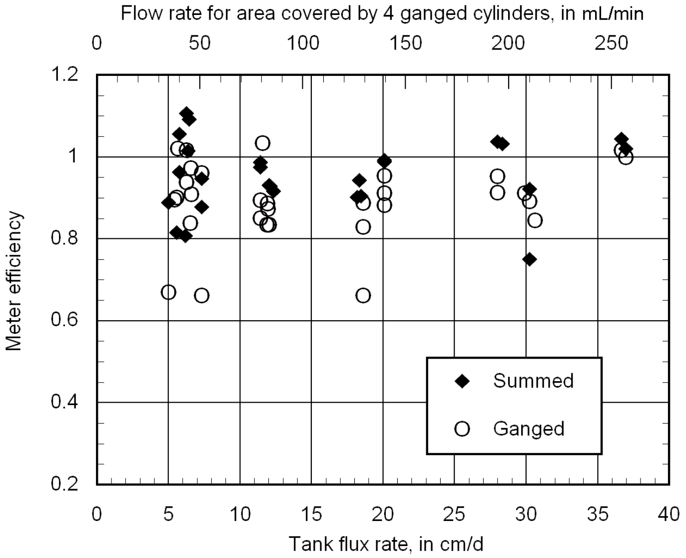

Fig. 8. Meter efficiency (ratio of measured to known seepage rates) for summed and ganged seepage cylinders related to controlled seepage flux rate.

test tank (Fig. 8). This suggests that the head loss associated with ganging the meters was not a function of flow velocity within the ganged system over a range of 5 to 37 cm d^{-1}.

Discussion

Ganging seepage meters is a simple yet effective means of reducing the labor associated with making seepage-meter measurements. Depending on the number of meters ganged together, the number of bag measurements could be reduced by a factor of 2 to 4 or more. The time required for making a seepage-meter measurement can be reduced by like amounts since all of the seepage is routed to one bag, and only one bag needs to be serviced for each ganged set of seepage cylinders. At Mirror Lake, individual bag measurements took from 1 to 80 min, depending on the seepage rate. Ganged measurements took from 1 to 10 min. At Shingobee Lake, individual meter measurement took from 5 to 40 min. Ganged measurements took from 5 to 10 min. Substantial spatial heterogeneity in seepage rate was observed at both sites. This small-scale heterogeneity is integrated by ganged measurements, which are more likely to represent seepage flux at the spatial scale that water managers are interested in. In addition, because of the added convenience and time savings, additional seepage cylinders can be used to better characterize and integrate spatial heterogeneity than is likely if every seepage cylinder has to be individually measured.

Ganging meters also can allow a convenient positioning of the collection bag. If meters are located in an area that is difficult to reach, or in deep water, connection hoses can be routed to position the collection bag in a location best suited for efficient bag measurements during subsequent site visits. This method already has been employed for single-cylinder seepage-meter measurements made in deep water (Boyle 1994).

Use of seepage meters in streams or areas where fast currents exist is problematic (Libelo and MacIntyre 1994; Packman and Brooks 2001; Shinn et al. 2002; Murdoch and Kelly 2003). Ganging meters with tubing can allow the positioning of the collection bag in a nearby area where currents are much weaker or nonexistent. This would reduce or eliminate the velocity-head problem resulting from placing a seepage bag in a moving flow field. For the same reasons, the placement of a protective housing at the end of the ganged system to contain the seepage bag is strongly recommended when either currents or waves are present (Libelo and MacIntyre 1994; Sebestyen and Schneider 2001).

Observational errors may also be reduced by use of a ganged system. Rosenberry and Morin (2004) observed a measurable change in hydraulic head within a seepage cylinder when an observer walked past the cylinder. The bag-attachment location can be positioned far from all of the ganged seepage cylinders, reducing the chance that standing near the meter during bag attachment or removal would induce artificial seepage through the cylinder.

The shallow, relatively wave-free conditions at both field sites were ideal for deployment of seepage meters as well as ganging seepage cylinders. Installations in near-shore areas where large waves are common would likely result in seepage-cylinder instability and exposure of seepage bags to currents. Water flowing past either seepage cylinders or seepage bags can induce substantial measurement errors due to the development of velocity-head gradients (Sebestyen and Schneider

2001; Shinn et al. 2002). However, the ganging system is unlikely to be impacted by these influences. Substantial release of gas from sediments could adversely impact ganged measurements. If sufficient gas is allowed to collect inside the ganged tubing, large gas bubbles could reduce or prohibit the flow of water through the tubing.

The concept of ganging seepage cylinders to integrate spatial heterogeneity of seepage can be used for automated as well as manual seepage meters. Most automated devices have a minimum measurable flow velocity, and their use is limited where exceptionally slow seepage rates are common, such as in fine-grained sediments or in areas where hydraulic-head gradients that drive seepage flux are small. Increased discharge from the larger area provided by ganged seepage cylinders would minimize this problem for several of the automated seepage devices that have been developed (Krupa et al. 1998; Paulsen et al. 2001; Taniguchi and Iwakawa 2001; Tryon et al. 2001; Sholkovitz et al. 2003; Rosenberry and Morin 2004). In addition, slow seepage rates would make inconsequential any head losses associated with ganging hardware.

Comments and recommendations

Results presented here indicate that seepage meters can be ganged together to integrate seepage heterogeneity and reduce labor costs with little loss of seepage-meter efficiency for slow to relatively fast rates of seepage. Loss of efficiency resulting from ganging meters is amplified when large rates of seepage occur in a highly permeable substrate. These conditions may occur in gravel-pit lakes or in some reservoirs, but they are relatively rare in natural settings.

Readily available, inexpensive ball valves, Y connectors, and garden hose were used for this study. The 9.5-mm ID ball valves on the shut-off valves and Y connectors were the restriction points that generated most of the pressure-head loss when seepage flows were greater than about 150 mL min^{-1}. If large flows are expected, larger diameter valves and Y connectors are available and could be used to minimize loss of ganged-meter system efficiency. Additional testing in a seepage-meter test tank would be needed to evaluate the improvement in system efficiency associated with the use of larger-diameter fittings and tubing.

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