THE SEEPAGE METER: PROGRESSING A SIMPLE METHOD OF DIRECTLY MEASURING WATER FLOW BETWEEN SURFACE WATER AND GROUNDWATER SYSTEMS

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Abstract: Many important water issues such as over-allocation, stream salinity and environmental flows are influenced by the interaction between rivers and underlying aquifers. There are many indirect ways of estimating this flux (such as using hydrographs, tracers or geophysics) but the most common direct method is the use of seepage meters. Over recent decades, various modifications have been made to the basic seepage meter to address potential sources of measurement error and to handle operational issues. These aim to reduce the impact of factors such as upward advection of interstitial water (the Bernoulli effect), venturi effects of stream flow on the collection bag, anomalous short-term influx due to bag properties, gas accumulation in the chamber, frictional resistance causing head losses, ineffective seals and capture of shallow throughflow (rather than groundwater). We have attempted to incorporate these improvements in our seepage meter design and development of simple field procedures, which were trialled in two contrasting catchments (Border Rivers and Lower Richmond) in Australia. The field trials had mixed success, highlighting the potential for spurious seepage flux measurements due to these operational issues.

Keywords: seepage meter, seepage flux, stream aquifer interaction, connectivity

INTRODUCTION

Historically, groundwater and surface water in Australia have been perceived and managed as isolated resources. However, there is growing acknowledgement that surface water features such as rivers and lakes can exchange water with underlying aquifers, and this movement of water can have significant implications for water quantity and quality. Key water issues in Australia, such as over-extraction, environmental flows, contamination and river salinity, are all influenced by the degree and nature of the connectivity between surface water and groundwater resources.

The flow of water at the interface between the surface water feature and aquifer (such as a stream bed) is called the seepage flux. This flux is measured in terms of the volume of water per unit area per unit time, translated to units of m^3/m^2/day or alternatively m/d. The convention is that positive seepage flux values indicate flow of groundwater to the surface water feature (also referred to as discharge or outflow) and negative flux values indicate flow from the surface water feature to the aquifer (also referred to as recharge, reverse flow or inflow), refer Figure 1.

Most methods of estimating seepage flux are indirect, in that the nature and magnitude of water flow is inferred from the measurement of other parameters such as hydraulic head, hydraulic conductivity, temperature, resistivity, chemical concentrations or isotopic signatures. There is a need for methods of directly measuring seepage flux at the interface between stream and aquifer. The challenge is to devise a direct method that is robust, cost-effective and simple to use. In this paper, we describe the development and testing of a simple seepage meter design and field operating procedure, highlighting some of the operational issues involved.

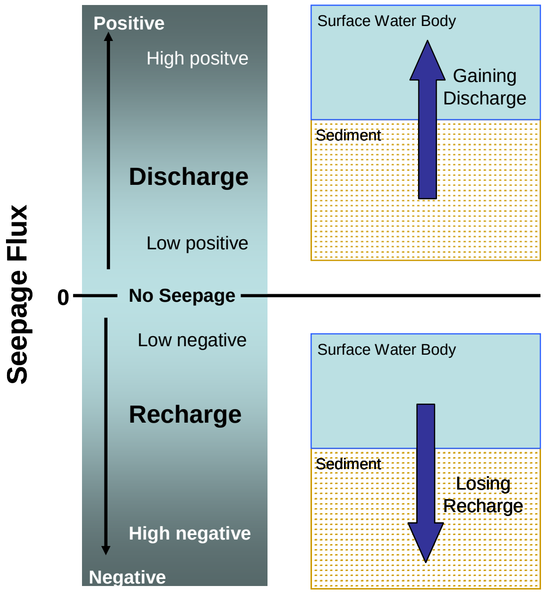

Figure 1: Magnitude and direction of seepage flux between surface water body and underlying aquifer (after Sebestyen and Schneider, 2001)

Various configurations of seepage meters were constructed and trialled in two contrasting field situations – one being drains within estuarine sediments of a coastal wetland in the Richmond River catchment (north coast NSW) and the other being in alluvial sediments associated with larger streams within the Border Rivers catchment (Murray-Darling Basin), refer Figure 2. These trials were part of an assessment of methods to investigate groundwater – surface water interactions in these catchments (Baskaran *et al* 2005; Brodie *et al* 2005).

