CHAPTER 6

GROUNDWATER

6.1 **GENERAL** [HOMS L]

Groundwater underlies most of the Earth's land surface. In many areas it is an important source of water supply and supports the flow of rivers. In order to understand the full extent of the hydrological system, it is necessary to understand the groundwater system (Fetter, 1994; Freeze and Cherry, 1979). The purpose of this chapter is to provide an overview of those basic concepts and practices that are necessary to perform an appraisal of groundwater resources. Generally, a groundwater resource appraisal has several key components:

(a) Determination of the types and distribution of aquifers in the area of investigation;
(b) Evaluation of the spatial and temporal variations of groundwater levels (potentiometric surface) for each aquifer, resulting from natural and man-made processes. The construction of wells and measurement of water levels facilitates this aspect;
(c) Assessment of the magnitude and distribution of hydraulic properties, such as porosity and permeability, for each aquifer. This is a requirement for any type of quantitative assessment;
(d) An understanding of the processes facilitating or affecting recharge to and discharge from each aquifer. This includes the effective amount of precipitation reaching the water table, the effects of evapotranspiration on the water table, the nature of groundwater–surface water interaction, and the location of and amount of discharge from springs and pumped wells;
(e) An integration of the groundwater data in order to corroborate information from multiple sources, understand the relative importance of the various processes to the groundwater system, and appraise the capacity or capability of the groundwater system to meet general or specific (usually water supply) goals. This can be facilitated with the development of predictive tools using various analytical options that range from water budgets to computer-based digital groundwater flow modelling.

6.2 OCCURRENCE OF GROUNDWATER

6.2.1 Water-bearing geological units

Water-bearing geological material consists of either unconsolidated deposits or consolidated rock. Within this material, water exists in the openings or void space. The proportion of void space to a total volume of solid material is known as the porosity. The interconnection of the void space determines how water will flow. When the void space is totally filled with water the material is said to be saturated. Conversely, void space not entirely filled with water is said to be unsaturated.

6.2.1.1 Unconsolidated deposits

Most unconsolidated deposits consist of material derived from the breakdown of consolidated rocks. This material ranges in size from fractions of a millimetre (clay size) to several metres (boulders). Unconsolidated deposits important to groundwater hydrology include, in order of increasing grain size, clay, silt sand and gravel.

6.2.1.2 Consolidated rock

Consolidated rocks consist of mineral grains that have been welded by heat and pressure or by chemical reactions into a solid mass. Such rocks are referred to as bedrock. They include sedimentary rocks that were originally unconsolidated, igneous rocks formed from a molten state and metamorphic rocks that have been modified by water, heat or pressure. Groundwater in consolidated rocks can exist and flow in voids between mineral or sediment grains. Additionally, significant voids and conduits for groundwater in consolidated rocks are fractures or microscopic- to megascopic-scale voids resulting from dissolution. Voids that were formed at the same time as the rock, such as intergranular voids, are referred to as primary openings (Figure I.6.1). Voids formed after the rock was formed, such as fractures or solution channels, are referred to as secondary openings (Figure I.6.1). Consolidated sedimentary rocks important in groundwater hydrology include limestone, dolomite, shale, siltstone and conglomerate. Igneous rocks include granite and basalt, while metamorphic rocks include phyllites, schists and gneisses.

6.2.1.3 Aquifers and confining beds

An aquifer is a saturated rock formation or deposit that will yield water in a sufficient quantity to be considered as a source of supply. A confining bed is a rock unit or deposit that restricts the movement of water, thus does not yield water in usable quantities to wells or springs. A confining bed can sometimes be considered as an aquitard or an aquiclude. An aquitard is defined as a saturated bed which yields inappreciable quantities of water compared to the aquifer but through which appreciable leakage of water is possible. An aquiclude is a saturated bed which yields inappreciable quantities of water and through which there is inappreciable movement of water (Walton, 1970).

6.2.1.4 Confined and unconfined aquifers

In an unconfined aquifer, groundwater only partially fills the aquifer and the upper surface of the water is free to rise and fall. The water table aquifer or surficial aquifer is considered to be the stratigraphically uppermost unconfined aquifer. Confined aquifers are completely filled with water and are overlain and underlain by confining beds. The impedance of flow through a confining bed can allow the water level to rise in a well above the top of the aquifer and possibly above the ground. This situation can result in wells that flow naturally. Confined aquifers are also known as artesian aquifers.

6.2.2 Development of a hydrogeologic framework [HOMS C67]

Information about aquifers and wells needs to be organized and integrated to determine the lateral and vertical extent of aquifers and confining beds. On that basis, determination of such characteristics as the direction of groundwater flow, and effects of hydrological boundaries, can be undertaken. The compilation of the lateral and vertical extent of aquifers and confining beds is commonly referred to as the hydrogeologic framework. To be useful, this concept of a framework needs to be based, as much as possible, on actual and quantitative data about the existence, orientation and extent of each aquifer and confining unit where applicable. Where

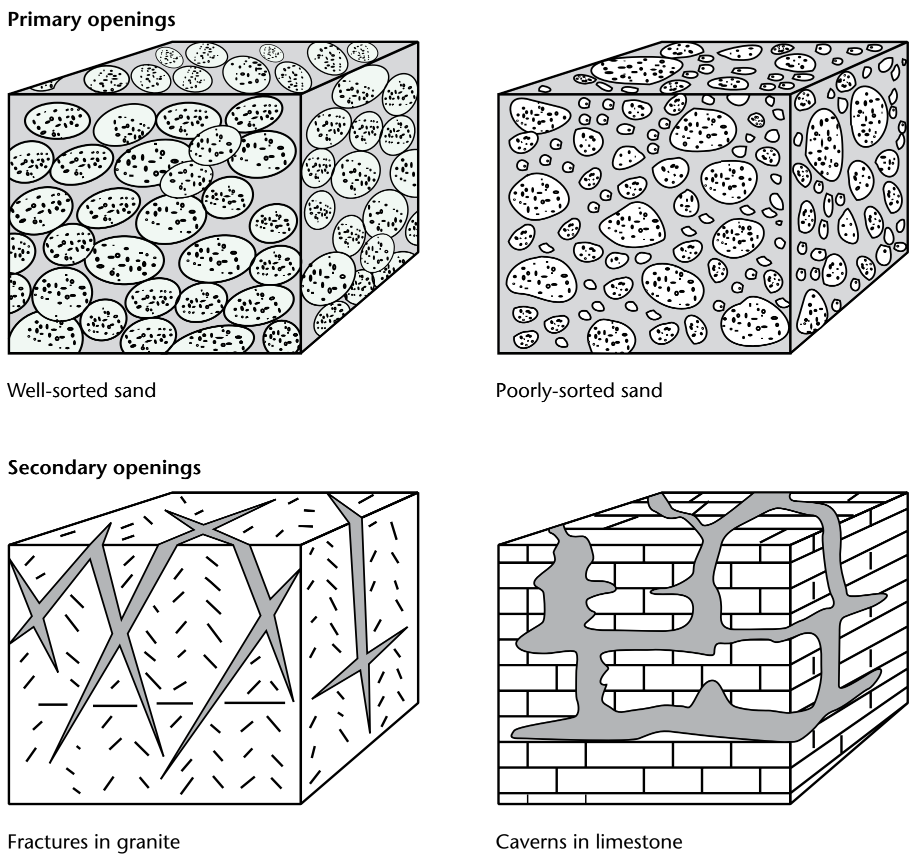


Figure I.6.1. Examples of water-bearing sediments of rocks with primary (intergranular is shown) and secondary (fractured and dissolution are shown) pore space (Heath, 1983) actual data are not available, one must rely on the conceptual knowledge of the subsurface conditions.

The development of a hydrogeological framework requires an accurate view, in a real sense, of the subsurface conditions. This can be accomplished in several direct and indirect ways. Direct methods include recovery of aquifer and confining bed material during the process of drilling, in the form of cuttings and core samples. Indirect methods include sensing earth properties using borehole or surface geophysical properties. A robust approach to collect these data involves combining all available methods, ultimately piecing together information to produce a detailed picture of the aquifer and confining unit extents, thicknesses, orientations and properties.

6.2.2.1 Well-drillers' and geologists' logs

Information about the nature of subsurface materials can be found in the records of construction of wells, mine shafts, tunnels and trenches, and from descriptions of geological outcrops and caves. Of particular usefulness to groundwater studies is the record of conditions encountered during the drilling of a well. This can be done either by the driller or a geologist on site monitoring conditions, by bringing the drill cuttings to the surface and examining any core samples taken. A driller's log or geologist's log (depending on who prepared the information) is a continuous narrative or recording of the type of material encountered during the drilling of a well. Additionally, these logs may contain remarks such as the relative ease or difficulty of drilling, relative pace of advancement and amount of water encountered.

6.2.2.2 Borehole geophysical methods

Borehole geophysical logging is a common approach to discerning subsurface conditions. A sonde is lowered by cable into a well or uncased borehole. As it is lowered or raised, a sensor on the sonde makes a measurement of a particular property or suite of properties. These data are then transmitted up the cable as an analog or digital signal that is then processed and recorded by equipment at the land surface. The data are typically shown in strip chart form, referred to as a log. These measurements provide more objectivity than that of a geologist's log of core or drill cutting samples, allowing for more consistency between multiple sources of data. Table I.6.1 provides a brief overview of the borehole geophysical methods commonly used in groundwater investigations: caliper, resistivity including spontaneous potential (SP), radiation logs including natural gamma, borehole temperature and borehole flow (Keys and MacCary, 1971).

6.2.2.3 Surface geophysical methods

Surface geophysical methods are used to collect data on subsurface conditions from the land surface along transects. Depending on the instrument, various types of probes are either placed in contact or close proximity with the ground surface to produce the measurements. There are four basic surface geophysical methods: seismic, electrical resistivity, gravimetric and magnetic (Zohdy and others, 1974). These are summarized in Table I.6.2. Accurate interpretation is greatly aided by core samples or bore hole geophysical data.

6.2.2.4 Hydrostratigraphic correlation

The integration of hydrogeological information collected from a network of individual wells, surface geophysical transects and geologic outcrops to formulate a large-scale, comprehensive understanding of the lateral extent and vertical nature of aquifers and confining beds in an area, referred to as the hydrogeological framework, relies on the process of correlating those data from different locations. Correlation, in this sense, can be defined as the demonstration of equivalency of units observed at different locations. The essence of the problem for the practitioner is to determine whether an aquifer identified at one location is connected or equivalent to one at other locations. When approaching this type of task, geologists focus on equivalent geologic age units or rock types. The hydrogeologist, however, must be concerned with equivalence from a hydraulic standpoint that may transcend rock type or geologic age. The reliability and accuracy of the resultant hydrogeological framework is directly related to the density of well and transect information. In areas of complex geology and topography, a relatively higher data density is required than in simpler areas.

