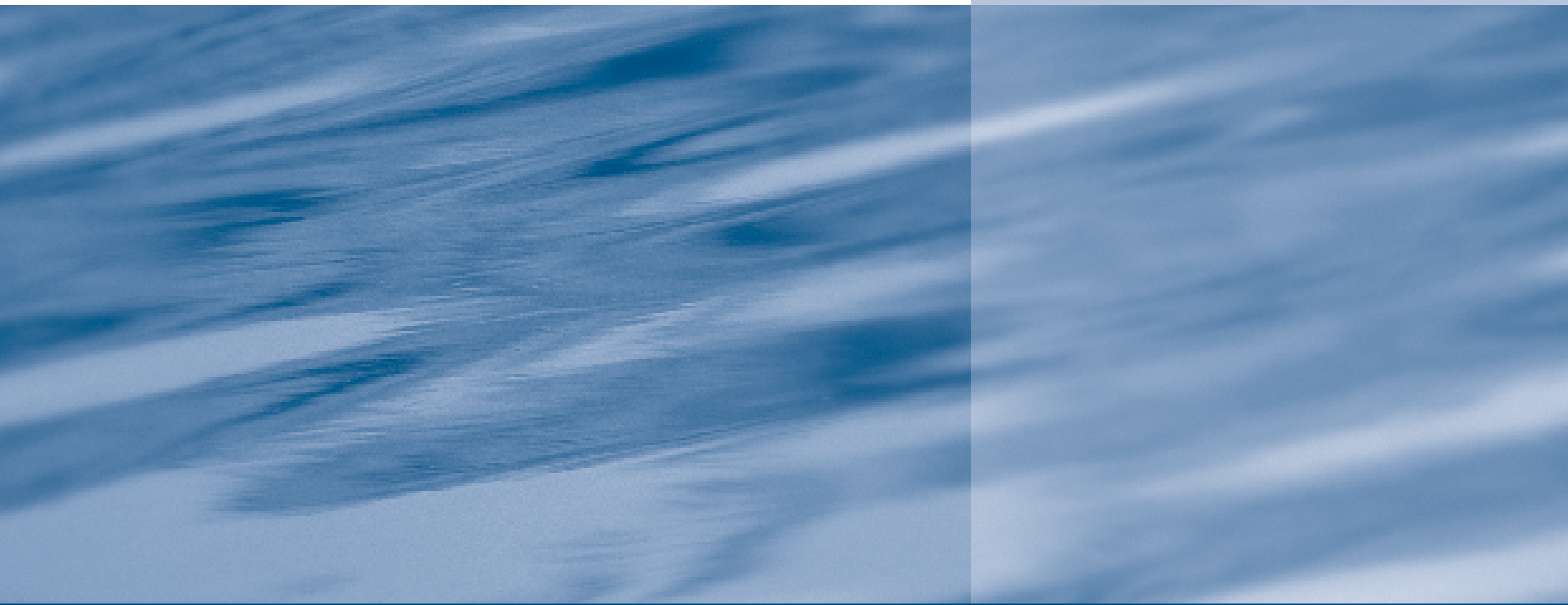

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High-resolution in situ monitoring of flow between aquifers and surface waters

Science Report SC030155/SR4

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Professor Mike Depledge   Head of Science

Executive Summary

The measurement of groundwater flow at the small scale is vital if hydrogeologically heterogeneous systems like the hyporheic zone are to be better characterised. In such complex systems measurements must be made at high spatial and temporal resolutions, which poses a challenge if sufficient measurements are to be made without incurring excessive cost or experimental complexity. This report reviews several current or emerging methods and technologies that may be used in studies of this kind.

Seepage meters offer an inexpensive approach to direct flux measurement. Traditional flexible-bag systems have been augmented by a wide range of methods to measure directly and log the flow from the collection chamber. Of these, the heat-pulse systems seem to offer the best option in terms of cost, simplicity and suitability for long-term remote field operation.

Heat tracing is a method that uses inexpensive technologies to enable measurement at high densities. Its disadvantage is that it is indirect; the distribution of the physical properties of the sediments must be estimated, and the fluxes derived by numerical modelling.

Three-dimensional in situ *flow meters* offer potentially an ideal means of examining the flow field at the small scale. Only one commercial system is currently available for this purpose; however, this system is relatively expensive and has high power consumption, which limits its value for typical field investigations. A simplified system could provide a valuable contribution to hyporheic zone research.

Geophysical methods have limited value for flow quantification studies in the hyporheic zone and are probably best suited to studies at larger scales and to the delineation of sites of interest.

Traditional borehole methods will remain a mainstay of hydrogeological investigation and now may be augmented by three-dimensional and two-dimensional borehole flow meters.

Owing to the variability of test sites and experimental aims, it is unlikely that any one method will be uniquely suited to the characterisation of a system. Therefore a combination of techniques may provide the best solution.

Contents

1 Introduction

This report reviews methods that might be applied to the high-resolution monitoring of water flow rates in hyporheic zone studies. It draws on work undertaken in a wide range of disciplines, including hydrogeology, hydrology, geophysics, limnology, oceanography and non-environmental fields.

A fundamental issue in measuring fluxes is that of heterogeneity and scale. Quantification of water fluxes between aquifers and surface water bodies is challenging, especially so given that in the hyporheic zone fluxes may vary dramatically within very short distances (Sophocleous 2002). It is therefore important to take measurements at the appropriate spatial scales, which has implications for the choice of method. If the heterogeneity is to be mapped out, very high-resolution measurement methods may have to be used (Committee on Hydrologic Science, 2004) – if an integrated flow rate is required, sampling of flows needs to be large enough to provide adequate averaging. This report considers only those relatively small-scale methods that could be used for very high-resolution flow monitoring, and that can be up-scaled to provide suitable integrated flow estimates up to the decametre scale. The techniques described are grouped into borehole methods, buried flow meter methods, seepage meter devices, geophysical methods, and thermal methods:

- Borehole methods (Section 2):
  - Darcy calculations;
  - Borehole flow meters:
    - KVA flow meter,
    - acoustic Doppler velocimeter,
    - 'colloidal borescope',
    - 'Florida' passive flux meter;
- Buried flow meter methods (Section 3):
  - Sandia flow sensor;
  - Labaky *in situ* probe;
  - KVA flow meter;
- Seepage meter methods (Section 4):
  - Lee type devices;
  - Automated flow measurement devices:
    - heat pulse technique,
    - solute detection technique,
    - electromagnetic technique,
    - ultrasonic technique;
- Geophysical methods (Section 5):
  - Electrical methods;
- Thermal methods (Section 6):
  - Using natural temperature variations.

Each of these methods has its own advantages and disadvantages in terms of ease of use, sensitivity, range and cost (e.g., *Figure 1.1*). Larger-scale approaches, such as baseflow separation techniques, are not considered.

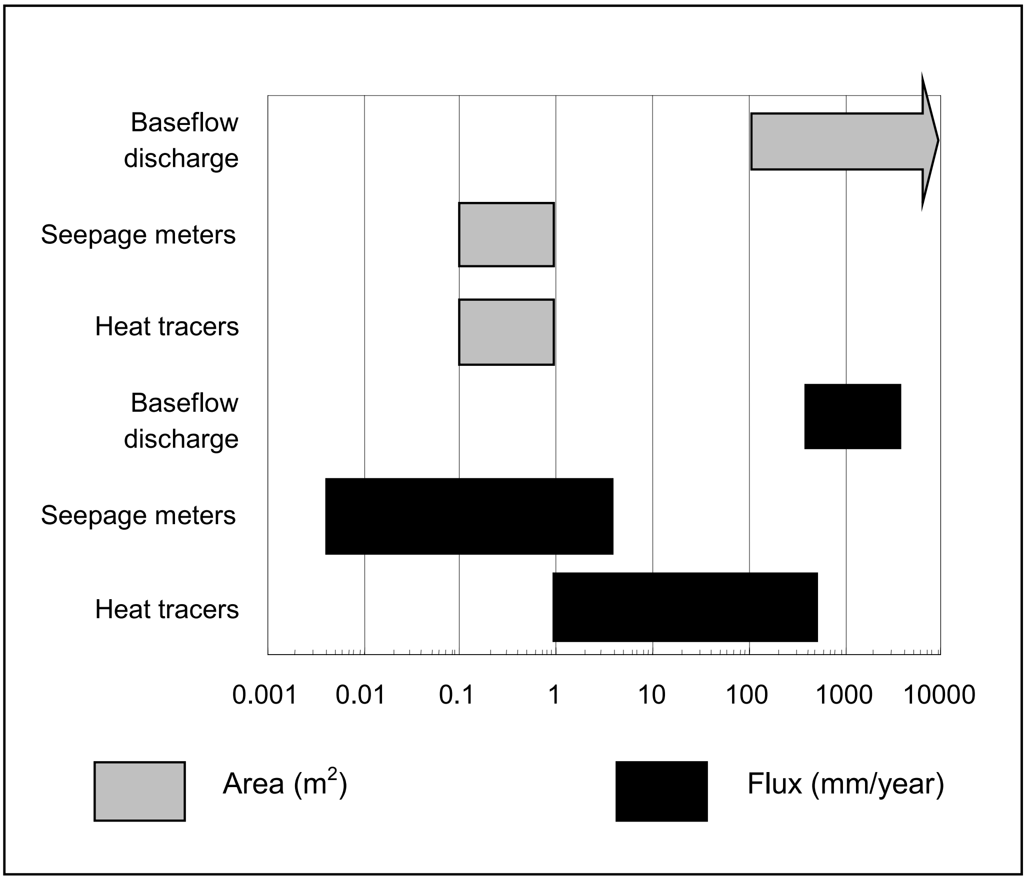

Figure 1.1 Comparison of scales of measurement and rates of flux between various methods of determining recharge from surface waters, after Scanlon *et al*. (2002).

2 Borehole-based techniques

2.1 Flow rates using Darcy's law and borehole and piezometer head measurements

'Traditional' approaches to estimate groundwater flow have relied on the installation of boreholes and piezometers to obtain head gradient information, and the use of hydraulic or, more rarely, tracer tests to derive estimates of hydraulic property distribution to calculate flow. The scale of measurement is based upon the extent of the array, though the measurements of hydraulic properties may only reflect those local to the tested well.

To better define head distributions in time and space, mini-piezometers and multi-level arrays can be used. In hydrogeologically complex systems, data from small-scale measurements such as these may be a significant aid to characterisation, though disturbance to the sediments because of drilling or piezometer installation may modify the local properties. Advances in installation techniques (Dean *et al*. 1999, Baxter *et al*. 2003), as well as the existence of commercial devices such as the Waterloo and Westbay multi-level systems, have made the practical application of these approaches somewhat easier.