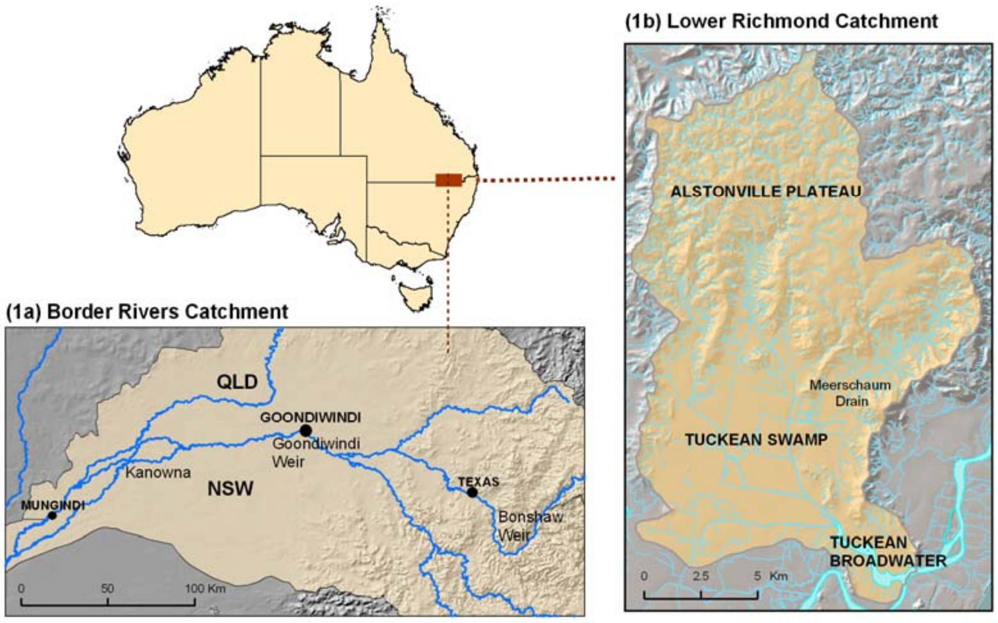

Figure 2: Location of the seepage meter trial sites in the (1a) Border Rivers and (1b) Lower Richmond catchment

THE SEEPAGE METER

Seepage meters are the most commonly used devices for the direct measurement of seepage flux. These were initially developed in the 1940s to measure loss of water from irrigation channels (Israelson and Reeve 1944) and resurrected in the 1970s for use in small lakes and estuaries (McBride and Pfannkuch 1975; Lee, 1977; John and Lock 1977; Lee and Cherry 1978). Seepage meters have since been used in numerous studies of seepage fluxes in rivers (Lee and Hynes 1978; Libelo and MacIntyre 1994; Cey *et al* 1998; Landon *et al* 2001), the near-shore marine zone (Bokuniewicz and Pavlik 1990; Valiela *et al* 1990; Cable *et al* 1997; Taniguchi *et al* 2003), tidal zones (Belanger and Walker 1990; Robinson *et al* 1998), coral reefs (Simmons and Love 1984; Lewis 1987), large lakes (Cherkauer and McBride 1988) and water-supply reservoirs (Woessner and Sullivan 1984). A constant-head variant of the seepage meter (the Idaho meter) has been used to measure leakage from irrigation channels into aquifers under Australian conditions (Byrnes and Webster 1981; ANCID 2000).

The basic concept of the seepage meter is to cover and isolate part of the sediment-water interface with a chamber open at the base and measure the change in the volume of water contained in a bag attached to the chamber over a measured time interval. The classic design of Lee (1977) consists of a 15-cm end section of a 55-gallon (~200L) drum, which is inserted into the sediment. A stopper with a tube is inserted into a hole in the top of the drum and a plastic bag partially filled with water is attached to the tube with rubber bands. The time when the bag is connected and when it is subsequently disconnected is recorded, as well as the change in the volume of water in the bag.