The approach is to identify a preferably unique lithologic or hydraulic feature that is directly related to an aquifer or confining bed at one location. The feature could be, for example, the presence of a certain layer with a particular composition or colour within or oriented near the aquifer or confining bed under study. This is referred to as a marker unit. A unique signature of particular strata on a borehole geophysical log may be of use. Once identified in the data related to a particular well or location, data from nearby wells are examined for the existence of the same marker. Because of variations in geology and topography, the depth at which the

Table I.6.1. Summary of borehole geophysical methods commonly used in groundwater investigations

Type of log	*Measured property*	*Utility*	*Limitations*
Caliper	Diameter of borehole or well; relationship between the diameter of the hole and the depth	When used in an uncased borehole that shows the nature of the subsurface materials, the borehole is usually washed out to a larger diameter when poorly consolidated and non-cohesive materials are penetrated by the hole. In consolidated rock may reveal the location of fractured zones. May indicate the actual fracture, if large enough, or may indirectly indicate the presence of a fractured zone by an increase in the hole diameter resulting from the washout of friable material.	Caliper sonde has a maximum recordable diameter.
Temperature	Temperature; relationship of temperature to depth	Used to investigate source of water and inter-aquifer migration of water. Frequently recorded in conjunction with other logs, such as electrical logs, to facilitate determination of temperature compensation factors.	
Electrical	Single electrode electrical resistivity or conductivity measurements	Single electrode measurements yield spontaneous potential (SP) and resistance measurements. SP measurements are a record of the natural direct-current potentials that exist between subsurface materials and a static electrode at the surface that vary according to the nature of the beds traversed. The potential of an aquifer containing salty or brackish water is usually negative with respect to associated clay and shale, while that of a freshwater aquifer may be either positive or negative but of lesster amplitude than the salty water. Resistance measurements are a record of the variations in resistance between a uniform 60-Hz alternating current impressed on the sonde and a static electrode at the surface. Resistance varies from one material to another, so it can be used to determine formation boundaries, some characteristics of the individual beds, and sometimes a qualitative evaluation of the pore water. The single electrode log requires much less complex equipment than other types of methods. The data can usually be readily interpreted to show aquifer boundaries near to the correct levels, and the thickness of the formation if greater than about one third of a metre (1 foot). The true resistivity cannot be obtained, only the relative magnitude of the resistivity of each formation. With sufficient records from a uniform area, these relative magnitudes can sometimes be interpreted qualitatively regarding the quality of the water in the various aquifers.	Electrical logs cannot be run in cased holes. Satisfactory logs may not be obtained in the vicinity of power stations, switchyards and similar installations. The sonde must be in contact with the sidewall of the borehole. This may be difficult in boreholes of large diameter.
	Multiple electrode electrical resistivity or conductivity measurements	The multiple electrode log consists of SP, and two or more resistivity measurements. SP is identical to that of the single electrode log. The resistivity measurements show the variations of potential with depth of an imposed 60-Hz alternating current between electrodes spaced at varying distances apart on the sonde. Commonly used electrode spacings are: "short-normal", 0.4064 to 0.4572 m (16 to 18 in); "long-normal", 1.6256 m (64 in) and "long lateral", 5.6896 m (18 ft, 8 in). The radius of investigation about the hole varies with the spacing. The logging instrument consists of a sonde with three or more electrodes spaced at various distances, supported by a multiple conductor cable leading to the recorder, an alternating-current generator and an electrode attached to the recorder and grounded at the surface to complete SP resistivity circuit and cables, reels, winches and similar necessary equipment.	

Type of log	*Measured property*	*Utility*	*Limitations*
Radiation	Radiation from natural materials, usually gamma radiation	Nearly all rocks contain some radioactive material. Clay and shale are usually several times more radioactive than sandstone, limestone and dolomite. The gamma ray log is a curve relating depth to intensity of natural radiation and is especially valuable in detecting clays and other materials of high radiation. The radiation can be measured through the well casing, so these logs may be used to identify formation boundaries in a cased well. Also, they may be used in a dry hole whether cased or uncased.	
	Radiation transmitted through, from, or induced in the formation by, a source contained in the sonde, such as a neutron radiation	Neutron logging equipment contains a neutron radiation source in addition to a counter and can be used in determining the presence of water and saturated porosity.	Exreme care must be taken in the transportation, use and storage of the sonde containing the radioactive source. Governmental licensing may be required.
Borehore flow	Flow velocity; instantaneous or cumulative fluid velocity with depth	A mechanical or electronic flow meter senses variations in fluid velocity in the borehole. When water is pumped from the borehole during logging, variation in contribution of flow with depth can be determined. Can indicate primary sources (fracture zones, sand beds, etc.) of water to borehole. Flow meters based upon heat-pulse methods are best for low velocities.	Can only be used in fluid-filled boreholes or wells

marker is found may be different. If the marker is then identified, it may be postulated that the aquifer or confining bed at a similar relative location as identified in the original well is correlated, and thus may indicate that the aquifer or confining unit is continuous between the data points. If a particular marker is not identifiable at other nearby locations, the available data must be re-examined and additional attempts at correlation made. The inability to make a correlation and define continuity may indicate the presence of a fault, fold or some type of stratigraphic termination of the unit. Knowledge of the geology of the area and how it is likely to affect the continuity and areal variation in the character of aquifer and confining beds is essential. It may be necessary to consult with geologists familiar with the area in order to proceed with this task. It cannot be overstressed that geological complications and the possible non-uniqueness of a marker unit could lead to erroneous conclusions.

6.3 OBSERVATION WELLS

6.3.1 Installation of observation wells

Since ancient times, wells have been dug into water-bearing formations. Existing wells may be used to observe the static water table, provided that the well depth extends well below the expected range of the seasonal water level fluctuations and that the geological sequence is known. An examination should be made of existing wells to ascertain which, if any, would be suitable as observation wells. Existing pumped wells can also be incorporated into the network if the annular space between the outer casing of the well and the pump column allow free passage of a measuring tape or cable for measuring the water level. Whenever existing drilled or dug wells are used as observation wells, the water level in those wells should be measured after the pump has been turned off for a sufficient time to allow recovery of the water level in the well. Abstractions in the vicinity of an observation well should also be stopped for a time long enough for the depth of the cone of depression at the observation well to recover. If new wells are required, the cost makes it necessary to plan the network carefully.

In those parts of aquifers with only a few pumped or recharge wells that have non-overlapping cones of influence, it is generally preferable to drill special observation wells far enough from the functioning wells in order to avoid their influences. The principal advantage of dug wells is that they can be constructed with hand tools by local skilled

Table I.6.2. Summary of surface geophysical methods commonly used in groundwater investigations

Methods	*Property*	*Approach*	*Utility and limitations*
Seismic	The velocity of sound waves is measured. The propagation and velocity of seismic waves are dependent on the density and elasticity of the subsurface materials and increase with the degree of consolidation or cementation.	Sound waves are artificially generated using mechanical means such as blows from a hammer or small explosive charges. Seismic waves radiate from the point source, some travel through the surface layers, some are reflected from the surfaces of underlying materials having different physical properties, and others are refracted as they pass through the various layers. Different approaches are used for reflection and refractions data.	Can provide detailed definition of lithologic contacts if lithologies have contrasting seismic properties. Commonly used in groundwater studies to determine depth to bedrock below soil and unconsolidated sediment horizons. Computer processing of data collected using a gridded approach can provide very detailed 3-dimensional views.
Electrical resistivity	Earth materials can be differentiated by electrical resistivity. Electrical resistivity is also closely related to moisture content and its chemical characteristics, i.e., salinity. Dry gravel and sand have a higher resistivity than saturated gravel and sand; clay and shale have very low resistivity.	Direct or low frequency alternating current is sent through the ground between two metal electrodes. The current and resulting potential at other electrodes are measured. For depth soundings, the electrodes are moved farther and farther apart. As a result of these increasing distances, the current penetrates progressively deeper. The resistivity of a constantly increasing volume of earth is measured and a resistivity versus electrode spacing plot is obtained.	Applicable to large or small areas and extensively used in groundwater investigations because of response to moisture conditions. Equipment is readily portable and the method is commonly more acceptable than the blasting required for seismic methods. The resistivity method is not usable in the vicinity of power lines and metal structures.
Gravimetric	Gravity variations result from the contrast in density between subsurface materials of various types.	The force of gravity is measured at stations along a transect or grid pattern.	The equipment is light and portable, and the field progress is relatively rapid. Altitude corrections are required. The gravimetric survey is a valuable tool in investigating gross features such as depth to bedrock and old erosional features on bedrock, and other features such as buried intrusive bodies. This method is applicable to small or large areas. The results of this method are less detailed than those from seismic or resistivity methods
Magnetic	The magnetic properties of rocks affect the Earth's magnetic field; for example, many basalts are more magnetic than sediments or acid igneous rocks.	The strength and vertical component of the Earth's magnetic field is measured and plotted. Analysis of the results may indicate qualitatively the depth to bedrock and presence of buried dykes, sills and similar phenomena.	Magnetic methods are rapid and low cost for determining a limited amount of subsurface information. The results of this method are less detailed than those from seismic or resistivity methods. It is best suited for broadly outlining a groundwater basin.

labourers. Depths of 3 to 15 m are common, but such wells exist as deep as 50 m or more. Dug wells may be constructed with stone, brick or concrete blocks. To provide passage of the water from the aquifer into the well, some of the joints are left open and inside corners of the blocks or bricks are broken off.

When the excavation reaches the water table, it is necessary to use a pump to prevent water in the well from interfering with further digging. If the quantity of water entering the well is greater than the pump capacity, it is possible to deepen the well by drilling. The technique of excavating wells to the water table and then deepening the well by drilling is common practice in many parts of the world. The finished well should be protected from rain, flood or seepage of surface waters, which might pollute the water in the well and hence the aquifer. The masonry should extend at least 0.5 m above ground level. The top of the well should be provided with a watertight cover and a locked door for safety purposes. A reference mark for measuring depth to water (levelled to a common datum) should be clearly marked near the top of the well.

Where groundwater can be reached at depths of 5 to 15 m, hand boring may be practical for constructing observation wells. In clays and some sandy looms, hand augers can be used to bore a hole 50 to 200 mm in diameter that will not collapse if left unsupported. To overcome the difficulty of boring below the water table in loose sand, a casing pipe is lowered to the bottom of the hole, and boring is continued with a smaller diameter auger inside the casing. The material may also be removed by a bailer to make the hole deeper.

In areas where the geological formations are known in advance and which consist of unconsolidated sand, silt or clay, small-diameter observation wells up to 10 m in depth can be constructed by the drive-point method. These wells are constructed by driving into the ground a drive point fitted to the lower end of sections of steel a pipe. One section is a strainer (filter) consisting of a perforated pipe wrapped with wire mesh protected with a perforated brass sheet. Driven wells, 35 to 50 mm in diameter, are suitable for observation purposes.

To penetrate deep aquifers, drilled wells are constructed by the rotary or percussion-tool methods. Because drilling small-diameter wells is cheaper, observation wells with inner diameters ranging from 50 to 150 mm are common. Hydraulic rotary drilling, with bits ranging in diameter from 115 to 165 mm, is often used. The rotary method is faster than the percussion method in sedimentary formations except in formations containing cobbles, chert or boulders. Because the rock cuttings are removed from the hole in a continuous flow of the drilling fluid, samples of the formations can be obtained at regular intervals. This is done by drilling down to the sampling depth, circulating the drilling fluid until all cuttings are flushed from the system, and drilling through the sample interval and removing the cuttings for the sample. Experienced hydrogeologists and drillers can frequently identify changes in formation characteristics and the need for additional samples by keeping watch on the speed and efficiency of the drill.

The percussion-tool method is preferred for drilling creviced-rock formations or other highly permeable material. The normal diameter of the well drilled by percussion methods ranges from 100 to 200 mm to allow for the observation well casing to be 50 to 150 mm in diameter. The percussion-tool method allows the collection of samples of the excavated material from which a description of the geological formations encountered can be obtained.

