Use of Monitoring Wells, Portable Piezometers, and Seepage Meters to Quantify Flow Between Surface Water and Ground Water

By Donald O. Rosenberry, James W. LaBaugh, and Randall J. Hunt

Chapter 2 of

Field Techniques for Estimating Water Fluxes Between Surface Water and Ground Water

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Techniques and Methods Chapter 4–D2

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Introduction

This chapter describes three of the most commonly used methods to either calculate or directly measure flow of water between surface-water bodies and the ground-water domain. The first method involves measurement of water levels in a network of wells in combination with measurement of the stage of the surface-water body to calculate gradients and then water flow. The second method involves the use of portable piezometers (wells) or hydraulic potentiomanometers to measure gradients. In the third method, seepage meters are used to measure directly flow across the sediment-water interface at the bottom of the surface-water body. Factors that affect measurement scale, accuracy, sources of error in using each of the methods, common problems and mistakes in applying the methods, and conditions under which each method is well- or ill-suited also are described.

Water-Level Measurements and Flow-Net Analysis

The flow-net analysis method, often called the "Darcy approach," is probably the most frequently used method for quantifying flow between ground water and surface water, especially on a whole-lake or watershed scale. In this method, a combination of measurements of water levels in near-shore water-table wells and measurements of water stage of adjacent surface-water bodies are used to calculate water-table gradients between the wells and the surface-water body. Two approaches commonly are used. One approach segments the shoreline of the surface-water body, depending on the number and location of nearby wells. The second approach generates equipotential lines based on hydraulic-head and surface-water stage data, and uses flow-net analysis to calculate flows to and from the surface-water body. Both methods are described in the following section.

Values of hydraulic conductivity (*K*), which also are needed to quantify flow, commonly are determined from single-well slug tests conducted in the same wells in which water levels are measured to calculate hydraulic gradients (although a multiple-well aquifer test that encompasses a large volume of aquifer often provides a better indication of hydraulic conductivity appropriate to a lake or watershed scale). Spatial resolution of hydraulic-head gradients and flow between ground water and surface water is directly related to geologic heterogeneity; the greater the heterogeneity of an aquifer, the larger the number of data points (wells) that will be needed to accurately determine hydraulic conditions. Heterogeneity often is difficult to determine in practice, and in many instances, ranges of reasonable values for *K* are used to estimate the range of flows.

Segmented Approach

In this approach, the shoreline of a surface-water body is divided into segments, with the number of segments depending on the location and number of nearby monitoring wells (fig. 1). For each shoreline segment and associated well, hydraulic conductivity and the gradient between the well and the surface-water body are applied to the entire segment. The length of the shoreline segment, *m*, is multiplied by the effective thickness of the aquifer, *b*, to determine the area, *A*, of a vertical plane at the shoreline through which water passes to either enter or leave the surface-water body (fig. 2). The Darcy equation commonly is used to calculate the flow of water that passes through the vertical plane associated with each segment:

$$Q = KA\frac{(h_1 - h_2)}{L}, \qquad (1)$$

where

Q is flow through a vertical plane that extends beneath the shoreline of a surface-water body (L^3/T);

K is horizontal hydraulic conductivity (L/T);

A is the area of the plane through which all water must pass to either enter or leave the surface-water body, depending on the direction of flow [shoreline length (*m*) × effective thickness of the aquifer (*b*)] (L^2);

h_1 is hydraulic head in the well of interest (L);

h_2 is surface-water stage (L);

and

L is distance from the well to the shoreline (L).

Flows to or from the surface-water body are summed to calculate net flow for the entire surface-water body. This method assumes that:

1. All water that exchanges with a surface-water body passes horizontally through a vertical plane positioned at the shoreline that extends to a finite depth (*b*) beneath the surface of the surface-water body. At depths greater than *b*, ground water flows beneath the surface-water body and does not exchange with the surface-water body;
2. The direction of water flow is perpendicular to the shoreline as flow enters or leaves the surface-water body;
3. The gradient (water-table slope) between the well and the surface-water body is uniform; and
4. The aquifer is homogeneous and isotropic within the segment.

Although the Darcy equation is most commonly used in calculating flows between ground water and surface water, its assumption of a constant aquifer thickness is violated where the water table slopes in the vicinity of a surface-water body.

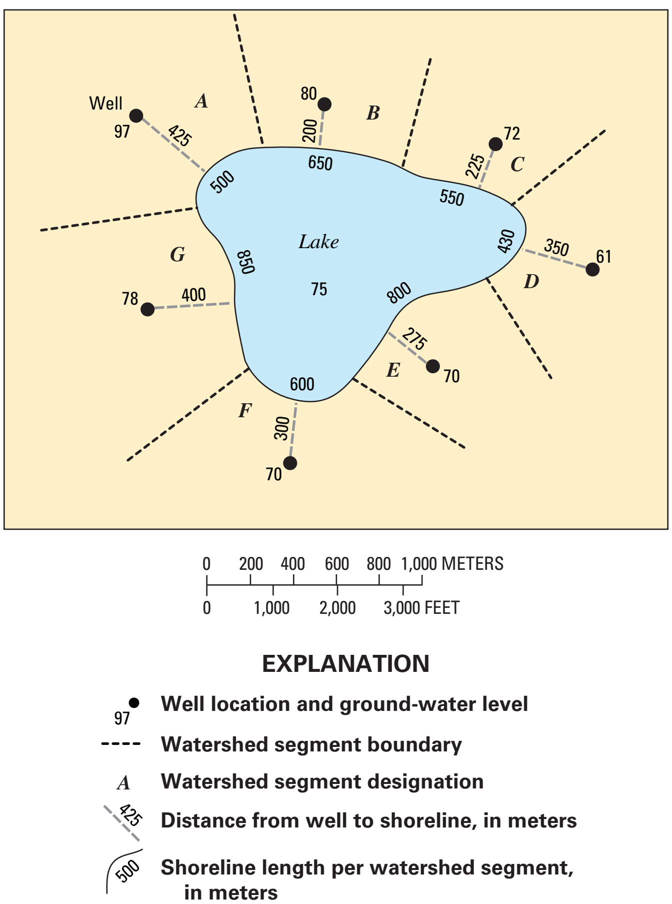


Figure 1. A hypothetical lake segmented based on positioning of near-shore water-table wells. Values are hydraulic head and surface-water stage.

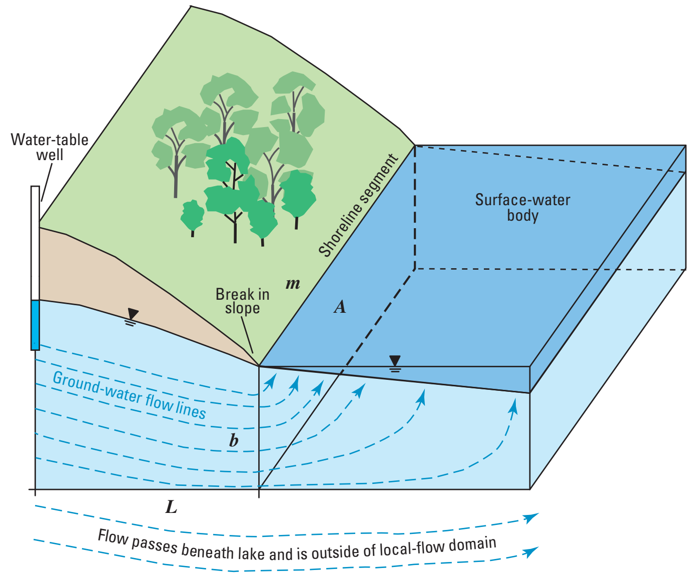


Figure 2. Typical hydraulic conditions in the vicinity of the shoreline of a surface-water body. (Artwork by Donald O. Rosenberry.)

In these near-shore, unconfined aquifer settings, the use of the Dupuit equation may be more appropriate because it allows the sloping ground-water table to be the upper boundary of the ground-water domain. The Dupuit equation can be written as:

$$Q = Km\frac{(h_1^2 - h_2^2)}{2L}, \qquad (2)$$

where

h_1 = aquifer thickness at the well,

and

h_2 = aquifer thickness at the edge of the surface-water body.

The Dupuit equation assumptions are:

1. The sediments are homogeneous and isotropic;
2. Flow in the aquifer is parallel to the slope of the water table; and
3. For small water-table gradients, ground-water flow lines (also called streamlines) are horizontal.

These assumptions require that equipotential lines (lines of equal hydraulic head) are perpendicular to the ground-water flow lines and are vertical.

As indicated in figure 2, near the shoreline, where water-table gradients typically steepen, these assumptions are violated to some degree. If flow is parallel to the water table, and the water-table gradient is sufficiently steep, then flow in the ground-water system obviously cannot be horizontal. Errors that result from violating these assumptions typically are minor relative to the uncertainty in determining *K*.

Another source of uncertainty in applying the Dupuit equation is the determination of h_1 and h_2. As with use of the Darcy equation, h_1 and h_2 should include only ground-water flow lines that intersect the surface-water body and exclude those flow lines that pass beneath the surface-water body, in which case $h_2 = b$ as shown in figure 2. This is especially important in cases where a lake, stream, or wetland occupies only the shallow, surficial part of a thick aquifer. As discussed later, h_2 or b often is one of the more difficult parameters to determine.

Although the use of the Dupuit equation is more appropriate for unconfined aquifer settings, the error that results from using the Darcy equation instead of the Dupuit equation commonly is small relative to the uncertainty in determining K. For a small water-table gradient, the errors are very small, and errors are small even for a relatively large water-table gradient. For example, assuming a large water-table gradient of 0.1 and the following values for a 1-meter shoreline reach ($h_1 = 60$ meters, $h_2 = 50$ meters, $L = 100$ meters, $K = 10$ meters per day), the Dupuit flow (Q) = 55 cubic meters per day, and the Darcy flow (Q) = 50 cubic meters per day.

An example of the use of the Darcy approach to calculate flows to and from a surface-water body using values obtained from figure 1 is shown in table 1. The example assumes that K is 30 meters per day and is uniform throughout the watershed, and that b is 20 meters. The method assumes that the hinge lines, the locations where flow direction changes from flow into the lake to flow out of the lake, occur at the ends of the adjacent shoreline segments where a change in flow direction is indicated. Considering the uncertainty associated with positioning of the hinge lines, the difference between total flow into the lake and total flow out of the lake is remarkably small in this example.

Flow-Net Analysis

The flow-net analysis is a graphical method for solving steady-state two-dimensional ground-water flow. The analysis uses the Darcy equation to solve for flow, the distribution of which is dependent on the flow net that is generated manually or with computer software. The method assumes that steady-state flow is two-dimensional (either in plan view, as applied here, or along a cross section), the aquifer is homogeneous and isotropic, and that b (the effective thickness of the aquifer) is known. Rules regarding construction of flow nets are described in Fetter (2000) and in other hydrogeology texts (for example, Davis and DeWiest, 1991). A detailed analysis of the method is provided in Cedergren (1997). In brief, the flow net consists of equipotential lines (lines of equal hydraulic head) and flow lines (also called streamlines). Equipotential lines are drawn on the basis of hydraulic head in the wells and the stage of the surface-water body. They intersect no-flow boundaries at right angles. Assuming the porous medium is homogeneous and isotropic, flow lines are drawn perpendicular to the equipotential lines. A sufficient number of flow lines are drawn so that the resulting rectilinear shapes form approximate squares. The areas between the flow lines are called streamtubes. The intervals between equipotential lines are termed "head drops." Once the flow net is constructed, a form of the Darcy equation is used to approximate flow to or from the surface-water body:

$$Q = \frac{MKbH}{n}, \tag{3}$$

where

- M = the number of streamtubes across a flow net,
- H = total head drop across the area of interest (L),
- n = number of equipotential head drops over the area of interest, and Q, K, and b are as defined previously.

An example of the flow-net approach is shown in figure 3. The flow net is created using the same hypothetical setting shown in figure 1. The flow domain has been rotated

Table 1. Data for calculating flows to and from the lake shown in figure 1, and total flow per segment (Q), using the segmented Darcy approach.

[m/d, meters per day; m, meter; m^3/d, cubic meters per day]

Watershed segment	Horizontal hydraulic conductivity (K) (m/d)	Effective thickness of the aquifer (b) (m)	Hydraulic head in well—surface-water stage (h_1–h_2) (m)	Distance from the well to the shoreline (L) (m)	Length of shoreline segment (m) (m)	Water flow (Q) (m^3/d)
A	30	20	22	425	500	15,529
B	30	20	5	200	650	9,750
C	30	20	–3	225	550	–4,400
D	30	20	–14	350	430	–10,320
E	30	20	–5	275	800	–8,727
F	30	20	–5	300	600	–6,000
G	30	20	3	400	850	3,825

Total flow into lake = 29,104 cubic meters per day.

Total flow out of lake = 29,447 cubic meters per day.

so that equipotential lines are approximately perpendicular to the no-flow boundaries on the top and bottom of the figure, and streamlines are approximately perpendicular to constant-head boundaries to the left and right of the figure. The equipotential lines represent hydraulic-head intervals of 10 meters. The total flow of water that exchanges with the lake is apportioned into seven streamtubes. Using the same values for *K*, *b*, hydraulic head, and lake stage as for the segmented Darcy method, and values of 7, 35, and 3.5 for *M*, *H*, and *n*, respectively, the total *Q* into the lake is 42,000 cubic meters per day. Total *Q* out of the lake, based on the same values as for the segmented Darcy method of 7, 15, and 1.5 for *M*, *H*, and *n*, respectively, also is 42,000 cubic meters per day. These values are substantially larger (44 percent) than total flows into and out of the lake calculated by the segmented Darcy method.

