6 Water Level and Groundwater Flow Measurements

In the first part of this chapter we discuss instruments for measuring water level in dynamic and quasi-static conditions; in the second part, modern methods for measuring ground water flow are presented.

6.1 Water Level Measurements

As stated in Chapter 2, requirements for water level measurements in environmental problems may be classified into two broad categories, one associated with static or average levels which requires low spatial and temporal resolution, and another related to fast changing levels which needs measuring in small areas and short times. Measurements of water table in aquifers, water level in rivers and tides correspond to the first category. In these cases, spatial integration of several meters and sample periods of a few minutes result adequate for most applications. The second category is represented by wave measurements in lakes, rivers, oceans, wave tanks and hydraulic physical models. In these cases the time scale imposes that several samples per second be taken, and the spatial scale is in the range of centimeters for field measurements and in the order of millimeters for models.

Because in water level measurements there exist different applications with dissimilar requirements there are several instruments and distinct operating principles. Some of the most familiar instruments used for level measurements will be presented below. The basic ideas supporting a number of operating principles used by instruments described in this chapter have already been explained in previous chapters and therefore, the reader will be referred to those sections for the sake of synthesis.

6.2 Wave Measurements

Wave measurements in the sea and in hydraulic models have many characteristics in common, although different spatial and temporal scales. Because of the size of the waves in models they need better resolution in both scales. Some operating principles used in wave meters are similar for both applications, but others only measure properly in one of the scales.

Ocean waves are a critical variable for many marine problems that can be found in basically two quite different scenarios: near-shore and open oceans. Users of wave meters in each one of these cases have different measuring needs. In general, temporal and spatial resolution requirements increase from the open ocean to the coast (Alliance for coastal technologies, 2007).

Tests in hydraulic models and wave tanks require measuring waves with smaller amplitudes and sampled at higher frequencies than sea waves, calling for instruments with higher spatial and temporal resolution. Increasing temporal resolution is not a problem because it is simple to get more samples per second, but to increase spatial resolution requires that some of the methods used for sea waves be discarded and to search for new ones. Basically it is necessary to reduce the size of the sensors to minimize the spatial sample over which the instrument takes the wave information. In other words it is desired to reduce the spatial integration introduced by the sensor itself.

Some of the modern technologies identified for wave measuring (Alliance for coastal technologies, 2007) will be described below, indicating which are the most suited for each scenario.

6.2.1 Submerged Pressure Sensors

Pressure sensors are mainly used in field scale (seas, rivers, lakes, etc.). They are of little use for dynamic measurements in wave models, although they may be used for average level estimations. These sensors were described in Section (4.8.2) and their application to water level measurements were discussed as examples of practical uses of sensors in Section (4.8.4). When pressure sensors are used to evaluate field waves they sense the dynamic pressure generated by the change in water height produced by the passing wave plus the average hydrostatic pressure due to the water column below the still water level, as in any static fluid. Therefore, they have to be mounted at a constant depth and the sensor mounting plays an important role in the quality of the measured data. Sensors may be installed on platforms fixed to the sea floor or attached to subsurface mooring. The first are employed for long term wave data collection in near-shore places; the second are needed in deep waters or when the cost of fixed platforms is off-budget.

The subsurface mooring is frequently composed of an anchor, a subsurface float and a line which links the anchor and the float. In general, pressure sensors are attached to the line. In order to pull the line and minimize movements due to waves, the float has to be always some meters underwater, even at low water.

Because sensors are at a certain depth, fast changes in sea surface height are low-pass filtered by the water column. Thus, sensors record a version of the actual signal whose higher frequencies are attenuated. The characteristics of the low-pass filter depend on the sensor depth and can be predicted approximately.

Using linear wave theory and knowing the depth of the sensor, the time series of pressure recorded at some depth can be converted into sea surface elevation (Van Rijn et al., 2000). This conversion has some limitations because the problem is nonlinear, errors in the depth produce errors in the calculated water surface elevation, and there is also a maximum frequency for which the conversion equations may be applied.

In the case of platforms fixed to the bottom in places where the average sea surface varies by several meters a day due to the tide, the characteristics of the filter varies. If the mooring depth used in the reconstruction equations is considered constant some errors will be introduced in calculating the wave height. Underwater pressure sensors also measure variations due to changes in the atmospheric pressure, which should be taken into account. In subsurface mooring, the movement of the line due to wave forces on the float will introduce lateral and vertical motions of the sensor, producing additional errors.

In general, submerged pressure sensors process and store wave information on board for a later retrieval, but some instruments placed close to shore may have a cable for power supplying and data pickup. The onboard processing generally consists of the wave spectral analysis and the computation of some parameters representative of the wave characteristics in the time domain.

The installation of three or more submerged pressure sensor adequately located may be used to obtain the wave directional spectrum.

A more frequently way used to attain wave direction is to combine one pressure sensor with a current meter similar to those described in Sections (5.3.2) and (5.4.6). The current meter measures two orthogonal components of the horizontal water particle orbital velocity, and by means of a magnetic compass or a magnetometer these components are converted into the well-known u and v components. With this information the directional spectrum referred to the geographical coordinates is obtained.

6.2.2 Buoys

Buoys are often used for field studies and they are well suited to measure in deep waters because they do not need a platform or a pier fixed to the bottom as was the case of pressure sensors. Floating buoys may follow, up to some extent, sea surface movements. Measuring the buoy displacements allow wave characteristics to be known. Usually, two kinds of buoys are referred to according to their operating principle and size (Barstow et al., 2003). Some of the buoy types are known as pitch, roll and heave buoys or wave slope buoys. They are medium size buoys used for the installation of oceanographic and meteorological instruments in the sea. They usually have a disc shape some meters in diameter and, due to their hydrodynamic characteristics, they are slope followers. The other types are called displacement buoys or orbital following buoys. They are spherical buoys with a diameter smaller than 1 m and because their shape, size, weight and mooring, they follow the sea surface water particle orbit (Lawrence, 2012). Sensors frequently used to measure buoy movements include accelerometers as those described in Section (4.11).

6.2.3 Displacement Buoys (Orbital Following Buoys)

In order for a displacement buoy to follow the waves the mooring must allow the buoy to move freely. Therefore, the installation requires a slack mooring line attaching the buoy to the anchor; usually an elastic rubber cord is used as parte of the mooring line.

The early displacement buoys measured wave parameters by means of only one accelerometer which measured the vertical displacement of the sea surface. Buoys transmitted wave information to a shore station as an analog signal modulating a radio frequency carrier. The wave analog information was recorded at the receiver unit at regular intervals over certain periods for later analysis. With this information non directional wave spectra were obtained. This way of data transmission limits the maximum distance from the buoy to the coast to a few tens of kilometers.

Buoys that follow the wave movement and use only one accelerometer calculate wave height by integrating the vertical acceleration twice (Fig. 6.1). To avoid unwanted acceleration due to roll and pitch of the buoy, the accelerometer has a special gimbals and pendulous mechanism, also known as a gravity stabilized platform. The platform is formed by a suspended disk in a fluid of equal density and the disk is made sensitive to gravity force adding a small weight. The set forms a pendulum with low natural frequency of oscillation and the pendulum is mounted in gyroscopic gimbals. This platform remains almost horizontal because it works as a mechanical low-pass filter for the higher frequencies existing at sea. The accelerometer axis is mounted perpendicularly to the horizontal platform to measure only the vertical acceleration (Datawell, 2009).

Fig. 6.1: A buoy that follows wave movement is being deployed in the sea. The top white pole is the transmitting antenna.

A further extension of the previous idea permits wave direction to be recognized, thus giving directional wave spectra. The information from the vertical sensor mounted on the stabilized platform is combined with data from two orthogonal horizontal accelerometers, pitch and roll sensors, and a three axis fluxgate compass. The latter is used to refer the spectra to the geographic coordinates (Barstow et al., 2003).

Buoys following the wave movement can also use accelerometers installed on three orthogonal axes on board the buoy to sense buoy displacements. By integrating the output of these accelerometers (Eq. (4.16)) it is possible to describe the motion of the buoy in space without a reference platform. If the assumption that the buoy follows the wave is correct, the movement of a water particle as a function of time can be calculated from the buoy displacement. The vertical displacement of the buoy permits wave height and period to be estimated, whereas the orbital motion of the buoy allows knowing wave direction. By means of a three axis fluxgate compass the directional spectra are referred to the geographic coordinates.

6.2.4 Pitch, Roll and Heave Buoys (PHW) (Wave Slope Buoys)

Other types of buoys, generally bigger buoys designed for long time unattended operation in the open sea, use a single-axis accelerometer with its measurement axis perpendicular to the deck of the buoy (NDBC, 1996). For perfect slope following buoys, the accelerometer axis is perpendicular to the wave surface. Spectral analyses are derived from the acceleration time series. Measured accelerations are corrected for frequency-dependent responses of the buoy hull and its mooring. In order to estimate directional wave spectra, buoy pitch and roll time series are measured and the buoy slope time series is referenced to east-west and north-south direction by means of a magnetometer which obtains the azimuth of the buoy from measurements of the Earth's magnetic field. Some PHW buoys also use an accelerometer with a stabilized platform as described for displacement buoys (NDBC, 1996; Lawrence et al., 2012).