In many cases, the aquifer under study is a confined aquifer separated by a much less permeable layer from other aquifers. Upper aquifers penetrated during drilling must be isolated from the aquifer under study by a procedure known as sealing (or grouting). The grout may be clay or a fluid mixture of cement and water of a consistency that can be forced through grout pipes and placed as required. Grouting and sealing the casing in observation wells are carried out for the following reasons:

(a) To prevent seepage of polluted surface water to the aquifer along the outside of the casing;
(b) To seal out water in a water-bearing formation above the aquifer under study;
(c) To make the casing tight in a drilled hole that is larger than the casing.

The upper 3 m of the well should be sealed with impervious material. To isolate an upper aquifer, the seal of impervious material should not be less than 3 m long extending above the impervious layer between the aquifers.

In consolidated rock formations, observation wells may be drilled and completed without casings. Figure I.6.2 shows a completed well in a rock formation. The drilled hole should be cleaned of fine particles and as much of the drilling mud as possible. This cleaning should be done by pumping or bailing water from the well until the water clears.

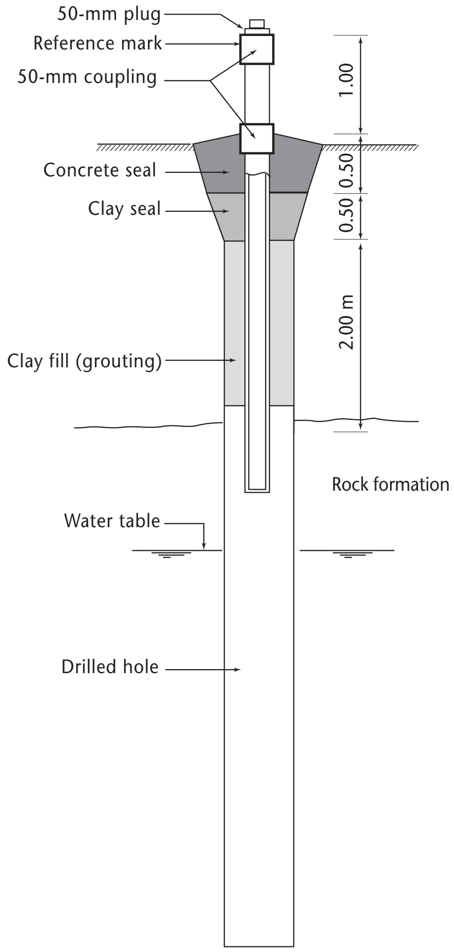


Figure I.6.2. Observation well in a rock formation

Casing is installed in wells in unconsolidated deposits. The main features of such an installation are shown in Figure I.6.3. It should be noted that:

(a) The normal diameter of the casing in observation wells is 50 mm;
(b) At the bottom of the hole, a blank length of casing (plugged at the lower end) is installed. This blank casing should be at least 3 m long and serves to collect sediment from the perforated part of the casing. This is referred to as the debris sump;
(c) A perforated or slotted length of casing, known as the strainer or screen, is secured to the debris sump and ensures free interchange of water between the aquifer and the observation well. The screen should be about 2 m long;
(d) The blank casing above the screen should be long enough to protrude above ground level by about 1 m. The top of this blank casing forms a convenient reference point for the datum of the observation programme;
(e) Centring spiders ensure proper positioning of the screen column in the drilled hole;
(f) In aquifers with fine or silty sand, the mesh jacket and slotted casing should be protected from clogging by fine material. Graded coarse material should be packed around the screen to fill the annular space between the screen and the wall of the drilled hole. In the case of a 150-mm hole and 50-mm casing pipe, the normal thickness of the gravel packing should be approximately 45 mm but should not be less than 30 mm thick. The material may be river gravel, ranging from 1 to 4 mm in diameter. The gravel should be placed through a guide pipe of small diameter, introduced into the space between the casing and the wall of the hole. The amount of gravel that is used should be sufficient to fill both the annular space and the bottom of the hole, that is, the whole length of the debris sump as well as the length of the screen and at least 500 mm of the casing above the perforation;
(g) At ground level, a pit should be excavated around the casing. The recommended dimensions of the pit are 800 x 800 mm at ground level going down as a cone with a lower base approximately 400 x 400 mm at a depth of 1 m. Clay grout should be placed around the casing to a depth of 2 m to make the casing tight in the drilled hole and to prevent seepage of polluted surface water into the aquifer. The pit should be filled partly by a clay seal and the upper part with concrete. The concrete should be poured to fill the pit and form a cone around the casing to drain precipitation and drainage water away from the well;
(h) The upper end of the protruding casing above the concrete cone should be closed for security purposes. Figure I.6.3 shows details of the installation of the well. The outer 50-mm plug is screwed to the casing by using a special tool, and the iron plug inside the casing can be lifted by the observer using a strong magnet.

The part of the casing extending above ground level should be painted a bright colour to make it easy to detect from a distance. Depth-to-water table is measured from the edge of the casing (after removal of plugs). This reference mark should be levelled to a common datum for the area under investigation.

Observation wells should be maintained by the agency responsible for the monitoring or investigation. The area around the well should be kept clear of vegetation and debris. A brass disc may be anchored in the concrete seal at ground level bearing the label "observation well" and the name of the agency or organization. This brass disc may also serve as a benchmark for survey purposes.

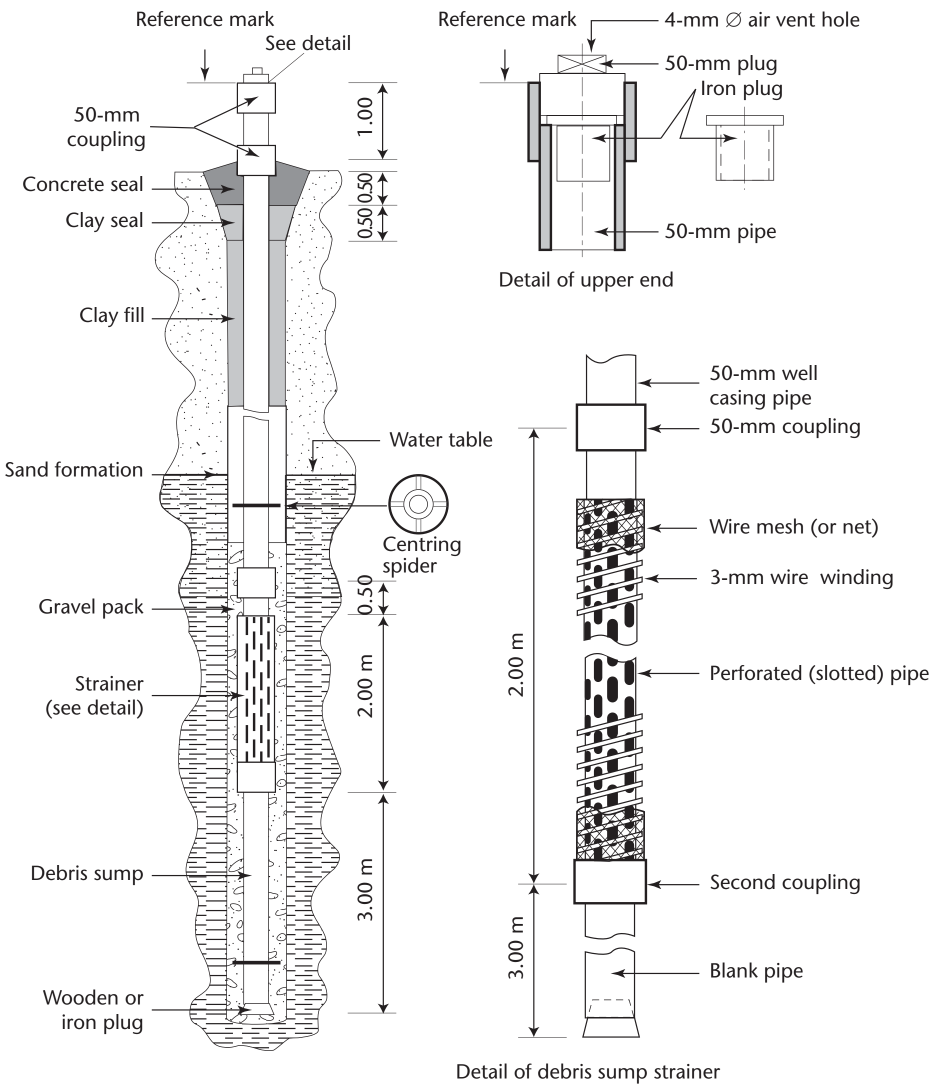


Figure I.6.3. Observation well in a sand formation

Should the protruding part of the well casing be replaced because of damage, then the levelling of the new reference mark is simplified by the proximity of the benchmark. Pre-existing wells that serve as observation wells should be maintained and labelled in the same manner as wells drilled specifically as observation wells.

In the area under study, several aquifers at different levels may be separated by impervious layers of different thicknesses. In such cases, it is advisable to observe the following routine (Figure I.6.4):

(a) A large diameter well should be drilled, by the percussion-tool method, until the lowest aquifer is penetrated;
(b) A small-diameter observation pipe with a proper screen is installed in the lowest aquifer;
(c) The outer casing is lifted to reach the bottom of the impervious layer above this aquifer. A gravel pack is then placed around the screen of the observation pipe and the top end of the lower aquifer is then sealed by cement or other suitable grout;
(d) Another small-diameter observation pipe with a screen is then lowered to the next higher aquifer that is again gravel packed and sealed off by grouting from the aquifer lying above it;
(e) Steps (c) and (d) are repeated for each additional aquifer that is penetrated.

In this case, the sealing of each of the aquifers should be done very carefully to prevent damage to the water-bearing formation either by the interchange of water with different chemical properties or by loss of artesian pressure. If the geology of the area is well known and the depth to each of the aquifers can be predicted, it may be advisable to drill and construct a separate well in each aquifer.