A comparison of results from the two methods indicates the relative accuracy of these methods. Substantial errors can result with the segmented Darcy method if conditions along each shoreline segments are not uniform. For example, determination of flow across the curving segment on the northwest side of the lake assumes that an arc of hydraulic head 22 meters higher than the lake surface exists a distance of 425 meters from shore along the entire shoreline segment. Common sense and the flow-net analysis (fig. 3) indicate that this is a poor assumption. Also, incorrect placement of the hinge-line location can result in shoreline segments drawn adjacent to the hinge line that poorly represent the actual local flow into and out of the surface-water feature. Figure 4 shows the flow lines drawn in figure 3 in addition to the shoreline segments indicated in figure 1. Positioning of hinge lines in figure 4 is based on the flow-net analysis. If the segmented Darcy method was used to place hinge lines, they would be located at the boundaries between segments *B* and *C*, and between segments *F* and *G*. Fortunately, a misplacement of the hinge line commonly does not result in substantial error because flow across the sediment-water interface commonly is small where ground-water flow is primarily parallel to the shoreline.

The flow-net analysis method provides a simple, initial estimate of the exchange of water between a surface-water body and ground water. The accuracy of the method depends on the degree to which the simplifying assumptions are met in the setting being analyzed and on how well the mesh is drawn. Errors can be minimized by ensuring that areas contained by the streamtubes and equipotential lines form approximate squares. Cedergren (1997) provides additional information for minimizing mesh-related errors. Uncertainties associated with accurate representation of *K* commonly are significantly larger than errors associated with improperly constructed flow-net meshes. With a larger number of wells, equipotential lines can be placed more precisely and a finer grid then can be generated. Accuracy also depends on how the flow net is interpreted. For example, in the setting shown in figure 3, streamtubes that partly intersect the lake were ignored. Those streamtubes might instead have been considered as half streamtubes, in which case the total flow into and out of the lake would have been larger. Alternately, streamtubes 1 and 7 could have been drawn so as to bypass the lake, in which case only five streamtubes would intersect the lake. If the number of streamtubes was five instead of seven, the flow-net-derived fluxes to and from the lake (30,000 cubic meters per day) would be nearly identical to the segmented Darcy-generated fluxes.

The domain shown in figure 3, although rotated to be aligned with flow lines and equipotential lines, was drawn with the same dimensions as the domain shown in figure 1. One could argue, however, that the domain should have been made larger because many of the flow lines and equipotential lines do not intersect the boundaries at right angles.

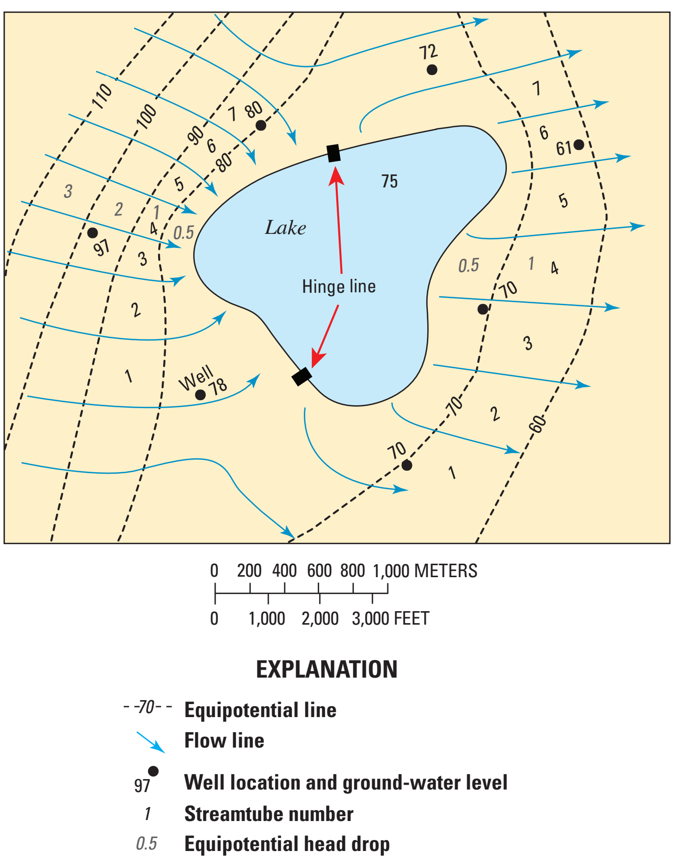


Figure 3. A flow net generated to indicate flow of water to and from a hypothetical lake. Ground-water flow direction is indicated by flow lines (blue lines), and lines of equal hydraulic head (equipotential lines) are shown with dashed lines. Values shown are hydraulic head in the wells and surface-water stage.

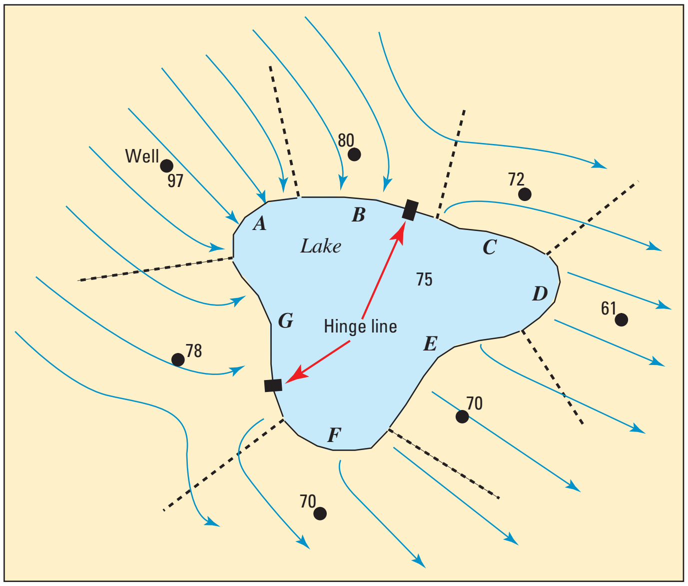


Figure 4. Conceptualization of flow based on flow-net analysis and segmented Darcy fluxes. The position of the hinge line changes depending on the method of analysis used.

Sources of Error

Sources of error in applying the segmented-shore or flow-net-analysis approach to the determination of the exchanges between a surface-water body and ground water, in addition to errors in interpretation presented above, include:

1. Inadequate physical characterization of conditions or properties that affect flow,
2. Measurement error,
3. Improperly constructed wells,
4. Improperly maintained wells,
5. Unstable wells and stage gage, and
6. Violation of underlying assumptions.

Each item is discussed in detail below.

Inadequate Physical Characterization

In the examples given above, horizontal hydraulic conductivity (*K*) was assumed to be uniform across the entire watershed. This is a poor assumption because erosional and depositional conditions near the shoreline commonly are different than for the larger watershed. Where lower-*K* sediments line lakes or wetlands, *K* within a meter of the sediment-water interface can be the dominant control on flow (Rosenberry, 2000). This is especially well documented in fluvial settings (for example, Brunke, 1999; Hiscock and Grischek, 2002; Schubert, 2002; Sheets and others, 2002; Fleckenstein and others, 2006). It usually is beneficial to install additional wells near the shoreline of the surface-water body to gain a better understanding of the distribution of hydraulic head and of the spatial variability in *K*.

A slug test can be expected to provide only an approximate estimate of the actual *K* that controls flow between ground water and surface water. First, slug tests measure horizontal *K,* but aquifers commonly are anisotropic; vertical *K* typically is smaller, sometimes orders of magnitude smaller, than horizontal *K*. Second, measurements of *K* are to some extent scale dependent and single-well slug tests may provide values that are too small to be representative of the larger scale flow in the aquifer. Rovey and Cherkauer (1995) found that *K* of a carbonate aquifer in Wisconsin increases linearly with the scale of the measurement up to a radius of influence of between 20 and 220 meters, after which point *K* was constant with increasing radius. Schulze-Makuch and others (1999) indicated that scale dependence of *K* depends on the hydraulic properties of an aquifer. They reported that *K* is relatively insensitive to scale for homogeneous aquifers but increases by half an order of magnitude for every order of magnitude increase in spatial scale of heterogeneous aquifers. Unless the well is installed in the lake, the approaches outlined herein do not attempt to quantify exchange between ground water and surface water at the surface-water feature itself. Rather, they estimate the flow into and out of the ground-water system near the surface-water feature, at the locations of the monitoring wells and assume that water that crosses the vertical plane at the shoreline must either originate from or flow into the lake.

Determination of the effective thickness of the aquifer (*b*) through which water flows to interact with a surface-water body also can be difficult. Investigators may resort to hypothetical flow modeling or to tracers to address this issue. Siegel and Winter (1980) and Krabbenhoft and Anderson (1986) used finite-difference ground-water flow models to estimate the part of an unconfined aquifer that interacts with a lake. Taniguchi (2001) used a one-dimensional advection-dispersion model calibrated to chloride data to determine that *b* for Lake Biwa, Japan, was 150 meters. Lee and Swancar (1997) used vertical ground-water flow divides to determine *b* for their flow-net analysis for a lake in Florida. Perhaps the most thorough investigation to date is a study of flow between two lakes in northern Wisconsin. Flow-net, isotopic and geochemical, and numerical modeling approaches have been used to determine the relative volumes of water that flow from the upgradient lake to the downgradient lake and water that flows from the upgradient lake, beneath, and ultimately beyond the downgradient lake (for example, Kim and others, 1999).

Conceptual models of hypothetical settings can be useful in constraining estimates of exchange between ground water and surface water when sufficient field data are not available. Simply knowing the size, shape, and depth of a lake relative to its watershed can aid in determining the degree of interaction between the lake and its watershed. Two-dimensional and three-dimensional numerical and analytical tools can visually present the types and relative scales of flow paths associated with exchange between ground water and surface water (Townley and Davidson, 1988; Nield and others, 1994; Townley and Trefry, 2000). Recent updates of ground-water flow models allow more realistic simulation of exchanges between ground water and surface water than was previously possible. Hunt and others (2003) provide an overview of the usefulness of these improvements associated with the U.S. Geological Survey MODFLOW model (Leake, 1997; Harbaugh and others, 2000; Harbaugh, 2005).

Compared to errors associated with conceptualizing flow paths and determining aquifer properties, the remaining sources of error listed here usually are relatively minor. They are included, however, for completeness, and because in some situations they can represent a significant part of the total error associated with quantifying flow between ground water and surface water.

Measurement Error

Errors in making water-level measurements in wells and in observing surface-water stage generally are not significant relative to errors in determining *K* or *A*. Errors associated with determining the elevation of the top of the well casing relative to surface-water stage also typically are small. Increasing accuracy and availability of global positioning systems are reducing errors associated with determining well location. These errors can be significant, however, if the well is within a few meters of the surface-water body or if hydraulic gradients are very small. In this instance, greater care and more accurate methods should be used in determining the position of the well and the elevation of the top of the well casing relative to the surface-water stage.

Improperly Constructed Wells

Water-table wells in which water levels will be measured to calculate fluxes between ground water and surface water should be constructed so the water level in the well represents the phreatic surface of the aquifer (the water table). The screened interval of the well should be placed so it intersects the water table over the expected range of water-table fluctuations. Typical well-screen lengths for water-table monitoring wells range from 0.3 to 3 meters. Wells with long screens will integrate hydraulic head over the length of the well screen, and wells with short screens that are placed substantially below the water table will provide hydraulic head at depth in the aquifer that may be considerably different from the water-table head, especially within two to three aquifer thicknesses from the lake (Hunt and others, 2003).

Improper well construction also can alter hydrologic representation, particularly if the completion method results in the well screen being isolated from the aquifer. If drilling mud is used during well construction, for example, the well must be sufficiently developed following completion of the drilling to ensure that the well is in good hydraulic connection with the aquifer. For wells that are driven or pounded to the desired depth, a common installation method near the shoreline where the depth to water is shallow, care also needs to be given to proper development of the well. Well screens often are smeared with fine-grained sediment during the driving process and can be completely clogged if they are not flushed following installation. Hand-augered wells commonly are installed with the bottom of the well screen a short distance below the water table. It is difficult to auger through sand much beyond 1 meter below the water table because the sand collapses into the part of the hole below the water table. The consequence of the water table dropping below the bottom of the well screen is a dry well. A word of caution is in order for water-level measurements in wells constructed so the screen does not extend all the way to the well bottom (that is, when an impervious cap or drive point extends beyond the bottom of the screen); a small amount of water can be trapped inside the cap or drive point and remain in the well even if the water table has dropped below the bottom of the well. In such instances, the observer can still make a water-level measurement in the well and may not realize that the actual water table is below the bottom of the well.

The well screen also needs to be selected with a slot size (width of the openings in the screen) that is appropriate for the geologic material in which the screen is installed. If the slot size is too small, water levels in the well will lag behind changes in hydraulic head in the aquifer (Hvorslev, 1951). If the slot size is too large, particles will pass through the screen and may fill the well bore. Improper slot size may not be important when monitoring water levels on a weekly or less frequent interval, but can be very important if water-level change is recorded as part of a slug test or aquifer test.

Improperly Maintained Wells

Water-table monitoring wells can become clogged with sediments or bacterial growth, in part because so little water typically flows through a monitoring-well screen. Chemical precipitates (scale) also can clog the openings of a well screen. These processes decrease the connectivity of the well with the aquifer, creating a delayed response between the water level in the well and the hydraulic head in the aquifer. In extreme instances, the water level in the well becomes unresponsive to temporal changes in aquifer hydraulic head. Monitoring wells should be flushed occasionally to test and maintain connectivity with the aquifer.

The top of the well casing is vulnerable to accidental damage or vandalism. Protective devices for wells should be maintained and records kept in order to document any changes in the elevation of the top of the well casing to which water levels in the well typically are referenced.