The seepage flux *(Q)* is calculated as:

$$Q = \frac{(V_f - V_o)}{tA} \qquad \textit{Equation 1}$$

where V_o is the initial volume of water in the bag, V_f is the final volume of water in the bag, t is the time elapsed between when the bag was connected and disconnected, and A is the surface area of the chamber. In this way, seepage meters are equally capable of measuring gains to or losses from the stream.

SEEPAGE METER DESIGN

Over recent decades, various modifications have been made to the basic seepage meter to address potential sources of measurement error and to handle operational issues. We have attempted to incorporate these improvements in our seepage meter design (Figure 3).

The inverted open drum is still the basis of the chamber. A wide range of options have been used by previous investigators including capped PVC casing (Schincariol and McNeil 2002), plastic buckets (Cey *et al* 1988; Alexander and Caissie 2003), a purpose built rectangular stainless-steel funnel (Paulsen *et al* 2001), fibreglass domes (Shinn *et al* 2002) or a cut-down galvanised water tank (Rosenberry and Morin 2004). A chamber with a relatively large radius is recommended as laboratory tests indicate that variability in seepage measurements decreased with increasing diameter of the chamber (Isiorho and Meyer 1999). We initially used 200-L plastic storage drums with a radius of 0.285 metres cut in half as they were lighter to transport and handle than steel drums, but sufficiently robust. However, in the trials these chambers proved difficult to embed to sufficient depth into the sediments. Instead, a chamber was purpose-built using relatively thin gauge (1.5mm) galvanised steel sheeting for the cylinder to facilitate deeper installation (Figures 3-4). The top of the chamber was manufactured from thicker gauge (3-mm) galvanised steel plate to provide rigidity and robustness.

There may be a requirement for the chamber to be even more robust and stable for use in dynamic flow conditions. We used a simple approach of placing concrete besser blocks or similar weights to reduce lateral movement of the chamber due to water flow. This was adequate for the low velocity flows in the Lower Richmond coastal drains, but failed under higher stream flow conditions in the Border Rivers. In a particular seepage study of Lake Michigan the chamber used was modified by adding a 50-70kg layer of concrete to the inside of the chamber, with the lower surface of the concrete conically-shaped to direct upwards flow of water (and gas) to the chamber outlets (Cherkauer and McBride 1988). However, such chambers may be too heavy for use in soft sediments.

Other modifications to the chamber include incorporating lugs onto the top (Figures 3-4). This allows a rod to be inserted across the chamber top, to facilitate rotation of the chamber during installation. The rod or a lightweight notched steel picket can be hooked onto the chamber (or alternatively ropes attached) to remove it from the sediment. A central fitting can also be incorporated to allow attachment of a rigid vertical pole to help position or remove the chamber. Also, the top of the chamber can be made removable to minimise disturbance of the sediment bed during installation. The vertical pole and removable lid have been incorporated into the Idaho meter design (Worstell and Carpenter 1969). The top of the chamber can also be painted white to help find and recover the meter in turbid or deep water.

The tube for the collection bag is placed to the side of the chamber and another tube at the chamber top is extended above the water surface so it is open to the atmosphere (Figure 3). This configuration is useful in shallow water to keep the bag submerged, while allowing venting of any gas. We used 12.5-mm ID clear polythene tubing for the gas venting tubing. In trials, smaller tubing (4-mm) tended to clog or kink allowing gas to accumulate within the chamber and effect seepage measurements. This was a major issue in the trials undertaken in the coastal wetland drains of the Lower Richmond, which had large biogenic gas production. Alternatively, a small pipe with a ball valve can be added to the top of the chamber, and used to vent any trapped air when the chamber is initially placed into the water body (Cherkauer and McBride 1988). After the air is released the valve is closed, so this approach does not allow release of gas accumulated during the actual operation of the meter.