The long-term monitoring of hydraulic heads in wells is now readily achieved with pressure transducers and multiplexed central dataloggers or stand-alone devices that incorporate both pressure transducer and logging system, such as the devices made by Keller, Schlumberger and In-situ Inc. Where space is limited such that the pressure transducer cannot be installed within the diameter of the piezometer, or cost is a significant factor, a suitable logging device can be constructed easily using basic components for under £100 (Ellis 2002).

2.2 Direct measurement of groundwater flow within boreholes

2.2.1 Principle

Borehole flow surveys provide a way to investigate the variation of natural groundwater flows with depth. Devices that can monitor vertical flows within boreholes are a common component in the arsenal of geophysical logging tools often used for down-hole investigations. However, they are usually relatively insensitive and can only measure the vertical component of flow. They are therefore not suitable to estimate the natural velocity vector, which may provide useful information on local flow fields and their variation with depth. Boreholes situated close to water bodies may be monitored using a range of sensitive two-dimensional or three-dimensional flow meters which, after taking into account the affect of the borehole itself upon flow, may be used to help determine the local flow regime. Four devices exist for this purpose, each operating on different principles and ranges of measurement.

2.2.2 The KVA flow meter (model 40 GeoFlo meter)

This device is manufactured by K-V Associates Inc. (www.kva-equipment.com) and is based on a variation of the heat perturbation method common to several of the devices described in this document. A central electric heating element is surrounded by several temperature sensors (thermistors), which are placed equidistantly from the heater on a horizontal plane and 90^{o} apart (*Figure 2.1*). For use in a borehole, the heater and sensors are contained within a perforated tube and the space filled with 2 mm glass beads. To take a measurement, the heater is briefly powered up (~30 s) to produce a pulse of heat, which (under conditions of no flow) spherically dissipates outward through the beads. Under flowing conditions, the cooling effect on the beads by the water is most pronounced in the upstream direction, which (combined with the advection of the heat pulse) distorts the heat dissipation pattern in the direction of groundwater flow. The resulting distribution of temperature is related to the direction and magnitude of the flow. Data from opposite pairs of thermistors are analysed to derive the flow direction (referenced to the thermistor alignment) and magnitude. By orientating the device to a geographical reference point, the horizontal component of the groundwater flow vector can be derived. To limit flows around the system within the borehole, the outer surface of the perforated tube is covered in a pile-fabric, referred to as ‘a fuzzy packer’, which fits closely between the device and borehole wall. To account for any differences between the hydraulic conductivity of the device and the surrounding media, which may cause diffraction of the stream-lines, a calibration is performed under laboratory conditions at known conductivity differentials.

The sensor head is designed to be lowered into a borehole and is connected to a combined logger and processing unit that records, analyses and displays the results. The range of flows that the device can measure is from 3.5×10^{-5} to 0.2 cm/s.

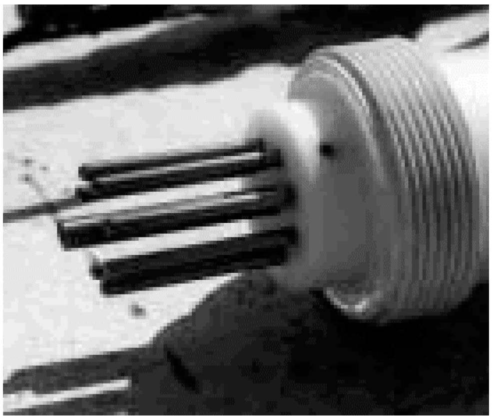

Figure 2.1 Head of KVA flow meter showing central heater and surrounding thermistor probes (Wilson *et al*. 2001).

2.2.3 Acoustic Doppler velocimeter

An experimental version of an acoustic device, the acoustic Doppler velocimeter (ADV) manufactured by SonTek Inc. (www.sontek.com), that uses the Doppler effect to measure velocity was evaluated by Wilson *et al*. (2001) and Newhouse and Hanson (2002). It consists of a central acoustic transmitter and three receivers mounted on radial arms (*Figure 2.1*). Water movement is measured by tracking acoustically the movement of particles within the water stream, which are assumed to be moving at the same velocity as the groundwater itself. *X*, *Y* and *Z* velocity components are calculated and displayed in real time using a surface-based computer to calculate the flow vector by reference to a flux-gate magnetometer (compass) mounted within the down-hole sonde. Flows can be measured from 0.01 cm/s to 250 cm/s.

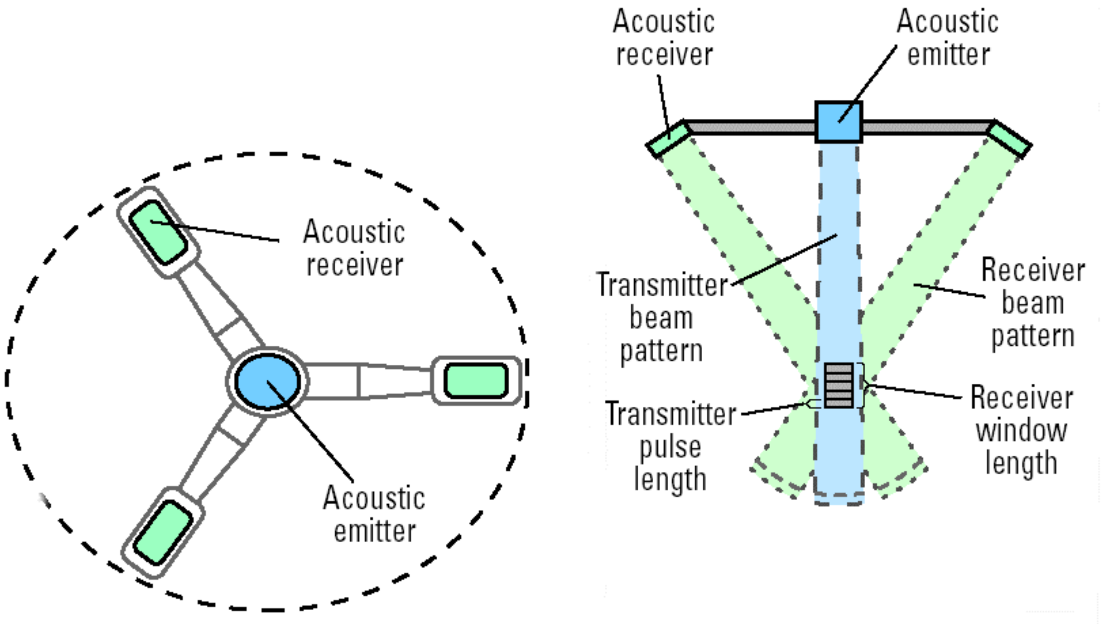

Figure 2.2 Components of the Acoustic Doppler velocimeter showing acoustic emitter and receiver array (Wilson *et al*. 2001).

2.2.4 The colloidal borescope

The colloidal borescope was developed by The Oak Ridge National Laboratory and is distributed by AquaVision Environmental LLC (www.aquavisionenv.com) in the USA. It operates using a video camera to track optically the naturally occurring particles that move in the water stream (*Figure 2.3*). As they move past the field of view a video frame of the image is 'grabbed' and digitised. Particles are tracked from one frame to the next by software, from which the velocities and flow direction (by reference to an onboard fluxgate magnetometer) can be calculated. However, only flows that are essentially laminar in nature are suitable for analysis. Flow rates that can be measured range from ~0 cm/s (stagnant water) to 250 cm/s. Although it is claimed to operate by observing colloids, it seems likely that a lower limit to particle size must exist, below which the particle cannot be resolved by the optical system, and also that sufficient numbers of observable particles are necessary for the measurements to be made.

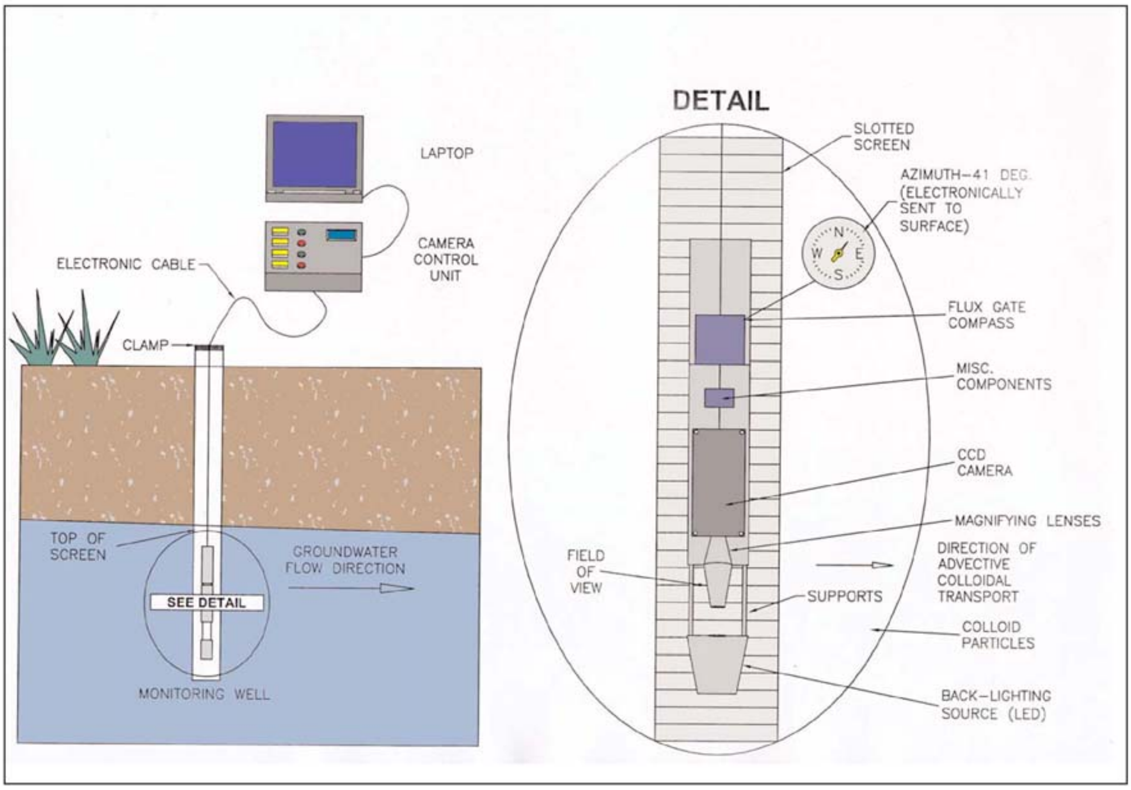

Figure 2.3 The colloidal borescope (Newhouse and Hanson 2002).