Unstable Wells and Staff Gages

Water-table monitoring wells located near surface-water bodies commonly are quite shallow because the depth to the water table is shallow. Shallow well casings can move vertically in response to pumping for water-sample collection, frost, and settling of well cuttings placed in the annular space between the well casing and undisturbed sediments. This is particularly common for wells installed in wetland sediments. Shallow wells constructed with plastic casing can break from ice expansion during subfreezing temperatures. Wells and surface-water staff gages located near a downwind shoreline also can be tilted, moved horizontally, or broken if surface ice is pushed onto the shoreline during fall freeze or spring thaw. For longer term studies, it may be cost effective to install a sturdy surface-water monitoring station so that sources of environmental damage are minimized (Buchanan and Somers, 1982). A less expensive means for obtaining greater stability in a surface-water stage record is the installation of a siphon gage that allows measurement of surface-water stage in a protected environment (McCobb and others, 1999). Annual leveling surveys are necessary for surface-water staff gages, as well as many near-shore wells, in order to document changes in the elevation of the staff gage or the top of the well casing. Multiple survey benchmarks can aid in maintaining long-term elevational accuracy for staff gages and shallow, near-shore wells.

Violation of Underlying Assumptions

The previously discussed assumptions of homogeneity and isotropy, inherent in most calculations of exchange between ground water and surface water, are rarely met or appropriate for near-shore settings and can result in large errors in quantifying exchange between ground water and surface water. Assumptions of two-dimensional areal flow also typically are violated in near-shore regions (two to three aquifer thicknesses from the surface-water feature) where convergences and divergences of flow lines are common. The Darcy approach also assumes that the system is in a steady-state condition. Although the natural world is rarely if ever at true steady state, the system often will have periods when water levels are not changing appreciably over time, during which representative estimations of average flows can be made. It often is instructive to construct a simple computer model of the physical hydrologic setting, even if the entire hydrogeologic framework is not adequately known. Such a tool facilitates testing of the significance of one or more of these assumptions. In addition, a preliminary model can be used to help identify sensitive parameters and locate areas in the watershed where additional data collection would be most beneficial.

Hydraulic Potentiomanometer

The hydraulic potentiomanometer, sometimes referred to as a mini-piezometer, is a portable drive probe connected to a manometer (fig. 5). The manometer provides a comparison between the stage of a surface-water body and the hydraulic head beneath the surface-water body at the depth to which the screen at the end of the probe is driven (Winter and others, 1988). The difference in head divided by the distance between the screen and the sediment-water interface is a measurement of the vertical hydraulic-head gradient. By driving the probe to different depths beneath the sediment-water interface, the probe can provide information about variability in vertical hydraulic-head gradient with depth. The device does not give a direct indication of seepage flux, but when used in combination with a seepage meter, which does measure water flux, the two devices can yield information about the hydraulic conductivity of the sediments (for example, Kelly and Murdoch, 2003; Zamora, 2006). Because this device provides a quick characterization of the direction and magnitude of the vertical hydraulic gradient, it is useful as a reconnaissance tool in lakes, wetlands, and streams. It also is useful in areas where near-shore water-table wells or piezometers do not exist, are sparsely distributed, or are impractical to install and maintain.

The original hydraulic potentiomanometer design (fig. 6) consists of two nested stainless-steel pipes separated by O-rings that rest in grooves machined into the inner pipe. A screen with a machined point is threaded onto the inner pipe. The outer pipe acts as a shield for the screen; it covers

Figure 5. Hydraulic potentiomanometer showing drive probe inserted into lakebed and manometer indicating a very small vertical hydraulic-head gradient (blue arrows indicate water levels on manometer). (Photograph by Donald Rosenberry, U.S. Geological Survey.)

the screen and prevents damage to the screen and smearing of fine-grained sediments during insertion of the probe. A manometer is connected to the probe to allow measurement of the difference between head at the exposed well screen and the stage of the surface-water body.

Once the probe is pushed to a desired depth beneath the sediment-water interface, the outer pipe is retracted to expose the screen. At this point, one could simply measure from the top of the well pipe to the water level inside the probe and to the surface-water level outside of the probe. The difference between these measurements is the head difference. For convenience, and to better resolve small head differences, a manometer is attached to the probe. A vacuum is applied at the top of the manometer, pulling water through tubing connected to the probe and the surface water. Greater resistance of flow through the well screen may require that the surface-water tube be clamped to allow development of sufficient suction to pull water through the well screen and tubing. When all of the tubing is full of water and free of bubbles, air is bled into the top of the manometer until the menisci are visible in the tubing on both sides of the manometer (fig. 5). The difference in height of the menisci equals the difference between head at the screen in the sediment and the stage of the surface-water body.

The hydraulic potentiomanometer works well in fine sands and coarser materials. It becomes difficult to pull water through the screen if the sediments contain significant amounts of silt, clay, or organic deposits. The probe is difficult to insert in rocky or cobbly sediments because of

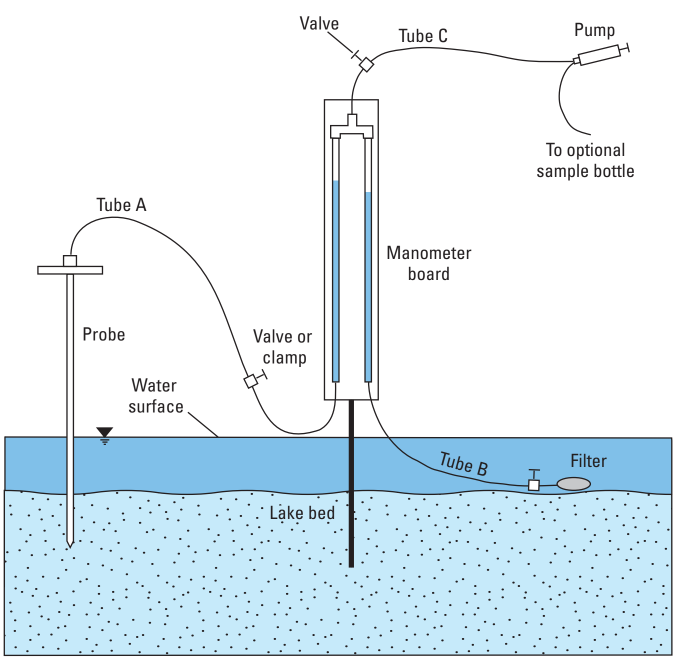


Figure 6. Components of the hydraulic potentiomanometer system. (Modified from Winter and others, 1988; copyright 1988 by the American Society of Limnology and Oceanography, Inc., used with permission.)

the difficulty of driving the probe past the rocks and also because it is difficult to obtain a good seal between the outer pipe of the probe and the sediments. Rocks and cobbles near the shoreline often are only a surficial veneer; however, a measurement usually is possible if the probe can penetrate the surface layer.

Variability in the direction and magnitude of horizontal hydraulic-head gradient with distance from shore can be determined by making measurements along transects oriented perpendicular to the shoreline. The probe should be inserted to the same depth beneath the sediment-water interface at each measurement location. Otherwise, it is impossible to distinguish spatial variability in horizontal gradients from spatial variability in vertical gradients. One end of each transect typically extends to the shoreline, but measurements also can be made onshore in places where the probe can be driven deeply enough to reach the water table. For onshore measurements, the hydraulic potentiomanometer probe provides data equivalent to that of a shallow, near-shore monitoring well, while the tubing in the lake serves as a surface-water gage. Where the near-shore land-surface slope is small, the probe can be inserted a considerable distance from the shoreline, although the tubing needs to be long enough to extend from the well probe to the surface-water body. The vertical distribution of vertical hydraulic-head gradients can be determined by driving the probe to multiple depths beneath the sediment-water interface at each measurement location. This provides information about geologic heterogeneity with depth beneath the sediment-water interface, which can have a large influence on depth-integrated hydraulic-head gradients. In rivers, it is common for sediments to be composed of alternating layers of organic and inorganic sediments or fine-grained and coarse-grained sediments. Measurements often cannot be made in the organic or fine-grained layers, in which case measurements should be attempted in the more permeable layers. Differences in head between the transmissive layers often are large because the intervening low-permeability layers limit the equalization of pressure between the transmissive layers. Biogenic gas, which is common in many riverine sediments, can make obtaining bubble-free measurements difficult.

Differences in hydraulic head, although dependent on the depth to which the probe is inserted, typically range from 0 to 10 centimeters, but head differences as much as 30 centimeters are not uncommon. In some settings, the head difference can be very large, primarily because of local-scale geologic heterogeneity. In rare instances, head differences are greater than the length of the manometer, in which case the manometer can be raised, allowing the lower-head meniscus to be situated in the clear flexible tubing connected to the base of the manometer. For example, a head difference of approximately 2.4 meters was reported at a site where water was flowing from a lake to ground water (Rosenberry, 2000). The extreme gradient was present because a nearby lake had a water level 14 meters lower than the upper lake. Coarse sand was present between the two lakes, and much of the head difference between the two lakes was distributed across a 20-centimeter-thick layer of organic-rich, sandy sediment at the sediment-water interface of the upper lake. Although still quite permeable compared to other lake sediments in the area, the permeability of the top 20 centimeters of sandy lake sediment was one to two orders of magnitude lower than that of the underlying coarse sand. The manometer had to be raised well above the lake surface in order to measure the large head difference.

Early versions of the hydraulic potentiomanometer used a vacuum bottle for collection of the water because hand-held pumps did not work well if they became wet (fig. 6). However, hand-cranked or motorized peristaltic pumps work well for pulling water through the manometer system. A cordless drill attached to a peristaltic pump head also can be used as a portable pump (J. Lundy, Minnesota Department of Health, oral commun., 2005). For a small-volume well and manometer system, a large syringe can serve as a pump (D.R. LeBlanc, U.S. Geological Survey, oral commun., 2005).

Water samples can be collected with the hydraulic potentiomanometer. Many investigators choose to bypass the manometer when collecting samples to minimize the potential for sample contamination from the tubing.

Sources of Error

Several sources of error attend the use of a hydraulic potentiomanometer:

1. Measurement error,
2. Improper leveling of the manometer,
3. Unstable hydraulic head,
4. Improper seal between outer pipe and the sediments,
5. Large bubbles entrained in tubing,
6. Leaks or clogging, and
7. Waves, standing waves, and seiches.

Each item listed above is discussed in detail below.

Measurement Error

Errors in measurement can result from improperly reading the menisci on the manometer. For very small differences in head, a common occurrence in highly permeable sediments, this error can result in a misinterpretation of the direction of flow of water across the sediment-water interface. Capillarity typically is not an issue unless very small diameter plastic tubing is used or the tubing diameters on the manometer are different. Hydrophobicity, however, may become significant if small-diameter plastic tubing is used, in which case the water menisci in the tubing may resist movement in response to small changes in hydraulic-head gradient.

Head differences can be amplified by use of a light oil in place of air at the top of the manometer (Kelly and Murdoch, 2003). The degree of amplification depends on the density of the light oil relative to the density of water:

$$dh = dh_{oil}\left(\frac{\rho_w - \rho_{oil}}{\rho_w}\right), \tag{4}$$

where

dh is difference in hydraulic head over the distance between the sediment-water interface and the piezometer screen (L),

dh_{oil} is difference in elevation between the oil-water interface on the piezometer side of the manometer and oil-water interface on the surface-water side of the manometer (L),

ρ_w is density of water ($M\ V^{-1}$),

and

ρ_{oil} is density of oil ($M\ V^{-1}$).

Kelly and Murdoch (2003) used vegetable oil with a density of 0.9 gram per cubic centimeter, which increased the head difference tenfold.

Another source of measurement error is the determination of the depth to which the screened interval of the probe is inserted. An easy solution for determining this depth is to use an engraving tool to mark the outer pipe with depth increments. This distance should be recorded before the outer pipe is retracted to expose the screen. Distance typically is relative to the center of the screened interval of the probe.

Improper Leveling of the Manometer

This common problem becomes important when the two sides of the manometer are separated by a considerable distance (as is the case with the manometer shown in fig. 5), or when the difference in head is small. Out-of-level error can be minimized by installing a bubble level on the manometer and by constructing the manometer so the two parallel tubes are positioned close to each other (fig. 7).

Unstable Hydraulic Head

Most measurements of difference in head stabilize in a matter of seconds to minutes. In low-permeability sediments, it can take from tens of minutes to hours for head at the probe screen to stabilize. In such cases, observations of difference in head are repeated until the difference in head stops changing, indicating stabilization. Stabilization time also can provide a relative indication of the permeability of the sediments at the location of the probe screen.

Improper Seal Between Outer Pipe and the Sediments

If the hydraulic potentiomanometer is inserted in rocky or gravelly sediments, or if the probe is not inserted cleanly into the sediments (that is, if the probe is rocked back and forth during insertion), or if the probe is inserted a very short distance into the sediments, water can flow vertically along the

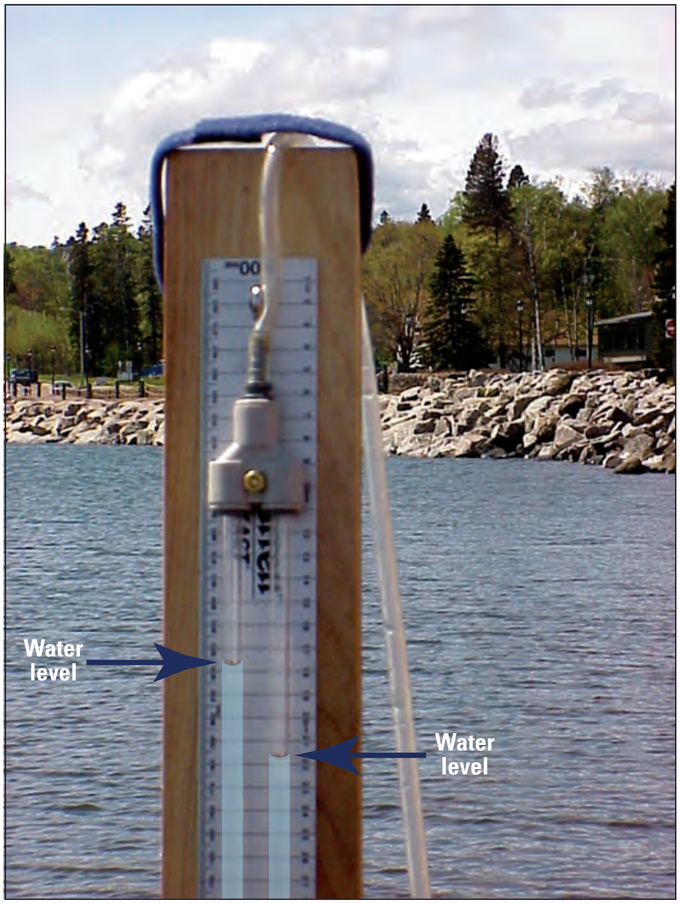


Figure 7. Hydraulic potentiomanometer designed to place the manometer tubes connected to the drive probe and to the surface-water body close together to minimize out-of-level errors. (Photograph by Jim Lundy, Minnesota Department of Health.)

outer surface of the probe, with the result that the difference in head between the screen and the surface water is less than the actual difference. This "short circuiting" of head can be prevented by driving the probe straight into the sediments, or by driving the probe farther into the sediments.