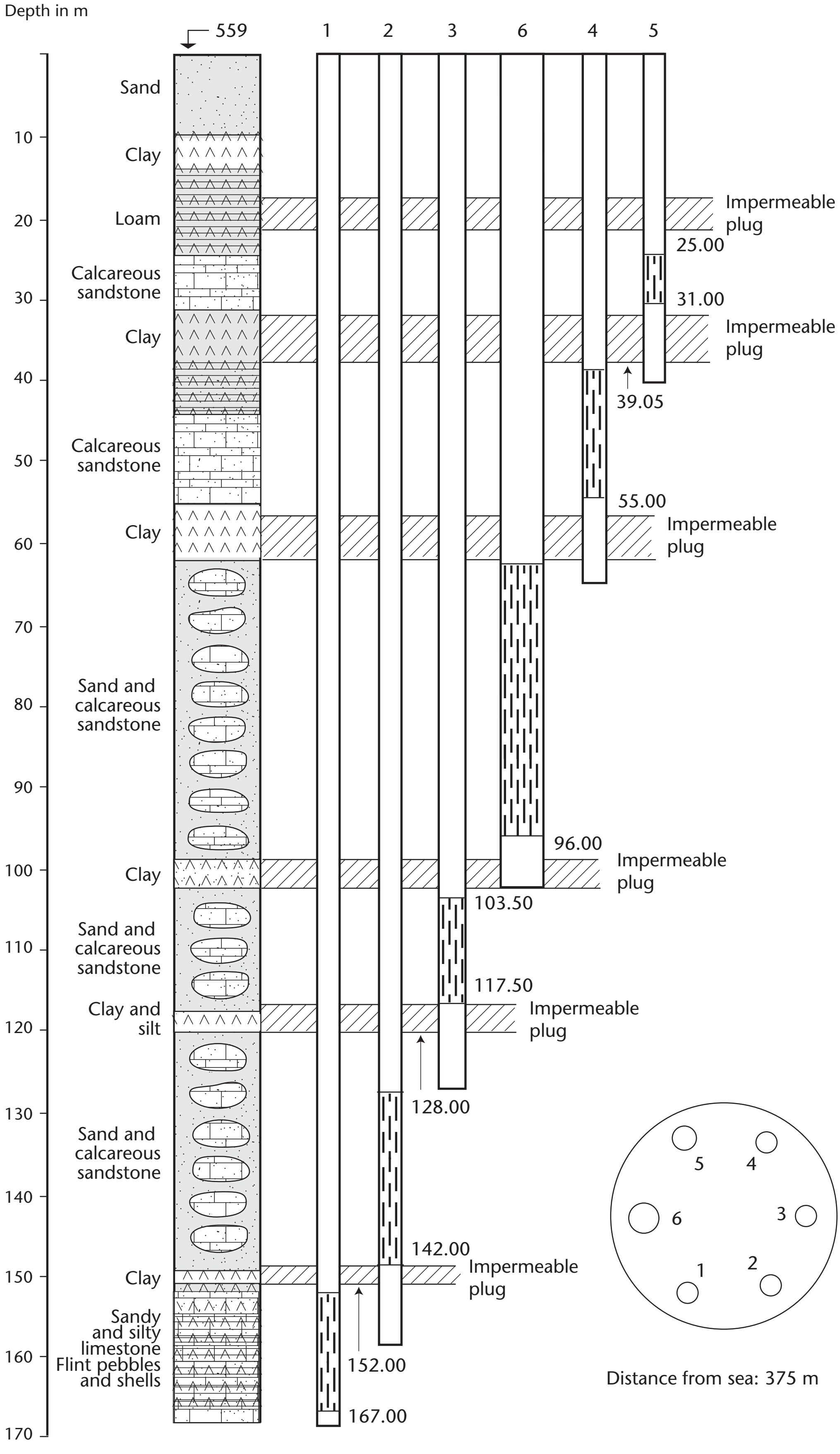


Figure I.6.4. Schematic vertical cross-section of an observation well in a multiple aquifer system

Such boreholes are spaced only a few metres apart. This procedure may prove to be more economical.

Where privately owned pumping wells are incorporated into the observation network, arrangements could be made for such wells to be maintained by the owners.

6.3.2 Testing of observation wells

The response of an observation well to water-level changes in the aquifer should be tested immediately after the construction of the well. A simple test for small-diameter observation wells is performed by observing the recharge of a known volume of water injected into the well, and measuring the subsequent decline of water level. For productive wells, the initial slug of water should be dissipated within three hours to within 5 mm of the original water level. If the decline of the water level is too slow, the well must be developed to remove clogging of the screen or slots and to remove as much as possible of the fine materials in the formation or the pack around the well. Development is achieved by alternately inducing movement of the groundwater to and from the well.

After cleaning the well, the depth from the reference mark to the bottom of the well should be measured. This measurement, compared with the total length of casing, shows the quantity of sediment in the debris sump. This test should be repeated occasionally in observation wells to check the performance of the screen. If the measurement of the bottom of the well shows that debris fills the whole column of the sump and the screen, then the water level in the well might not represent the true potentiometric head in the aquifer. If the reliability of an observation well is questionable, there are a number of technical procedures that can be used to make the well function adequately again.

6.3.3 Sealing and filling of abandoned wells

Observation wells and pumping wells may be abandoned for the following reasons:
(a) Failure to produce either the desired quantity or quality of water;
(b) Drilling of a new well to replace an existing one;
(c) Observation wells that are no longer needed for investigative purposes.

In all these cases, the wells should be closed or destroyed in such a way that they will not act as channels for the interchange of water between aquifers when such interchange will result in significant deterioration of the quality of water in the aquifers penetrated.

Filling and sealing of an abandoned well should be performed as follows:
(a) Sand or other suitable inorganic material should be placed in the well at the levels of the formations where impervious sealing material is not required;
(b) Impervious inorganic material must be placed at the levels of confining formations to prevent water interchange between different aquifers or loss of artesian pressure. This confining material must be placed at a distance of at least 3 m in either direction (below and above the line of contact between the aquifer and the aquiclude);
(c) When the boundaries of the various formations are unknown, alternate layers of impervious and previous material should be placed in the well;
(d) Fine-grained material should not be used as fill material for creviced or fractured rock formations. Cement or concrete grout should be used to seal the well in these strata. If these formations extend to considerable depth, alternate layers of coarse fill and concrete grout should be used to fill the well;
(e) In all cases, the upper 5 m of the well should be sealed with inorganic impervious material.

6.4 GROUNDWATER-LEVEL MEASUREMENTS AND OBSERVATION WELL NETWORKS [HOMS C65, E65, G10]

6.4.1 Instruments and methods of observation

Direct measurement of groundwater levels in observation wells can be accomplished either manually or with automatic recording instruments. The following descriptions relate to principles of measurement of groundwater levels. The references include descriptions of certain instruments.

6.4.1.1 Manually operated instruments

The most common manual method is by suspending a weighted line (for example, a graduated flexible steel or plastic-coated tape or cable) from a defined point at the surface, usually at the well head, to a point below the groundwater level. On removal of the tape, the position of the groundwater level is defined by subtracting the length of that part of the tape which has been submerged from the total length of the tape suspended in the well. This wetted part can be identified more clearly by covering the lower part of the tape with chalk before each measurement. Colour changing pastes have been used to indicate submergence below water, although any such substance containing toxic chemicals should be avoided. Several trial observations may have to be made unless the approximate depth-to-water surface is known before measurement. As depth-to-water level increases and the length of tape to be used increases, the weight and cumbersome nature of the instrument may be difficult to overcome. Depths-to-water surface of up to 50 m can be measured with ease and up to 100 m or more with greater difficulty. At these greater depths, steel tapes of narrower widths or lightweight plastic-coated tapes can be used. Depths-to-water level can be measured to within a few milimetres but the accuracy of measurement by most methods is usually dependent on the depth.

Inertial instruments have been developed so that a weight attached to the end of a cable falls at constant velocity under gravity from a portable instrument located at the surface. On striking water, a braking mechanism automatically prevents further fall. The length of free cable, equivalent to the depth-to-water level, is noted on a revolution counter. The system is capable of measurement within 1 cm, although with an experienced operator this may be reduced to 0.5 cm.

The double-electrode system employs two small adjacent electrodes incorporated into a single unit of 10 to 20 cm in length at the end of the cable. The system also includes a battery and an electrical current meter. Current flows through the system when the electrodes are immersed in water. The cable must have negligible stretch and plastic-coated cables are preferred to rubber sheathed cables. The cable is calibrated with adhesive tape or markers at fixed intervals of 1 or 2 m. The exact depth-to-water level is measured by steel rule to the nearest marker on the cable. Measurement of water level down to about 150 m can be undertaken with ease and up to 300 m and more, with some difficulty. The limits to depths of measurement are essentially associated with the length of the electrical cable, the design of the electrical circuitry, the weight of the equipment (particularly the suspended cable), and the effort in winding-out and winding-in the cable. The degree of accuracy of measurement depends on the operator's skill and on the accuracy with which markers are fixed to the cable. The fixed markers should be calibrated and the electrical circuitry should be checked at regular intervals, preferably before and after each series of observations. This system is very useful when repeated measurements of water levels are made at frequent intervals during pumping tests.

In deep wells that require cable lengths in the order of 500 m, the accuracy of the measurement is approximately ±15 cm. However, measurements of change in water level, where the cable is left suspended in the wells with the sensor near the water table, are reported to the nearest millimetre.

The electrochemical effect of two dissimilar metals immersed in water can be applied to manual measuring devices. This results in no battery being required for an electrical current supply. Measurable current flow can be produced by the immersion in most groundwaters either of two electrodes (for example, magnesium and brass) incorporated into a single unit, or of a single electrode (magnesium) with a steel earth pin at the surface. Because of the small currents generated, a microammeter is required as an indicator. The single-electrode system can be incorporated into a graduated steel tape or into a plastic-coated tape with a single conductor cable assembly. The accuracy of measurement depends upon the graduations on the tape, but readings to within 0.5 cm can be readily achieved.

A float linked to a counterweight by a cable that runs over a pulley can be installed permanently at an observation well. Changes in water level are indicated by changes in the level of the counterweight or of a fixed marker on the cable. A direct reading scale can be attached to the pulley. The method is generally limited to small ranges in fluctuation.

When artesian groundwater flows at the surface, an airtight seal has to be fixed to the well head before pressure measurements can be undertaken. The pressure surface (or the equivalent water level) can be measured by installing a pressure gauge (visual observations or coupled to a recording system) or, where practicable, by observing the water level inside a narrow-diameter extension tube made of glass or plastic, fitted through the seal directly above the well head. Where freezing may occur, oil or an immiscible antifreeze solution should be added to the water surface.

All manual measuring devices require careful handling and maintenance at frequent intervals so that their efficiency is not seriously impaired. The accurate measurement of groundwater level by manual methods depends on the skill of a trained operator.

6.4.1.2 Automatic recording instruments

Many different types of continuous, automatically operated water-level recorders are in use. Although a recorder can be designed for an individual installation, emphasis should be placed on versatility. Instruments should be portable, easily installed, and capable both of recording under a wide variety of climatic conditions and of operating unattended for varying periods of time. They should also have the facility to measure ranges in groundwater fluctuation at different recording speeds by means of interchangeable gears for time and water-level scales. Thus, one basic instrument, with minimum ancillary equipment, can be used over a period of time at a number of observation wells and over a range of groundwater fluctuations.

Experience has shown that the most suitable analogue recorder currently in operation is float actuated. The hydrograph is traced either onto a chart fixed to a horizontal or vertical drum or onto a continuous strip chart. To obtain the best results with maximum sensitivity, the diameter of the float must be as large as practicable with minimum weight of supporting cable and counterweight. As a generalization, the float diameter should not be less than about 12 cm, although modifications to certain types of recorders permit using smaller-diameter floats. The recording drum or pen can be driven by a spring or by an electrical clock. The record can be obtained by pen or by weighted stylus on specially prepared paper. By means of interchangeable gears, the ratio of drum movement to water-level fluctuation can be varied and reductions in the recording of changes in groundwater levels commonly range from 1:1 up to 1:20. The tracing speed varies according to the make of instrument, but the gear ratios are usually so adapted that the full width of a chart corresponds to periods of 1, 2, 3, 4, 5, 16 or 32 days. Some strip-chart recorders can operate in excess of six months.

Where float-actuated recorders have lengths of calibrated tape installed, a direct reading of the depth (or relative depth) to water level should be noted at the beginning and at the end of each hydrograph when charts are changed. This level should be checked against manual observations at regular intervals. The accuracy of reading intermediate levels on the chart depends primarily upon the ratio of drum movement to groundwater-level fluctuations, and therefore is related to the gear ratios.