Advances in electronics resulted in small integrated sensors that permit lighter, smaller and lower cost sensitive buoys (Teng et al., 2009). The motion detection of these buoys is achieved by sensors from different manufacturers: three single-axis angular rate sensors, two dual axis accelerometers, and a single 3-axis magnetometer. The result is an unprecedented amount of motion information on nine measurement channels: acceleration, angular rate and magnetic flux density along three orthogonal axes at a rate of 35 hertz. By digitally processing the angular rates they are converted into pitch and roll angles, and then the directional wave spectra and other wave parameters are extracted.

Modern buoys have the possibility of analyzing the information on board, so that only the results of the analysis are transmitted. In this way the information can be sent through a satellite link (as will be seen in Chapter 9). In general, the results from the onboard analysis contain information in the time and frequency domains. Among other wave characteristics reported are the period corresponding to the frequency where the non directional spectrum is a maximum, the average and zero-crossing periods, the significant wave height, the full directional wave spectra, the mean wave direction and parameters which describe the directional spreading about the main directions.

6.2.5 GPS Buoys

These are displacement buoys with no sensor on board, but only a GPS receiver and some electronics. GPS stands for Global Positioning System; this system will be described in detail in Chapter 9. It is a system based in 24 satellites for the positioning in real time of military and civilian platforms. It works 24 hours a day and under any climatic conditions. The platform must have a special receiver to take information from several satellites simultaneously in order to calculate its position.

Buoys based on GPS receivers can measure directional and spectral wave data and they can be deployed free-floating or moored. Because the receiver and the associated electronics are of reduced size and consume little power, they can be housed in small buoys with diameters smaller than half a meter. As GPS signals do not break through water, signals may be blocked by high ocean waves and sometimes data may be lost. Some manufacturers claim that resolution direction of their buoys is 1.5°.

Some methods of buoy positioning require a differential GPS strategy which needs an additional GPS reference station on shore. Thus, the use of this technology limits the applications to near-shore buoys. Other buoys use a single GPS receiver; they are based on the determination of the moving speed of the buoy as computed from the Doppler shift of the frequency received at the buoy. The buoy speed is then integrated to estimate its motion.

There are other buoys that also use a GPS receiver to obtain information on the wave movement, but the velocity information output is directly derived from the receiver (Doong et al., 2011). The authors of these studies express that the main concept behind this method is to transfer the velocity spectrum to the vertical displacement spectrum to obtain the water surface elevation. Velocities in three-directions were used to derive the directional wave spectrum. Authors found, after a field test comparing simultaneously buoys equipped with accelerometers and equipped with a GPS receiver, that the one-dimensional spectra and the directional wave spectra are similar for both methods. Wave parameters compared between both types of buoys showed a correlation coefficient higher than 0.95.

6.2.6 Acoustic Level Measurements

Acoustics principle for level measuring is the same either in field (Fig. 6.2) or laboratory (Fig. 6.3) studies. Sometimes the same manufacturer offers two models, each one suited for each application.

Fig. 6.2: Acoustic sensor measuring ocean waves (Courtesy of General Acoustics)

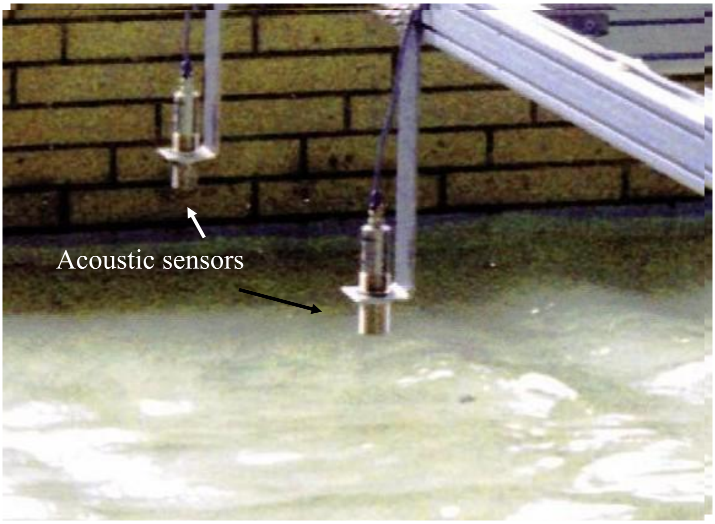

Fig. 6.3: Acoustic sensors measuring small waves (Courtesy of General Acoustics)

In structures close to the shore or in platforms fixed to the seabed it is possible to install an acoustic transducer as shown in Section (2.3.3). The transducer must be installed a few meters higher than the maximum level reached by the waves. The acoustic transducer emits pulses downwards and measures the transit time (or time of flight) (Section (5.4.1)). By knowing the speed of sound in air, the distance to the sea surface is calculated. Taking several samples per second, a time series with the wave information is acquired. In order to have a good spatial resolution (measuring on a small area of the wave), the transducer beamwidth must be narrow (should have a few degrees).

Because the speed of sound in air varies with temperature, a correction to the calculated distance has to be done by measuring air temperature or by a direct measure of the sound speed. The last is done by determining the time of flight of an acoustic pulse to an object placed at a known distance.

Acoustics measurements of sea surface level can also be done offshore by using submersible acoustic transducers pointing upwards and placing them at a fixed distance from the seabed. Now sound travels through the water to the surface and is reflected backwards by the water-air interface. Again, the time of flight is measure and the distance to the surface calculated. The same requirements for a narrow beamwidth have to be met.

Mounting of transducers to seabed fixed platforms is similar to that shown for acoustic profilers (Section (5.4.4)); in this case there is just one beam. In sand moving seabeds, precautions should be taken to avoid sediment deposition on the transducers. Also, in deep waters transducers can be attached to the line of a subsurface mooring as described above (Section (6.2.1)).

There are also miniature acoustic instruments to measure distances in the laboratory. They can measure the surface elevation of the fluid or the moving sand bottom in models. They work by sending an ultrasonic pulse and measuring the travel time (Section (5.4.1)). The acoustic sensor is a piezoelectric transducer (Section (4.13.3)) that works at frequencies about 1 Mhz.

Some commercial equipment has an accuracy of 1% of the measuring range and a maximum resolution of 1 mm. The sampling rate may usually range from 10 to 100 samples per second. Some manufacturers claim that the footprint of the sensor beam on the water surface (spatial resolution) is less than 10 mm for a distance of 1 m. Also, corrections for changes in temperature have to be done, either manually or automatically.

6.2.7 ADCP

Acoustic Doppler Current Profilers, already described in Section (5.4.4), are also useful to measure waves. The method provides measures of both directional and non-directional waves. The principle behind this application is that because ADCP can measure the velocity profile, they are also able to estimate the wave orbital velocities below the surface (Lawrence et al., 2012). Remember that the velocity is measured for several cells at different depths, then processing the data of the cell array, directional information is obtained. Linear wave theory is used to translate the data from velocity spectra to surface displacement.

ADCPs for directional wave measurement purposes use a magnetic compass and a tilt sensor to refer measures velocities to the north-south and east-west planes and include a pressure sensor. The pressure sensor is used to measure the mean water depth, which increases accuracy in applying the linear theory. Also, it provides a second source for non-directional wave statistics

6.2.8 Radar

The use of radar as a remote sensing system in environmental sciences will be addressed later in Chapter 8 with some detail. Here radar application to the particular case of local (at a point) sea level measurements is introduced briefly, the operating principle being similar to that of the acoustic equipments described above.

The installation of a radar level meter, as in the acoustic sensors case, requires also a structure on the shore or a platform fixed to the seabed, but the electromagnetic wave only travels in air and cannot be used from underwater to the surface as in the acoustic case. Radars cannot be used underwater because due to the electrical properties of water the electromagnetic wave results attenuated within short distances.

Radars use as transducer a radiofrequency antenna pointing down to the sea surface. The radar antenna emits pulses downwards to measure the distance from the antenna to the sea surface by means of the time of flight. In this case the radar emits an electromagnetic wave whose traveling speed is much higher than that of the sound in air. Then, because the time of flight is very short, the electronics involved in the process of measuring the water height has to be more sophisticated than in the acoustic case.

6.2.9 Resistive (Conductive)

These sensors are used to measure waves in models and wave tanks. In the literature, these sensors can be found as resistive or conductive gauges. The wave sensor is composed of two vertical parallel conductive rods or wires, generally made of stainless steel (Fig. 6.4). The sensor has a head containing the electronic circuits; the head may include a transmission link to a central station which is responsible for acquiring the signal from several sensors. The spacer, at the lower end, keeps the rods at a constant distance from each other because it is essential that the geometry of the staff remains unchanged.

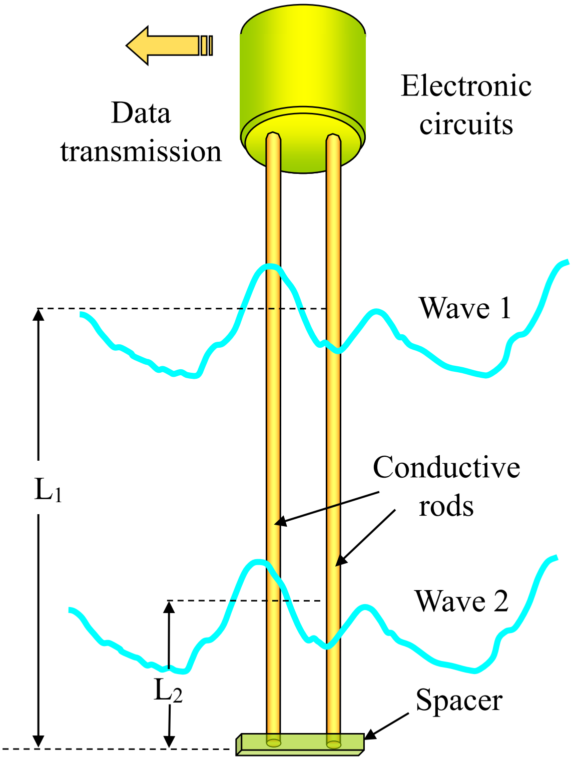

Fig. 6.4: Schematic of a resistive probe

The rods are submerged at a certain depth and the electronic circuit measures the resistance of the rods plus the water. Because the resistance of the rods is low and constant, the change in resistance as "viewed" by the circuit is due to the change in water height. The measured water electrical resistance is given by

$$R = \frac{C}{L\sigma} \tag{6.1}$$

where L is the length that the rods are submerged, σ is the conductivity of the water and C is a constant which depends on rod's diameter and distance between rods. This equation is valid from a certain distance from the lower end of the sensor, for example 5 to 10 % of the rods length. Closer to the lower end the relation between resistance and water height is no longer linear.