Large Bubbles Entrained in Tubing

At many sites, biogenic gas is pulled through the probe and is visible in the tubing connecting the probe to the manometer. Gas bubbles inside the tubing can change volume with a change in temperature and thereby corrupt the difference in head displayed by the manometer. Care should be taken to ensure that large bubbles (large enough to extend across the entire cross section of the tubing) are removed prior to bleeding air back into the top of the manometer to take a reading. Very small bubbles also may appear when a strong vacuum is applied to pull water through the well screen. These bubbles are the result of the water degassing in response to the suction pressure. Typically, they do not present a problem because they occupy a very small volume, but over time they may grow as the water warms. The problem can become significant with increased equilibration time.

Occasionally, small lenses or zones of sediments beneath surface-water bodies are unsaturated, commonly because of discrete pockets of gas generated from organic decomposition. Larger scale areas of unsaturated sediments also have been identified, in which case the tubing from the probe is filled primarily with air and very little water. Although it is not possible to measure a hydraulic-head difference in these instances, the hydraulic potentiomanometer remains useful in that it can identify these sometimes unexpected hydrologic conditions. Rosenberry (2000) reported a large, apparently permanent wedge of unsaturated sediments beneath the edge of a lake that was identified on the basis of measurements made with the hydraulic potentiomanometer. This unsaturated sediment was in direct connection with the adjacent unsaturated zone onshore and extended up to 20 meters beyond the shoreline of the lake. The hydraulic potentiomanometer also was used at a small pond to determine the vertical and areal extent of pockets of gas beneath the pond that were several meters in diameter. The gas likely was trapped when the pond stage rose and the shoreline rapidly moved laterally to cover formerly unsaturated near-shore sediments (Rosenberry, 2000).

Leaks or Clogging

Leaks can form (1) at the O-rings that separate the inner and outer pipes, (2) between the inner rod and the tubing to which it is connected, and (3) between the tubing and the manometer. Leaks also can occur within the manometer plumbing. Leaks can cause formation of bubbles in the water contained within the probe and tubing, which can cause the manometer to indicate an erroneous difference in head. O-ring leaks can be prevented by liberal use of O-ring grease. Other leaks can be eliminated by using clamps, sealant or tape. The entire system can be clogged if the well screen is torn or absent and sediments are pulled through the tubing. Clogging also is likely if the end of the surface-water tubing settles into the bed sediments. A screen can be placed over the end of the surface-water tube to prevent sediments from entering the tubing. Also, a weight often is applied to the surface-water tube to keep the tube from floating to the surface and allowing air to be pulled through the tubing.

Waves, Standing Waves, and Seiches

Difference in head between the surface-water body and the screened interval of the hydraulic potentiomanometer can vary with short-term changes in surface-water stage caused by waves, seiches, or even standing waves in fast-moving streams or rivers. Waves make it difficult to make a measurement if the head difference is small. The surface-water tube can be placed inside a small stilling well (even something as simple as a coffee can) with holes drilled in the side to dampen stage fluctuations from waves. Seiches (internal waves) are common on large lakes and rivers and can be dealt with by making measurements at the same location multiple times over a period that is appropriate for the periodicity of the seiche.

Other Similar Devices

Numerous other devices have been constructed to measure difference in head between surface-water bodies and the underlying ground water, involving a modification of the probe, the method for measuring head difference, or both. Squillace and others (1993) modified the hydraulic potentiomanometer by making the probe longer and adding a drive hammer in order to place the screened interval at depths as great as 3 meters below the sediment-water interface. This device was used by Rosenberry (2000) to determine the horizontal and vertical extent of unsaturated sediments beneath a lake (fig. 8). Another drive-hammer device has the manometer connected to the drive probe to minimize components that need to be carried in the field (fig. 9). Mitchell and others (1988) clamped the well and lake tubing to a metric ruler to create a simple manometer for making measurements of difference in head.

Members of the Cullen Lakes Association in northern Minnesota modified a well probe to eliminate the manometer. They used a “mini dipper” small-diameter electric tape to make measurements of depth to water inside and outside the probe. The measurement outside of the probe was made through a length of semirigid tubing; the top of the tubing was flush with the top of the probe, and the bottom extended to the surface water (fig. 10) (Ted P. Soteroplos and William (Bill) J. Maucker, Cullen Lakes Association, written commun., 1995). A commercially available, retractable, stainless-steel soil-gas vapor probe was used to avoid having to manufacture a retractable well screen.

Several other small-diameter devices also have been developed to measure vertical-head gradients beneath surface-water features. Lee and Cherry (1978) describe the use of a flexible plastic tube with a screen attached to the end. The tube is driven to depth inside a larger diameter rigid steel pipe that is removed once the insertion depth is reached, allowing the sediment to collapse around and seal the tube in place in the sediment. With the tubing extended above the surface, the water level inside the tube is compared to the surface-water stage. More recently, a root-watering device, commonly available at hardware stores, has been used to measure vertical hydraulic-head gradients beneath surface-water bodies (Wanty and Winter, 2000). A coil of tubing is connected to the top of the probe, and when positioned properly with respect to the water surface, is used to indicate difference in head between that in the probe and that of the surface-water body (fig. 11). A commercially available probe (MHE PP27) is used to collect water samples and to make measurements of difference in head beneath the sediment-water interface in much the same method (Henry, 2000). This device also makes use of clear tubing placed at the water surface to measure difference in head (fig. 12).

Several investigators have developed methods for determining head gradients at multiple depths beneath the sediment-water interface. Duff and others (1998) designed a device for collecting water samples from multiple depths beneath a streambed. If clear tubing is used, hydraulic heads also can be related to stream stage. Lundy and Ferrey (2004) used a combination of drive points and multilevel samplers that could be left in place for the duration of the study. Their study design allowed repeat measurement of head gradients and collection of water samples so the investigators could determine the extent and growth of a contaminant plume that intersected a stream. Both devices allowed rapid measurements and convenient collection of water samples from multiple depths.

Figure 8. Hydraulic potentiomanometer probe with drive hammer shown driven about 2 meters beneath the lakebed. Manometer and hand-crank peristaltic pump are visible in background. (Photograph by Donald Rosenberry, U.S. Geological Survey.)

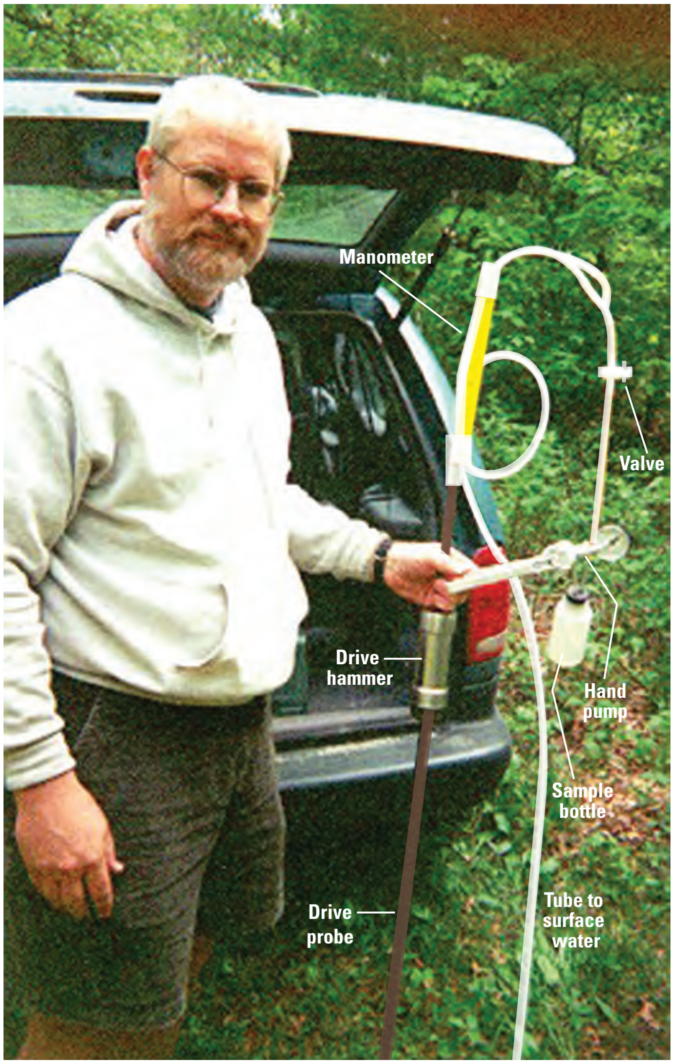


Figure 9. Hydraulic potentiomanometer (created by Joe Magner, Minnesota Pollution Control Agency) with manometer connected to drive probe. Note the proximity of the lake and drive-point tubes to minimize out-of-level errors. Note also the in-line water bottle to keep the vacuum pump dry. (Photograph by Donald Rosenberry, U.S. Geological Survey.)

Calm surface-water conditions are required for all of these designs that make use of a length of clear tubing inserted into the surface-water body. A manometer could be used with any of these devices, although most of these alternative approaches were developed to avoid use of a manometer in order to simplify the measurement system.

Cautions and Suggestions Related to Use of the Hydraulic Potentiomanometer

Buried debris, such as logs, rocks, and even old tires, often is encountered when driving the hydraulic potentiomanometer probe. In most instances, it is possible to reinsert the probe 0.5 meter away and drive the probe to the desired depth.

The observer should not stand within 1 meter of the probe when making a measurement. The weight of the observer can compact sediments and cause a several-centimeter change in the measured head difference. This artifact is especially notable in soft sediments.

If a considerable amount of trapped gas is encountered, thus making it difficult to get a bubble-free measurement, it is sometimes possible to pull water rapidly through the screen, evacuating much of the gas from the sediments near the probe screen. After waiting a few minutes, water then can be pulled slowly through the screen without pulling additional gas bubbles into the tubing.

The screened interval commonly will break when using a drive hammer to position a hydraulic potentiomanometer probe, especially if many blows are required and the probe is made from stainless steel. Stainless steel is relatively brittle, and the many holes drilled in the screened interval weaken the metal tube, which may lead to failure from the shock of the drive hammer. It is advisable to build the device with the screen as a separate part that is threaded onto the interior rod of the probe, so damaged or broken screens can be removed and replaced. It also is advisable to tighten the screen frequently because the shock of driving the probe often loosens the threads connecting the screen to the rest of the probe.

The screen should be retracted inside the outer sheath before removing the probe after a measurement has been completed. This prevents the screen from being damaged during removal of the probe and also traps the sediment that surrounds the screen while making the measurement. This allows a qualitative description of the sediments at the depth at which the measurement is made.

Seepage Meters

The seepage meter is one of the most commonly used devices for making a direct measurement of the flux of water across the sediment-water interface. Early versions were developed to measure water losses from irrigation canals (Israelson and Reeve, 1944; Warnick, 1951; Robinson and Rohwer, 1952; Rasmussen and Lauritzen, 1953). Many of these devices were expensive and unwieldy and were little used beyond the application to canals. Carr and Winter (1980) provide an annotated bibliography of the early literature on seepage meters, including drawings of some of the devices. Lee (1977) developed an inexpensive and simple meter that has changed little during the decades since its inception. Lee's meter consists of the cut-off end of a 208-liter (55-gallon) storage drum, to which is attached a plastic bag that is partially filled with a known volume of water (fig. 13). The drum, or chamber, is submerged in the surface-water body and placed

Figure 10. Portable well probe consisting of a commercially available retractable soil-gas vapor probe connected to threaded pipe with tubing inside the pipe connected to the vapor probe. A separate tube taped to the outside of the pipe extends to the lake-water surface. (Photograph by Donald Rosenberry, U.S. Geological Survey.)

in the sediment to contain the seepage that crosses that part of the sediment-water interface. The bag then is attached to the chamber for a measured amount of time, after which the bag is removed and the volume of water contained in the bag is remeasured. The change in volume during the time the bag was attached to the chamber is the volumetric rate of flow through the part of the bed covered by the chamber (volume/time). The volumetric rate of flow then can be divided by the approximately 0.25-square-meter area covered by the chamber to express seepage as a flux velocity (distance/time). Flux velocity is useful because it normalizes the area covered by the seepage meter and allows comparisons of results with other studies (and other sizes of seepage meters). Seepage flux velocity typically is multiplied by a coefficient that compensates for inefficiencies in flow within the meter, restrictions to flow through the connector between the bag and the chamber, and any resistance to movement of the bag as it fills or empties.

The range of seepage rates that have been reported from coastal and fresh-water settings is approximately five orders of magnitude. Values as small as 0.01 centimeter per day have been reported (for example, Cherkauer and McBride, 1988; Yelverton and Hackney, 1986), although some studies indicate that values less than 0.01 centimeter per day (Lee and Cherry, 1978), 0.04 centimeter per day (Harvey and others, 2004), or 0.08 centimeter per day (Cable and others, 1997a) are too small to be measured accurately. A recently developed meter designed for use in benthic ocean settings is capable of measuring exceptionally slow seepage rates as small as 3×10^{-5} centimeters per day (Tryon and others, 2001). Several values of 100 centimeters per day or greater have been reported (100 centimeters per day—Asbury, 1990; 130 centimeters per day—Belanger and Walker, 1990; 240 centimeters per day—Rosenberry, 2000; 275 centimeters per day—Paulsen and others, 2001). Duff and others (1999) measured a flux of nearly 5,200 centimeters per day from a 2- to 3-centimeter-diameter, boiling-sand spring in a small stream in northern Minnesota.