The continuous measurement of groundwater level in small-diameter wells presents problems because a float-actuated system has severe limitations as the diameter of the float decreases. Miniature floats or electrical probes of small diameter have been developed to follow changes in water level. The motivating force is commonly provided by a servomechanism (spring or electrically driven) located in the equipment at the surface. The small float is suspended in the well on a cable stored on a motor-driven reel that is attached to the recorder pulley. In the balanced (equilibrium) position, the servomotor is switched off. When the water table in the well moves down, the float remains in the same position and its added weight unbalances the cable (or wire), causing the reel to move and, by this small movement, causing an electrical contact to start the small motor. The reel operated by this motor releases the cable until a new equilibrium is reached, and the motor is switched off. When the water level in the well rises, the cable is retrieved on the reel until the new equilibrium is reached. This movement of the cable on or off the reel actuates the pen of the recorder, and water-level fluctuations are recorded. The servo-motor, which rotates the cable reel, may be activated by an electrical probe at the water table in the well. This attachment consists of a weighted probe suspended in the well by an electric cable stored on the motor-driven reel of the water-level recorder. Water-level fluctuations in the well cause a change in pressure that is transmitted by a membrane to the pressure switch in the probe. The switch actuates the reel motor, and the probe is raised or lowered, as required, until it reaches a neutral position at the new water level. Float and float-line friction against the well casing can affect the recording accuracy of water-level recorders, especially in deep wells.

The largest error is caused by float line drag against the well casing. A small-diameter float may be provided with sliding rollers (fixed at both ends of the float) to reduce friction against the casing. Round discs (spiders) with small rollers attached to the cable at 10-m intervals keep the cable away from the well casing and significantly reduce friction. Figure I.6.5 shows some details of this device. The sensitivity of water-level recorders with attachments for small-diameter floats may be 6 mm of water-level movement, but the switching mechanism of the float may not be this sensitive. The accuracy of the mechanism is decreased by weak batteries. To avoid this effect, the batteries should be replaced after a maximum of 60 to 90 days of normal use.

An alternative approach is an electrode suspended in an observation well at a fixed distance above the water level. At specified time intervals, the probe electrically senses the water level and the movement occurs by a servo-mechanism at the surface. The depth-to-water level is then recorded. This system can be adapted to various recording systems.

Although these instruments have particular value in small-diameter wells, they can be installed in wells of any diameter greater than the working diameter of the probe.

Analogue-to-digital stage recorders used for stream discharge measurements can be readily adapted to the measurement of groundwater levels.

Automatic recording instruments require comprehensive and prompt maintenance otherwise records will be lost. Simple repairs can be undertaken on the site, but for more serious faults, the instrument should be replaced and repairs should be undertaken in the laboratory or workshop. Adequate protection from extremes of climatic conditions, accidental damage and vandalism should be provided for these instruments. Clockwork is particularly susceptible to high humidity, thus adequate ventilation is essential, and the use of a desiccant may be desirable under certain conditions.

In some research projects, instruments have been designed to measure fluctuations in groundwater level by more sophisticated techniques than those described above, such as capacitance probes, pressure transducers, strain gauges, and sonic and high-frequency wave reflection techniques. At present, these instruments are expensive when compared with float-actuated recorders, have limitations in application, particularly in the range of

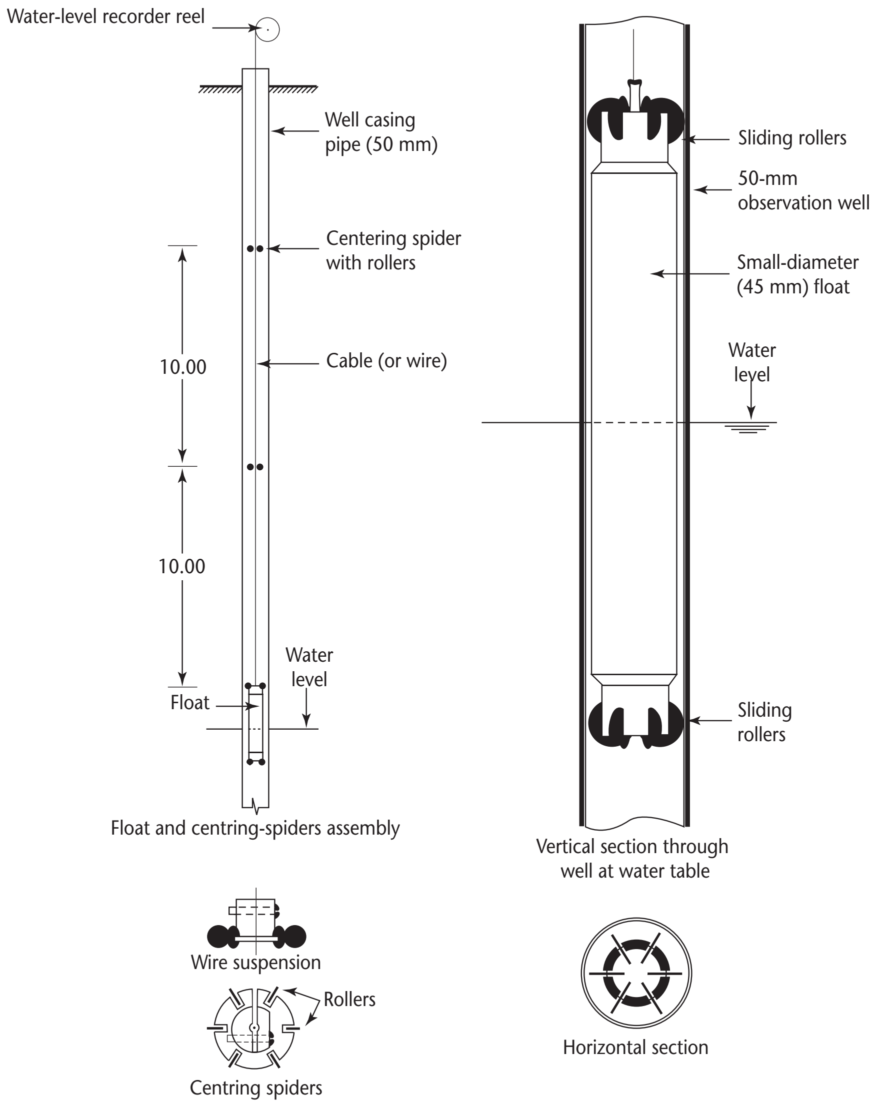


Figure I.6.5. Small-diameter float with sliding rollers in an observation well

groundwater fluctuations, and commonly require advanced maintenance facilities. Float-actuated systems are considered more reliable and more versatile than any other method, although future developments in instrument techniques in the sensor, transducer and recording fields may provide other instruments of comparable or better performance at competitive costs.

6.4.1.3 Observation well network

An understanding of the groundwater conditions relies on the hydrogeological information available; the greater the volume of this information the better the understanding as regards the aquifers, water levels, hydraulic gradients, flow velocity and direction and water quality, among others. Data on potentiometric (piezometric) heads and water quality are obtained from measurements at observation wells and analysis of groundwater samples. The density of the observation well network is usually planned on the data requirement but in reality is based on the resources available for well construction. Drilling of observation wells is one of the main costs in groundwater studies. The use of existing wells provides an effective low-cost option Therefore, in the development of an observation network, existing wells in the study area should be carefully selected and supplemented with new wells drilled and specially constructed for the purposes of the study.

6.4.1.4 Water-level fluctuations

Fluctuations in groundwater levels reflect changes in groundwater storage within aquifers. Two main groups of fluctuation can be identified: long-term, such as those caused by seasonal changes in natural replenishment and persistent pumping, and short-term, for example, those caused by the effects of brief periods of intermittent pumping and tidal and barometric changes. Because groundwater levels generally respond rather slowly to external changes, continuous records from water-level recorders are often not necessary. Systematic observations at fixed time intervals are frequently adequate for the purposes of most national networks. Where fluctuations are rapid, a continuous record is desirable, at least until the nature of such fluctuations has been resolved.

6.4.1.5 Water-level maps

A useful approach to organize and coordinate water-level measurements from a network of observation wells is to produce an accurate map of well locations and then to contour the water-level data available at each well. Two types of maps can be produced, based on either the depth-to-water level measured in a well from the land surface or the elevation of the water level in the well relative to an established datum, such as sea level. Generally, these maps are produced on a single aquifer basis using data collected on a synoptic basis for a discrete period of time, to the extent possible. Seasonal fluctuations in water levels, changes in water levels over a period of years as a result of pumping, and similar effects can cause disparate variations if a mixture of data is used.

6.4.1.5.1 *Depth-to-water maps*

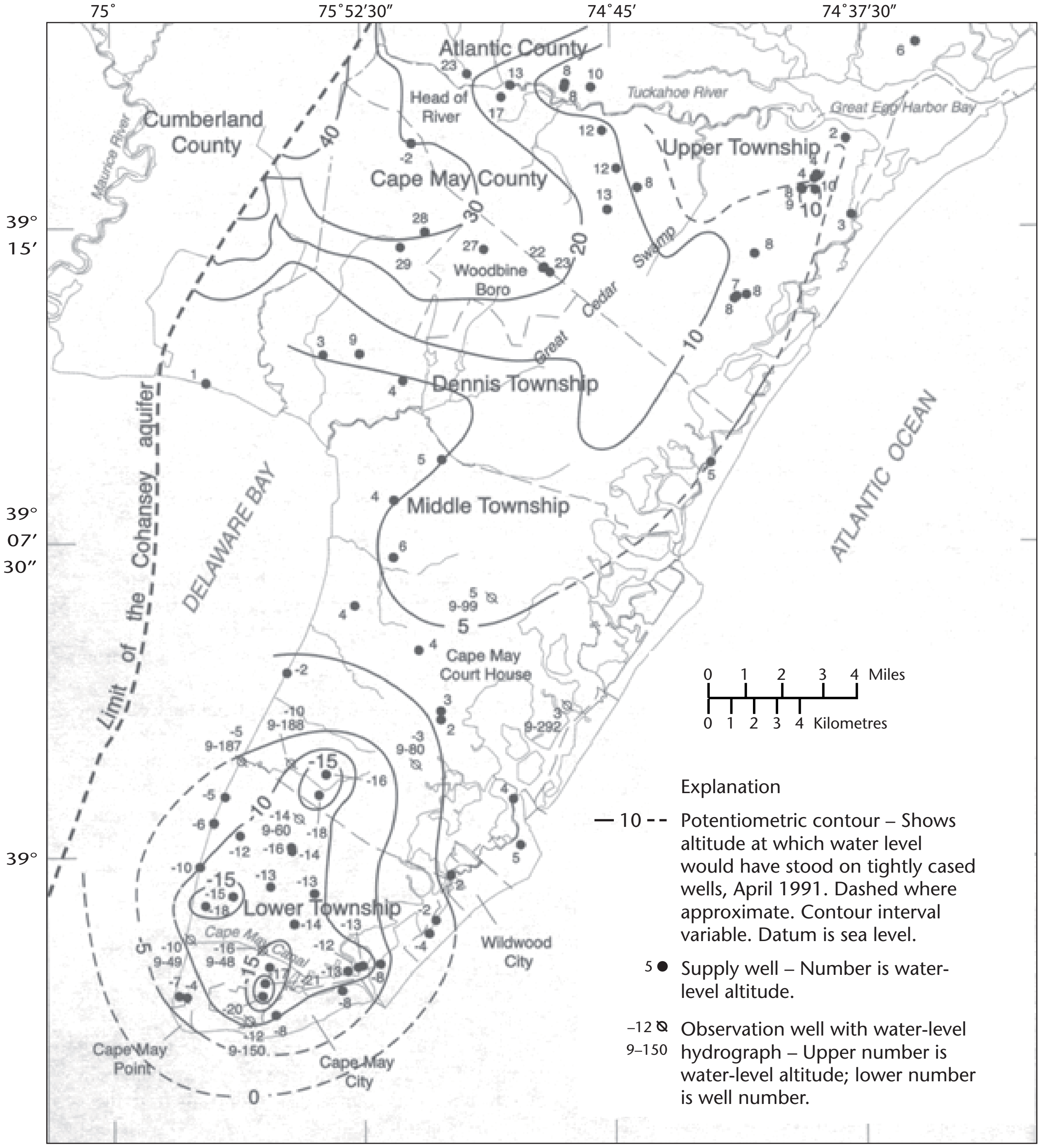
The simplest map to produce is based on the measurement of the depth-to-water level in a well relative to land surface. This is referred to as a depth-to-water map. Maps of this type provide an indication as to the necessary depth to drill to encounter water, which can be useful in planning future resource development projects. A map based on the difference in depth to water between two measurement periods could be used to show, for example, the areal variation of seasonal fluctuations. A significant limitation of a depth-to-water map is that it cannot be used to establish the possible direction of groundwater flow because of the independent variation of topographic elevation.