2.2.5 The 'Florida' passive flux meter

Passive samplers are devices usually placed within a borehole such that the flux and nature of any contaminant within the groundwater may be assessed. They are commonly made from permeable membrane bags that contain hydrophobic and/or hydrophilic chemicals to which contaminants within the water may readily sorb. Hatfield *et al*. (2004) describe a device that may also be used to estimate groundwater flux. This is achieved by adding one or more 'resident tracers' to the sorptive media, which are slowly lost as they dissolve into the groundwater as it flows through the device (*Figure 2.4*). The time-averaged water flux over a known period may be calculated as it is inversely proportional to the tracer mass that remains on the sorbent. By creating a stack of passive flux meter (PFM) cells that pack within a borehole, the flux at different horizons may be investigated.

The advantages of the device are its simplicity and that both contaminant and groundwater fluxes may be measured simultaneously. Field estimates of water flux have been shown to be within 15 percent of the imposed flow (Annable *et al*. 2005), provided the amount of resident tracer remaining at the end of the experiment is within 20 to 70 percent of the original mass. By simultaneously using several resident tracers with different solubilities, the device may be used in groundwater systems for which the flux is unknown, as at least one tracer is likely to remain within the critical range for the duration of the experiment. The groundwater flows over which the device has been tested range from 0.5 cm/d to 50 cm/d (Annable, M.D., 2005, personal communication).

The device has disadvantages compared to other techniques:

- Flow measurement is cumulative such that flow variations will be averaged;
- The device has to be exhumed for the sorptive media to be analysed;
- Direction of flow is not measured – though laboratory trials have been undertaken with a segmented device that provide a two-dimensional flow estimate (Hatfield *et al*. 2003);

➢ The effects of diffusion become increasingly significant as the natural groundwater velocity decreases, such that there exists a lower limit to flux measurements.

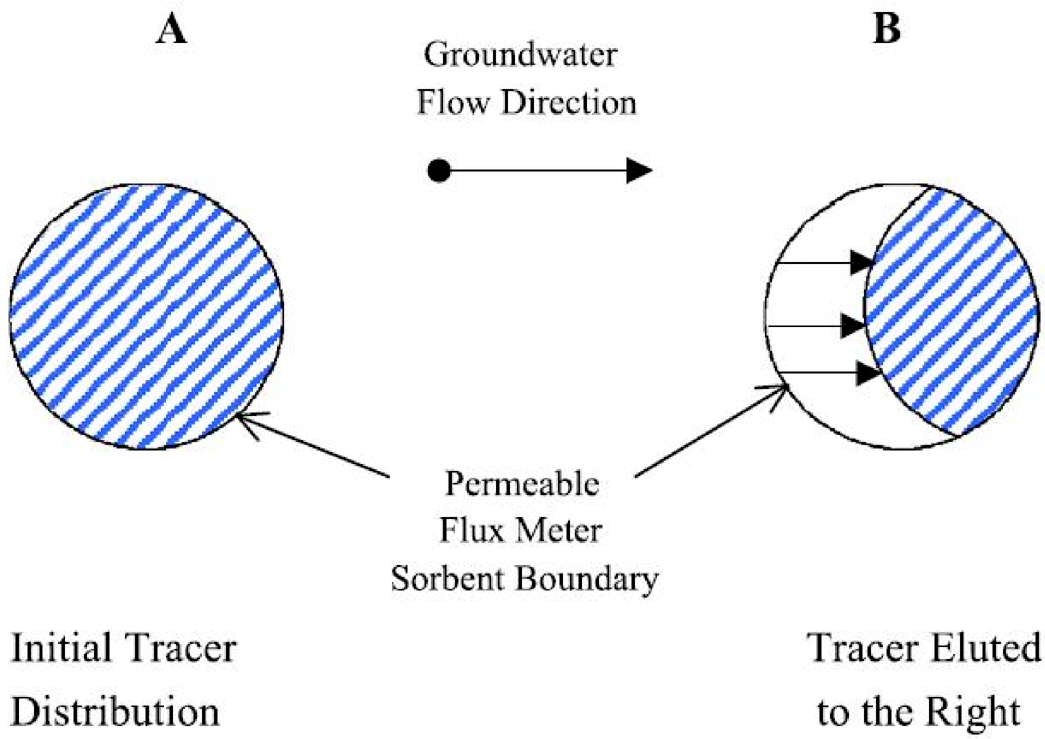

Figure 2.4 Conceptual diagram of resident tracer distribution in two cross-sections of a passive flux meter showing (a) the meter before and (b) after exposure to groundwater flow (Hatfield *et al*. 2004).

2.3 Summary and conclusions

A field evaluation of the three electronic devices in a fractured limestone (Wilson *et al*. 2001) concluded the measurements from the KVA flow meter gave lower values than the other two devices, but these values compared better with estimated flow velocities based on point-dilution tracer tests. Overall, the repeatability of the measurements was poor, but may have been partly attributable to natural variations in flow at the test site over the period of comparison.

The ADV and colloidal borescope are borehole logging tools and as such are designed for short-term deployments rather than *in situ* monitoring. Both have bulky and expensive attendant surface hardware. The KVA flow meter is more compact (the sensor head itself is only a few centimetres in length), but it is also designed for short-term measurement.

The ‘Florida’ PFM is a useful device for the simultaneous measurement of groundwater and contaminant flux, and is probably best suited for deployment in groundwater systems in which flows are relatively constant. In more complex systems, such as the hyporheic zone, it has the disadvantage of only measuring time-averaged flow and, unless the ‘directional flow’ version is developed for field use, it cannot provide an indication of this parameter.

The above devices can each measure the water velocity in boreholes. While this may be of intrinsic value, it does not provide direct information on seepage velocity within the formation. Only by estimating the hydraulic conductivity of the formation adjacent to the point of measurement may a 'borehole magnification factor' be derived that accounts for the increase in groundwater velocity within the borehole compared to that of the formation. Complications arise where flows are not ideal, such as where eddies produce a disturbed local field, where changes in density occur or when a significant vertical flow component may be present.

3 Buried flow meter methods

3.1 Introduction

Section 2.1 describes the traditional approaches of using boreholes or piezometers to derive head and hydraulic conductivity data from which estimates of the velocity field between boreholes may be made. The main disadvantages of this method are the cost of installation and testing of the boreholes, the uncertainty of the hydraulic conductivity distribution of the sub-surface from which the velocity field is derived and the generally large scale of the measurement.

Direct measurement of flow within boreholes (Section 2.2) also has the disadvantage of the cost of installation of the borehole. In addition, the flows within the well are affected by the presence of the borehole itself.

To address at least some of these issues, methods have been developed that allow the direct measurement of fluid flow using buried devices.

3.2 The Sandia *in-situ* permeable flow sensor

A device developed by the Sandia National Laboratories (www.sandia.gov; Ballard 1996) uses a heat-perturbation method to derive the flow velocity vector. This is now marketed by Hydrotechnics in the USA as the VECTOR® system (www.hydrotechnics.com). It consists of a 6 cm diameter, 160 cm long cylindrical probe, upon the surface of which is an array of both heating elements and 30 thermistor-based temperature sensors. The heater is continuously powered and under conditions of no-flow the heat distribution to the thermistors is uniform. However, where flow is present the heat is transported away from the upstream sensors to create a temperature distribution that varies as a function of direction and groundwater velocity. The aspect ratio of the cylinder is such that the vertical component of flow is identified by differences in temperature over the length of the device (*Figure 3.1*). The suggested installation of the device is by hollow stem auger, after which the hole is backfilled. Monitoring of the sensor array is achieved by datalogger, with subsequent numerical analysis of the data sets performed to derive the full three-dimensional velocity vector. Remote logging is possible by radio or telephone connection. The device is non-recoverable, but can be monitored continuously provided a 100 W power supply is available. The range of flow velocity measurement of the instrument is approximately 5×10^{-6} to 1×10^{-3} cm/s, depending on the thermal properties of the system. Field trials (Alden and Munster 1997) showed that groundwater flow velocities derived from the probe compared well with those determined from piezometric gradient measurements. The accuracy of direction measurement was estimated to be within ±10^{o}.

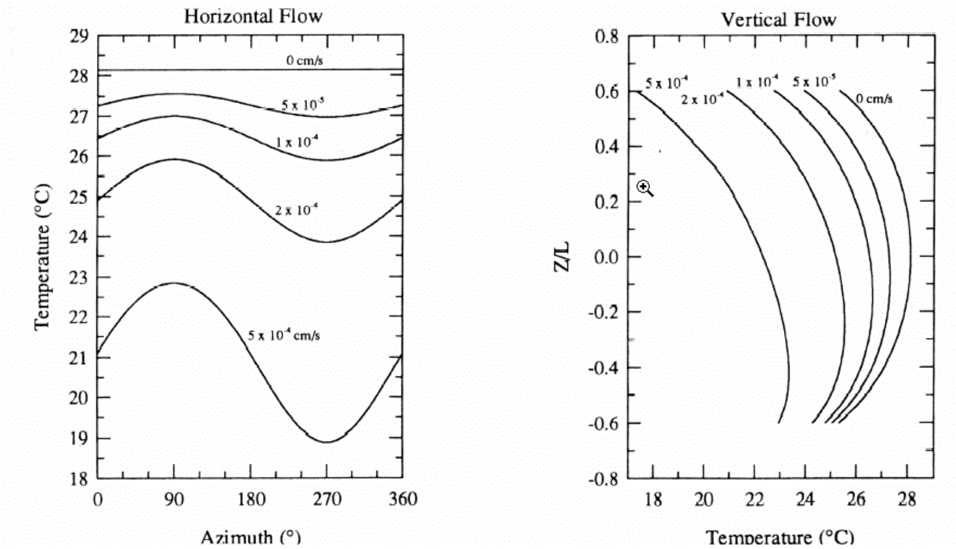

Figure 3.1 The distribution of temperature on the surface of the *in-situ* permeable flow sensor as a function of azimuth and flow velocity under conditions of purely horizontal flow (left) and vertical downward flow (right), from Ballard (1996).