The change in resistance measured by the electronic circuit is inversely proportional to the water height. When the sensor measures "Wave 2" (Fig. 6.4), the resistance of the water "seen" by the electronic circuit is R_2; when the water level increases to "Wave 1" the resistance is R_1, and $R_1 < R_2$. The decrease in resistance is because when the rods are more submerged, some resistance is added in parallel to the initial R_2. As explained in Section (3.7.6), the value of the equivalent resistance of two resistors connected in parallel is always less than the smaller of the two resistors; this is why the resistance decreases with the increase in water level.

The measured resistance, and then the voltage output, is an average of the wave height between the rods (Fig. 6.4). Therefore, when the wavelength of the water wave is comparable to the distance between the rods, the sensor works as a low-pass spatial filter for the measured waves.

If sensors were used in a tank where waves travel in just one direction, one way to minimize sensor spatial averaging is to install the plane containing the rods parallel to the wave front. In a bi dimensional hydraulic physical model where waves can travel in any direction, one way of reducing filtering is by decreasing the diameter of electrical conductors and their separation distance. Wires are thus used for replacing rods. Wires require a tension to be exerted between both ends to keep them parallel, for example, fixing the lower end to the bottom of the model.

The dynamic response of the wave staffs can also be limited by the water meniscus on the probe at the water-air interface. Also, when the water falls down around the staff, there is a physical phenomenon developed on the probe surface called *wetting* of the probe which can be more extended in length that the meniscus itself (Clayson, 1989). This physical behavior also produces some kind of low-pass filtering of the wave. In simple terms, wetting is a phenomenon that results from the action of cohesive and adhesive forces acting upon the molecules of a liquid near a solid surface (the walls of the recipient containing the liquid or any structure submerged in it). Cohesive forces are exerted by other molecules within the liquid, whereas adhesive forces are exerted by the molecules of the solid surface. Since liquids cannot maintain any shear stress, the resultant force between cohesive and adhesive forces must be normal to the surface of the liquid at the point of contact with the solid surface. The angle that the tangent line to the liquid surface at the point of contact makes with the solid surface is called the *contact angle*. On the whole, if the adhesive forces are greater than the cohesive ones, the contact angle is small, and it is said that the liquid *wets* the surface. Conversely, if the contact angle is large, the liquid *does not wet* the surface. Water wets clean glass (contact angle near zero), whereas mercury does not (contact angle about 140°). It is worth noting, however, that small quantities of impurities, such as humectants, detergents and waterproofing agents, can produce large variations of the contact angle (Sears & Zemansky, 1964).

Because the resistance is inversely proportional to wave height, in order to have an output voltage directly proportional to the height some simple electronic circuits have to be used. In general alternating signals in the audio range are used in these circuits.

Generally, wave tanks and hydraulic models use fresh water and the conductivity of the water could be considered constant during short time tests. Thus, changes in σ can be controlled by calibrating before and after each measuring cycle. In some cases where σ changes during the test, a compensating circuit that measure the conductivity of the water simultaneously with the wave height is used.

Calibration of the probes is achieved by raising or lowering them a known amount and simultaneously measuring their output voltages. Contaminants in the water, such as oil, may have an important effect on the calibration.

6.2.10 Capacitive

Devices known as capacitive gauges are used in model and field measurements. Field use requires a shore construction, a platform, or a pier fixed to the bottom.

They have a sensor consisting of a metallic rod (or wire) covered by a sheath of dielectric material (electrical insulator) (Fig. 6.5). Usually, the wire is made of copper, and the dielectric of Teflon. In order to have a linear transference, the dielectric thickness must be constant along the wire length. As in the case of the resistive gauge, if a wire is used, some mechanism to tense the wire should be used.

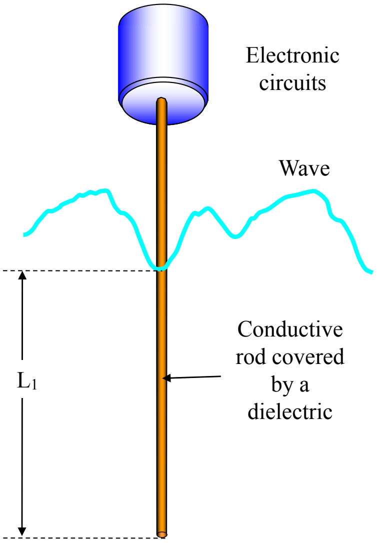

Fig. 6.5: Schematic of a capacitive probe

The internal rod is one of the electrodes of a capacitor. The other electrode may be a second, non-insulated rod, placed close to the first, or may be the water itself, which is at the electrical ground potential of the tank (Payne, 2008). In the second case, the capacitance C between the internal electrode and the water is given by (Clayson, 1989).

$$C = K\,h \tag{6.2}$$

where K is a constant which includes the diameter of the rod and the dielectric sheath and the permittivity of the dielectric, and h is the immersed depth of the sensor. Thus, the capacitance is proportional to the water level. Some electronic circuits, appropriated for measuring capacitive impedance are used to convert changes in the capacitance to voltages. Thus, output voltages represent changes in the water height. In general, signals in the range of radio frequencies are used to excite the sensors.

The capacitive sensor will average the level measured to a certain area around the wire (or rod). The size of this integrating surface and so the spatial averaging was not found in the manufacturers' specifications. Theoretically, it depends on the spatial distribution of the electromagnetic field in the real distributed capacitor, which depends on where the connection of the outer electrode is made, the impedance of the water and the reactance of the capacitor.

In order to achieve high capacitance values, which are less prone to noise, the dielectric material cover is usually made thin and can therefore be easily damaged. Manufacturers of capacitive gauges recommend that the sensing wire does not come into contact with sharp objects, and when not in use, care should be taken to avoid putting any weight on the sensing wire. Also, probes should not be exposed to very hot or cold temperatures (RBR Limited, 2011).

These capacitive staffs also suffer from the problem of meniscus and wetting (already mentioned for resistive sensors) and to have a constant sensitivity the temperature must be held constant (Lawrence et al., 2012). They can be used either in fresh or salt water and the calibration process is similar to that for resistive probes.

6.2.11 Optical

It would be very useful to have an optical method to measure water waves in models without any contact with the water, and with high temporal and spatial resolution (Mulsow et al., 2006), and some efforts have been made in this sense (Mulsow et al., 2006; Payne et al., 2009). The operating principles of the methods are simple, but the recording and processing of the acquired images are complex.

One of the systems consists of a laser source whose beam is vertically installed and pointing downwards at the water surface, and a camera whose line of sight forms a certain angle with the beam (Fig. 6.6). The relative position of the laser and camera is kept constant by mounting them on the same frame. The laser beam produces a spot on the water surface and the camera digitally records images of it as the water moves. Unfortunately, because the beam light is not only reflected by the surface but also scattered by subsurface water, the recorded spot image will not be sharp but diffused. After some statistical image processing, the surface spot is estimated.

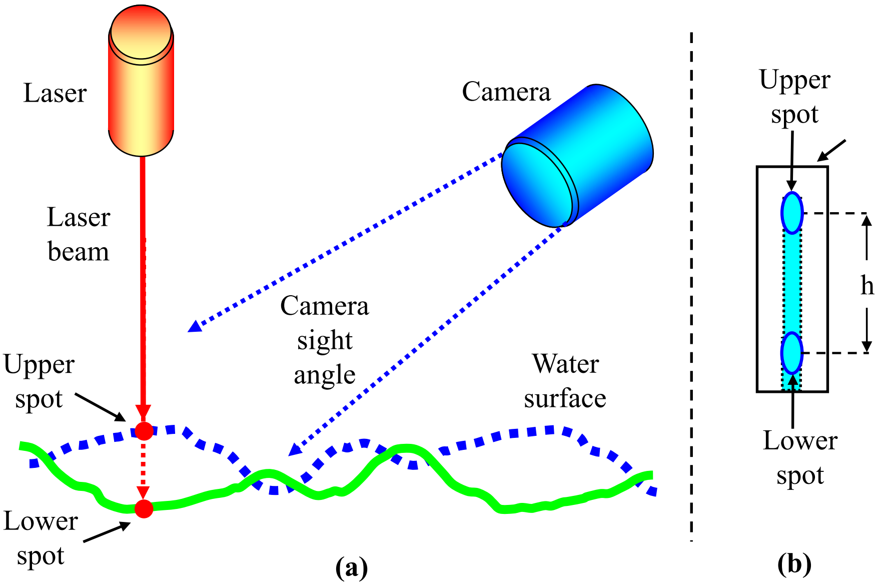

Fig. 6.6: (a) Laser and camera setup. (b) Camera registers. Water surface in dashed and continuous line corresponds to two different instants. The same goes for the upper and lower spot showed on the camera register. When the spot on the surface at both instants is obtained by statistical analysis from the register, the change in water level (*h*) can be estimated.