6.4.1.5.2 *Potentiometric (Piezometric) surface maps/water table maps, potentiometric cross-sections*

A water-level map based on the elevation of the water level in a well relative to a common datum, such as sea level, is referred to as a potentiometric surface map (Figure I.6.6). When produced for the water table or the surficial aquifer, this map may be referred to as a water table map. This type of map is more difficult to produce than a depth-to-water map because it requires accurate elevation data for the measuring point at each observation well. Each depth-to-water measurement collected must be subtracted from the elevation of the measuring point relative to the datum to produce the necessary data. A significant benefit of this type of map is that it can be used to infer the direction of groundwater flow in many cases.

The accuracy of the map is dependent on the accuracy of the measuring point elevations. The most accurate maps will be based on elevations that have been established using formal, high-order land-surveying practices. This can entail substantial effort and expense. Several alternatives exist. These are the use of elevations determined from topographic maps, if they exist for the study area, or the use of an altimeter or GPS unit to provide elevation information. Any report showing a potentiometric surface map must have an indication of the source and accuracy of the elevation data.

Maps portray information in two spatial dimensions. As groundwater flows in three dimensions, another view is required to understand the potentiometric data in all directions. With potentiometric surface data from multiple aquifers or depths at each or many data sites of an observation well network it is possible to produce potentiometric cross-sections (Figure I.6.7). Potentiometric cross-sections are an accurately scaled drawing of well locations along a selected transect indicating depth on the vertical axis and lateral distance on the horizontal axis. A particular well's water level is plotted with respect



Based on United States Geological Survey digital data, 1:100 000, 1983. Universal Transverse Mercator Projection, Zone 18.

Figure I.6.6. Example of a potentiometric surface map (Lacombe and Carleton, 2002) to the depth axis. It is customary to also indicate a well's open interval on the diagram. These cross-sections can show the relative differences in water levels between aquifers and can be very useful in determining the vertical direction of groundwater flow.

6.4.1.6 Well discharge measurements

Pumping wells can have a significant effect on groundwater flow and levels. The measurement of a pumping well's discharge is important to facilitate comparisons of drawdown effects and for quantitative analysis. The common methods of measurement include the timed fill of a calibrated volume, flow meters and orifice discharge measurements (American Society for Testing and Materials International: ASTM D5737-95, 2000). The discharge of a pumping well will vary with changes in groundwater level. This may require repeated measurements to keep track of the rate. When a pump is turned on, the water level in a well drops accordingly, thereby causing the discharge to vary. Stability in pumping rate is generally reached in a matter of minutes or hours. Water-level changes that could affect pumping rate can also occur as a result of recharge from precipitation or changes in pumping of nearby wells. Changes in the configuration of the discharge plumbing, such as pipe length or diameter to a point of free discharge, can also have an effect and should be avoided. These flow measuring procedures can also be applied to measuring the discharge of a naturally flowing well.

6.4.1.6.1 *Calibrated volume*

The simplest method of determining the rate of discharge from a pumping well is by measuring the time the pumped discharge takes to fill a calibrated volume. Dividing that volume by the time yields the unit pumping rate. The accuracy of the measurement is dependent on the accuracy of the time measurement and the logistics of filling the calibrated volume. For relatively low pumping, this measurement is easily handled using a bucket or drum with calibration marks. However, at relatively high discharge rates, a measurement of this type may require some logistical planning in order to direct the discharge into an appropriate vessel or container for measurement. The force of the discharge stream or the presence of entrained air can complicate the situation.

6.4.1.6.2 *Flow meters*

A variety of mechanical, electrical and electronic meters have been developed to measure fluid flow inside a pipe. Many of these can be easily used to measure the rate of discharge from a pumped well. Some meters provide an instantaneous discharge reading while others compile a totalized reading of flow. Either type can be used. Some versions have

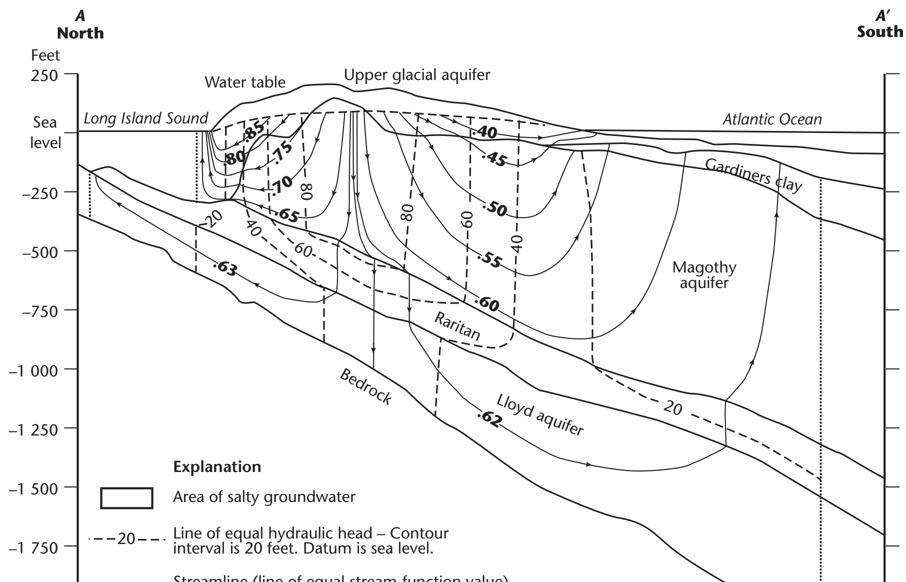


Figure I.6.7. Example of a potentiometric cross-section indicating the vertical head relation between several aquifers (Buxton and Smolensky, 1999) the ability to interface with electronic data logging equipment. The appropriate instructions from the manufacturer should be followed to ensure an accurate measurement. Flow meter readings can be sensitive to the presence of turbulence in the flow. Operational instructions may require that a prescribed length of straight pipe precede the meter to minimize turbulence effects. Additionally, a full-pipe condition is required for most meters. When a relatively large-diameter pipe serves as a conduit for a relatively small discharge rate, the pipe may not be entirely filled with water. To maintain a full-pipe condition, a valve positioned downstream of the meter can be partially closed. Entrained air or sediment in the flow can possibly affect the accuracy of the reading and in the case of sediment, can possibly damage the sensing equipment.

6.4.1.6.3 *Orifice discharge*

Another common method for measuring the discharge from a pumped well is the use of a free discharge pipe orifice. An orifice is an opening in a plate of specified diameter and beveled-edge configuration that is fixed, usually by a flange, over the end of a horizontal discharge pipe (Figure I.6.8). The diameter of the orifice should be smaller than the diameter of the pipe. The water flowing through the discharge pipe is allowed to freely exit through the orifice. As the orifice somewhat restricts the flow, a back pressure results that is proportional to the flow. This pressure is measured, usually by direct measurement of a manometer tube, located about three pipe diameters upstream of the orifice and at the centre line of the pipe. The measured pressure value, the discharge pipe diameter and the orifice diameter are used to enter an "orifice table" to determine the flow. These tables and the specific requirements for the design of the discharge pipe and orifice can be found in ISO 5167-2 (2003*b*).

6.4.1.6.4 *Specific capacity*

A useful index to facilitate a comparison of water-level drawdown and discharge rates among wells is specific capacity. This parameter is defined as the well's steady-state discharge rate divided by the drawdown in the pumped well from its non-pumping state to the steady-state pumping level ($m^3 s^{-1} m^{-1}$).

6.4.1.7 **Drawdown from a pumped well; cone of depression**

The movement of water from an aquifer into a pumped well is impeded by frictional resistance with the aquifer matrix. This resistance results in a lowering or decline in the water level in a well being pumped and in the adjacent parts of the aquifer. This decline is referred to as drawdown. Drawdown is defined as the change in water level from a static pre-pumping level to a pumping level. Water-level decline resulting from pumpage diminishes non-linearly with distance away from the pumped well. The resulting shape is referred to as a cone of depression. The drawdown and resulting cone of depression in an unconfined aquifer is the result of gravity drainage and desaturation of part of the aquifer in the vicinity of the well (Figure I.6.9 (left)). In a confined aquifer, the cone of depression is manifested as a decline in the potentiometric (piezometric) surface, but does not represent a desaturation of the aquifer (Figure I.6.9 (right)). The relation between pumping rate, water-level decline and distance from the well is a function of the prevailing permeability of the aquifer material and the availability of sources of recharge.

6.5 AQUIFER AND CONFINING-BED HYDRAULIC PROPERTIES

Quantitative analysis of groundwater flow involves understanding the range and variability of key hydraulic parameters. Many data-collection networks and surveys are organized to collect data for the purpose of determining aquifer and confining bed properties.

6.5.1 **Hydraulic parameters**

The movement of groundwater is controlled by certain hydraulic properties, the most important being the permeability. For the study of the movement of water in earth materials the parameter for permeability is calculated assuming the physical properties (viscosity, etc.) of water and is termed hydraulic conductivity. Hydraulic conductivity is defined as the volume of water that will move in a unit time under a unit hydraulic gradient through a unit area, which results in units of velocity (distance per time). The typical ranges of hydraulic conductivity for common rock and sediment types are shown on Figure I.6.10. A related term is transmissivity, which is defined as the hydraulic conductivity multiplied by the aquifer thickness. The difference between the two are that hydraulic conductivity is a unit property, whereas transmissivity pertains to the entire aquifer.