3.3 The Labaky *in-situ* probe (University of Waterloo)

The Labaky *in-situ* probe (Labaky 2004) provides an *in situ* means of two-dimensional velocity measurement by conducting a small-scale tracer test around the circumference of a 3 cm diameter probe upon which are mounted an injection port and two conductivity detectors (*Figure 3.2*). By knowing the initial orientation of the injection port, the direction and magnitude of the horizontal flow can be determined based on the theory of ideal flow around a cylinder. Laboratory experiments in a flow tank accurately measured flows that ranged from 6 x 10^{-5} to 1 x 10^{-3} cm/s. One advantage of the device is the possibility that it could be installed using drive-point techniques. However, as the device has only recently been developed as part of a PhD project it is not yet possible to assess fully its potential for long-term application.

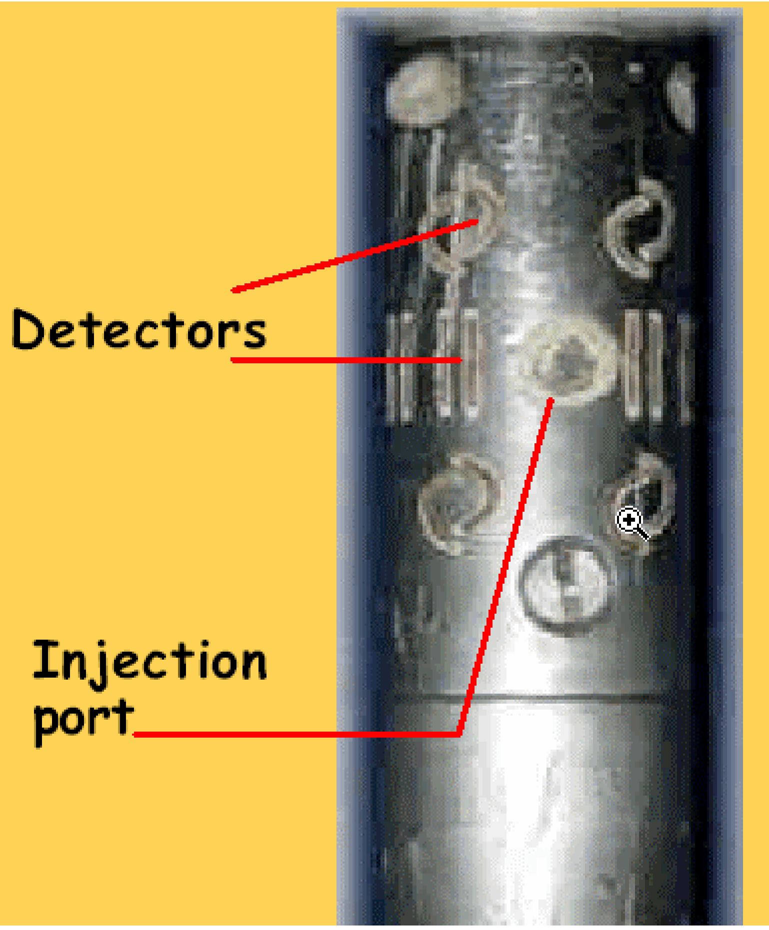

Figure 3.2 Tip of probe showing injection port and detectors (Labaky *et al.* 2002).

3.4 The KVA flow meter

This two-dimensional device, discussed in Section 2.2, may also be used in unconsolidated sediments directly after the removal of the glass-bead/packer components used for down-hole operation. In this mode, the device can measure flows from 3.5 x 10^{-6} to 0.1 cm/s. The device is not designed for permanent installation and is recovered after the measurements are taken.

3.5 Discussion and conclusions

These devices provide means of small-scale *in-situ* direct measurement of groundwater velocity within unconsolidated sediments. This offers significant potential in the context of hyporheic zone studies.

- Although the Sandia/Hydrotechnics system uses 'disposable' probes and monitors remotely, the sensors alone are still relatively expensive – $2500 (Ballard 1996). The power requirement is significant at 100 W and therefore the system is unsuited to long-term remote deployment unless a mains supply is available.
- Labaky's system is novel and promising, but relatively untried. For remote long-term applications a control and logging system needs to be developed. The use of a liquid tracer injection system means that it is a relatively complicated technique in comparison with heat-perturbation techniques, though this practical disadvantage may be offset to some extent by the probe design, which lends itself to drive installation. Field duration is presumably limited by both power supply and tracer reservoir capacity.

- The KVA flow meter is comparable to the Sandia system, but only works in two dimensions. However, the use of a heat pulse rather than a continuous source reduces the power requirements, though the system as a whole is not designed for permanent *in situ* monitoring.

The ability to measure the velocity vector *in situ* is very useful. Heat perturbation is a tried-and-tested way to achieve flow measurement. Unfortunately, none of the above solutions seem ideal for long-term remote field-based studies. To address this problem, a fusion of the Sandia and KVA devices could be envisaged whereby a relatively inexpensive three-dimensional sensor could be buried permanently and connected when required to a control–logger system similar in function to that proposed to measure seepage fluxes in Section 4.4.

4 Direct measurement of flux at the surface water–groundwater interface

4.1 Flexible bag seepage meters

Seepage meters were developed from about the middle of the 1940s to measure directly the seepage to and from surface water bodies, mainly for the study of seepage loss from irrigation canals (Carr and Winter 1980). Of these devices, the flexible bag system became predominant. Although widely attributed to Lee (1977), devices using this principle were described earlier by Israelson and Reeve (1944) and Warnick (1951). Lee's device (*Figure 4.1*) represented a breakthrough in simplicity and has become notable for its widespread adoption. It is therefore not surprising that the flexible bag seepage meter is commonly referred to as the 'Lee type' or 'drum type' by most authors. The device consists of a bottomless container (often the end of an oil drum) that is pushed into the sediment of the system under investigation. An offset vent hole is positioned at the highest part of the container to allow trapped air to escape. After a period of settling (often 24 hours), a flexible plastic bag is attached to a short length of tubing connected to the vent hole. Where water seeps into the surface water body, an empty bag is attached for a timed period at which point it is removed and the gain in volume measured. For water that seeps into the sediment, the bag is pre-filled with a known volume of water prior to connection to the tube. The seepage flux *Q* can be calculated from the change in volume of the bag over the timed period and the area covered by the cylinder.

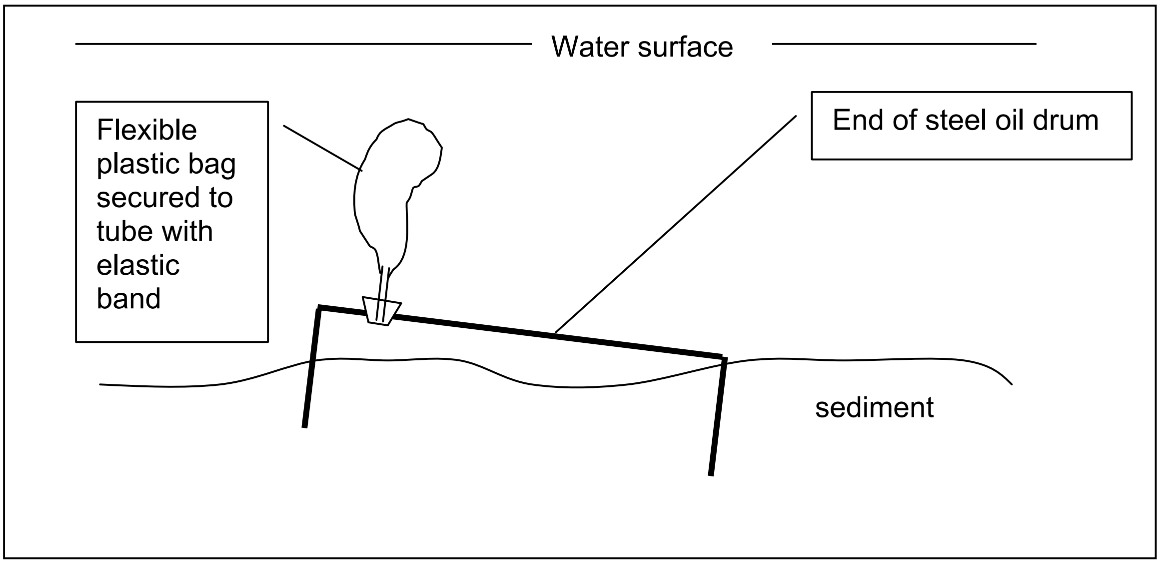

Figure 4.1 Flexible bag seepage meter (after Lee 1977).

Many studies of surface water–/groundwater interaction have used seepage meters in lakes. These include (Lee 1977, Taniguchi and Fukuo 1993, Rosenberry and Morin 2004, Sebestyen and Schneider 2004), streams (Cey *et al*. 1998, O'Rourke *et al*. 1999, Paulsen *et al*. 2001a, 2001b, Burnett *et al*. 2001, Conlon and Lee 2002), coastal and marine environments (Cable *et al*. 1997, Tryon *et al*. 2001, Taniguchi *et al*. 2003b), canals (Anderson 2003) and peatlands (Ingram *et al*. 2001).

The widespread use of the flexible bag system has highlighted concerns regarding the method, from which may be drawn the following general conclusions:

- The drum should be pushed into the sediment with care to minimise sediment disruption (Lee 1977), and, following installation, a period of several hours may be necessary before the system is stabilised sufficiently for the bag to be attached to the drum (Shaw and Prepas 1989).
- In coarse sediments it may be difficult to produce an adequate seal between drum and bed, which results in a failure to detect any flow (Cey *et al*. 1998).
- To prevent by-pass flow around the drum, the flow tube that connects the drum to the collection bag must be wide enough not to create a pressure drop over its length (Fellows and Brezonik 1980, Rosenberry and Morin 2004). A correction factor can be determined and applied to measurements to account for such effects (Belanger and Montgomery 1992).
- A short-term unusually rapid influx of water has been observed during the early stages of filling of some bags, which it appears can be caused by the bags not having attained elastic equilibrium after manufacture (Shaw and Prepas 1989). This problem can be overcome by partly pre-filling the bags with water or by using a control device. The latter consists of identical pre-filled bags and tubing tethered to the sediment, but not connected to a drum. These may subsequently gain or lose water through bag effects or any processes other than seepage (Cable *et al*. 1996, Sebestyen and Schneider 2004).
- Flume studies show that if the flexible bag is exposed to flow in the overlying surface water, a decrease of head results within the seepage meter (Libelo and MacIntyre 1994, Cable *et al*. 2003). The effect of the moving water can result in increases in hydraulic gradient of 50 percent or more and give rise to erroneously high fluxes. By enclosing the bag within a rigid container the effects may be reduced significantly.
- To minimise error, many seepage meters are required in sites that exhibit significant natural spatial and temporal variation (Shaw and Prepas 1990), as the seepage measurement is typically representative of a scale of only a few metres (Cable *et al*. 2003).