The calibration of this measuring system is achieved by displacing the laser/camera set vertically on a motionless water surface. The set displacement is measured and compared with the position of the spot on the recorded image and from these values the transference of the system is obtained.

Another optical wave meter uses a slanted laser beam which forms a light sheet that is reflected on the water surface and projected on two parallel vertical surfaces (Mulsow et al., 2006). The images produced by the reflected laser beam on these surfaces are recorded by a camera. By processing the image on the two vertical planes it is possible to separate water-level induced effects from slope-induced effects. The data processing and calibration procedure is more complicated than in the previous measuring system.

Optical systems have the advantage that they do not perturb the water surface as in the case of the conductive or capacitive staffs. But they depend on surface reflection; any floating material or surface turbulence could cause measurement errors. Also, they require considerable data processing.

6.3 Quasi Static Level Measurements

6.3.1 Mechanical Systems for Measuring Level

The old instruments for recording tidal level used a float and counterweight to move a mechanical system, thus converting linear level variations into rotational motion. This rotational motion was associated with a pencil and a recording paper chart. The chart was advanced by means of a mechanical clock. The pencil registered on the paper chart a distance proportional to the water level change.

The same principle is still in use in some instruments to measure slow water level changes such as tide, water table and liquid level in tanks. Nowadays instruments have great modifications of the method through which the information is recorded, in the clock and in the way the mechanical information is transformed into an electrical signal. The rotation produced by the float and counterweight on a pulley is used to move a variable potentiometer or an optical sensor as those described in Section (4.14). Because mechanical systems are easy to understand and their description can be found in many reports (GWPD 14, 2010) they will not be described any further here.

6.3.2 Radar and Acoustic Meters for Low Spatial and Temporal Resolution

Radar and acoustic meters as those explained before for measuring waves are also used to measure slow level changes. Because these technologies were already described they are only mentioned here. These kinds of meters have similar operating principles and installation requirements when they are used either for measuring fast or slow changes in water surface elevation. The main difference is that in low spatial resolution problems, the beam width of the transducers and antennas is not required to be narrow. Also, level time series are low-pass filtered to remove all undesired perturbations.

6.3.3 Pressure

Pressure sensors are well suited for measuring slow changes in the water level and their applications were explained in Section (4.8.4). The more appropriate type of pressure sensor for each case was described in detail, stressing the convenience of using vented gauges in some applications.

6.3.4 Applications of Quasi Static Level Measurements in Hydrology

Quasi static levels in hydrology are extensively measured for multiple purposes. Among them are: tests to evaluate hydraulic conductivity, monitoring of aquifers exploitation and determination of groundwater flow.

The methods used to estimate groundwater flow require monitoring a network of at least three wells and to know the hydraulic conductivity of the soil. With this information water speed is calculated using Darcy´s law and water direction is estimated from the gradients inferred from the piezometric heads.

In general, these methods have low spatial resolution and are prone to errors because the hydraulic conductivity distribution is not well known, as pumping or slug tests do not extend a great distance from the wells. In order to have good data quality it is necessary to increase the number of wells involved in the measurements, which increases costs and efforts employed for each test.

A different concept has been developed in the last two decades to evaluate groundwater flow. Thus, the so-called direct or point-measurement methods that measure the water velocity in just one point of the aquifer, giving local results emerged. At present, there is not a prevalent method that stands out among the few existing; on the contrary, most of them are still under development. These methods will be described in the rest of this chapter. They seem to be methods with a promising future because they require only one borehole and a short time to perform a measurement. Also, as technology evolves they will probably allow collecting data at lower costs than traditional indirect methods.

Perhaps the material here presented on groundwater velocity measurements could be considered too meticulous for an introductory work, but it was done this way for two main reasons: first, this subject was not found addressed in other books, and second, the detailed explanation of these operating principles is necessary to advise the reader about instruments limitations and operational problems that these technologies still entail.

6.4 Measuring Groundwater Velocity

6.4.1 Introduction

Instruments for measuring currents in channels, rivers and seas have reached such a degree of development that almost any research requirement is fulfilled by commercially available equipment (Chapter 5). The situation is quite different with groundwater measurements because flow is very slow and in some circumstances its direction changes in short distances. The selection of instruments for this application should be of special concern because no method has yet been adopted by researchers as standard.

6.4.2 Review of Direct Methods

For the sake of a more structured description, direct methods will be grouped according to their hydrological applications. For this reason, an explanation follows on some quite different potential hydrologic applications where these methods could be employed. The application characteristics taken into account to form these groups are: the range of groundwater speed, the relevance of measuring flow direction, and the environment surrounding the sensor. Obviously, as in most cases, this classification is arbitrary and some measuring methods can be used for more than one application.

6.4.3 Some Quite Different Flow Measurements Needed in Hydrology

6.4.3.1 Vertical Flow

The study of vertical flow in boreholes during pumping tests is a classical application of flowmeters in hydrology. In some applications the instrument for measuring pumping rates has to be lowered at great depths and should withstand large water pressures. The range of speeds for this application is from 0.001 to 0.1 m/s. Flowmeters must work in direct contact with water, but they do not need to measure flow direction (Hess, 1986). From the point of view of instrumentation complexity, this is the simplest case to solve because velocities are still high enough to be measured with simple technological solutions and direction is of no interest.

6.4.3.2 Horizontal Groundwater Flow

The magnitude and direction of horizontal groundwater velocity is a very important hydrological parameter that can be measured in direct contact with the soil or from inside boreholes. In the first case, instruments are permanently buried in “ad-hoc” drilled boreholes and relocation of the instrument is difficult. The second case allows using the same instrument in different wells, or at various depths in the same well. Moreover, already existing boreholes could be used. For this application, instruments can be used at hundreds of meters from the surface. The flow speed ranges approximately from 1×10^{-6} to 8×10^{-4} m/s and flow direction is of great interest. The higher velocities correspond to mountain recharge zones or fractured rock soils, and the lower ones to soils in plain areas.

6.4.3.3 Seepage Flow

Instruments for measuring submarine groundwater discharge are known as seepage meters. They use a funnel inserted into the bottom sediment to collect groundwater. In automatic seepage meters the funnel has a discharge outlet connected to a flowmeter.

The flowmeter sensors are in direct contact with water. The outlet area is much smaller than the funnel mouth area so that flow at the outlet is about 10^3 higher than at the mouth, which simplifies the flowmeter design. A measurement range of seepage velocity from 2×10^{-7} to 5×10^{-6} m/s has been reported (Taniguchi & Fukuo, 1993).

6.4.3.4 Flow in Remediation Works Where Velocities Are Very Low

The monitoring of waste remediation activities and post-closure performance of remediate waste sites requires measuring fluid velocities (in magnitude and direction) as low as 3×10^{-8} m/s. Sometimes the fluid is biphasic (water plus air) and has some degree of corrosive components. Instruments have to be installed in direct contact with the soil and should measure, hopefully, during years without recalibration. In general they are installed close to the surface and should record continuously.

6.5 Direct Methods and Their Hydrological Applications

6.5.1 Vertical Flow in Boreholes

6.5.1.1 Thermal-Pulse Flowmeter

When vertical velocities are small (below 10 mm/s) or a great resolution is required conventional spinner flowmeters cannot be used, and an alternative is to use a method developed by the U.S. Geological Survey (USGS) based on a thermal-pulse flowmeter (Hess, 1986). The device consists of a heater and two temperature sensors separated a distance $d = 40$ mm, arranged as shown in Figure 6.7. It can measure in a flow range from 1 to 100 mm/s. The heater grid is contained in a plane perpendicular to the flow. Sensors are glass bead isolated thermistors, separated 20 mm from the heater.

Flow velocity (V) is measured by recording the time elapsed between the electrical pulse is applied to the heater and the response peak of the sensors (Δt).

The volume flow is obtained from calibration charts developed in the laboratory using pipes of similar diameters to those used in the borehole. The thermal pulse response time may range from 1 to 60 s. Water is heated about 0.1 °C above the ambient temperature. The buoyancy of the heated water causes some asymmetry in the calibration curve for up and down flows.

Because flow is obtained from time measurements, and $V = d/\Delta t$, the transference curve which relates V and Δt is quite non linear (flow is inversely proportional to the elapsed time).

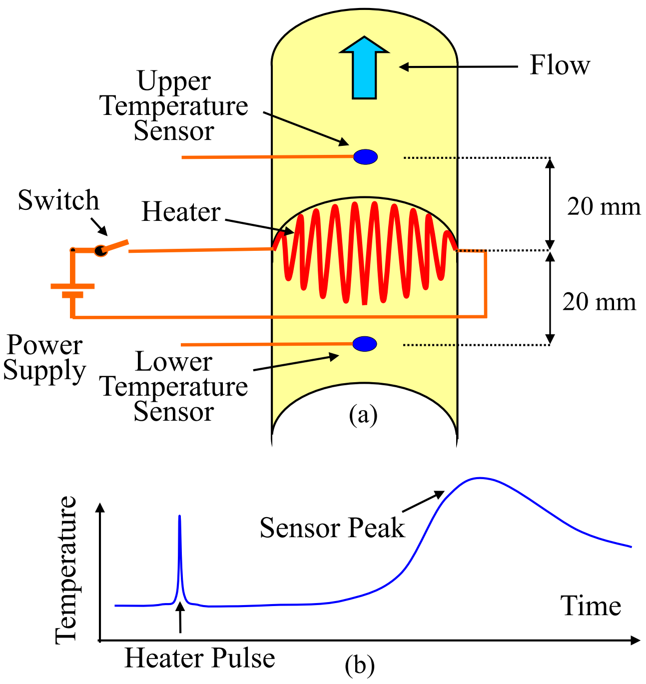

Fig. 6.7: (a) Schematic of heater and sensors. (b) Sensor heat pulse response showing the instant when the electric pulse is applied.