A flexible bag is used rather than a rigid container for the water storage device as the water in the bag needs to be in hydraulic equilibrium with the chamber and surface water body. The principle is that any discharge of groundwater across the surface area of the bed should displace water trapped within the chamber into the bag, likewise any recharge of water to the aquifer would be reflected in loss of water from the bag. The selection of an appropriate bag is based on the objective of minimising the energy required to exchange water between the bag and the chamber. Hence, the bag should be robust but flexible, smooth, compliant and thin-walled to reduce head losses. For these reasons we used the bladders from 4-litre wine casks. We also trialled bladders from hydration systems but these were not as effective due to the inflexibility of the plastic laminates that the bladders were manufactured from, or difficulty in connecting the in-built tubing. In many studies, hospital dialysis or intravenous bags are used as they are relatively rugged and designed to be attached to tubing. Oven basting bags have also been used (Shinn *et al* 2002). Small-volume elastic bags such as balloons or condoms have been trialled previously but are not recommended as the elastic stretch in the bag can create artificial pressure differences (Harvey and Lee 2000; Schincariol and McNeil 2002).

The bag is housed in a protective cover such as an open length of PVC pipe or a perforated bucket (Figure 3). Field and laboratory studies have shown that surface water movement like waves, currents or streamflow can cause a venturi effect that reduces the hydraulic head in the collection bag and hence the chamber by a centimetre or more. This head loss is significant compared to the natural hydraulic gradient and can induce anomalous upwards groundwater seepage under gaining conditions (Libelo *et al* 1994). Hence, measurements from seepage meters are more reliable in slow-moving water with velocities less than 0.6m/s (ANCID 2000). The relatively high stream flow encountered in the Border Rivers was a significant issue and required the use of a perforated bucket which was weighed down by a concrete block.

We used 12.5-mm ID clear polythene tubing to connect the bag to the chamber (Figure 4). The tubing should be sufficiently rigid to avoid kinking or flexing. Again, the objective is to minimise head losses by using relatively large diameter tubing and avoiding the use of small-diameter fittings that constrict water flow. This is because frictional head loss is inversely proportional to the diameter of the flow conduit. Laboratory tests recommend that tubing diameter should exceed 7.9mm to reduce the hydraulic resistance that can cause measurement error (Fellows and Brezonik 1980; Rosenberry and Morin 2004).

The tubing is connected to the wine bladder by a garden irrigation threaded elbow fitted into the bladder mechanism. A valve has been incorporated between the chamber and the collection bag, located as close as practical to the bag (Figure 3). The valve can be opened to commence the test and closed to finish the test. A two-way valve can also be used, with one tubing connected to the bag, and the other being a short length of tubing open directly to the surface water body. The valve can be manually operated, but remotely operated versions, using a solenoid-controlled switch (as used in fuel-lines in trucks) have been applied (Cherkauer and McBride 1988). Initially the valve directs flow to the short open tube to allow equilibration of water pressure between the inside and outside of the chamber. After a period of stabilisation, the valve is switched to allow connection between the chamber and the bag.

A hose fitting has been attached to the end of the tubing located near the seepage chamber (Figures 3-4). This is used to easily connect and disconnect the tubing (and bag) from the chamber.