In spite of these problems, many studies, such as those referred to above, demonstrate that it is possible to derive sufficiently accurate data from drum-type devices, provided adequate care is taken in their use. In those cases where sufficient detail is recorded, it appears that a range of ways to circumvent the problems has been adopted.

Although simplicity of the meter is one of its virtues, it can also be one of the major disadvantages as the cost of labour and practical difficulties associated with servicing the device can be significant. Problems include the remoteness of some sites, the frequency of sampling, the presence of large numbers of meters and the water depth. The last problem prompted the development of approaches such as that of Boyle (1994) for lake studies, whereby the sampling tube is extended from a drum on the lake bed to the near surface, where the collection bag can be readily accessed by boat.

Another issue is that only the average seepage flux over the sampling period may be derived from such measurements. Any temporal variations in flux, such as those caused by tidal effects, can be missed unless the bag is checked more frequently than the period of the natural perturbation. To address these problems a wide range of methods have been developed to replace the flexible bag with an *in situ* flow-measuring device connected to a logging system.

4.2 Automated methods of measuring flow from drum-type seepage meters

4.2.1 Heat pulse

Taniguchi and Fukuo (1993) developed an automated seepage meter using a heat-pulse system to measure the flow in the discharge tube. The device (Figure 4.2) consists of a plastic tube with a central heating coil and two temperature sensors (thermistors) placed equidistantly from the heater along the centre line of the tube. A short pulse (a few seconds) of electricity is applied to the coil, which heats the water within the tube. If water is flowing through the tube, the heat will be carried downstream and the rise in temperature detected by the downstream thermistor. By frequently logging the temperature it is possible to derive the time at which the temperature peak passed the thermistor. As the distance between the heater and the thermistor is known, the water velocity can be calculated. By utilising two thermistors it is possible to measure flow in either direction. The concept is widely used, simple and reliable, and may be found in other groundwater-related applications such as borehole flow meters and even devices used to measure the flow rate of sap in plants. For remote operation, Taniguchi and Fukuo (1993) used a datalogger to record the temperatures of the thermistors and applied heat pulses every 5 minutes. Water velocities in the tube ranged from 0.044 cm/s to 1.062 cm/s, when using a 50 cm drum collector – this corresponds to a range of seepage velocities from 2.13 x 10^{-5} cm/s to 5.14 x 10^{-4} cm/s.

Krupa *et al*. (1998) also devised a meter based on the heat-pulse system, but incorporated a range of water-quality sensors within the device and environmental sensors within its onshore base station.

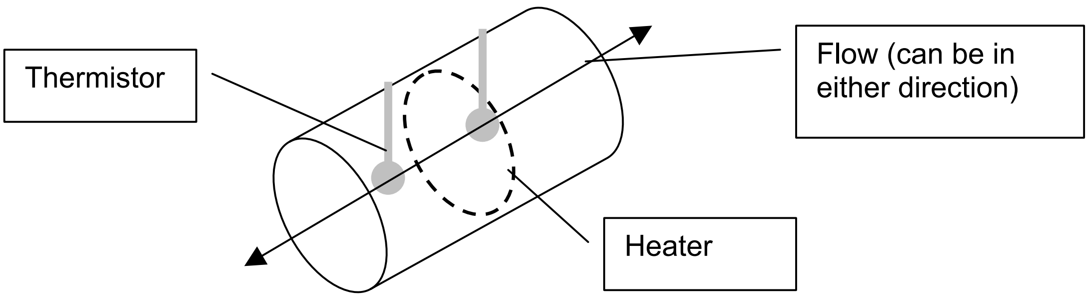

Figure 4.2 Schematic diagram of a heat pulse flow meter.

4.2.2 Solute dilution

Sholkovitz *et al*. (2003) used the principle of dye dilution to measure the flow in the discharge tube from the drum (*Figure 4.3*). The concept is based on the principle that the change in concentration of a liquid in a fully mixed vessel of known volume is proportional to the rate of dilution. In this application a known volume of dye is injected into a chamber, which is kept mixed by a recirculation pump. By monitoring the decay in concentration over time (based on an analysis of its absorbance), the rate flow into the chamber can be calculated and hence seepage inflow derived. To determine flow direction (to or from the surface water,) the concentration of dye is also measured at the inflow and outflow ports of the mixing chamber. The range of measurable flow rates is between 5 x 10^{-6} cm/s and 2 x 10^{-3} cm/s.

Tryon *et al* (2001) describe an ingenious device (*Figure 4.4*) for a deep water (~6 km) installation to measure benthic flux. The device measures flow based on the degree of dilution of a chemical tracer that is injected at a constant rate by an osmotic pump into the water stream flowing to or from the drum. A sub-sample from the water stream is withdrawn and pumped into sample coils that effectively ‘store’ a serial record of the changes in concentration over time. After retrieval of the device from the ocean floor, fluid is removed from the coils and the concentration measured over its length, from which the rate of flow may be derived. The use of two coils allows the direction of the flow to be determined. The key to the device is the osmotic pump, which must provide a constant rate of flow to maintain the accuracy of the instrument. Fortunately, the ambient conditions in the deep oceans are relatively constant and effects such as temperature variation have a minimal consequence on the flow rate. The device is able to measure very low flows, on the order of 0.1 mm/year to 15 mm/year.

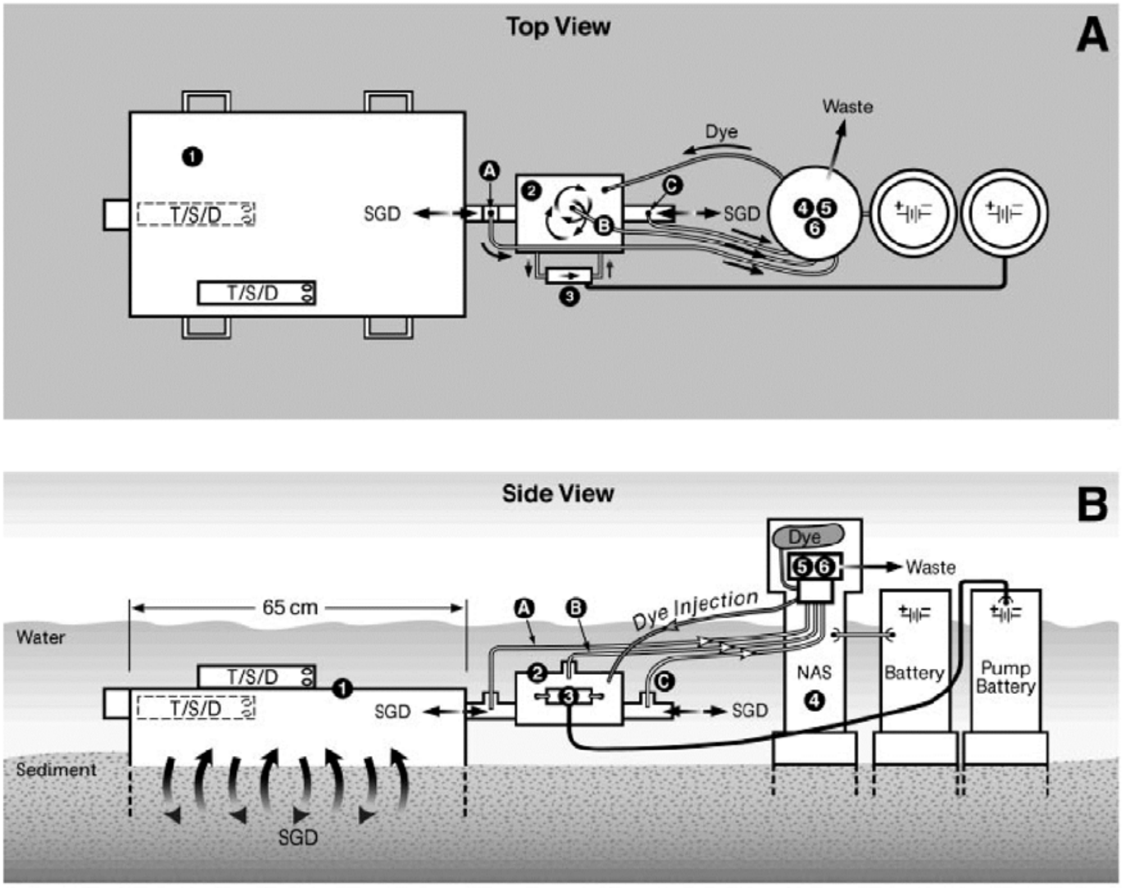

Figure 4.3 The dye-dilution seepage flow meter (Sholkovitz *et al*. 2003). The seepage chamber (1) contains probes (T/S/D) to measure temperature, salinity and depth. Discharge (SGD) passes into the dye mixing chamber (2), where it mixed by a submersible pump (3) with dye injected from a chamber (4) that also houses a spectrometer to measure the concentration from sampling ports A, B and C.

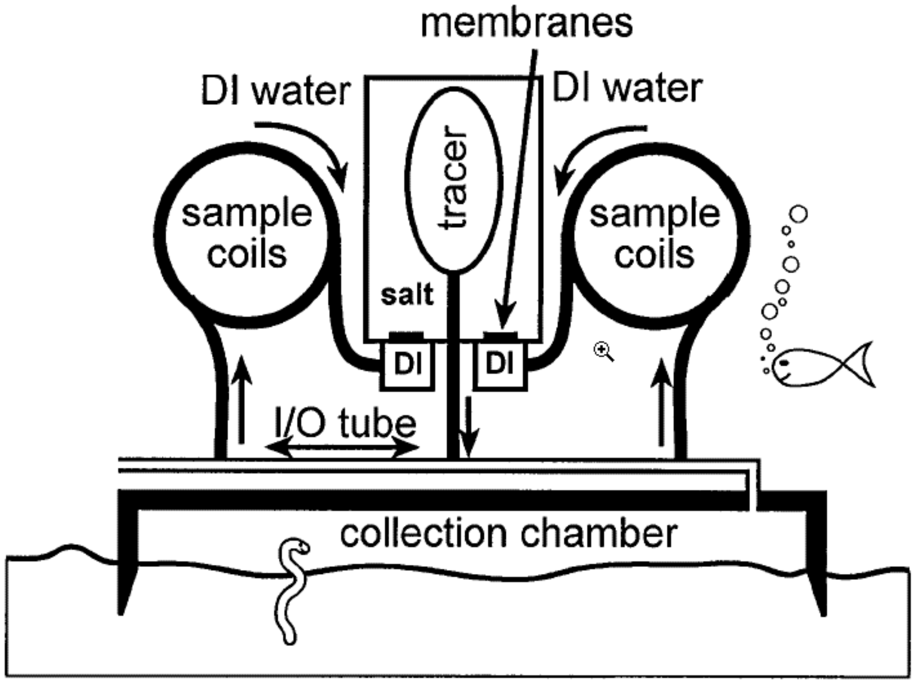

Figure 4.4 The benthic flux seepage meter of Tryon *et al*. (2001). DI = De-ionised (water).