6.5.1.2 Electromagnetic Flowmeter

An electromagnetic flowmeter based on Faraday's law (Section (3.7.12)) was reported for this same application (Moltz & Young, 1993). Authors claim that it is possible to measure velocities as low as about 1 mm /s with errors less than 10%. They use two electrodes and an electromagnet (coil) as the operating principle already mentioned in Section (5.3.3). The main differences with that described before are that the size and power consumption of these flowmeters are smaller, and that they are designed to work at several hundred of meters underwater.

6.5.2 Flowmeters for Horizontal Groundwater

6.5.2.1 Colloidal Borescope (CB)

The instrument, described by Kearl (1997), attempts to measure groundwater velocity by observing the motion of particles inside a well. It consists of two CCD (charged-couple device) cameras, a ball compass, optical magnifying lenses, an illuminating source, and housing (Fig. 6.8). This device is about 0.9 m long and 0.044 m in diameter.

When placed inside a borehole it is capable of transmitting amplified images of the particles to the surface. Due to the insertion of the instrument in the well the flow is disturbed, but after half an hour laminar horizontal flow predominates. Particles illuminated by the back-light source, as in a microscope, are zoomed by one of the cameras while the other focuses the compass to reference the images to the magnetic north. A digitizing system records video frames at selected intervals and a software compares them, gathering information about average particle size, number or particles, speed and direction.

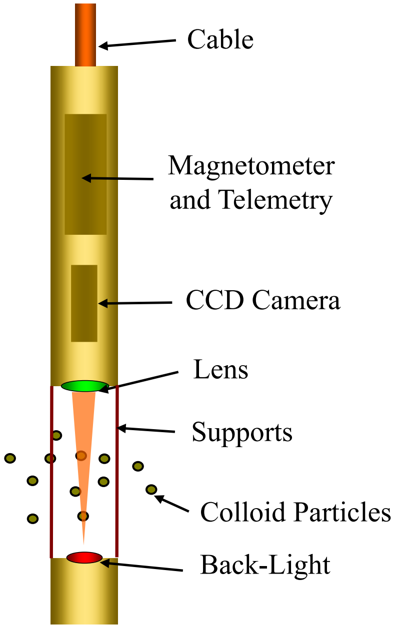

Fig. 6.8: Scanning colloidal borescope flowmeter (SCBFM).

An improved version of this instrument (James et al., 2006), called a scanning colloidal borescope flowmeter (SCBFM), allows investigating three-dimensional flow on an interval of 0.5 m depth inside the borehole without relocating the instrument. The best results are for particles that move at a rate below 12×10^{-3} m/s. A U.S. patent (Foster & Fryde, 1990) presents a similar idea to that described above, but with some technological differences.

6.5.2.2 Groundwater Laser Velocimeter (GLV)

This instrument measures the motion of the particles suspended in the groundwater of a borehole (Momii et al., 1993) as the CB flowmeter, but with a different technology. For this purpose a laser beam is split into two resulting beams that are focused by a lens on a point where interference fringes are formed with a spacing *d*. Figure 6.9 shows the illuminated volume with the interference fringes. The moving particles passing the fringes reflect light from the regions of constructive interference. The illuminated volume is a cylinder of about 100 µm long and 30 µm in diameter; very small particles (a few microns in diameter) are thus detected. The reflected light is received by a photo detector, and by measuring the Doppler frequency shift (*fd*) of the scattered light it is possible to calculate the velocity of the tracer particles, and hence to estimate the water velocity. The velocity of the particles (*V*) is related to the Doppler frequency and the distance between interference fringes (*d*) by Eq. (6.3). No laboratory calibration of the instrument is thus needed.

$$V = d\,fd \tag{6.3}$$

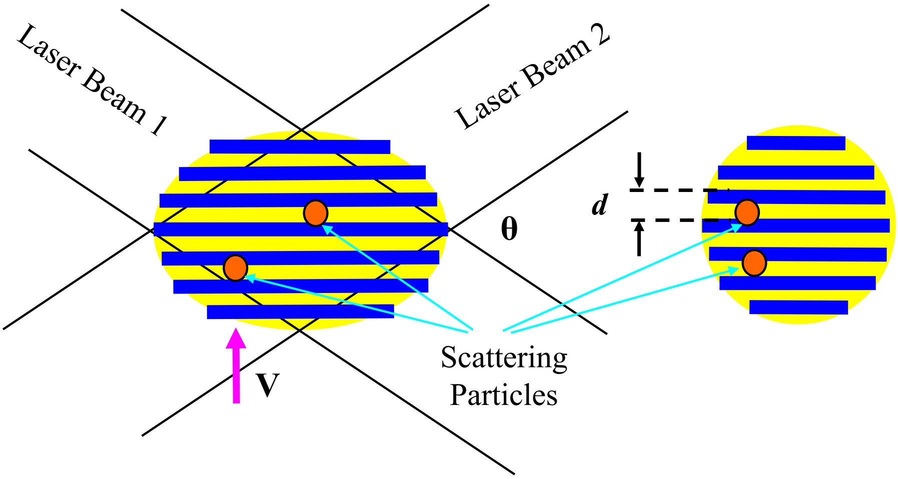

Fig. 6.9: The groundwater laser velocimeter illuminates a volume of water with interference fringes.

The distance *d* is a function of the angle θ between the two laser beams, and the laser wavelength λ. Due to its high spatial resolution, this method needs short observation times, but as in the CB flowmeter, when introduced in the borehole the flow is disturbed and some time is required to restore laminar flow conditions. This instrument cannot be used when the flow is turbulent.

The working speed range of this instrument is from 3×10^{-7} to 1.4×10^{-4} m/s. At the low end of the range, errors are of about 8%, decreasing to 1.4% at the highest velocities.

6.5.2.3 Thermal Flowmeters

6.5.2.3.1 Horizontal Heat Pulse Flowmeter (HHPF)

The most widespread heat pulse flowmeter to measure horizontal flow consists of a probe containing a heater surrounded by a circular array of thermistors. The U.S. patent of Kerfoot & Skinner (1983) describes an array of 8 thermistors; other authors (Melville et al., 1985), an array of 10. The manufacturer recommends placing a nylon mesh end cap at the end of the probe. The external diameter of the nylon mesh end cap matches the internal diameter of the well casing and is filled with glass beads (Fig. 6.10). Thus, when it is lowered into the well and immersed in water, the probe is surrounded by a saturated porous media. When a heat pulse is applied a transient temperature field is generated. While the heat diffuses radially, the water displacement produces some advection of the heated water.

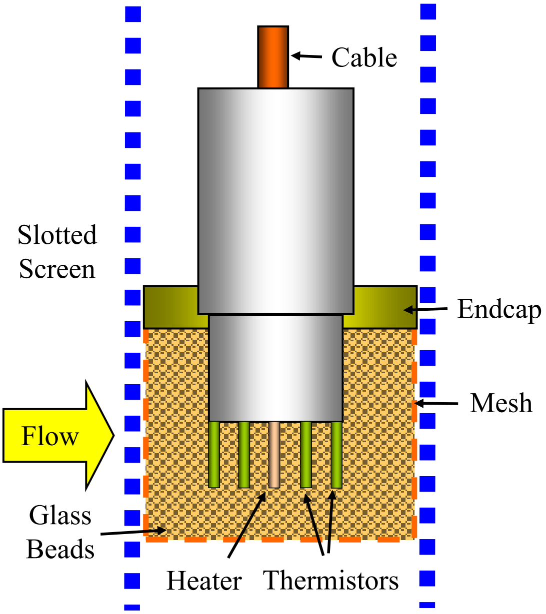

Fig. 6.10: Horizontal heat pulse flowmeter. The instrument is shown inside a slotted screened borehole and the space between the screen and the heater/thermistor array is filled with glass beads which create a saturated porous media around them.

For stagnant water heat diffusion produces a symmetric distribution of heat, so opposite thermistors measure the same temperature. When water moves, an asymmetric distribution of heat causes temperature differences between thermistors. These differences are supposed to be proportional to the component of the water velocity along the direction defined by opposite thermistors. Water velocity is estimated by calibrating the temperature difference vs. water velocity. The probe is hold in the borehole from the surface by means of connecting rods. In order to relate measured velocities to the magnetic north, a particular pair of thermistors is referenced by placing a compass at the top of the connecting rods.

The power pulse applied to the heater is about 15 W, it lasts for approximately 30 s and its effects on the thermistors are measured during 3 minutes. The diameter of the probe is 0.044 m. The velocity range is from 0.35×10^{-7} to 0.35×10^{-5} m/s (Melville et al., 1985). In order to get reliable results the instrument must be calibrated under similar conditions to those of real use.