Storage coefficient is defined as the volume of water that an aquifer releases from or takes into storage

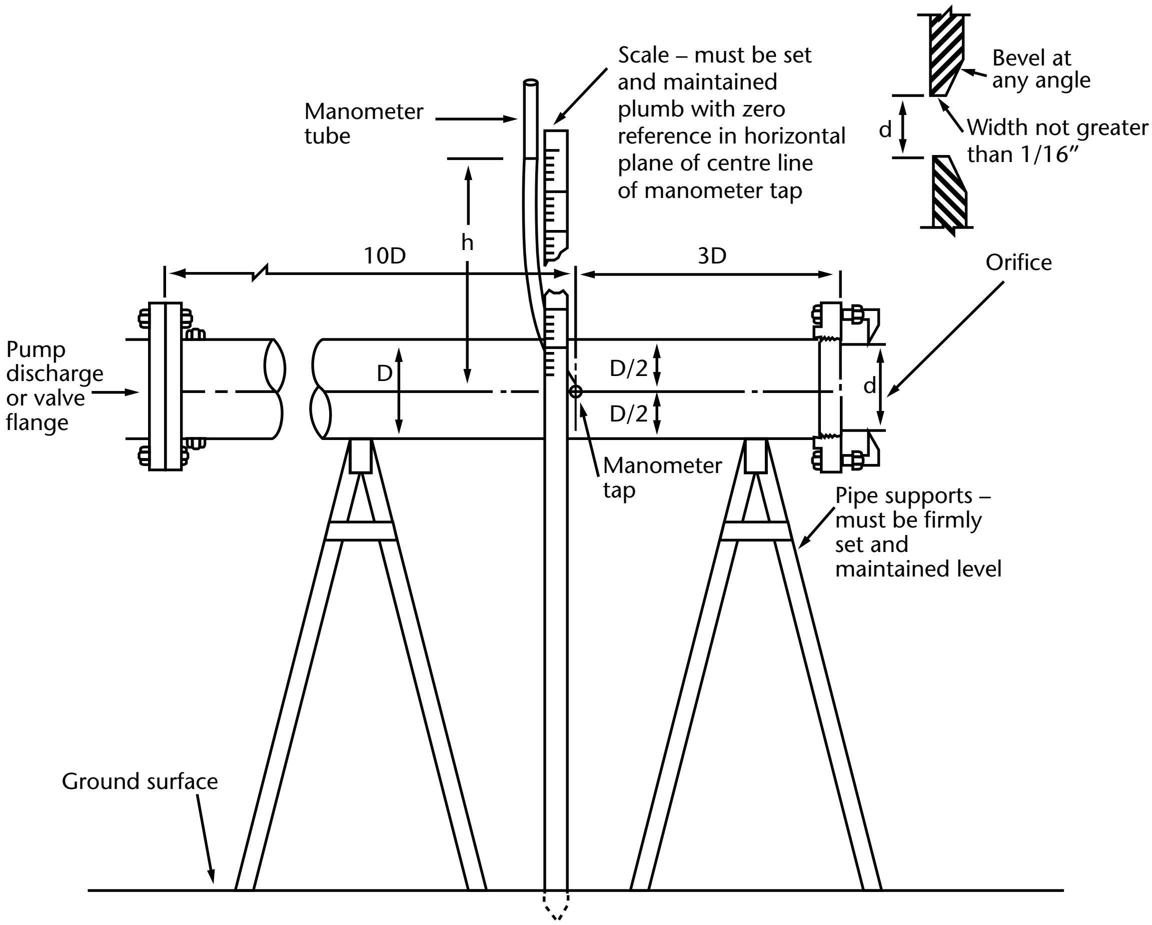


Figure I.6.8. Schematic diagram of how the free discharge orifice is set up for measuring discharge from a pumped well (United States Department of the Interior, 1977)

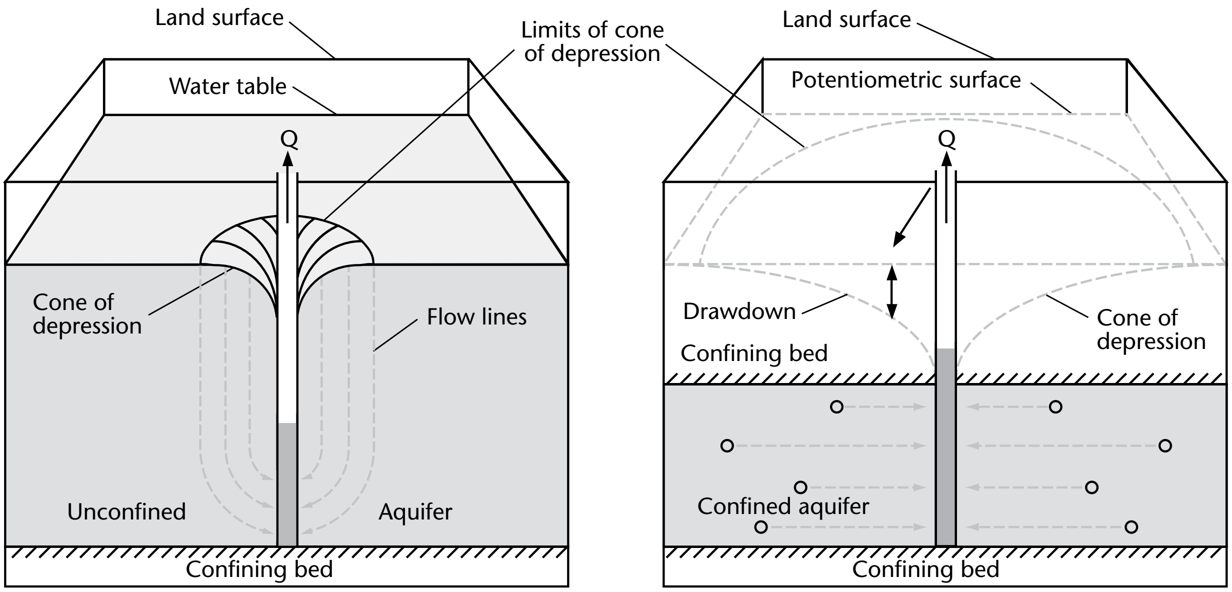


Figure I.6.9. Drawdown from a pumped well in (left) an unconfined aquifer and (right) in a confined aquifer (Heath, 1983)

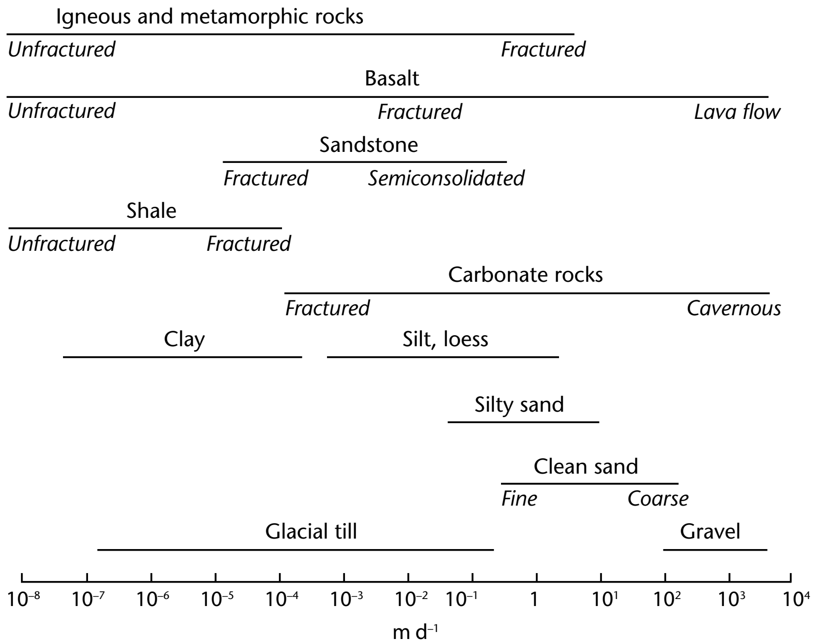


Figure I.6.10. Hydraulic conductivity of common rock and sediment types (Heath, 1983)

per unit surface area of the aquifer per unit change in head. Storage coefficient is a dimensionless parameter. For an unconfined aquifer, the storage coefficient is essentially derived from the yield by gravity drainage of a unit volume of aquifer, and typically ranges from 0.1 to 0.3 in value. For a confined aquifer, where saturation remains full, the storage results from the expansion of water and from the compression of the aquifer. The storage coefficient for a confined aquifer is therefore usually several orders of magnitude smaller than for an unconfined aquifer, typically ranging from 0.00001 to 0.001 in value.

Hydraulic conductivity and storage coefficient can be determined for confining units as well as aquifers. The differentiation of an aquifer from a confining unit is relative. For a given area, aquifers are considered to have hydraulic conductivities that are several orders of magnitude larger than confining units.

6.5.2 Overview of common field methods to determine hydraulic parameters

The determination of the hydraulic conductivity and storage coefficient specific to a particular aquifer or confining unit is generally accomplished through tests conducted in the field, referred to as aquifer or pumping tests. These aquifer tests are devised to measure the drawdown resulting from pumping or a similar hydrological stress and then to calculate the hydraulic parameters. The magnitude and timing of drawdown related to a specific test is directly related to the hydraulic conductivity and storage coefficient, respectively.

6.5.2.1 Aquifer (pumping) tests

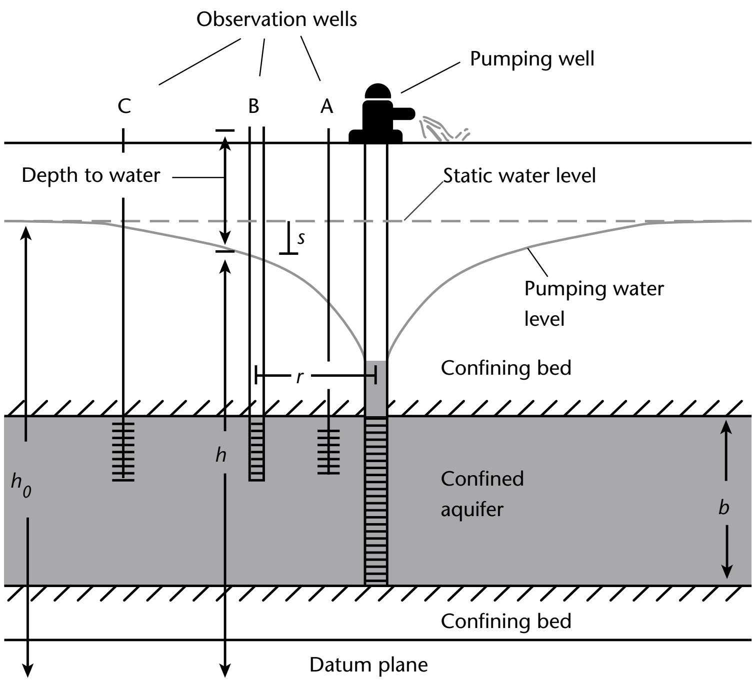
The general aim of an aquifer test is to determine hydraulic parameters where pumping is controlled and generally held constant and water levels in the pumped well and nearby observation wells are measured. Figure I.6.11 shows a schematic diagram of the set-up of a typical test of a confined aquifer of thickness, b. Three observation wells, labelled A, B and C, are located at various radii (r at well B) from the pumped well. The pumping, of known discharge, causes a cone of depression in the aquifers potentiometric (piezometric) surface to form which results in a drawdown, s, measured at well B, which is the difference between the initial head, h_0, and the pumping head, h. Water-level data in each well including the pumping well are collected prior to the start of pumping to establish the pre-test static water level, and thereafter throughout the test. The pump discharge is also monitored.

Aquifer tests typically are run from 8 hours to a month or longer, depending on the time required to achieve a steady pumping water level. When the pump is turned on, water levels will drop. The largest drawdown will be in the pumped well with drawdown decreasing non-linearly with distance away from the pumped well and increasing non-linearly with time. The observed values are the changing drawdown with time. This is referred to as a transient test, because of the changing drawdown with time. The data are generally plotted in two ways, as either log-log or semi-log graphs of distance and drawdown, or time and drawdown. The distance drawdown plot is for data from all wells for a particular instant in time, whereas the time-drawdown plot is for all data collected at one well. Generally, the analysis of the test data proceeds by either a manual, graphically based method or through the use of a computer program for aquifer-test analysis. The manual, graphically based method relies on an approach where the data plots are overlaid and matched to established "type curves" to calculate a solution for hydraulic conductivity and storage coefficient. The multiple plots are analysed individually and an average or consensus value for the test is determined.