The half-barrel seepage meter is relatively easy to use and conceptually simple to operate. The cylindrical seepage chamber (with bag detached) first is placed on the submerged sediment and slowly inserted into the bed with a twisting, sediment-cutting action. Care must be taken to ensure a good seal between the chamber and the sediment. Buried rocks

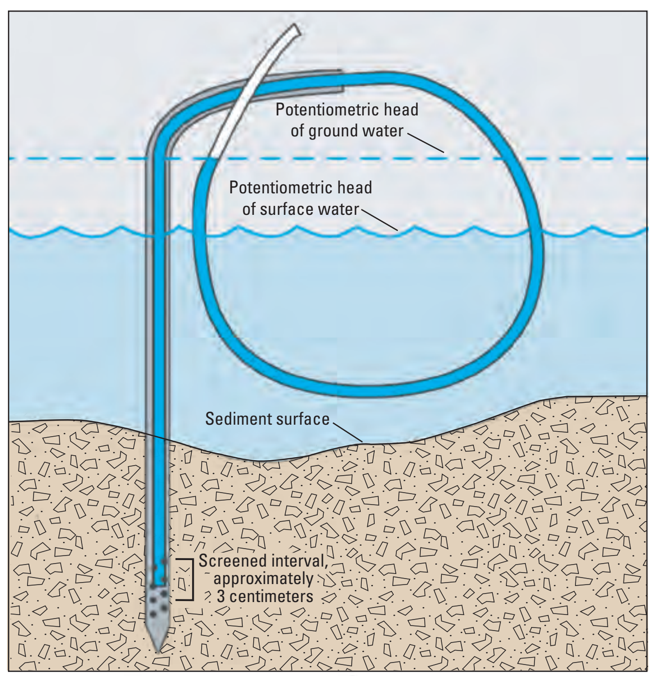


Figure 11. Well probe constructed from a commercially available root feeder with the coiled tubing substituting for a manometer. (Modified from Wanty and Winter, 2000.)

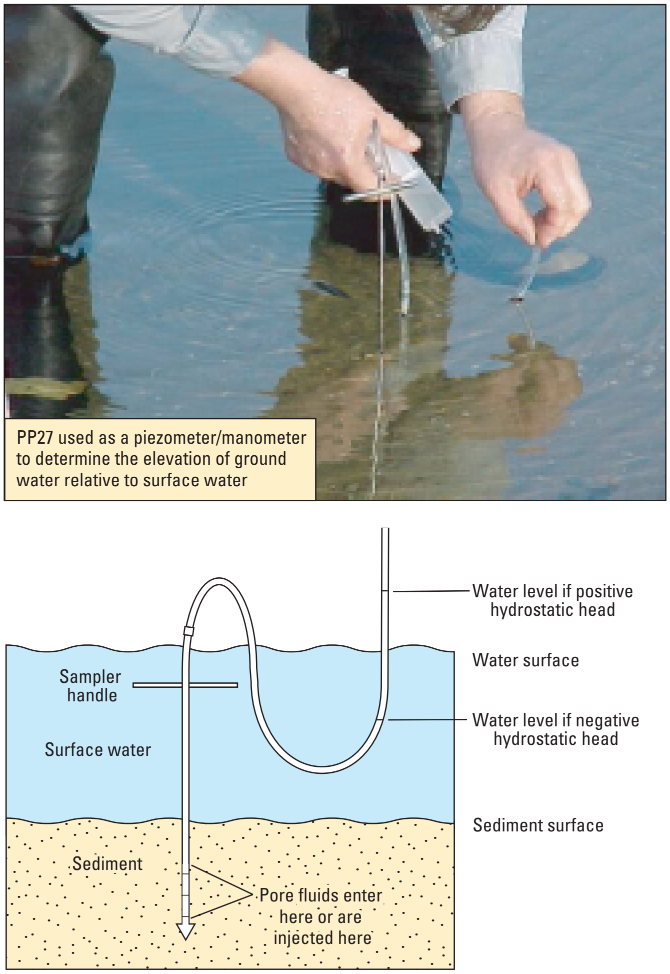


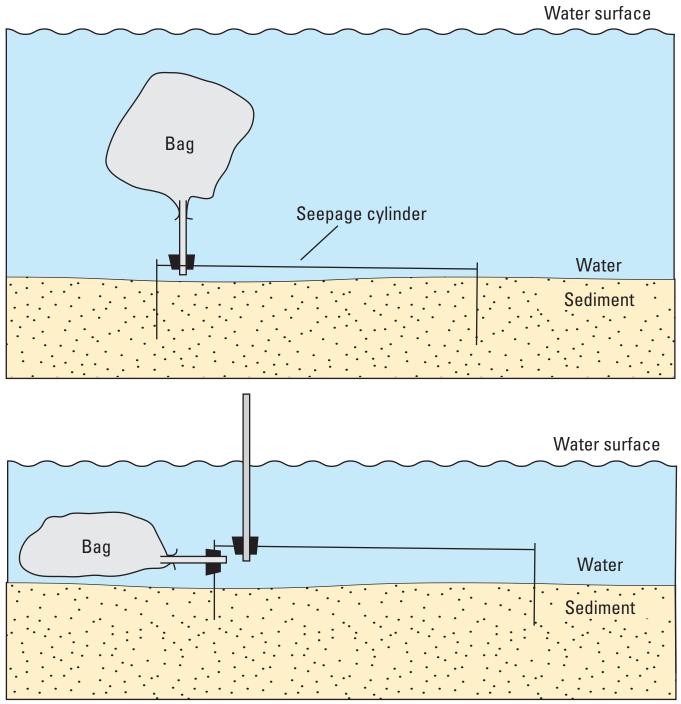
Figure 12. MHE PP27 probe used to indicate difference in head (modified from Henry, 2000). (Photograph by Mark Henry, Michigan Department of Environmental Quality.)

or woody debris can prevent the edges of the chamber from extending into the sediment and may allow short-circuiting of water beneath the edge of the chamber. Some investigators have packed sediments around the outside of the chamber to create a good seal (Cable and others, 1997a). Occasionally, in sandy or gravelly settings, it is necessary to stand on the chamber and gently rock it back and forth to force it into the sediment. Sometimes this action is necessary in weedy settings where the meter needs to cut through a part of the weed bed in order to achieve a good seal. Harvey and others (2000) made circular vertical slits in the fibrous peat in order to install seepage meters in wetlands in the Florida Everglades. Standing on the chamber should be a last resort, however, because rapid emplacement can cause “blowouts” of the sediment adjacent to the chamber (Lee, 1977), or compress sediments beneath the chamber, and disturb the natural rate of water flow through the sediments. The chamber should be emplaced with a slight tilt so that the opening to which the bag is attached is near the uppermost edge of the meter, which facilitates the release of gas from the sediment. Sediments often are compressed beneath the seepage-meter chamber during meter insertion, and flow is temporarily disrupted. The sediments and flow need to equilibrate before a bag is attached. Substantial error can result if measurements are made too soon following meter installation.

Lee (1977) originally used the cut-off end of a 208-liter (55-gallon) drum, but many other types and sizes of chambers also have been used, including coffee cans (Asbury, 1990), inverted plastic trash cans (S.E. Hagerthey and D.O. Rosenberry, U.S. Geological Survey, written commun., 1998), lids from desiccation chambers (Duff and others, 1999), fiberglass domes cemented to a limestone bed (Shinn and others, 2002), and even galvanized stock tanks (Landon and others, 2001; Rosenberry and Morin, 2004). The size of the chamber should be selected for convenience and for the expected rate of seepage across the sediment-water interface. A large-diameter meter can measure more accurately an extremely small flow across the sediment-water interface, and it also better integrates small-scale spatial variability in seepage flux. A large meter, however, can be unwieldy and it also is more difficult to ensure a good seal in uneven, rocky, or debris-laden settings. Alternately, flow from several normal-sized chambers can be routed to one seepage bag to increase the surface area and integrate spatial heterogeneity (Rosenberry, 2005). Large-diameter seepage meters often are difficult to remove from the sediments following their use, as are smaller-sized chambers inserted into silty or clayey sediment. A simple solution is to insert a length of tubing inside of the chamber and blow air into the chamber until the buoyancy force lifts the chamber out of the sediments. Some users have installed additional openings in the top of the chamber that are opened prior to removal of the chamber in order for water to flow into the chamber as it is pulled from the sediments. Additional openings also reduce the chance for “blowouts” or sediment compression during chamber installation.

Much has been written regarding the type and size of the bag attached to the chamber (for example, Erickson, 1981; Shaw and Prepas, 1989; Cable and others, 1997a; Isiorho and Meyer, 1999). Bags as small as condoms (Fellows and Brezonik, 1980; Duff and others, 1999; Isiorho and Meyer, 1999; Schincariol and McNeil, 2002) to as large as 15-liter trash bags (Erickson, 1981) have been used, with 4-liter sandwich bags among the most common choices. Most plastic bags have a “memory effect” caused by the manufacturing process that results in a slight pressure created by the bag as it moves to a more relaxed position. This can result in errors in measurement that become substantial in low-flux settings. Shaw and Prepas (1989) reported an anomalous influx of water during the first 30 minutes following bag installation that they were able to eliminate by prefilling the bags with 1,000 milliliters of water. Cable and others (1997a) reported similar results. Shaw and Prepas (1989) suggested using a 4-liter-sized bag and adding a known volume of water (1 liter or more), even in settings where flow of water was from ground water to surface water, because these procedures tended to minimize the memory effect. Shaw and Prepas also suggested prewetting the bags prior to installation on the chamber to

A



B

C

Figure 13. *A*, Half-barrel seepage meter (modified from Lee and Cherry, 1978, used by permission of the Journal of Geoscience Education). The top panel shows typical installation with bag connected to a tube inserted through a rubber stopper. The bottom panel shows installation in shallow water with vent tube to allow trapped gas to escape. *B*, Standard half-barrel seepage meter in place in the field. (Photograph by Donald Rosenberry, U.S. Geological Survey.) *C*, Electromagnetic seepage meter (foreground) installed next to a half-barrel seepage meter. Cable extending from seepage cylinder connects to signal conditioner and power supply located on nearby anchored raft. (Photograph by Donald Rosenberry, U.S. Geological Survey.)

avoid bias related to the loss of water from adhesion of water to the inside of the bag. Blanchfield and Ridgway (1996) indicated that seepage rates were inflated by as much as one order of magnitude if unfilled bags were used instead of bags prefilled with 1,000 milliliters of water. Asbury (1990), reporting results from seepage measurements made where water was rapidly flowing from a lake to ground water, indicated that the sides of the bag came into contact when the volume of water was 500 milliliters or less, which caused a reduction of flow out of the bag. Murdoch and Kelly (2003) indicated that the hydraulic head necessary to fill a 3,500-milliliter seepage bag was smallest when the bag was initially empty, increased to a relatively constant value once the bag contained about 100 to 200 milliliters of water, and then increased rapidly when the bag was within 500 to 800 milliliters of being full. They also determined that the resistance to filling the bag depended on the bag thickness.

Several studies have reported a preference for thin-walled plastic bags to minimize resistance to flow to or from the bag. Others have reported problems with fish chewing holes in the bags and switched to thicker walled bags (Erickson, 1981). One solution to the fish problem is to place one bag inside another. If this is done, however, it is important to place small holes in the corners of the outside bag to allow water between the bags to drain prior to measurement and to allow air to escape from between the bags prior to bag insertion. Another solution is to place the bag in a shelter, which also serves the purpose of minimizing the effects of waves and currents, described later. Thick-walled bags also have been used; intravenous-drip bags or urine-collection bags are especially convenient because the tubing that extends from the bag already is attached. Recent studies, however, which are discussed in the following section on sources of error, indicate that bag resistance induces substantial error to seepage measurements, so the use of thick-walled bags should be avoided.

In addition, cautions have been issued regarding collecting water-quality samples from a seepage meter (Brock and others, 1982; Belanger and Mikutel, 1985). Because the residence time of water contained inside the seepage chamber or bag may allow the chemistry of the water to change, samples may not be representative of the chemistry of water discharging across the sediment-water interface.