6.5.2.3.2 Rotary Device Probe (RDP)

It has been developed for measuring groundwater in recharge zones (Guaraglia et al., 2009). The thermal rotary device probe consists of a central heater and four thermistors symmetrically placed around the heater, forming two orthogonal axes (Fig. 6.11a). When the probe is lowered in a monitoring well to the desired depth, a temperature step is applied to the heater and its temperature kept constant. Then the probe is slowly rotated 360° clockwise and counterclockwise. The average power supplied to the heater and the thermistor temperatures are recorded.

If flow is not null the thermistor temperatures increase downstream and decrease upstream. As the thermistors rotate, a kind of temperature waveform as a function of the angular position is recorded (Figure 6.11b). By processing these waveforms the direction of the flow is found. When flow velocity increases, the heater's power has to be increased to keep its temperature constant, so the average heater's power gives information on the flow rate.

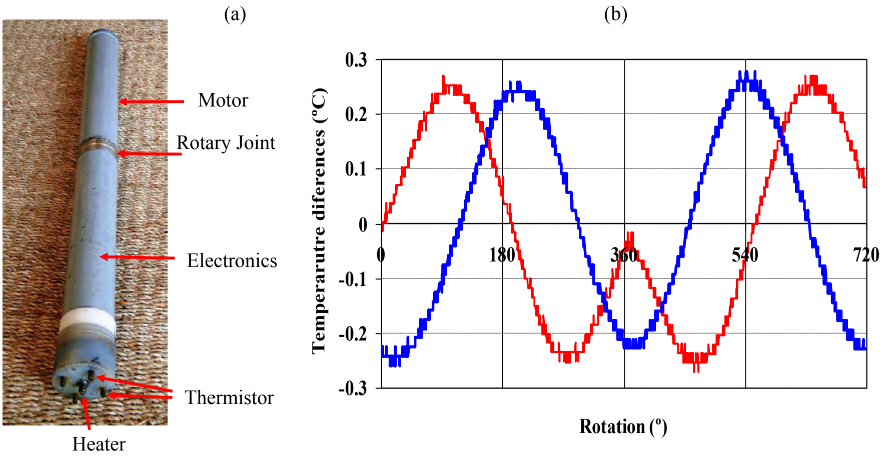

Fig. 6.11: (a) Rotary Device Probe. (b) Temperature waveform.

6.5.2.3.3 Groundwater Acoustic Doppler Velocimeter (GADV)

Type 1

There is a U.S. patent describing a method based on the Doppler shift of an acoustic wave (Yankielun, 1998). The sound source and sensors provided as examples are piezoelectric transducers working at 4 and 10 MHz. Acoustic pulses are generated by a central sound source and detected by sound sensors positioned at a short distance from it. If four sensors are used, they can be positioned exactly north, east, south and west of the sound source. The ensemble is lowered in a screened borehole and placed below the water table. When the water moves, frequencies in the sensors will differ from the source frequency due to the Doppler effect. The patent claims that frequency differences are mathematically related to the water velocity by

$$V = \frac{c\,\Delta f}{2\,f_S} \tag{6.4}$$

where V is the water velocity, f_s the sound source frequency, Δf the difference in frequency and c the speed of sound in water. The direction and magnitude of water velocity is obtained by vector addition of the north-south and the east-west components.

Differences in frequencies are obtained by pulse counters which count the number of pulses detected during a predefined counting interval. Some examples are given in the patent. One of them shows that an instrument having a 10 MHz sound source needs 12 h to measure a water velocity of 2.3×10^{-6} m/s with good resolution. This time could be unsuitable in some applications. For example, if the relation of groundwater dynamics to the tidal level has to be studied, such counting times are undesirable, and perhaps other methods should be used.

Type 2

Another GADV, quite different from the above, is described by Wilson et al. (2001). This flowmeter does not measure fluid velocity directly, but tracks the velocity of suspended particles in the water column. It is similar to the Acoustic Doppler Velocimeter described in Section (5.4.6). It is approximately 1.2 m long with a 0.075 m external diameter. It can be deployed in wells with an inner diameter of 8.75×10^{-2} m.

The probe consists of one centrally mounted acoustic emitter and three receivers positioned on radial arms. A guard cage protects the probe from potential damage during field work. The maximum sample volume of the probe is 1.6×10^{-9} m^3 and the frequency of measurement is 25 samples per second. The instrument is deployed with a cable that provides the power and communication capability. It uses a flux-gate magnetometer as a compass. Borehole flows from 1×10^{-4} to 2.4 m/s are measured accurately.

6.5.3 Seepage Meters

As stated above, groundwater discharge in coastal zones may be estimated by collecting the water coming out of the sea bottom in a funnel buried in the sediment. The water captured by the funnel is conducted through a tube where a flowmeter, which is part of the seepage meter, measures the flow as a function of time (Fig. 6.12).

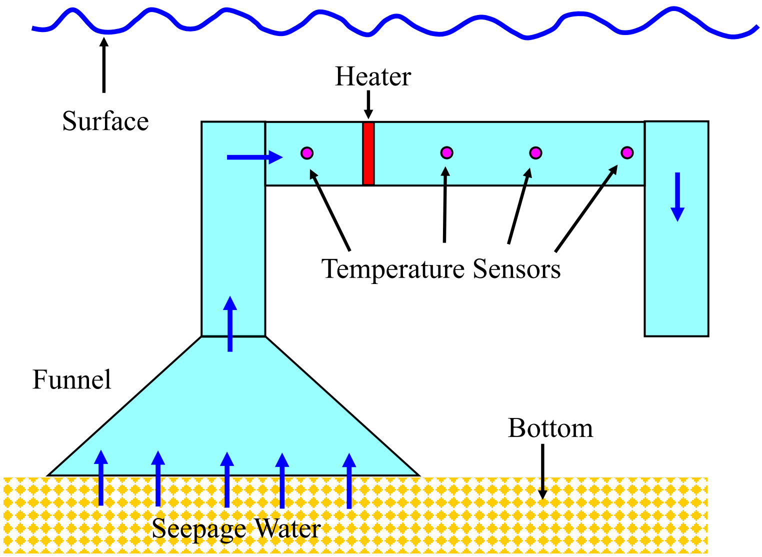

Fig. 6.12: Thermal seepage meter. A funnel buried in the sediment collects the seepage water from the bottom discharge. Heater and sensors measure the flow.

A thermal method for measuring the flow velocity in the tube (V_t) consists in producing a pulse heat in the water inside the tube and measuring the temperature at 0.05, 0.1 and 0.15 m downstream the heater, and at 0.05 m upstream it (Taniguchi & Fukuo, 1993; Taniguchi et al., 2007). The downstream sensors are measuring the ambient temperature plus the temperature due to the injected heat. The upstream temperature has to be subtracted from the downstream ones to exclude the natural changes in water temperature. The heat pulse is applied for two seconds every five minutes and the time when the temperature measured by the thermistors reaches a maximum (t_{max}) recorded. Since the relationship between log V_t and log t_{max} is almost linear, the calibration curves allow V_t to be estimated from t_{max}. Then the groundwater velocity (V_g) is calculated by multiplying the velocity V_t by the ratio of the cross-sectional areas of the tube and the funnel. In this kind of application the flowmeter requires measuring water flow velocities in the range from 4.5×10^{-4} m/s to 0.01 m/s.

An ultrasonic seepage meter has been patented that differs from the former one, basically in the way that flow velocity is measured in the tube. It uses two piezoelectric transducers that continually generate burst of ultrasonic signals from one end of the tube to the other. The speed of the water affects the speed of the ultrasonic signal. The measurement of the ultrasonic signal speed provides information to get the speed of water in the tube. It is claimed that speeds of water as low as 10^{-7} m/s are measured.

6.5.4 Flow in Remediation Works Where Velocities Are Very Low

6.5.4.1 In Situ Permeable Flow Sensor (ISPFS)

The instrument called In Situ Permeable Flow Sensor is used to measure the direction and magnitude of the three-dimensional groundwater flow vector in unconsolidated, saturated porous media (Ballard, 1994). The sensor is permanently buried in direct contact with the porous media and measures, approximately, the average velocity in a cubic meter around the sensor. It is claimed that the instrument is able to measure flow velocities in the range from 5×10^{-8} to 1×10^{-5} m/s. Being in direct contact with the formation the ISPFS avoids all problems related to the interaction between aquifer flow and observation wells (James et al., 2006; Lengricht & Kai-Uwe Graw, 2002), and there is no need to know the hydraulic conductivity of the formation.

The ISPFS consists of a rod of low thermal conductivity, 0.75 m long and 0.05 m in diameter, containing a heater and surrounded by an array of 30 thermistors capable of measuring within 0.01 °C (Fig. 6.13). When the rod is buried in some unconsolidated formation where groundwater velocity is to be measured, a thermal perturbation is applied to the media by the heater. The power applied is between 60 and 120 W, which increases heater temperature in about 20 to 25 °C over the temperature of the formation. Power should be as much as possible to get maximum sensibility, but not so much to produce natural convection of water.

If there are no asymmetries in the construction of the instrument, the heat flux leaving the rod should be uniform over the surface of the cylinder. In such a case, the distribution of temperature on the surface of the cylinder would vary as a function of the direction and magnitude of the groundwater velocity. Comparing the measured temperature distribution with theoretical temperature maps obtained from thermal equations, the three-dimensional vector velocity is estimated. The theory assumes a long cylinder, buried in perfect contact with an infinite saturated porous media whose thermal and hydraulic properties are homogeneous and isotropic. Buoyancy effects due to changes in water density are neglected.