4.2.3 Electromagnetic

Electromagnetic flow meters measure the velocity of a conducting fluid by passing it through an electromagnetic field. The movement of fluid within the magnetic field induces a voltage in electrodes placed on the inner wall of the flow tube. The magnitude of the induced voltage is proportional to the fluid velocity and the polarity is dependent on its direction. Rosenberry and Morin (2004) used two commercial electromagnetic flow meters (with 2.54 and 1.27 cm bores) able to measure flow rates from 30 ml/minute to 30 l/minute and 10 ml/minute to 10 l/minute, respectively (*Figure 4.5*). The output from the flow meters was logged to provide a continuous series of measurements. The minimum measurable seepage flux depends on the area of the collector drum, but the larger device connected to a 55 gallon oil drum measures a minimum seepage flux of 2×10^{-4} cm/s. Using the smaller flow meter, the minimum seepage flux velocity obtained was 6.5×10^{-5} cm/s. A device of similar construction is described by Swarzenski *et al*. (2004).

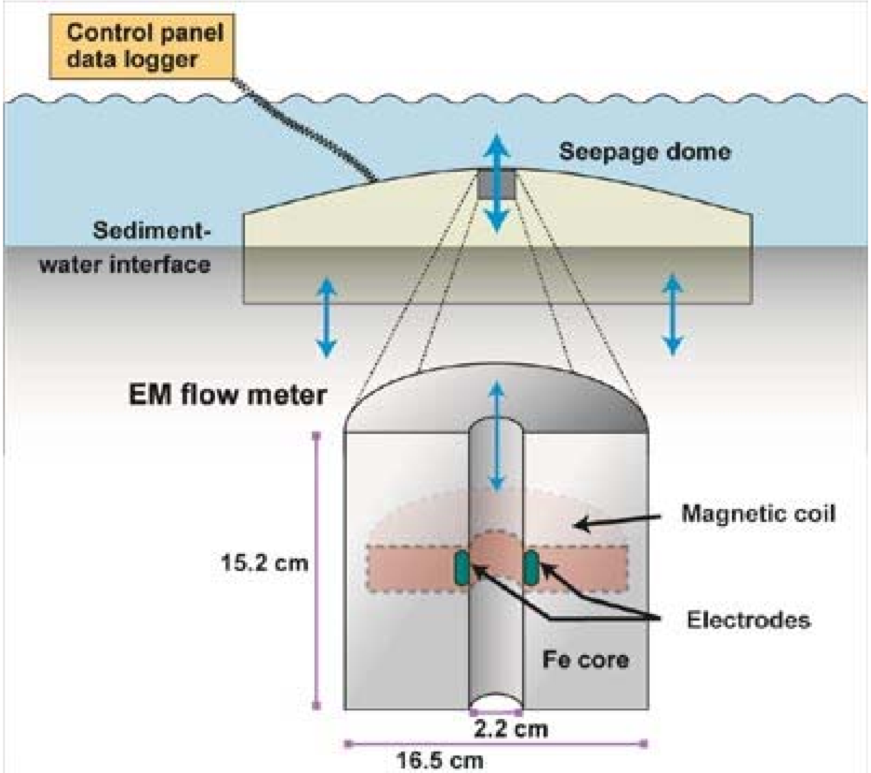

Figure 4.5 Electromagnetic (EM) seepage meter (Swarzenski *et al*. 2004).

4.2.4 Ultrasonic

Ultrasonic flow meters are based on the principle of measuring the perturbation of the velocity of sound in a flowing fluid. Two piezoelectric transducers are placed at opposite ends of a tube. Each produces simultaneously a train of sound waves that propagate through the liquid down the length of the tube. In a flowing liquid the sound waves travel more rapidly in the downstream direction than those that travel upstream (*Figure 4.6*). By comparing the travel times of the two sets of waves it is possible to calculate the velocity of the liquid. Paulsen *et al*. (2001a) developed a seepage meter using an adapted commercial ultrasonic flow meter to measure groundwater discharge rates with a resolution on the order of 1 x 10^{-5} cm/s.

The 'UltraSeep' meter (Chadwick *et al*. 2003) also uses an ultrasonic flow meter to measure flow velocities as part of an integrated groundwater-monitoring device. The flow-sensor sensitivity is about 1.5 ml/minute, which translates over the area of the sampling drum to minimum seepage rates similar to those of the device developed by Paulsen *et al*. (2001a).

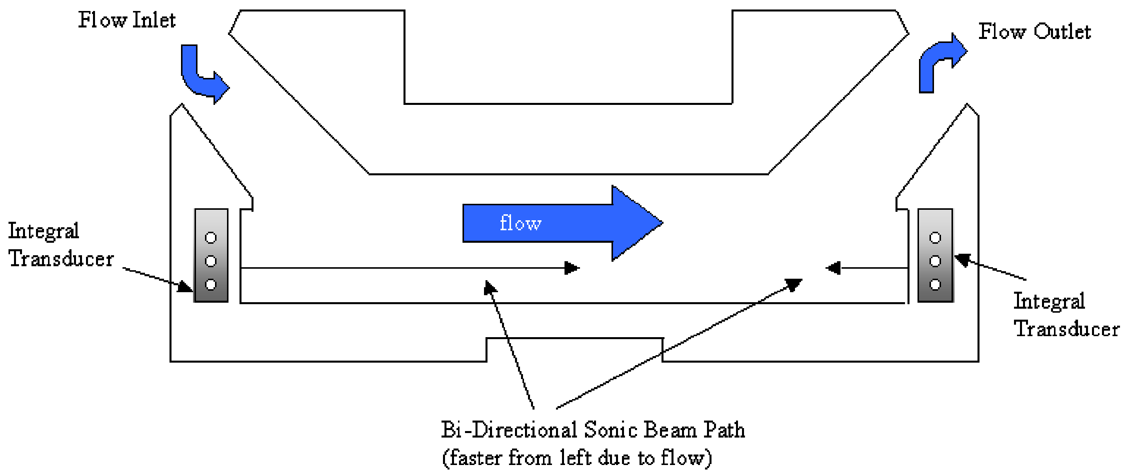

Figure 4.6 Principle of the ultrasonic seepage meter (after Paulsen 2001a).

A comparison of the seepage meter systems is given in *Table 4.1*.

Table 1. Comparison of seepage meter systems

Type of flow detection	**Relative complexity of system**	**Relative cost of flow meter component**	**Measurable flux rate ***	**Comments**
Collection of water in bag Lee (1977)	Very low	Very low	No data on limits	
Heat pulse Taniguchi and Fukuo (1993) Krupa *et al.* (1998)	Medium High	Low Low	2 x 10^{-5} cm/s to 5 x 10^{-4} cm/s Unknown	 Logger shore based
Tracer dilution Sholkovitz *et al.* (2003)	Very high	High	5 x 10^{-6} cm/s to 2 x 10^{-3} cm/s.	An absorption analyser was used to measure the concentration of dyes. Different chamber sizes allow a wide range of flows
Tryon *et al.* (2001)	Medium	Medium (est.)	0.1mm/year to 15 mm/year (3 x 10^{-10} to 5 x 10^{-8} cm/s)	Analysis performed after recovery. Resolution likely to be significantly lower in shallow water deployment
Electromagnetic Rosenberry and Morin (2004)	High	High	Sensitivity: 2 x 10^{-4}–cm/s (large meter) 6 x 10^{-5} cm/s (small meter)	Power supply/logger shore based
Ultrasonic Paulson *et al.* (2001) and Chadwick *et al.* (2003)	High	Unknown – likely to be medium	Sensitivity 1 x 10^{-5} cm/s	

** Depends on size of collector: figures quoted are for collectors used by authors.*

4.3 Field comparisons of methods of seepage estimation and types of seepage meter

A number of studies have been undertaken to compare seepage meter performance.

Conlon and Lee (2002) compared base flow, Lee type seepage meters and the temperature gradient method. Estimates by seepage meter were lower than those based on temperature and base flow, which was thought to result from differences in the scale of the measurements.

Burnett and Turner (2001), working with the Land-Ocean Interactions in the Coastal Zone (LOICZ) group, conducted a comparative study of techniques in Cockburn Sound, Australia. Results from seepage meters of the heat pulse and ultrasonic (Taniguchi and Fukuo 1993, Paulson *et al*. 2001a) types were compared with estimates of submarine groundwater discharge calculated from natural radon monitoring and estimates of flow using Darcy's Law. The latter indicated much lower apparent flow than was observed from the other methods.

O'Rourke (1999) found the traditional Lee type seepage meter to be comparable with the ultrasonic meter of Paulson *et al*. (2001a), and Paulson *et al* (2001b) showed there was consistency between ultrasonic, heat pulse and manual Lee-type meter when measuring tidally affected submarine groundwater discharge at rates higher 1 x 10^{-3} mm/s. Below this rate the ultrasonic device appeared to perform better.

Rosenberry and Morin's (2004) electromagnetic meter compared favourably with Lee-type devices at all but the highest flow rates during comparisons in a lake environment. The differences were attributed to the restrictiveness of the tubing that connected the bag in the Lee-type device.

4.4 Discussion and conclusions

The Lee type seepage meter is a cheap and simple device that can be used effectively to monitor flow between groundwater and surface water bodies. It is the only method that is able to measure this flux directly and, provided precautions are taken, has been shown to provide acceptable accuracy in many studies.

For deployment in difficult locations, or where rapid temporal changes are expected, the flexible bag system has limitations. Consequently, a diverse range of methods have been adopted to replace the flexible bag with a device that can measure the flow in the discharge tube from the collector drum. With the exception of the device of Tryon *et al*. (2001), the range of measurement of these devices is similar.

The influence of heterogeneity on measured values is described in Section 1. Shaw and Prepas (1990) used a modelling technique to show that the most sensitive parameter to affect the accuracy of seepage meter estimates of flux is the variability of the spatial distribution of seepage flux. On this basis it seems preferable to deploy many rather than few seepage meters and that absolute accuracy is less important than determining the range and distribution of fluxes. Assuming a number of meters are to be deployed simultaneously, an important criterion for selecting a seepage meter type is the cost.