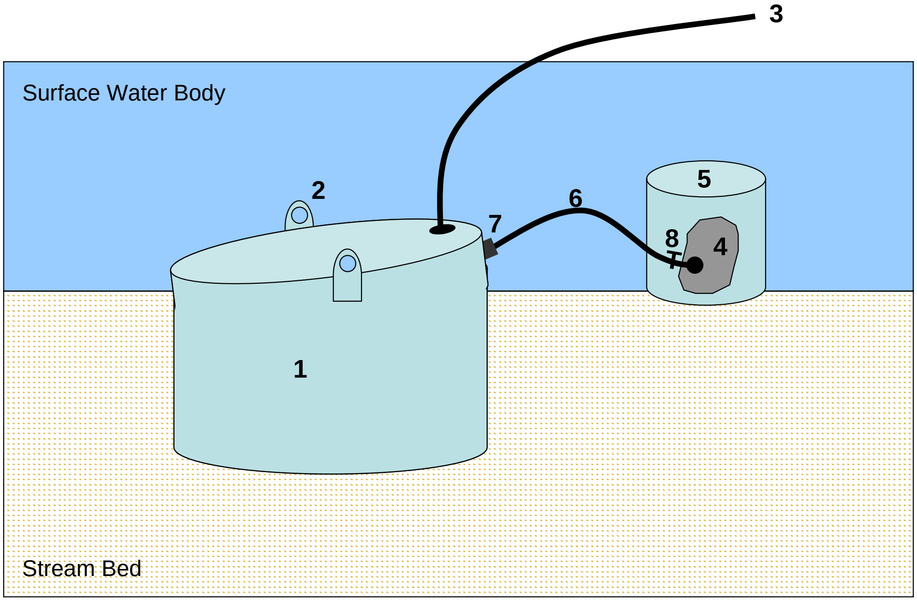

Figure 3: Basic design of a seepage meter with inverted open chamber (1) with flanges to assist in installation and recovery (2). The chamber has a sloping top with a gas venting tube (3) attached at the most elevated side. A 4-L wine bladder acts as a seepage collection bag (4) which is housed in an open protective housing (5). The connecting hose (6) has fittings (7) to enable quick release and a valve (8) near the bag.

Figure 4: Basic components of the seepage meter including seepage chamber and collection bag

SEEPAGE METER OPERATION

In terms of the actual operation of the seepage meter, the following procedures and practices are suggested:

(i.) After allowing the chamber to fill with water, embed it open-end down into the sediment. This is helped by slowly rotating the chamber (about 1 cm/s) into the sediment until the top is about 2 cm above the sediment surface. The top of the chamber should not stick up too much out of the bed because of upward advection of interstitial water (Bernoulli effect) caused by such positive relief in environments with waves, tides or currents. This process was interpreted to account for anomalous inflows into meters installed in a shallow marine and reef setting (Shinn *et al* 2002). Semi-analytical analysis suggests that a seepage chamber set at a depth that is the same as the chamber radius, will collect more than 90% of the ambient flow, assuming efficient design of the bag and tubing (Murdoch and Kelly 2003). The chamber should be installed sufficiently deep to limit the ingress of shallow throughflow or recirculated surface water. Capture of shallow throughflow and upwards advection were interpreted to be the key processes causing anomalous positive seepage results at some sites in the Border Rivers, where other methods of investigation suggested losing conditions. Placing the chamber too deep into the sediment so that the lid is directly on the sediment bed should be avoided. Also avoid pushing the chamber too rapidly into the sediment as this can cause blowouts that become preferred pathways for water flow (Lee 1977). In reality the depth of installation is largely predicated on the competence of the sediment, and the need to not excessively disturb the sediment profile. The chamber should be tilted slightly so that the vent hole is relatively elevated, as this allows any entrapped gas to escape freely.

(ii.) Minimise the activity around the meter during installation and operation. By monitoring the pressure within a chamber using a transducer, field studies have shown that walking past or stepping near the meter can effect hydraulic pressure and cause artificial inflows into the chamber (Rosenberry and Morin 2004). Subsequent measurements of seepage in areas of the sediment bed disturbed by previous installations or by repeated foot traffic can return larger seepage rates. This has been attributed to the disturbance of a thin, lower-permeability sediment veneer (Rosenberry and Morin 2004).

(iii.) Allow sufficient time between initial installation of the chamber and the commencement of measurements so that hydraulic pressures inside the chamber equilibrate with those of the surface water body. Laboratory tests suggest that 80% of this equilibration occurs in the first 10 minutes (Cherkauer and McBride 1988; Cable *et al* 1997) and investigators have used stabilisation times ranging from 10-15 minutes (Landon *et al* 2001) to 2-5 days (Shaw and Prepas 1989; 1990).

(iv.) The end of the vent tube can be fixed into position on the bank of the surface water feature using a stake or small star picket. This can be flagged to become a useful marker for the location of the seepage meter during its operation.