Fig. 6.13: In Situ Permeable Flow Sensor. Photography courtesy of Stanford Ballard, Sandia National Laboratories, Albuquerque, New Mexico, USA.

In practice it is complex to fulfill the theoretical assumptions underlying the method; drilling techniques deform the microstructure of the ground, sometimes compacting it (percussion) and sometimes making it less consistent (rotation), which is likely to change the uniformity required by the theory. Nor is it easy to achieve close contact with the saturated soil, because during the installation air may be trapped near the walls of the sensor. Although the air may be displaced by water, the porosity near the sensor could become anisotropic. Therefore, in order to succeed in measuring with the In Situ Permeable Flow Sensor a correct installation is a key topic.

6.5.4.2 Conductivity Flowmeters

6.5.4.2.1 Point Velocity Probe

This method was developed to measure groundwater velocity in unconsolidated non cohesive media such as sand (Labaky et al., 2007; Devlin, 2002; Devlin et al., 2009). It consists in measuring the velocity of a tracer on the surface of a cylinder (apparent velocity Va), which allows groundwater velocity to be evaluated far form the cylinder ($V\infty$). The tracer must have electrical conductivity other than the conductivity of groundwater; it may be deionized water or water with a given saline concentration.

The device used to implement this method consists of a cylinder with a supply of tracer solution connected to an injection port which releases the saline tracer. The injector is constructed drilling a hole on the cylinder and placing a diffuser stone through which pulses of the tracer are released (Fig. 6.14).

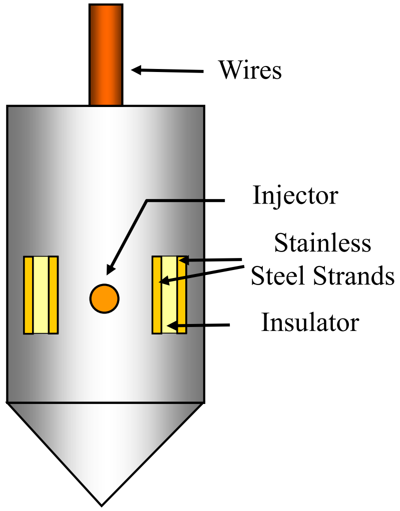

Fig. 6.14: Point Velocity Probe. This instrument is used in unconsolidated non cohesive media such as sand.

Two or more sensors are placed on the same horizontal plane than the injector to measure water electrical conductivity. Each conductivity sensor consists of two stainless steel strands.

An alternating current is applied to the strands, which work as a conductivity cell sensor (Section (4.10.1)), and voltage is measured on a constant resistor connected in series (Section (4.3)). When groundwater is over the sensors, they measure a background resistance attributable to the aquifer water. As the saline tracer passes over the sensor, the electrical conductivity between both strands decreases (the opposite happens if deionized water is used). The conductivity as a function of time is recorded at each sensor and these curves are used to estimate Va by fitting them to a solution of the advection-dispersion equation. Next, the angle α between the aquifer velocity direction and the injection port radius is estimated, and the velocity $V\infty$ calculated. The inaccuracy in the estimation of α can introduce errors in the estimation of $V\infty$. According to Labaky et al. (2007), laboratory test demonstrated that the method works between 5.8×10^{-7} and 1.13×10^{-5} m/s with errors within ± 15% and the direction is estimated with an error of about ± 8°.

6.5.4.2.2 Advection – Dispersion Velocity Meter (ADVM)

This method was developed to assess the safety of geological disposal of radioactive wastes. It is implemented by means of a probe which is introduced in a single well (Kawanishi et al., 1999). This probe consists of a screened cylindrical frame 0.06 m in diameter and 0.02 m in height filled with 1 mm diameter glass beads. The probe has a central common electrode and 12 equally spaced electrodes located around the central electrode on a circle 0.03 m in diameter (Fig. 6.15). The central electrode is a pipe through which the tracer solution (distilled water) is introduced. Distilled water has an electrical conductivity lower than that of the groundwater being measured.

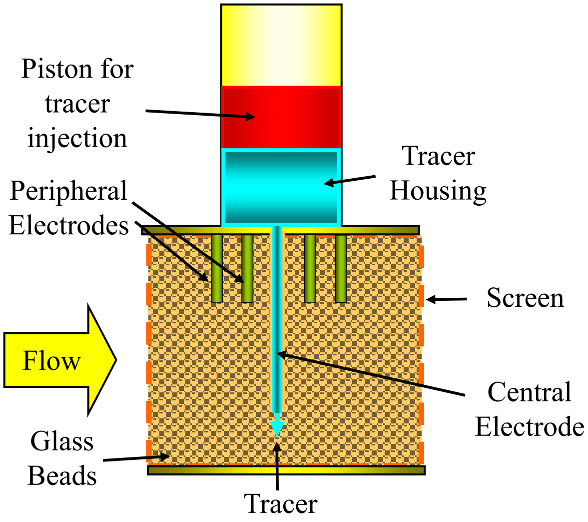

Fig. 6.15: Advection – Dispersion Velocity Meter.

The probe is lowered into the well where groundwater velocity is to be measured. Below it a rubber packer is placed to isolate the measuring section. Then the section is filled with a porous material such as sand to create a continuity of the porous medium inside the well, and an upper packer installed to isolate the section from vertical water displacements.

When groundwater enters the electrodes section and displaces the distilled water, the conductivity between the central electrode and the surrounding electrodes changes. The tracer injected through the central electrode will produce a migrating plume. When the plume is in the middle of the distance between the central electrode and the surrounding electrodes, the conductivity will be a minimum (or the electrical potential a maximum) (Kawanishi et al., 1999).

The velocity and direction of groundwater flow is evaluated by measuring the time at which the conductivity reaches a minimum (Δt). Theoretically, the velocity within the electrode section (V_0) is related to this time by

$$V_0 = \frac{\Delta x}{2\,\Delta t} \tag{6.5}$$

where Δx is the distance between the central electrode and the surrounding electrodes. The average flow inside the glass beads is different from the real flow velocity (V_r) due to the screen, glass beads and surrounding sand. Then a correction factor (β) has to be found empirically by a calibration process,

$$V_0 = \beta\, V_r \tag{6.6}$$

A measuring range from 10^{-9} to 10^{-5} m/s is reported in the literature (Kawanishi et al., 1999).

6.6 Discussion

Continuous research work is made having as a goal the measurement of groundwater flow in a single well by means of a simple, easy to operate and low cost measuring device. Some comparative field tests (Wilson et al., 2001) and many field and laboratory work seem to demonstrate that still more effort has to be dedicated to this objective before having a mature and reliable technology.

Wilson et. al. (2001) explain the importance of the search for a solution to the measurement of the horizontal component of groundwater flow velocity from inside a well. Their work compares the flowmeters previously described as HHPF, CB and GADV Type 2, with the technique called hydrophysical logging (Wilson et al., 2001). Unfortunately, because there are no standard methods for field use that allows the actual groundwater velocity to be known, it was not possible to determine which of the tested instrument gave a more accurately measurement, but some comparative results were found. Among the conclusions of this work, the following ones should be stressed:

1. "None of the tools consistently provided repeatable measurements of velocity and direction."
2. "A comparison of the measurements made in each well indicated that the three tested flowmeters rarely measured similar velocities and flow directions."
3. "The velocities estimated with the hydrophysical logging were typically very low and were most comparable to the velocities measured with the HHPF."
4. "The CB and GADV Type 2 measured similar velocities; however, the two tools seldom measured a similar flow direction."

6.6.1 Summary of Direct Methods Characteristics

Table 6.1 summarizes in each column the main characteristics of the direct methods described above: maximum and minimum velocities (*V*max and *V*min), the environment surrounding the probe (Environ), the time needed to perform one measure (Time) and the approximate volume sampled by the method (Volume). Values of volume and time are estimated from different literature sources that not always are coincident.

Table 6.1: Direct methods characteristics

Variable Method	V max (m/s)	V min (m/s)	Environ	Time (h)	Volume (mm^3)
USGS	1	10^{-3}	water	0.25	10^6
CB	3×10^{-2}	unclear	water	0.5 *(3)	1
GLV	10^{-4}	10^{-7}	water	Not reported *(4)	10^{-4}
HHPF	3.5×10^{-4}	7×10^{-7}	s.p.m.	0.5	10^6
RDP	$> 10^{-3}$	$< 10^{-4}$	Water	0.25	10^6
GADV 1	unclear	unclear	Water	12	10^6
GADV 2	2.4	10^{-4}	Water	0.16 *(2)	10^6
ISPFS	10^{-5}	5×10^{-8}	s.p.m.	*(1)	10^9
PVP	1.13×10^{-5}	5.8×10^{-7}	s.p.m.	Velocity dependent	10^6
ADVM	10^{-5}	10^{-9}	water	Velocity dependent	10^6

*(1) Initially it requires 20 h to reach thermal equilibrium. *(2) After Wilson et al. (2001). *(3) and *(4) require to reach laminar flow.
References: USGS = U.S. Geological Survey Vertical flowmeter; CB = Colloidal Borescope; GLV = Groundwater Laser Velocimeter; HHPF = Horizontal Heat Pulse Flowmeter; RDP = Rotary Device Probe; GADV1 = Acoustic Doppler Velocimeter (Type 1); GADV2 = Acoustic Doppler Velocimeter (Type 2); ISPFS = In Situ Permeable Flow Sensor; PVP = Point Velocity Probe; ADVM = Advection–Dispersion Velocity Meter; s.p.m. = saturated porous medium.