With the exception of the ocean-floor tracer dilution device of Tryon *et al*. (2001), there is little to choose between the methods in terms of resolution. For any given device, sensitivity can be changed by modifying the ratio between the collector and the diameter of the tube in which the metering device operates. With the exception of the electromagnetic flow meter, all the devices derive the flow in the discharge tube by an indirect method, and hence require some degree of data analysis. However, depending on the degree of complexity of the analysis, this may be achieved in future devices using *in situ* programmable micro-controllers that calculate the flow rate from the data on-line.

An important consideration for field-based operations is power consumption. Modern dataloggers require little power and the metering system itself may be powered down between readings. However, the tracer dilution system of Sholkovitz *et al*. (2003) requires a pump to stir the mixing cell continuously and power to run the adsorption analyser. The electromagnetic meter relies on a shore-based power supply and the ultrasonic meter of Paulson *et al*. (2001a) uses a commercial flow meter device (a Controlortron 1010), which consumes 12 W of power. It is not known if this device operates intermittently or continuously.

On balance, a heat-pulse based meter seems to offer the best solution for the automated measurement of seepage. It has a minimum of components, all of which are cheap. Its power consumption should be low as the heater need only be triggered for a short duration to create the heat pulse. Data interpretation is limited to that required to derive the period between the instigation of the pulse and the arrival time of the peak at the downstream thermistor. This is readily achieved with a simple commercial datalogger followed by analysis of the recorded thermistor temperatures. However, a better method would be to develop an integrated control–logger system with bespoke software that:

- Triggered the pulse at user defined intervals;
- Monitored the thermistors to determine the transit time of the pulse;
- Calculated the flow velocity and hence seepage flux;
- Stored each result in memory for later download.

Modern microcontrollers are cheap, widely available and may be programmed easily to perform such tasks. Once developed, such a system could represent the most cost-effective solution to the provision of multiple automated seepage measurements.

5 Geophysical techniques

5.1 The methods

The geophysical methods most commonly used to detect fluid flows are the electrical methods. To measure flow rates, a contrast in fluid conductivity is therefore required. Sometimes this contrast occurs naturally (Soldal *et al*. 1994, Acworth and Dasey 2003), but often a tracer has to be injected (e.g., White 1988, 1994). Where the degree of natural saturation is variable, such as in the vadose zone, the resulting contrast is often measurable and can be used to monitor recharge (Hatzichristodulu *et al*. 1998, 2002, Binley *et al*. 2002a) or, for example, to detect seepage from water bodies (Bradshaw *et al*. 1997).

The spatial resolution of the geophysical method is generally controlled by the distance between the transmission device and the receiver. In resistivity techniques, as the spacing is reduced, so is the depth of penetration that limits the vertical extent of the section that can be monitored. To overcome this, transducers can be emplaced within a single borehole or an array to produce a vertical sensing field. In recent years the development of tomographic techniques, such as electrical resistance tomography (*Figure 5.1*) has made it possible to produce two- and three-dimensional images of temporal and spatial variation changes caused by solute transport and flow, albeit with limits on spatial resolution (Daily *et al*. 2004). Imaging has been used in studies of controlled saline injections (Slater *et al*. 2000), flow in the vadose zone (Daily *et al*. 1992, Hatzichristodulu *et al*. 2002), and in combination with the use of cross-hole radar (Binley *et al*. 2002b).

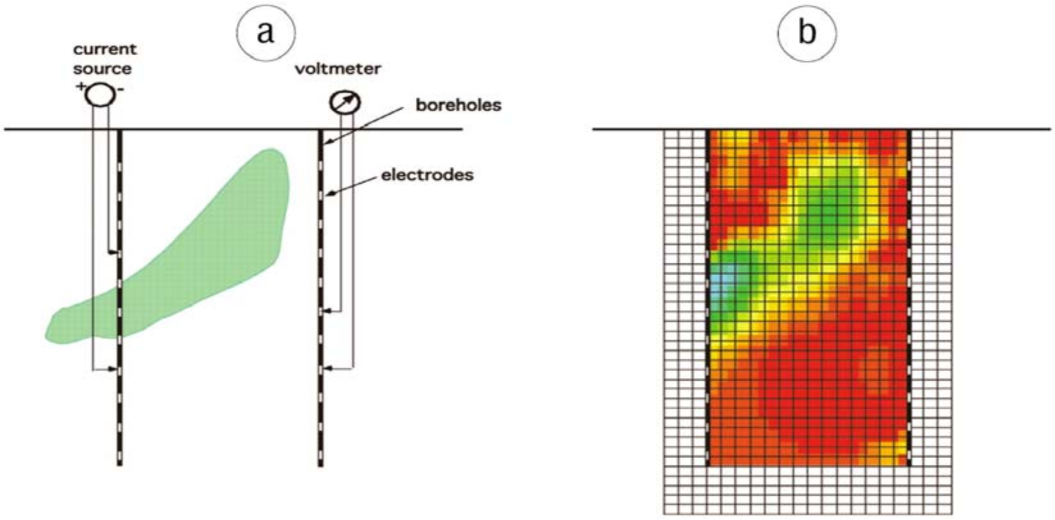

Figure 5.1 Schematic representation of electrical resistance tomography showing the (a) arrangement of electrodes in a cross-hole array and (b) modelled image (Dailey *et al*. 2004).

Vertical resistivity arrays with electrode spacing of a few centimetres could be driven into the sediments to provide high-resolution data of processes such as saturation change or saline water intrusion acting on the small scale. This approach has been used successfully to monitor capillary fringe movement in laboratory-based tank experiments (Moore 2003). For field-based studies, care would be required to minimise the disturbance of sediments during electrode emplacement.

5.2 Discussion and conclusions

Given that typically there may be only small natural variations in properties expected in hydrogeological studies, the use of geophysics may be somewhat limited. Further, the use of geophysics to monitor changes within the hyporheic zone appears particularly problematic:

- It is an environment in which sub-surface heterogeneity is often high, so interpretation of the features may be ambiguous.
- For gaining reaches, unless waters with sufficient contrast (e.g., saline, polluted or mine water) are present, it is unlikely that sufficient contrasts exist to track the flows.
- The techniques are predominantly qualitative.
- The resolution of tomographic techniques is limited and may be insufficiently accurate for studies of water bodies at small scales using a bed transect. Closely spaced vertical arrays emplaced within the bed may provide useful high-resolution data at small scales.
- To examine a section to sufficient depth and resolution may require the construction of boreholes to enable cross-hole techniques to be employed.

In conclusion, where it is possible to use them in studying the hyporheic zone, geophysical methods are probably better suited to processes that act on the larger scale, to constrain modelling approaches, to define regions of interest for subsequent investigation using other techniques and to study temporal change. Small resistivity arrays may provide useful data at the local scale to delineate depth and the lateral extent of fluvial sediments and the hyporheic zone.

6 Thermal techniques

6.1 The methods

Heat is transported by both conduction through the ground and advection caused by groundwater flow. Temperature can therefore be used as a natural tracer to evaluate groundwater fluxes. Surveys of temperature can, for example, indicate areas of groundwater discharge at times of year when surface–groundwater temperatures are in contrast (Oxtobee and Novakowski 2002). If the contribution of heat from groundwater is significant in comparison with the heat content of the stream, stream temperature can be used to estimate groundwater discharge (Becker *et al*. 2004). By monitoring constant, diurnal or annual temperature differences between a surface water body and the underlying sediments, it is possible to determine the heat flux from which the groundwater flux can be estimated (*Figures 6.1* and *6.2*) The method has been applied in a wide range of situations, from the determination of irrigation water movement in paddy fields to geothermal water beneath volcanoes (Stonestrom and Constantz 2003), as well as in the study of marine systems (Taniguchi *et al*. 2003a), streams and rivers (Bartolino 2003, Conlon *et al*. 2003, Hoffman *et al*. 2003, Becker *et al*. 2004).

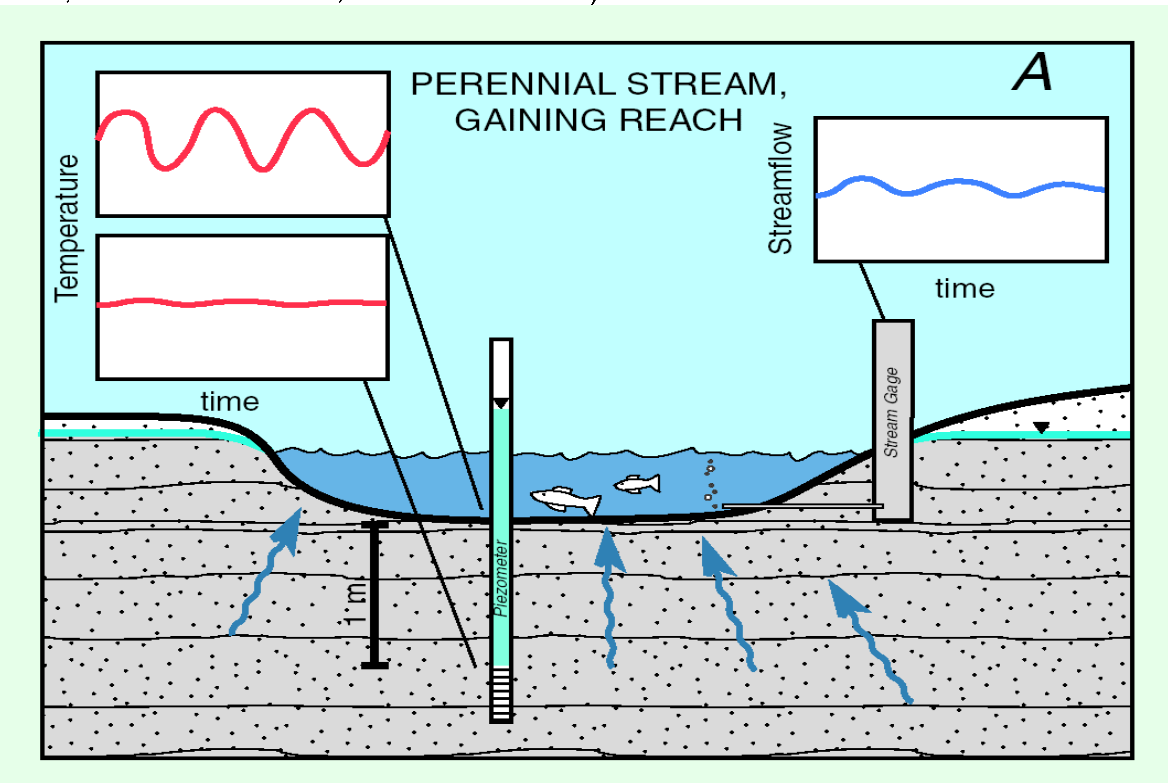

Figure 6.1 Temperature profile in a gaining reach (Constantz and Stonestrom 2003). The diurnal fluctuation of a water body is normally higher than that of the groundwater, which has a relatively constant temperature on this timescale. The variation of temperature in the sediment with depth reflects the dynamics of the system as heat is both transferred by conduction through the saturated sediment and advected by groundwater flow. For any given depth beneath the bed, higher groundwater flows give rise to smaller variations in sediment temperature, which also decrease with depth. To best detect temperature variation it is therefore necessary to install temperature-monitoring equipment at shallow depths below the bed.