Seepage meters have been modified for use in extreme environments. Cherkauer and McBride (1988) created a seepage meter that included a concrete collar for measurement of seepage in Lake Michigan, where energy from large waves would dislodge unmodified devices (fig. 14). Dorrance (1989) and Boyle (1994) each designed seepage meters for use in deep water. Both designs consisted of a seepage chamber connected via tubing to a seepage bag installed inside a separate housing. Dorrance allowed the bag shelter to float on the surface, whereas Boyle suspended the bag housing a short distance beneath the surface. Both designs allowed servicing of the bag without the aid of a diver (fig. 15). Hedblom and others (2003) modified a meter to measure gas flux and water flux from shallow, contaminated sediments. The device contained a mylar bag for collecting gas released from the sediments, and it also contained long rods that were driven into the sediment to hold the seepage chamber and prevent it from gradually sinking into the soft sediments. Shallow-water seepage meters also have been used to measure flows near the shoreline where seepage rates often are large (Lee and Cherry, 1978) (fig. 13, lower panel). Lee and Cherry simply attached the bag to the side of the seepage chamber rather than to the top. A bag also could be attached to the side of a seepage cylinder that extends

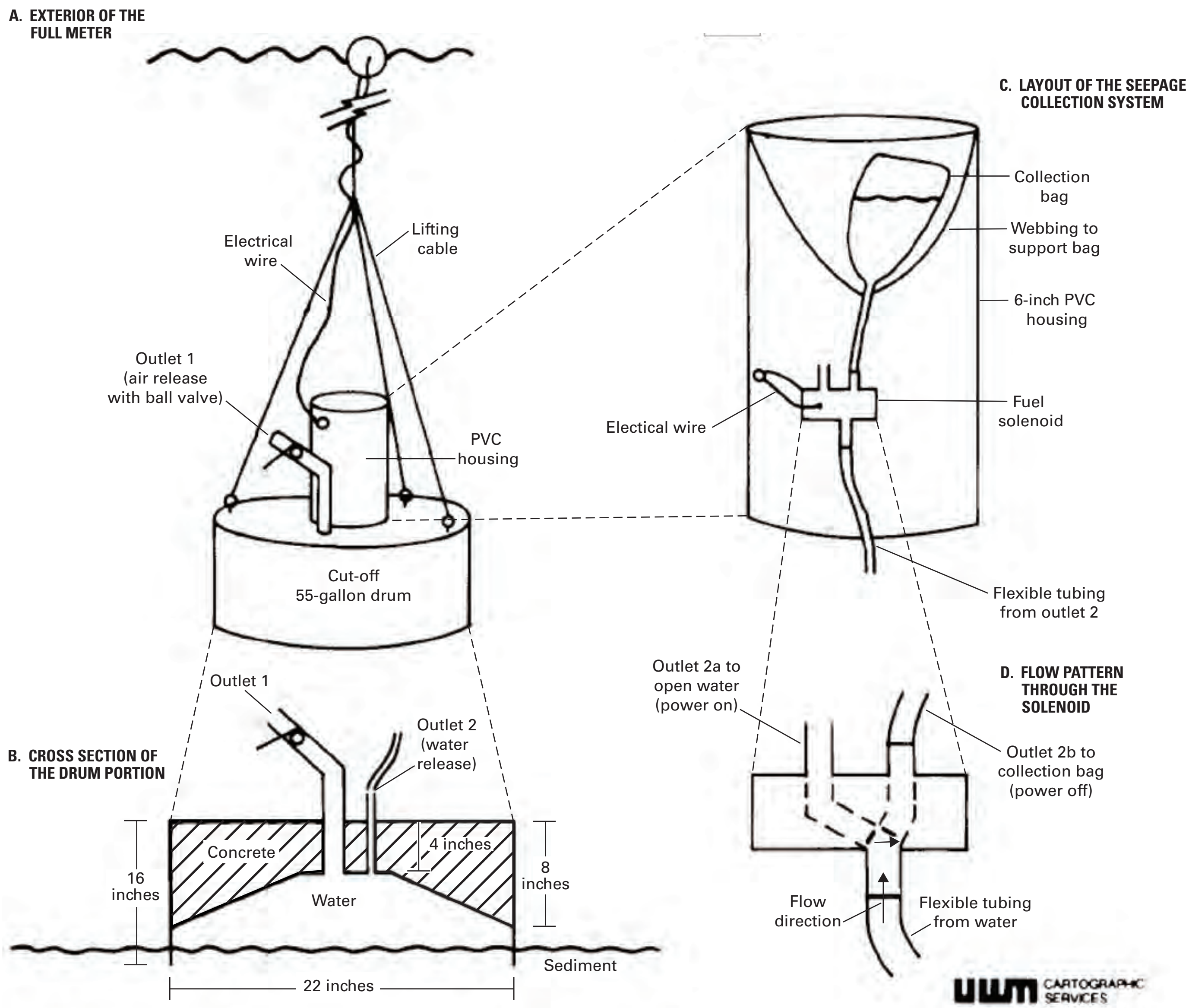


Figure 14. Seepage meter modified for use in large lakes (from Cherkauer and McBride, 1988. Reprinted from Ground Water with permission from the National Ground Water Association, copyright 1988).

above the water surface and contains a free water surface. Water then would flow into or out of the bag in order to maintain the same water level inside and outside of the seepage chamber. This procedure could allow measurement of seepage in the very shallow water closest to the shoreline where seepage rates often are the largest. Waves, however, could create potentially large flows through the submerged opening in the side of the chamber, leading to large measurement errors. Rosenberry and Morin (2004) reported instantaneous flow rates into and out of a near-shore seepage cylinder of more than 300 milliliters per second.

Seepage meters also have been modified for use in flowing water. In many streams and rivers, currents are sufficient to cause the bag to be deflected in a downstream direction, which may fold the bag across its connection to the chamber and either reduce or pinch off flow to or from the bag. Currents also may generate a pressure gradient across the bag membrane that could lead to erroneous measurements (described more completely in the next section on sources of error). Bags have been installed inside shelters to protect the bag from these currents. Designs have included shelters mounted to the top of the seepage cylinder (for example, Schneider and others, 2005) or shelters that rest on the sediment bed and are attached to the seepage cylinder via a short length of tubing or hose (for example, Landon and others, 2001). Bag shelters also protect the bag from wave action that may cause erroneously large seepage rates (Sebestyen and Schneider, 2001), and they maintain the bag in the proper orientation so it cannot swing with the current, which could pinch off the opening at the bag-connection point. David Lee (Atomic Energy of

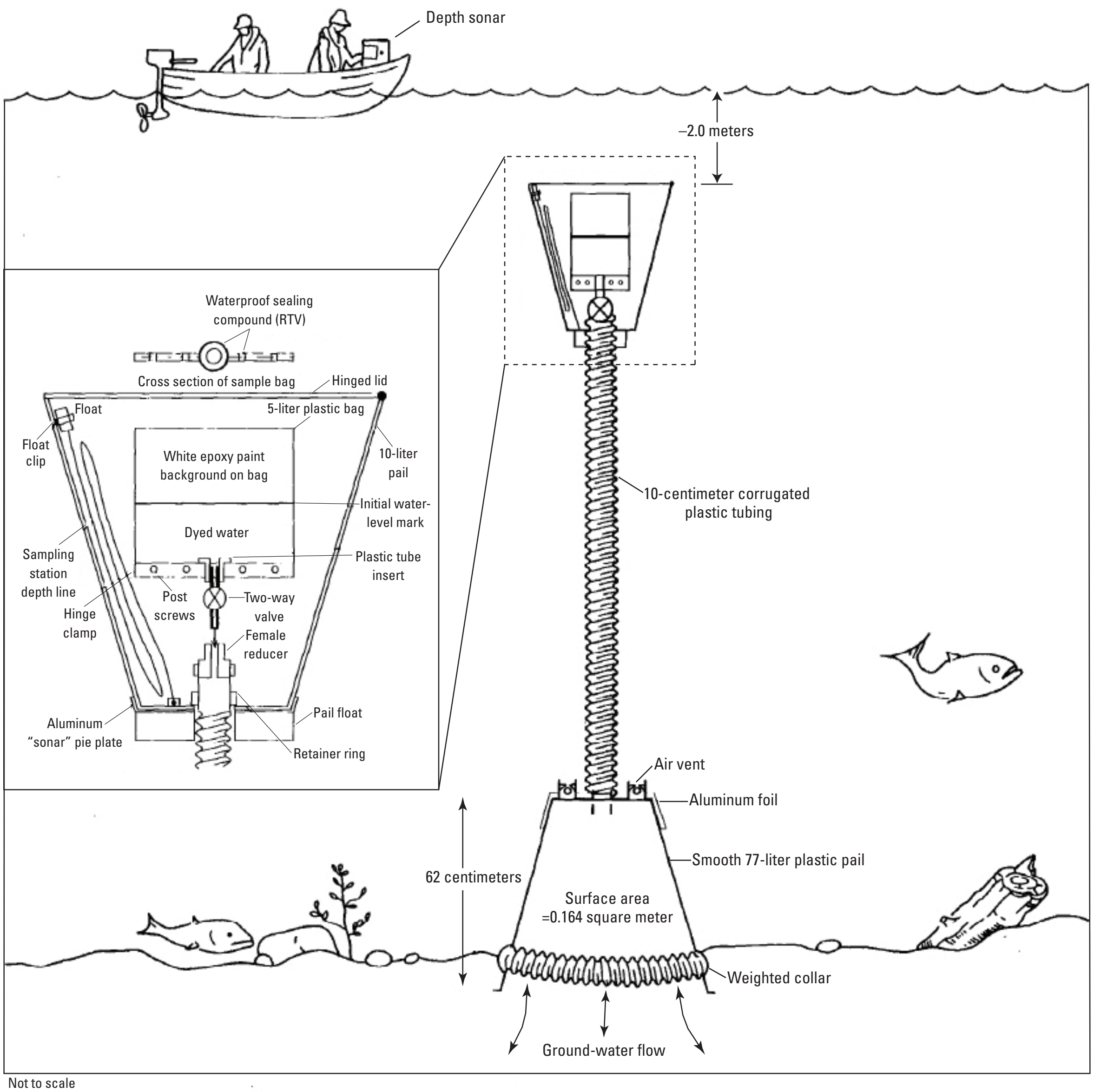


Figure 15. Ground-water seepage meter modified for use in deep water. (Modified from Boyle, 1994. Copyright 1994 by the American Society of Limnology and Oceanography, Inc., used with permission.)

Canada Limited, oral commun., 2006) suggested drilling small holes in the part of the tubing that extends inside of the bag to further prevent errors should the bag move to pinch off the end of the tube.

If a seepage meter is used in combination with the hydraulic potentiomanometer, local-scale values for vertical hydraulic conductivity can be obtained. A modification of particular interest is the “piezoseep” by Kelly and Murdoch (2003) that combines a seepage-meter chamber with a piezometer inserted through the center of the chamber. The authors replaced the seepage bag with a pump that pulls water at known rates from the area covered by the chamber. By accurately measuring the head difference between the piezometer point and the surface water in response to various pumping rates, they were able to calculate in-situ hydraulic conductivity. The relation between head gradient and seepage flux was determined for each meter, which allowed seepage rates to be monitored by simply measuring head differences at a desired time interval (Murdoch and Kelly, 2003).

Although numerous sources of error exist, especially associated with the seepage bag, the seepage meter is an attractive choice for quantifying flow across the sediment-water interface because of its simplicity and low cost. Perhaps as a result, care and training in the use and operation of seepage meters commensurate with their cost may have led to collection of poor-quality data for some studies. With proper understanding of the operating principles, knowledge of sources of error, and care in measurement, accurate determinations of flux across the sediment-water interface are possible, as has been demonstrated in many of the papers cited herein.

Sources of Error

Sources of error when using seepage meters include:

1. Incomplete seal between seepage-meter chamber and sediments, unstable cylinders;
2. Insufficient time between meter installation and first measurement;
3. Improper bag-attachment procedures, bag resistance, and moving water;
4. Leaks;
5. Measurement error;
6. Flexible seepage-meter chamber;
7. Insufficient or excessive bag-attachment time;
8. Accumulation of trapped gas;
9. Incorrect coefficient to relate measured flux to actual flux across the sediment-water interface; and
10. Insufficient characterization of spatial heterogeneity in seepage through sediments.

Each item listed above is discussed in detail below.

Incomplete Seal, Unstable Cylinder

Care should be taken to ensure that an effective seal exists between the seepage chamber and the sediments. After pushing the chamber into the sediments, one can feel around the base of the chamber to ensure that the bottom edge of the chamber cannot be felt. If the bed is rocky and a good seal is impossible, it may be possible to place a mud or bentonite seal against the edge of the meter to create a temporary seal. This practice, however, may introduce additional errors because the seepage immediately beyond the edge of the meter will be altered.

Meters installed in soft sediments also may be subject to a sealing problem of a different type. If sediments are not sufficiently competent to support the weight of the meter, the seepage chamber may slowly sink into the sediment following emplacement. This will displace water from inside the chamber that will flow into a seepage bag connected to the chamber. A solution to this problem is to use taller seepage chambers set deeper into the sediments (Fellows and Brezonik, 1980). If, for example, a 208-liter storage drum is used, it can be cut in half to make a seepage chamber with sidewalls that are about 45 centimeters tall. Another solution is to anchor the meter to rods driven deep into the sediments (Hedblom and others, 2003). Menheer (2004) designed a chamber with fins that rest on the bed surface so that the chamber is installed at a consistent depth in the sediments for every placement.

Insufficient Equilibration Time

This may be the most common source of error for scientists inexperienced in the use of seepage meters. It is tempting to install the seepage chamber and immediately begin making measurements. Sediments first need to be allowed to equilibrate following their compression during insertion of the seepage chamber. Time between chamber installation and first measurement typically is 1 day or more, but a few studies have reported waiting shorter times when working in sandy or gravelly sediments (table 2). Some investigations indicate that an equilibration time as little as 10 to 15 minutes is adequate (Lock and John, 1978; Lewis, 1987; Landon and others, 2001). Rosenberry and Morin (2004) used an automated seepage meter to demonstrate that most of the recovery to predisturbance seepage rates was achieved within 30 minutes after installation of the seepage chamber in a sandy lakebed.

Improper Bag-Attachment Procedures, Bag Resistance, and Moving Water

The procedure for attaching the bag to the seepage chamber depends on the attachment mechanism. With early designs, the bag was attached to a small-diameter tube that extended through a rubber stopper inserted into the chamber. It is important to not apply any pressure to the bag while pushing the rubber stopper into the chamber during bag

Table 2. Duration between emplacement of seepage meter and first installation of seepage-meter bag (equilibration time) from selected studies.

Reference	Site	Equilibration time
Lock and John, 1978	Lake Taupo, New Zealand	5–10 minutes
Landon and others, 2001	Platte River, Nebraska	10–15 minutes
Lewis, 1987	Coral reefs on Barbados	15 minutes
Rosenberry and Morin, 2004	Mirror Lake, New Hampshire	30–60 minutes
Libelo and MacIntyre, 1994	York River, Virginia	1 hour
Rosenberry, 2000	Lake Belle Taine, Minnesota	1–3 hours
Cable and others, 1997a	Gulf Coast, Turkey Point, Florida	At least 24 hours
Belanger and Kirkner, 1994	Mountain Lake, Florida	1 day
Erickson, 1981	Williams Lake, Minnesota	2 days
Shaw and Prepas, 1989	Narrow Lake, Alberta	2–3 days
Lee, 1977	Lake Sallie, Minnesota	Several days
Belanger and Montgomery, 1992	Laboratory tank tests	Several days
Shaw and Prepas, 1990a	Narrow Lake, Alberta	2–5 days
Boyle, 1994	Alexander Lake, Ontario	A few weeks

attachment. Significant volumes of water can be forced into or, more commonly, out of the bag during attachment. The same caution applies to removal of the bag from the chamber. A recent improvement in bag-connection design involves using a shutoff valve (Cable and others, 1997a) (fig. 16). A bag is attached to the shutoff valve and a fitting that connects to the threads of the shutoff valve is installed in the seepage chamber. Once the bag is properly filled and emptied of air, the valve can be closed for transport until the bag is threaded onto the meter, at which time the valve is opened and the measurement period begins. Upon measurement completion, the valve is closed and the bag removed for final volume measurement. This minimizes the possibility of the investigator inadvertently causing flow into or out of the bag during insertion and removal. Other connectors that do not require threads also can be used, but the user should test the connector to make sure that it does not leak under near-zero pressure conditions.