6.6.2 Limitation of Direct Methods

It was underlined in Chapter 1 (Section (1.1)) that a desirable condition of any measuring method is to disturb as little as possible the phenomenon being measured. Among the direct methods there are two groups with different measuring requirements: one group requires placing the instrument inside an observation well, and the other needs to install the instrument in close contact with the aquifer soil. In both cases there are some conditions that hinder the fulfillment of the assumptions made in the theory of the method, i.e. that the flow passing the instrument is the actual flow in the aquifer.

Among the problems observed in the first group, the most remarkable were: the presence of the observation well in itself modifies the actual groundwater flow, and it is not yet sufficiently understood how filter slots and the small-scale soil composition around the borehole interact to produce a representative sample of the groundwater flow of the aquifer inside the well (Lengricht & Kai-Uwe Graw, 2002).

Most of the time, flow inside the well follows an eddy flow pattern and seldom a rectilinear one. The positive and negative accelerations that water suffers in passing the screen slots contribute to the turbulence inside the screen (Lengricht & Kai-Uwe Graw, 2002; James et al., 2006). Flow at the well center was estimated to be one order of magnitude less than just inside the slots. Then calibration of the flowmeters under laboratory conditions is recommended (James et al., 2006) to estimate the flow in the surrounding formation from measurements made within the screened well.

The most important problem that affects the second group is to satisfy the premise of intimate contact of the instrument's probe with the saturated porous media required by the theory. It is not possible to introduce the instrument in the place where measurements are to be carried out without some degree of alteration of the porous matrix during the installation. Drilling procedures modify the characteristic of the soil where probes are placed, in some cases consolidating the soil and in others increasing the porosity. This change in the porosity with respect of the original soil also perturbs the flow around the instruments clearly.

References

Alliance for coastal technologies. (2007). *Workshop proceedings report. Wave sensors technology*. Indexing number ACT 07-03. St. Petersburg, Florida, March 7-9, 2007.

Ballard, S. (1994). The in situ permeable flow sensor: a ground-water flow velocity meter. *Ground Water*, *34*, 231-240.

Barstow, S. F., et al. (2003). *In*: Hauser, D., Kahma, K. K., Krogstad, H. E., Lehner, S., Monbaliu, J., & L.Wyatt, L. R. (Eds.), *Measuring and Analysing the Directional Spectrum of Ocean Waves, COST 714 Working Group* 3, Helsinki 18.10.2003.

Clayson, C. H. (1989). *Survey of instrumental methods for the determination of the high frequency wave spectrum*. Report no. 267, Institute of Oceanographic Sciences, Deacon Laboratory.

Datawell (2009). *Datawell Waverider Reference Manual WR-SG, DWR-MkIII, DWR-G*. Datawell BV Oceanographic Instruments, The Netherlands. Available at: http://cdip.ucsd.edu/documents/index/gauge_docs/mk3.pdf

Devlin, J. F. (2002). *Groundwater velocity probe*. U.S. patent no. 6,393,925 BI.

Devlin, J. F., Tsoflias, G., McGlashan, M., & Shilling, P. (2009). An inexpensive multilevel array of sensors for direct water velocity measurements. *Ground Water Monitoring and Remediation*, 29(2), 73-77.

Doong, D., Lee, B., & Kao, C. (2011). *Wave Measurements Using GPS Velocity Signals*. Sensors 2011, 11, 1043-1058; doi: 10.3390/s110101043. Available at: www.mdpi.com/journal/sensors

Foster, J. W., & Fryde, L. J. (1990). *Groundwater azimuth detection*. U.S. patent no. 4,963,019.

Guaraglia D., Pousa, J., Kruse, E., & Mayosky, M. (2009). A rotary thermal probe for measuring groundwater velocity. *Instrumentation Science and Technology*, *37*, 1-16.

GWPD 14. (2010). *Measuring continuous water levels by use of a float-activated recorder*. Groundwater Technical Procedures of the U.S. Geological Survey. Version: 2010.1 Available at: http://pubs.usgs.gov/tm/1a1/pdf/GWPD14.pdf

Hess, A. E. (1986). Identifying hydraulically conductive fractures with a slow-velocity borehole flowmeter. *Canadian Geotechnical Journal*, *23*, 69-78.

James, S. C., Beauheim, R. L., Mandell, W. A., Pedler, W. H., & Jepsen, R. A. (2006). Simulation to verify horizontal flow measurements from a borehole flowmeter. *Ground water*, *3*, 394-405.

Kawanishi, M., Miyakawa, K., & Hirata, Y. *Development and application of groundwater flow meter in fractured rocks: measurement of velocity and direction of groundwater flow in single well.*

International Atomic Energy Agency SM-357/80 (1999). Available at: http://www-pub.iaea.org/MTCD/publications/PDF/csp_006c/PDF-Files/paper-80.pdf

Kearl, P. M. (1997). Observation of particle movement in a monitoring well using the colloidal borescope. *Journal of Hydrology*, *200*, 323-344.

Kerfoot, W., & Skinner, S. (1983). *Groundwater flowmeter*. U.S. patent no. 4,391,137.

Labaky, W., Devlin, J. F., & Gilham, R. W. (2007). Probe for measuring groundwater velocity at the centimeter scale. *Environmental Science & Technology*, *41*(24), 8453-8458.

Lawrence, J., Holmes, B., Bryden, I., Magagna, D., Torre-Enciso, Y., Rousset, J. M., Smith, H., Paul, M., Margheritini, L., & Cândido, J. (2012). *D2.1 Wave instrumentation database*. Marine Renewables Infrastructure Network (Marinet).

Lengricht, J., & Kai-Uwe Graw. (2002). Interaction of aquifer flow and observation wells detected by particle image velocimetry. *Proceedings 13th Congress APD-IAHR*, *1*, 560-565. Singapore 2002. Available at: http://www.uni-leipzig.de/~grw/lit/texte_100/122_2002/122_2002_well_apd_iahr.pdf

Melville, J.G., Molz, F. J., & Guven, O. (1985). Laboratory investigation and analysis of a ground-water flowmeter. *Ground Water*, *23*(4), 486-495.

Moltz, F. J., & Young, S. C. (1993). Development and application of borehole flowmeters for environmental assessment. *The Log Analyst*, *January-February*, 13-23.

Momii, J. K., Jinno, K., & Hirano, F. (1993). Laboratory studies on a new laser Doppler velocimeter system for horizontal groundwater velocity measurements in a borehole. *Water Resources Research*, *29*(2), 283-291.

Mulsow, C., Schulze, M., & Westfeld, P. (2006). *An optical triangulation method for height measurements on instationary water surfaces*. Institute for Photogrammetry and Remote Sensing, Dresden Technical University, Germany, IAPRS Vol. XXXVI, Part 5. Available at: http://www.isprs.org/proceedings/XXXVI/part5/paper/MULS_657.pdf

NDBC. (1996). Nondirectional and Directional Wave Data Analysis Procedures. Technical Document 96-01. Stennis Space Center, National Data Buoy Center, National Oceanic and Atmospheric Administration, U.S. Department of Commerce.

Payne, G. (2008). *Guidance for the experimental tank testing of wave energy converters*. The University of Edinburgh. Available at: http://www.supergen-marine.org.uk/drupal/files/reports/WEC_tank_testing.pdf

Payne, G. S., Richon, J. B., Ingram, D., & Spinneken, J. (2009). Development and preliminary assessment of an optical wave gauge. *Proceedings of the 8th European Wave and Tidal Energy Conference, Uppsala, Sweden*. Available at: http://www.see.ed.ac.uk/~shs/Wave%20Energy/EWTEC%202009/EWTEC%202009%20(D)/papers/261.pdf

RBR Limited. (2011). *WG-55 Wave Gauge User manual*. Ottawa, Ontario, Canada. Available at: http://www.rbr-global.com

Sears, F. W., & Zemansky, M. W. (1964). *University Physics*. Reading, MA, USA: Addison-Wesley Publishing Company, Inc.

Taniguchi, M., & Fukuo, Y. (1993). Continuous measurements of groundwater seepage using an automatic seepage meter, *Ground Water*, *31*(4), 675-679.

Taniguchi, M., Ishitobi, T., Burnett, W., Wattayakorn, G. (2007). Evaluating ground water-sea water interactions via resistivity and seepage meters. *Ground Water*, *45*(6), 729-735.

Teng, C., Bouchard, R., Riley, R., Mettlach, T., Dinoso, R., & Chaffin, J. (2009). NDBC's Digital Directional Wave Module. OCEANS 2009, MTS/IEEE Biloxi - Marine Technology for Our Future: Global and Local Challenges.

Van Rijn, L. C., Grasmeijer, B. T., & Ruessink, B. G. (2000). *Coasted 3D measurement errors of instruments for velocity, wave height, sand concentration and bed levels in field conditions*. Department of Physical Geography; University of Utrecht WL, Delft Hydraulics.

Wilson, J., Mandell, A. W., Paillet, F., Bayless, E., Hanson, R., Kearl, P., Kerfoot, W., Newhouse, M., & Pedler, W. (2001). An evaluation of borehole flowmeters used to measure horizontal ground-water flow in limestones of Indiana, Kentucky, and Tennessee. *Water-Resources Investigations Report 01-4139*. U.S. Department of the Interior, U.S. Geological Survey.

Yankielun, N. E. (1998). *Doppler velocimeter for monitoring groundwater flow*. U.S. patent no. 5,796,679.