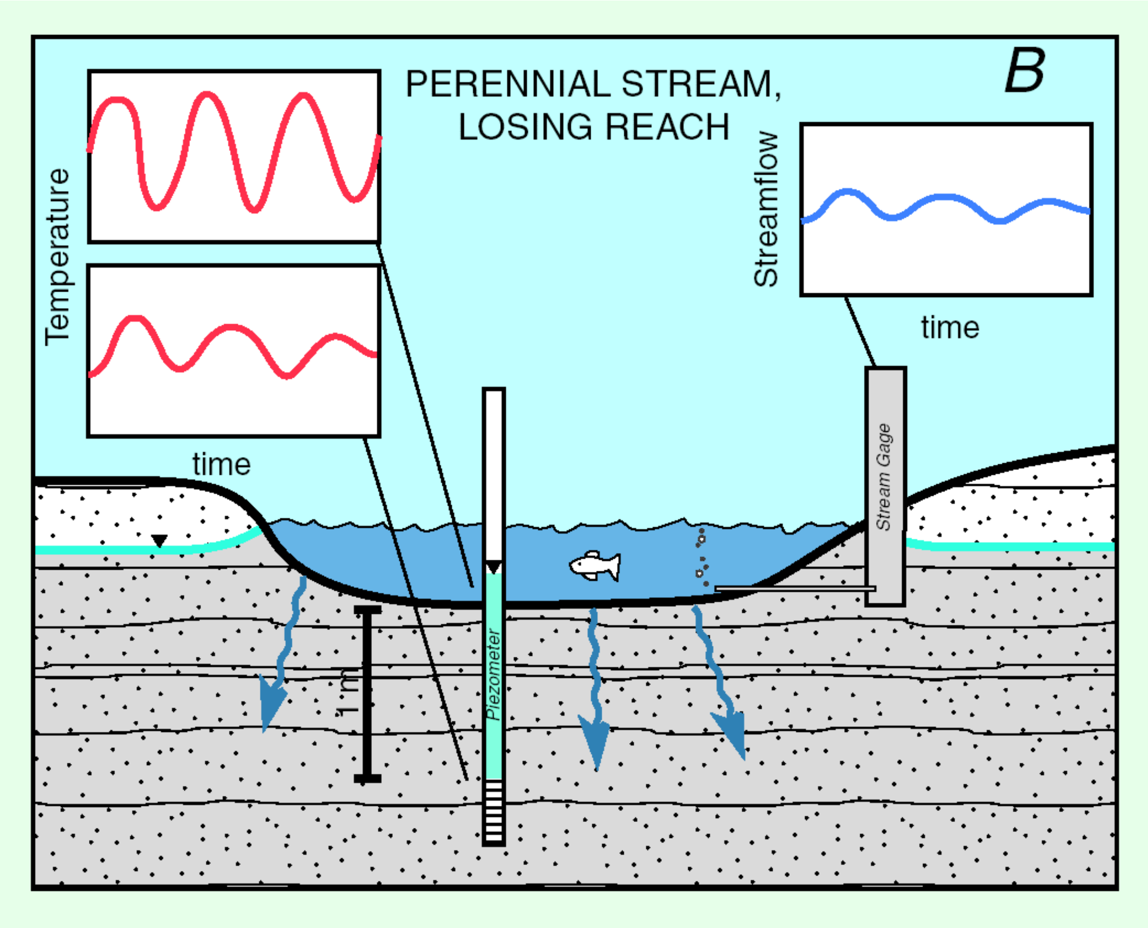

Figure 6.2 Temperature profile in a losing reach (Constantz and Stonestrom 2003). Heat is transported by both advection and conduction from the surface water body into the sediments. Unlike gaining reaches, in which the system is damped by the influx of groundwater at a relatively constant temperature, losing reaches are characterised by larger diurnal fluctuations in temperature within the sediments and the water body itself.

Diurnal temperature fluctuations are generally monitored at depths of ~0.05-1 m for fine-grained material and 0.3–3 m for coarse-grained material, with depths for monitoring annual variations an order of magnitude higher (Scanlon *et al*. 2002). Measurement is usually performed using thermocouples or thermistors with the signal recorded by datalogger over the period of interest. Using inexpensive sensors (thermistors or thermocouples), measurements can be made reliably to within 0.2^{o}C. Typical applications use a single vertical array of sensors to give an estimate of one-dimensional flow at a point, though recent work has begun to deploy arrays of sensors to provide two- and three-dimensional flux estimates (Scanlon *et al.* 2002).

The minimum net infiltration rate that can be estimated using heat as a tracer depends on the range of sub-surface water temperature fluctuations and the timescale considered. A minimum recharge rate of ~20 mm/day (diurnal fluctuations) and ~1 mm/day (annual temperature fluctuations) in natural media with average heat properties is suggested as the practical limit (Scanlon *et al*. 2002).

Temperature logging is normally achieved using a central multi-channel device connected to the sensing array. However, advances in logging methods, particularly those that arise from the need for cost-effective stand-alone environmental monitoring devices, has produced a range of cheap (<£70) self-contained temperature loggers that could be readily deployed at shallow depths below water bodies. The 'Tiny-tag aquatic' (*Figure 6.3*) by Gemini Instruments (www.geminidataloggers.com), for example, can take up to 7900 temperature readings (to 0.2^{o}C) at user-defined intervals from 1 s to 10 days (however, it appears that this device has not been evaluated for such an application). Devices such as these could be inserted at many points within the sediment, then collected and the data downloaded at the end of an experiment.

The primary disadvantage of a thermal survey is that it does not directly quantify water movement and so an estimate of groundwater flux cannot be obtained without additional information. Where appropriate, one-dimensional flux estimates can be derived from type-curves based on steady heat conduction–advection equations (e.g., Bredehoeft and Papadopulos 1965, Taniguchi *et al*. 2003b). Where the heat source is variable, the measured temperature is used with inverse modelling using a two-dimensional, code such as VS2DH or SUTRA, to estimate hydraulic conductivity of the sediments, and hence to derive the groundwater flux (Niswonger and Prudic 2003).

Figure 6.3 'Tiny-tag aquatic' fully submersible stand-alone temperature logger (www.geminidataloggers.com).

6.2 Summary and conclusions

- Where conditions of temperature difference are favourable, heat tracing represents a valuable tool to survey a surface water body to locate variations in flux.
- The use of arrays to monitor vertical temperature provides a high spatial resolution technique from which estimates of groundwater flux may be made.
- The method is simple to set up with a limited installation requirement compared with other techniques. The sensor technologies are reliable, accurate and inexpensive.
- Advances in logging equipment offer alternatives to centralised multiplexed logging systems that provide greater flexibility in array design. Remote long-term continuous logging is another approach that may have cost benefits.
- The method is indirect. Estimates of groundwater flux can only be derived using numerical techniques that account for the thermal properties of the sediment and estimation of hydraulic conductivity.

7 Overall conclusions and recommendations

The continual development of monitoring and measuring technologies is providing an increasing array of methods that can be used to investigate groundwater–surface water interactions.

For measurements at a small scale, it is important to account for the heterogeneity of the system such that the spatial and temporal distribution of measurements defines the range adequately. In hydrogeologically heterogeneous systems like the hyporheic zone this is particularly challenging.

Seepage meters offer a cheap and simple approach to direct flux measurement. The flexible bag method is reliable provided that adequate precautions are taken, particularly in shallow waters subject to high flow rates. Although many automated measurement approaches have been tried, none are available commercially and some require relatively expensive components. Of the methods tested, all appear to perform similarly well. The heat-pulse system seems to be best in terms of cost, simplicity and suitability for long-term remote-field operation, particularly if a bespoke control–logging solution is developed.

Where ambient temperature conditions are favourable, heat tracing is a method that can be used to provide information on the spatial distribution of flux. In recent years the use of the technique has been increasing, due in part to both the development of temperature logging devices and also the wider availability of computing solutions with which to model the processes. Its disadvantage is that it is indirect; the distribution of the physical properties of the sediments must be estimated, and the fluxes derived by numerical modelling. In spite of this drawback, it is the only current method that offers the potential of economic and simple measurements at large spatial distributions, but at high density.

Traditional borehole methods will, of course, remain a vital part of groundwater studies. Boreholes also provide a means by which sediments may be sampled during construction and, once completed, they provide a way to collect water samples. Generally, the hyporheic zone is limited in depth and therefore ideal for investigation by shallow drive-in devices such as mini-piezometers. The borehole flow meters discussed in Section 3 are interesting and offer great potential for specific studies, such as flow surveys of fractured rock systems, though they are probably of more limited use for studies of the hyporheic zone.

Geophysical methods have limited value for flow quantification studies in studies of the hyporheic zone unless a measurable contrast in properties exists between the surface waters and groundwaters. However, where applicable, studies of temporal change, variation at larger scales and delineation of sites of interest may benefit from the adoption of such approaches.

Three-dimensional *in situ* flow meters offer, potentially, an ideal way to examine the flow field at the small scale. This is of particular value in the hyporheic zone where the flow vector is likely to exhibit significant spatial variation. Only one commercial system is currently available for this purpose, but it has limited application for remote field-based studies because of its relatively high power consumption. An alternative Two-dimensional approach using a heat-pulse system is available, but it is not designed for long-term or multiple deployments. It seems possible to develop a relatively simple three-dimensional device using heat-pulse technology that is tailored for use (in terms of cost effectiveness and power consumption) as a multiple deployment system to investigate seepage velocities within the sediments of the hyporheic zone.

None of the devices described are ideal for all circumstances, and the best results are likely to be obtained by using a combination of methods. For example, resistivity imaging to map property variations followed by quantification using a combination of temperature and drum-type seepage meter monitoring.

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