As mentioned previously, use of thin-walled bags has been recommended in numerous seepage studies. Thick-walled bags generate a greater resistance to inflation or deflation, and a larger head gradient is required to effect a change in volume inside the bag. Because some bags are constructed with a tube already in place (for example, intravenous bags, urine-collection bags, solar-shower bags), several studies have reported use of these bags in seepage-meter studies. Unless a calibration coefficient is determined for measurements made with these bags, however, it is likely that the measured seepage rates will substantially underestimate fluxes across the sediment-water interface. Murdoch and Kelly (2003) reported that thicker bags required a much larger correction multiplier (1.88) compared to thin-walled bags (1.25); they also reported the measurement variance for thick-walled bags was greater than for thin-walled bags. Rosenberry and Menheer (2006) reported similar values, ranging from a correction multiplier of 0.95 for thin-walled bags to 1.89 for a solar-shower bag. Based on these observations, use of thick-walled bags is not recommended. Use of condoms as seepage-meter bags also is not recommended because they present a temporally variable bag resistance that is particularly difficult to account for during calibration for (Schincariol and McNeil, 2002).

Bags should be free of air bubbles prior to bag attachment. Bubbles exert a buoyant force on the bag, which can place a strain on the bag and either cause an artificial gain or loss of water in the bag as it deforms in response to the buoyant force, or prevent the bag from readily inflating or deflating to accommodate seepage gains or losses. Harvey and others (2000) indicated that excessive gas collected in a seepage bag led to artificially large fluxes of water into the bag. They designed their seepage meters so that the top of the bag rested on the water surface, which eliminated buoyant forces. A simple way to remove air from inside the bag is to pull the bag beneath the surface of the water body (or beneath the water surface in a bucket), with the opening of the bag pointing away from the water surface. As the bag is pulled beneath the water, air escapes through the opening. The bag can be pulled almost completely beneath the water surface until the opening of the bag is about to be submerged, at which point the opening is closed and the inside of the bag is virtually free of air.

Errors also can be introduced when the observer wades out to the seepage meter to attach the bag. In soft sediments, the weight of the observer standing next to the seepage meter may cause displacement of water from the sediments. This can be a problem even in sandy sediments. Rosenberry and Morin (2004) reported that seepage increased by more than one order of magnitude for several seconds when an observer walked within 1 meter of a seepage chamber installed in a sandy lakebed, but the seepage rate changed only slightly when averaged over a minute-long period. This source of error is most substantial for small rates of seepage and can be avoided if the observer floats in the water while attaching and detaching the bag. Servicing the meter from a small boat or raft (Harvey and others, 2000) works well if the meter can be reached from the water surface. Using a short piece of hose or tubing to locate the bag 1 to 2 meters away from the seepage chamber also minimizes this source of error.

Figure 16. Plastic bag attached to a garden-hose shut-off valve. Bag is filled with a known volume of water and then purged of air. Valve is closed. Bag is threaded onto male threads on seepage meter, and valve then is opened to begin seepage measurement. (Photograph by Donald Rosenberry, U.S. Geological Survey.)

If currents are present, seepage-meter measurements can be erroneously large or small, depending on the seepage direction. This is the result of velocity head associated with moving water,

$$h_v = \frac{v^2}{2g}\,, \tag{5}$$

where

v is velocity of water flowing past the seepage bag ($L\ T^{-1}$),

and

g is acceleration due to gravity ($L\ T^{-2}$).

Velocity head is one component of the total hydraulic head in a stream, which is the sum of velocity head, pressure head, and elevation head. Velocity head inside a seepage bag is zero because water is not moving appreciably inside the bag. Because the flexible plastic bag can easily respond to any pressure gradients across the bag surface, the pressure inside the bag is the same as outside of the bag. Therefore, the total hydraulic head inside the bag is equal to the hydraulic head outside of the bag minus the velocity-head component. If flow is from ground water to surface water, the velocity-head effect will induce additional water to flow into the seepage bag. If flow is from surface water to ground water, the velocity-head effect will reduce the loss of water from the seepage bag. Libelo and MacIntyre (1994) indicated that water flowing at a velocity of 0.2 meter per second or faster past an uncovered bag resulted in larger rates of seepage than for a bag placed inside a protective cover, and that the velocity-head effect could more than double the measured seepage flux. They indicated this type of error also could result from near-shore waves or currents. Murdoch and Kelly (2003) quantified the velocity-head effect and indicated it becomes substantial when the velocity of the moving water is 0.1 meter per second or greater. Both studies indicated that the velocity-head effect is proportional to the square of the surface-water velocity, consistent with equation 5. Landon and others (2001) used bag shelters for their seepage measurements in the Platte River in Nebraska. Sebestyen and Schnieder (2001) used a plastic shield to protect their seepage-meter bags in a lake in New York. Asbury (1990) noted that bags exposed to small currents could be pulled to the side by the current, folding the bag over the opening and closing off the tubing to which the bag was attached. This was an especially important problem for flow out of the bag and when the bag was nearly empty of water. Conversely, Cable and others (1997a) indicated that currents were not a problem for exposed seepage bags attached to meters installed in near-shore regions of the Florida Gulf coast, as long as windspeed was less than 15 knots.

A seepage chamber installed in moving water also may affect actual seepage rates in the vicinity of the meter. Shinn and others (2002) reported that measured seepage was always from ground water to surface water at their study sites near the Florida Keys, even during intervals when piezometer nests indicated reversals in the hydraulic-head gradient in response to tidal influences. They attributed this phenomenon to the effect of the seepage chamber extending into the flow field where ocean currents were relatively strong, which would cause water to be advected through the sediment beneath the seepage chamber and into the seepage bag. Huettel and others (1996) indicated that this process also occurs naturally where an uneven sediment bed (ripples, dunes) projects into a moving-water flow field. On the upstream side of the obstruction to flow (a dune or, in this instance, a seepage chamber), water velocity and, therefore, velocity head decreases, pressure head increases, and the pressure gradient drives flow into the sediments, beneath the rim of the chamber, and into the chamber. The same process occurs at the downstream side of the obstruction where an eddy forms to decrease velocity head and increase pressure head. Others who have made seepage measurements in marine settings indicated that the seepage cylinder is little affected by waves and currents (Corbett and Cable, 2003). Regardless of the net effect, the local flow field is undoubtedly altered by the presence of a seepage chamber positioned in a stream or river. Landon and others (2001) and Zamora (2006) reported scouring of the bed at several seepage-meter installations in a sand-bed river.

Leaks

A hole in the seepage meter bag is one of the most common types of leaks. This can be prevented by careful handling and frequent testing of the bag, and by "double bagging" the bag where fish or crustaceans may make holes in the bag. As mentioned previously, if bags are "double bagged," small holes should be placed in the corners of the outer bag to allow the evacuation of air trapped between the bags. Bag shelters also can minimize the potential for bag damage. The attachment between the bag and the device that connects the bag to the chamber is another potential location for leaks. The attachment method may involve electrical tape, rubber bands, or plastic cable ties, and care should be used to ensure a good connection to the tubing or other mechanical connector. One solution to this potential problem is to use a bag manufactured with an integral plastic tube or sleeve. As previously mentioned, however, many of these bags typically are much thicker than food-storage bags and likely resist movement in response to changing fluid volume inside the bag. One bag that shows promise is designed for use as shipping-protection material. The bag is designed to be inflated through a plastic neck that is manufactured as part of the bag. A tube is inserted through the neck and sealed with adhesive or electrical tape. The bag material is quite thin (25 micrometers), and tests conducted by Murdoch and Kelly (2003) and Rosenberry and Menheer (2006) indicate that it presents little resistance to filling.

Leaks also can occur in the seepage chamber because of rust, improper welds, or improper sealing where the tubing passes through the rubber stopper (if that is the mechanism used) or between the rubber stopper and the chamber. If the seepage chamber contains a bung, then a loose bung or a weathered or cracked bung gasket also can lead to leaks.

Measurement Error

The change in the volume of water in the seepage-meter bag commonly is measured by use of a graduated cylinder. Sources for error include misreading the meniscus on the graduated cylinder, not holding the graduated cylinder level when making a reading, not removing all of the water from inside the bag, spilling water during filling or emptying of the bag, and misrecording time of attachment and time of removal. A funnel is useful for eliminating spills during filling and emptying the bag. Another method of measuring volume change involves weighing the bag with an accurate, portable electronic scale before bag attachment and again following bag removal. Additionally, to reduce the uncertainty of volume- measurement error, many investigators commonly make three or more measurements at each site and average the values.

Flexible Seepage-Meter Chamber

Occasionally the flat, circular end of a half-barrel seepage meter can flex downward or upward (sometimes with a sudden, audible pop) in response to temperature changes or to pressure applied to the metal surface. Standing on the center of the meter during emplacement, for example, can cause such flexing. If the metal later returns to a more relaxed position while the bag is attached, an erroneous measurement will result. Allowing time for equilibration between installation and first measurement minimizes the likelihood of this occurring during subsequent measurements. Other types of chambers also may have insufficient rigidity. Plastic trash cans can flex if the walls of the plastic are too thin. Shinn and others (2002) constructed a seepage meter with a flexible top with the intent that the meter would flex with the passage of waves; associated pressure perturbations exerted on the ocean bed also would be exerted on the part of the bed covered by the meter. This was done to reduce water artificially advected into the meter; the experiment met with little success.

Insufficient or Excessive Bag-Attachment Time

Bags need to be attached to a seepage meter long enough for a measurable change in volume in the bag to occur, but not so long that the bag is either full or empty. Bag-attachment times can range from seconds to weeks, depending on the size of the bag, the diameter of the seepage chamber, and the rate of seepage. Problems related to insufficient or excessive attachment time are obvious when the bag is full or empty upon removal of the bag. A bag that is nearly full or nearly empty when being removed also may indicate an erroneous flux rate. As mentioned earlier, Murdoch and Kelly (2003) determined that the head required to move water into a bag increases markedly when the bag is within a few hundred milliliters of being full. Such a condition also is likely when the bag is losing water and approaches being empty. Conversely, the bag may contain nearly the same volume of water following removal as it contained during attachment, indicating that the bag-attachment time was too short. The solution to both problems is an iterative one. Subsequent measurement periods can be adjusted based on previous incorrect attachment times.

Accumulation of Trapped Gas

Release of gas from sediments is common where organic decomposition produces methane, carbon dioxide, hydrogen sulfide, or other gases. If gas accumulates within the seepage chamber, it can displace water from inside the chamber that then is forced into the bag. There are at least two solutions to this problem. A vent tube may be installed at the highest point of the meter that extends above the water surface to the atmosphere (fig. 13*A*, lower panel). This allows gas released from the sediments covered by the chamber to be released to the atmosphere instead of accumulating within the chamber. Alternatively, gas may be allowed to escape to the bag. Boyle (1994) designed a meter that automatically allowed gas to escape from the meter without being transmitted to the bag. Hedblom and others (2003) described a system designed to collect both gas and water released from contaminated sediments; they analyzed both gas and water to determine the rates of release of various chemicals.

Use of Improper Correction Coefficient

Numerous tests have been conducted to compare flow through seepage meters with the rate of seepage in a controlled-flow test tank (Lee, 1977; Erickson, 1981; Asbury, 1990; Cherkauer and McBride, 1988; Dorrance, 1989; Belanger and Montgomery, 1992; Murdoch and Kelly, 2003; Rosenberry, 2005; Rosenberry and Menheer, 2006). Results of these tests indicate that seepage meters undermeasure the flux of water across the sediment-water interface because of frictional flow loss within the meter, restrictions to flow through the connector between the bag and the chamber, and any resistance to movement of the bag. Coefficients typically are applied to the indicated flux to correct for this problem. Erickson (1981) determined that the coefficient was different depending on the direction of flow. His studies indicated a multiplier of 1.43 was required for flow from ground water to surface water and a multiplier of 1.74 for flow from surface water to ground water. Belanger and Montgomery (1992) indicated a multiplier of 1.30 was required to correct for measurements of flow from ground water to surface water. Cherkauer and McBride (1988) used a correction factor of 1.6 for flow from ground water to surface water, and Dorrance (1989) indicated that a multiplier of 1.61 was required for his seepage meter designed for quantifying loss of water from a reservoir. Asbury (1990) used a multiplier for flow either into or out of a surface-water body of 1.11; he attributed his lower multiplier to his using a larger diameter connector (19 millimeters) than other investigators. Murdoch and Kelly (2003) determined measurement inefficiency by using highly accurate manometers to measure head loss, and reported correction factors of 1.25 to 1.82, depending on the type of bag used. Rosenberry (2005) used large diameter (9.5-millimeter minimum inside diameter) connection materials and a thin-walled 4-liter bag with a Lee-type seepage chamber to obtain a correction factor of 1.05.