(v.) Pre-fill the collection bag with a known volume of water before attaching the bag to the meter. Plastic bags have an inherent tendency to expand slightly during operation of the meter, inducing a head loss. This causes an anomalous short-term influx of water into the bag after being attached to the chamber (Shaw and Prepas 1989; Blanchfield and Ridgeway 1996). This error was effectively eliminated in field trials when the bag was filled with 1000mL of water prior to attachment. Pre-filling the bag is obviously required when investigating losing streams.

(vi.) Before attaching the tubing (and bag) to the chamber ensure that the water in the bag is in hydraulic equilibrium with the surface water body. This is done by slowly lowering the bag into the water with the valve open and the chamber-end of the tubing above the water surface. This will expel any air within the bag through the tubing, however be careful not to lose any water from the bag. When this is completed, turn the valve closed.

(vii.) Attach the tubing to the chamber via the hose fitting. Before attachment, remove any air within the tubing between the hose fitting and the valve. This is done by submerging the bag and tubing, with the hose fitting directed upwards to allow air bubbles in the tubing to escape. Place the bag inside its protective cover and avoid folding, creasing or kinking the bag as these can result in anomalous and erratic head differences (Murdoch and Kelly 2003). Weights such as concrete blocks can be placed on both the chamber and the protective cover to prevent any lateral movement due to high stream flow.

(viii.) With the bag attached and inside its protective cover, the meter is ready for operation. Seepage measurement commences when the valve is opened – make sure that you record the time that this was done.

(ix.) A control bag can be used to quantify the effects of factors such as waves, wind or currents or the properties of the bag itself (Sebestyen and Schneider 2004). This is a pre-filled bag and tubing identical to that used in the meter that is submerged and tethered (with valve closed) about 0.15m above the sediment bed at the same time as the meter is installed and operated. The bag is positioned near the meter but not attached to the meter. Any changes in the water volume within the control bag reflects the magnitude of these effects. Field studies in the nearshore coastal environment have also used complete control meters set up in sand-filled plastic swimming pools on the bed, specifically to measure measurement artefacts (Cable *et al* 1997).

(x.) After a period of time the seepage measurement is ended by returning to the meter, turning the valve closed and recording the time that this was done. The duration of the test is based on the local seepage regime and can vary from less than an hour to several days, so a trial and error approach is required. The change in water volume in the bag should exceed 50ml, so this reflects the minimum seepage that effectively can be measured. Avoid letting the bag fill close to its maximum capacity due to significantly increased head losses, confirmed by laboratory tests (Murdoch and Kelly 2003). Likewise, avoid completely draining the contents of the bag in the situation of high negative seepage. If a 4-L bag is pre-filled with 1000mL, than 3000mL is the maximum positive seepage that effectively can be measured, and 1000mL the maximum negative seepage.

(xi.) Remove the tubing from the chamber via the hose fitting and measure the volume of water in the bag. This can simply be done with a measuring cylinder. An alternative approach is to weigh the pre-test and post-test bag, to define the change in water volume (assuming a density of 1, or alternatively correct for temperature or salinity effects). Use Equation 1 to derive the seepage rate.

(xii.) Investigators have incorporated a meter correction factor to the calculation of seepage rates, taking account of the measurement artefacts due to frictional resistance and head losses within the meter. Laboratory testing indicated a ratio of measured to actual seepage of 0.77 (Belanger and Montgomery 1992). For negative fluxes involving movement of surface water into the aquifer, correction factors have ranged between 1.11 and 1.74 (Rosenberry and Morin 2004). Such correction factors would be unique to a particular seepage meter and would require calibration in a laboratory flume.

(xiii.) The meter should be routinely inspected and cleaned. Potential problems include leaky fittings, perforations or split seams in the bag, plugging of tubing by algal growth and kinks in the tubing.