Fellows and Brezonik (1980) related seepage-meter efficiency to the diameter of the connector between the meter and the bag and to seepage velocity. Their results indicated that head loss increased with decreasing tubing diameter and with increasing seepage velocity (fig. 17); they suggested that a tubing diameter larger than 5 millimeters would not cause loss of efficiency for most fluxes commonly measured with seepage meters. On the basis of their experiments, however, they altered their seepage-meter design to use a 9-millimeter opening instead of a 5-millimeter opening between the bag and the meter. Rosenberry and Morin (2004) found a similar response by positioning a pressure transducer inside a seepage meter and recording pressure changes in response to routing seepage through a range of tubing diameters. Pressure changed by 21 millimeters of water head when seepage was forced to flow through 4-millimeter-diameter tubing, but the pressure change was only 4 millimeters of water head when flow was routed through 7.9-millimeter-diameter tubing. Harvey and others (2000) used a large-diameter (19-millimeter) connection system to eliminate any concern regarding tubing resistance in a study of seepage from wetlands in the Florida Everglades. Rosenberry and Menheer (2006) describe a seepage-meter calibration tank for determining the efficiency of various seepage-meter designs.

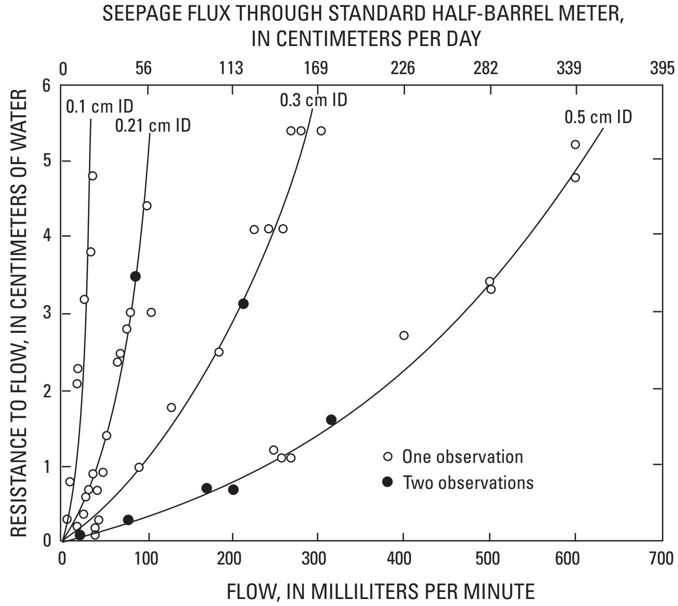


Figure 17. Resistance to flow related to tubing diameter and rate of seepage. Seepage flux assumes a 0.25-square-meter-area seepage meter. (Modified from Fellows and Brezonik, 1980; copyright 1980 by the American Water Resources Association, used with permission.)

Insufficient Characterization of Spatial Heterogeneity in Seepage Through Sediments

Successful extrapolation of point measurements of seepage to whole-lake systems requires that the seepage measurements adequately characterize the larger scale integrated exchange between ground water and surface water. This extrapolation can be difficult because small-scale spatial variability in flux across the sediment-water interface is common. Measurements at several locations may be required to adequately characterize seepage on a meaningful spatial scale. Shaw and Prepas (1990a) determined that seepage rates could vary by more than a factor of 2 when meters were installed only 1 meter apart (fig. 18). They found that seepage flux in a 2-square-meter area was lognormally distributed, and the variance in seepage increased with seepage velocity. They attributed seepage variability to variability in hydraulic conductivity of the lakebed. Shaw and Prepas (1990b) recommended making seepage measurements at additional transects in a lake rather than making replicate measurements at a single transect to best characterize spatial variability in lakebed seepage.

Asbury (1990) addressed the question of seepage-meter precision related to lakebed heterogeneity by installing 25 seepage meters on an 8-meter by 8-meter grid. His results (table 3) showed a large decrease in seepage with distance from shore and then a reversal in seepage direction farther from shore as was expected based on previous results. The five measurements made at each distance from shore showed remarkable consistency near the shoreline where seepage rates were largest, but seepage variability increased with distance from shore out to 6 meters from shore. Beyond that distance, seepage direction reversed and the variance decreased slightly.

Belanger and Walker (1990) tested small-scale spatial variability in seepage by placing two to three seepage meters 5 meters apart at seven different sites. They found very good reproducibility at five of the sites where seepage rates were relatively small. At the other two sites, where seepage rates were much larger, they attributed the greater spatial variability in seepage to the presence of springs in the area.

Michael and others (2003) used 40 seepage meters to measure seepage variability in four transects perpendicular from shore on a 50-meter spacing in a saltwater bay near Cape Cod, Massachusetts. They detected bands of seepage with distance from shore that were parallel to the shoreline and determined that as long as meters are arranged in transects, errors associated with reducing the number of transects are not unacceptably large. Departures from flux estimated with all four transects were 9, 4, and 3 percent when data from one, two, or three transects were used. They also placed seepage meters in clusters with 1-meter spacing and found spatial variability in seepage of the same magnitude as with the 50-meter spacing.

Approaches to characterizing seepage variability include either making numerous measurements in each area of interest, in a manner similar to the approach of Asbury (1990) or Michael and others (2003), or using larger seepage chambers that cover larger areas of the sediment-water interface and better integrate the heterogeneity in seepage. Typically, the scale of interest is a characterization of seepage for an entire surface-water body or shoreline reach. In this instance, resources may be better spent characterizing seepage along a number of transects positioned throughout the area of interest, which characterizes spatial variability on a scale appropriate for the interests of the study (for example, Michael and others, 2003). Rosenberry (2005) addressed the heterogeneity issue by routing flow from several seepage chambers to one collection bag. With such a system, spatial variability in seepage is averaged in one measurement, which also reduces bag-collection time and labor costs. Head loss did not substantially reduce the efficiency of the ganged seepage measurement when 3-meter lengths of garden hose (14-millimeter diameter) were used to connect the seepage chambers.

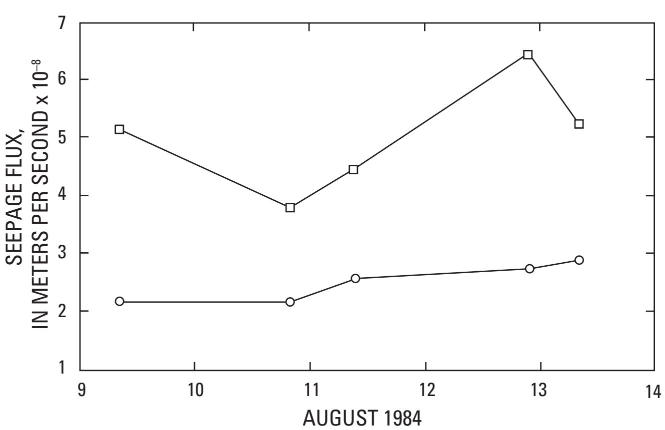


Figure 18. Seepage flux measured at two seepage meters located 1 meter apart. Flux values are in meters per second. (Modified from Shaw and Prepas, 1990a; copyright 1990, reprinted from Journal of Hydrology, used with permission from Elsevier.)

Best-Measurement Practices for Manual Seepage Meters

The following recommendations are presented for minimizing errors associated with making seepage-meter measurements:

1. Use a rigid seepage chamber. A diameter of approximately 0.5 meter seems to be a useful compromise between maximizing areal coverage and maximizing convenience of use. Make certain that the entire rim of the seepage chamber is seated at least a few centimeters into the sediment-water interface. For sandy sediments, 1 hour is probably a sufficient time to wait between installation and first bag measurements. For softer sediments, it may be prudent to wait 1 day to begin measurements.
2. Use several meters to characterize spatial heterogeneity at a scale that is appropriate for the interests of the study. Seepage chambers can be ganged to integrate seepage heterogeneity over a larger area and also to minimize the number of required bag measurements.
3. Use a shelter to protect the bag from waves and currents and to ensure that the bag orientation is maintained in a position that will not close or restrict the opening between the bag and the bag-connection system.
4. Use a large-diameter bag-connection system, especially when fast seepage rates are expected. A diameter 9 millimeters or larger is suggested.
5. Use thin-walled bags to minimize bag resistance. A bag size of 4 liters is convenient for most seepage rates.
6. Prefill the bag with 500 to 1,000 milliliters of water prior to bag attachment. If seepage from surface water to ground water is expected, a larger initial volume of water may be warranted. Do not fill the bag to more than about 75 percent of its capacity.
7. Seepage-meter correction coefficients have been decreasing over time as seepage-meter designs become more efficient. If the suggestions listed above are followed, a coefficient from 1 to 1.1 will provide a good estimate of true seepage rates for most meter designs.

Table 3. Seepage flux with distance from shore and distance along shore on an 8-meter by 8-meter grid (2-meter seepage-meter spacing) (from Asbury, 1990).

Distance from shore (meters)	Seepage flux (centimeters per day)						
	Distance along shore (meters)					Average	Variance
	0	2	4	6	8		
2	–11.3	–11.2	–11.4	–12.1	–11.8	–11.56	0.143
4	–8.4	–9.3	–10.4	–10.5	–6.5	–9.02	2.727
6	–3.5	–6.7	–6.4	–0.8	–4.5	–4.38	5.767
8	0.9	2.4	3.8	3.1	4.9	3.02	2.257
10	3.7	0.3	2.3	0.2	1.2	1.54	2.173

Automated Seepage Devices

Temporal variability in flux across the interface between ground water and surface water has been investigated on a seasonal scale (for example, Schneider and others, 2005; Michael and others, 2005), but temporal variability on a weekly or shorter time scale has not been extensively investigated. Several investigators have made numerous measurements over time to measure the temporal variability (Lee, 1977; Cable and others, 1997b; Sebestyen and Schneider, 2001), but this is a labor-intensive endeavor. Recently developed automated devices allow measurement of seepage responses to temporal events such as seiches (Taniguchi and Fukuo, 1996), tides (Paulsen and others, 2001, 2004; Taniguchi, 2002), and recharge events (Rosenberry and Morin, 2004).

Several of these automated devices use heat-pulse technology to measure flow. One such meter uses sensors originally developed for measuring sap flow in plants (Taniguchi and Fukuo, 1993, 1996) and records the data with a digital datalogger enclosed in the submerged seepage meter. Another design uses the same heat-pulse technology but also includes sensors for collection of water-quality data (Krupa and others, 1998). This device is tethered to a raft that is anchored above the submerged seepage meter. Taniguchi has recently improved the heat-pulse method with a continuous heat-source seepage meter (Taniguchi and others, 2003).

Paulsen and others (2001) developed an automated seepage meter that makes use of acoustic-velocity technology more commonly used to measure surface-water flow. Their sensor can measure flux velocity values ranging from about 1 to at least 275 centimeters per day over an exchange area of 0.21 square meter. Menheer (2004) also used an acoustic-velocity sensor to measure seepage in a benthic-flux chamber that was designed to quantify flow of mercury from ground water to surface water. Another automated seepage meter replaces the plastic bag with an electromagnetic flow meter typically used to measure flow velocity in boreholes (Rosenberry and Morin, 2004). With the flow meter attached to a 1.1-meter-diameter chamber, a modified version of their sensor can measure flux velocities ranging from 4 to 4,000 centimeters per day.

A device developed for use in deep-ocean environments uses a chemical tracer that is injected into an outlet tube of the seepage meter (Tyron and others 2001). A pair of sample-collection coils on either side of the injection point provides a record of the tracer based on dilution of the injectate relative to the seepage rate. Water in the coils is sampled upon retrieval of the meter and analyzed to provide time-series data of the seepage rate. This device can measure seepage rates ranging from 3×10^{-5} to 4 centimeters per day.

Dye-dilution seepage meters make use of dye-dilution chambers, the size of which can be adjusted to accommodate a wide range of seepage rates (Sholkovitz and others, 2003). The combination of chambers used with the meter developed by Sholkovitz and others can measure seepage rates ranging from less than 0.1 to more than 300 centimeters per day. The authors point out that smaller chambers could be used to measure smaller seepage rates at deep-ocean installations.

The Taniguchi and Krupa automated seepage meters have been in use for 10 to 15 years, but as of 2007, the other meters are in the early stages of use. These automated devices are not subject to the previously mentioned problems associated with the use of seepage bags. Although all of the automated devices are fitted to a seepage chamber and are subject to the chamber- and connection-related errors discussed above, those errors should be relatively small compared to bag-related errors.

Methods Selection

Selection of the appropriate methods of calculation and (or) measurement is one of the most important decisions to be made when quantifying exchange between ground water and surface water. Of the three methods presented in this chapter, each has advantages and disadvantages that may or may not be relevant to the study area of interest. Although it is not possible to anticipate all situations, table 4 provides a general guideline to conditions or situations in which each method is particularly well- or ill-suited. As indicated in Chapter 1, the use of more than one method to quantify the exchange between ground water and surface water can be informative and valuable to increasing the confidence in the flux values estimated or calculated.

Table 4. Conditions for which methods for quantifying flow between ground water and surface water are well- or ill-suited.

Method	Well-suited for:	Ill-suited for:
Calculations from water levels in network of wells and surface-water stage	• Basin-scale quantification • Distinguishing areas of inflow from areas of outflow • Determining large-scale aquifer characteristics • Relatively homogeneous aquifers	• Determining flux of some chemicals that enter or leave a surface-water body • Steep and (or) rocky shorelines where installation of wells is difficult or impossible • Low-lying terrain where shoreline migration is large and evapotranspiration is a significant factor • Areas with complex geology or vertical flow regimes where effective depth of aquifer is nearly impossible to determine
Hydraulic potentiomanometer and well-probe measurements	• Fine sand to medium gravel sediments • Quick reconnaissance for qualitative determination of direction of flow • Determining variability of vertical hydraulic gradient with depth • Collection of water-quality samples	• Fine-grained sediments • Rocky shorelines or bedrock • Surface-water body with any appreciable wave action • Fast-flowing water • Organic, gas-rich sediments
Seepage-meter measurements	• Direct measurement of seepage flux • Areal distribution of seepage flux • Sediments ranging from clayey-silt to fine-medium gravel • Calm-water settings • Shallow-water settings	• Surface-water body with any appreciable wave action • Areas with strong currents or fast-flowing water • Very soft, low-density sediments • Rocky sediment beds • Bed areas with dense vegetation

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