DISCUSSION AND CONCLUSIONS

Various configurations of seepage meters were trialled at sites in two contrasting catchments. In the Lower Richmond catchment, low discharge (<20 m^3/day/km) of groundwater into a drain traversing a coastal swamp was measured. This low positive flux is realistic considering the heavy clay evident at the base of the drain at the site. Soil profiles and shallow piezometers suggest that inflow of groundwater into the drain is more from the shallow oxidised zone (<1m) which intercepts the side of the drain rather than the base (Brodie *et al* 2005). A more robust estimate of seepage flux would require measurements at both the sides and the base of the drain. The main logistical problems encountered were the inability to adequately embed the meter into the clay profile and the accumulation of biogenic gas. In the Border Rivers, some of the seepage meters measured positive (gaining) seepage, contrary to other assessment methods (such as minipiezometers or hydrochemistry) which suggested downward river leakage. This was attributed to anomalous input of water to the bag due to capture of shallow throughflow and upwards advection (due to the inability to install the meter to sufficient depth). The main logistical problems were brought about by relatively high stream flows, such as kinking or submerging of the venting tube and displacement of the meter (Baskaran *et al* 2005). The trials in the two catchments highlighted the logistical issues surrounding the operation of seepage meters.

A seepage meter only measures flux at a point in space. This means that many measurements are required to derive meaningful interpolations, which is labour intensive and time consuming. High spatial and temporal variability in seepage characteristics can result in poor repeatability of measurements. Such variability can be attributed to variations in water levels through time, spatial variations in aquifer hydraulic conductivity, the presence of a thin clogging layer and changes in its hydraulic resistance, or variable seepage velocities across the stream profile, with velocity decreasing with increasing distance from the bank (Kaleris 1998). Also manual seepage meters only measure the aggregate seepage over the time period, and do not provide any data on how seepage changes during that time period.

Significant measurement errors can be introduced with the design and operation of the seepage meter. Processes such as upward advection of interstitial water caused by the chamber having a positive relief in a flowing stream (the Bernoulli effect), venturi effects of stream flow on the collection bag, hydraulic resistance along the internal boundaries of the meter causing head losses, or accumulation of sediment gas in the chamber can lead to misleading data. This means that measurements from seepage meters are generally not reliable enough to quantify seepage flux in absolute terms.

In low-flux environments (such as in heavy clay sediments or where hydraulic gradients are low) measurements may require days for an adequate change in bag water volume to derive a reliable estimate. The fluxes measured may not be entirely groundwater, but include other sources such as shallow throughflow or recirculation of surface water through the sediments. This can be a major issue if the seepage meter is not installed to a sufficient depth into the sediment. The meters are generally unsuitable for hard, gravelly or weedy sediment beds because of the difficulty in providing an effective seal and installation depth. Sand, silt or soft clay are the best sediment material for embedding the chamber. The installation and effectiveness of seepage meters is problematic in deep or fast-flowing waterbodies, being more suited to less dynamic environments such as drains, shallow lakes or lagoons.

Due to this range of potential sources of error, it is recommended that seepage meter measurements are accompanied by other indirect methods (such as using minipiezometers to measure head difference, geophysics such as resistivity, or hydrochemistry) to verify the direction and likely magnitude of seepage flux.

Despite these significant limitations, the seepage meter is still the method that is most commonly available for the direct measurement of water flow at the interface between aquifers and surface water features. As it is a direct measurement, seepage meters have the potential to validate indirect methods that involve measuring secondary indicators such as hydraulic head difference, chemical tracers or isotopes. However, this can only be undertaken when there is confidence that any potential measurement errors have been recognised and minimised. Seepage meters are based on a simple concept and are inexpensive to construct, using readily available components. Although not sufficiently reliable to measure seepage in absolute terms, the method can still be useful for defining relative differences in seepage flux. This is useful in identifying seepage hotspots for further investigation. Seepage meters can still be also useful in estimating the direction and order of magnitude of seepage flux. They can be easily incorporated into field investigations as they can be installed at the beginning of the trip, regularly monitored and then removed at the end of the trip. The seepage meter can be used as a valuable educational tool, to raise awareness of the connectivity between groundwater and surface water resources.

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