It is beyond the scope of this Guide to explain in detail the exact data collection and analysis approach because there are many variants of the procedure. The variants result from a wide range of factors that can substantially affect the operation of the test and the specific analysis procedure, such as whether the test is transient or steady state, run with many observation wells or one, whether flow (leakage) to the tested aquifer will be considered from adjacent aquifers or confining units, and whether the aquifer is confined or unconfined. The practitioner is directed to Walton (1996), Kruseman and others (1994) and Reed (1980), for both an overview of the many common methods and a detailed description of the analysis techniques. Additionally, standards for conducting and analysing aquifer tests have been developed by the International Organization for Standardization (ISO 14686, 2003*a*) and the American Society for Testing and Materials International (ASTM D4106-96, 2002). An example of spreadsheet-formulated aquifer test analysis is presented by Halford and Kuniansky (2002).

6.6 RECHARGE AND DISCHARGE, SOURCES AND SINKS IN A GROUNDWATER SYSTEM

Recharge and discharge are the pathways by which water enters and leaves the groundwater system. Understanding and quantifying these pathways are key to understanding the nature of the whole groundwater system and being able to predict potential changes. The significant sources of recharge are from precipitation and leakage from surface water bodies, such as streams, rivers, ponds and lakes. The significant sources of discharge are leakage to surface water bodies, such as streams, rivers, ponds, lakes and oceans; well pumpage; and evapotranspiration.



FigureI. 6.11. Schematic diagram of a typical aquifer test showing the various measurements (Heath, 1983)

6.6.1 Recharge from precipitation

Precipitation that percolates through the soil ultimately can recharge the groundwater system. This typically occurs in areas of relatively high topographic level and is controlled by the permeability of the soils. Individual recharge events can be identified as rises in water table hydrographs. If the porosity of the aquifer material is known, generally ranging from 5 to 40 per cent, an estimate of the recharge volume can be made for a unit area of aquifer, as water-level rise x porosity (as a fraction) x area.

6.6.2 Groundwater–surface water relationships

In many areas, the groundwater system is directly linked to the surface water system in such a way that even a large volume of water can flow from one to the other. It is important to understand this relationship.

6.6.2.1 Gaining and losing streams

The elevation of water levels in a stream relative to the adjacent water level in a surficial or water table aquifer will control the direction of flow between these two parts of the hydrological system. The situation where the stream level is below the water table in the underlying aquifer that drives flow upward to the stream is referred to as a gaining stream (Figure I.6.12, top). The reverse situation where the stream level is above the water table in the underlying aquifer that drives flow downward to the aquifer is referred to as a losing stream Figure I.6.12, middle). In some cases, especially in an arid setting, the aquifer may not have a saturated connection with the stream. This case is also a losing stream (Figure I.6.12, bottom).

The groundwater recharge from a losing stream or groundwater discharge to a gaining stream can be quantified or measured in several ways:

(a) For a gaining stream, examination of a long-term hydrograph record can indicate the base flow. The base-flow portion of a stream hydrograph (Volume II, 6.3.2.2.2) is likely to include the groundwater discharge. Other constant discharges from reservoirs or sewage treatment plants, for example, can also contribute to base flow;

(b) For either a losing or gaining stream, differential streamflow discharge measurements taken at an upstream and a downstream point on a reach will show the loss or gain within the uncertainty associated with the measurement (Chapter 5). The selected stream reach should not have any other inputs or outputs, such as tributaries, sewage treatment plants, water intake plants or irrigation returns;

(c) A direct measurement of the discharge to or from a stream can be made with seepage meters. These are instruments that are placed in the stream bed and that retain the volume of water seeping through the stream bed for subsequent measurement (Carr and Winter, 1980). Some of these devices may only be able to work in a gaining stream condition. These instruments are sensitive to, and may not be able to work

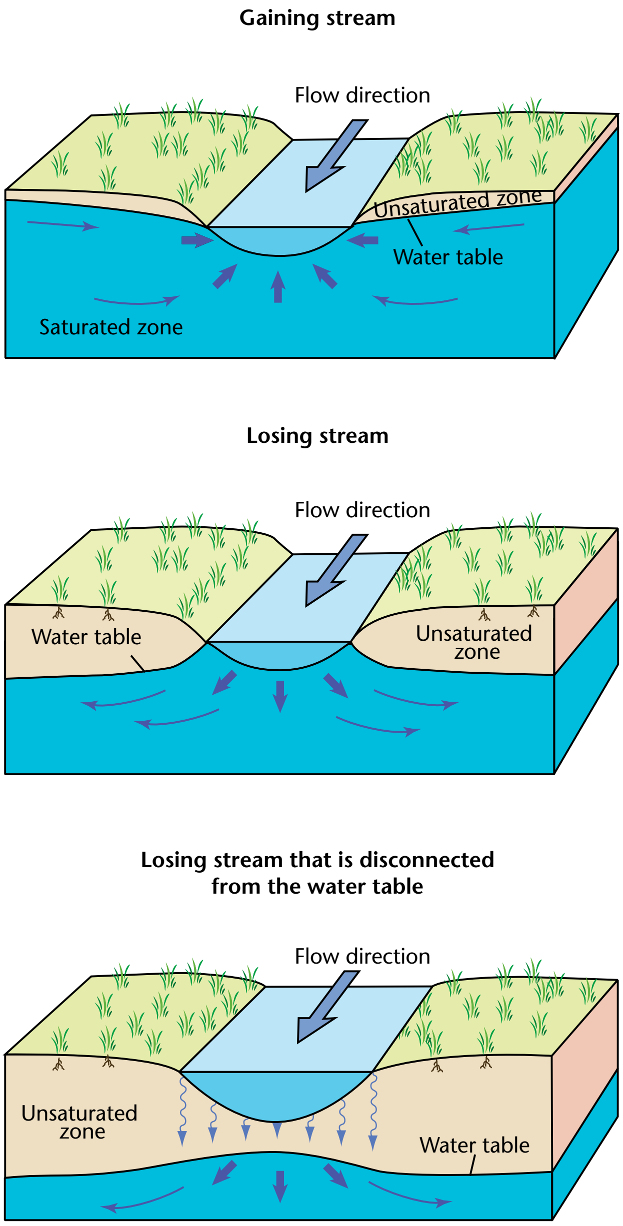


Figure I.6.12. Relative configuration of groundwater level and stream level for gaining and losing streams (Winter and others, 1998) in, relatively high stream velocities because of scour.

6.6.2.2 Springs and seeps

Discharge from springs and seeps, which represent localized groundwater discharge, can be measured using standard stream discharge measurement procedures (Chapter 5).

6.6.2.3 Effects of evapotranspiration on groundwater system

Deep-rooted plants and plants in general in areas of a shallow water table can derive water from the groundwater system. The standard methods to determine potential evapotranspiration rates can be implemented for areas where groundwater is likely to be involved (Chapter 4).

6.6.3 Well pumpage

Pumpage from individual wells and the cumulative effects of pumpage of many wells in an area can have a very significant impact on groundwater levels and the groundwater system in general. It is a common occurrence for the drawdown from a pumped well to cause a nearby stream to change from a gaining to a losing configuration, underscoring the importance of tracking the location and effect of well pumpage. In particular, wells for public supply, industrial or commercial use, and for irrigation pump the largest amounts. A quantification of the pumpage amounts requires a tallying of reports by the well owners, or lacking those reports, an effort to measure the significant users. The procedures detailed in 6.4 can be used to make those measurements. As pumping can change with the demands of the well users, keeping track of those changes can require much effort. It is possible to develop a relation between the pump discharge and the pump's electrical or fuel usage. If such data are available, this can ease the burden of compiling or collecting pumpage data for a large number of wells.

6.7 USE OF DATA IN GROUNDWATER MODELS

A primary role of a model is the integration of hydrogeological framework information, water-level data, pumpage, and recharge and discharge information in order to understand the relative importance of the various processes of the groundwater system, and to appraise the capacity or capability of the groundwater system to meet general or specific (usually water supply) goals. The commonly used modelling options range from development of a simple water budget to the development of a complex digital groundwater-flow model. It is beyond the scope of this Guide to provide the detailed background for the development, calibration and use of groundwater models; however the methods and approaches for the collection of data outlined in this chapter and in Table I.6.3 provide the necessary foundation to the development of models. Further discussion on the subject of groundwater modelling as well as references on the subject are provided in Volume II, 6.3.5.2.

Table I.6.3. Data requirements for groundwater models

Hydrogeological framework	Extent and thickness for each aquifer
	Extent and thickness for each confining bed
Hydrological boundaries and stresses	Amount and location of recharge (net precipitation, leakage from streams)
	Amount and location of discharge (well pumpage, leakage to streams, spring flow, evapotranspiration)
Distribution of hydraulic parameters	Aquifer hydraulic conductivity or transmissivity
	Aquifer storage coefficient
	Confining bed properties
Calibration data	Groundwater levels, with concurrent stream base flow, well pumpage, recharge, etc.

6.8 REMOTE-SENSING [HOMS D]

Currently, there are no direct remote-sensing techniques to map areas of groundwater. However, indirect information can be obtained from remote-sensing sources.

Remote-sensing techniques used to map areas of groundwater include aerial and satellite imagery in the visible, infra-red and microwave regions of EMS. In particular, satellite imagery enables a view of very large areas and achieves a perspective not possible from ground surveys or even low-level aerial photography. Although remote-sensing is only one element of any hydrogeological study, it is a very cost-effective approach in prospecting and in preliminary surveys. Owing to the intervening unsaturated zone of soil, most remote-sensing data cannot be used directly, but require substantial interpretation. As a result, inference of location of aquifers is made from surface features. Important surface features include topography, morphology and vegetation. Groundwater information can be inferred from landforms, drainage patterns, vegetation characteristics, land-use patterns, linear and curvilinear features, and image tones and textures. Structural features such as faults, fracture traces and other linear features can indicate the possible presence of groundwater. Furthermore, other features, such as sedimentary strata or certain rock outcrops, may indicate potential aquifers. Shallow groundwater can be inferred by soil moisture measurements, changes in vegetation types and patterns, and changes in temperature. Groundwater recharge and discharge areas within drainage basins can be inferred from soils, vegetation and shallow or perched groundwater (Engman and Gurney, 1991).

Airborne exploration for groundwater has recently been conducted using electromagnetic prospecting sensors developed for the mineral industry (Engman and Gurney, 1991). This type of equipment has been used to map aquifers at depths greater than 200 m (Paterson and Bosschart, 1987).

Aerial photography supplemented by satellite data from Landsat or SPOT are widely used for groundwater inventories, primarily for locating potential sources of groundwater. This technique permits inferences to be made about rock types, structure and stratigraphy. IR images are valuable for mapping soil type and vegetative surface features used in groundwater exploration. Springs can best be detected using IR and thermal imagery. Underwater springs can be detected by this method (Guglielminetti and others, 1982). Furthermore, through temperature differences, thermal IR imagery has the potential to deduce information on subsurface moisture and perched water tables at shallow depths (Heilman and Moore, 1981*a* and 1981*b*; Salomonson, 1983; van de Griend and others, 1985).

Passive microwave radiometry can be used to measure shallow groundwater tables. A dual frequency radiometer has been used on an aircraft to measure water table depths of 2 m in humid areas and 4 m in arid areas (Shutko, 1982; 1985; 1987).

Radar has an all-weather capability and can be used to detect subtle geomorphic features even over forested terrain (Parry and Piper, 1981). Radar is also capable of penetrating dry sand sheets to disclose abandoned drainage channels (McCauley and others; 1982; 1986), and can also provide information on soil moisture (Harris and others, 1984). Radar images may be used to detect water which is several decimetres below the ground surface in arid areas, owing to the increase in soil moisture near the surface. Near-viewing short pulse radars installed on mobile ground or aircraft platforms provide information on the depth to a shallow water table down to 5–50 m (Finkelstein and others, 1987). Radar imagery has the potential to penetrate the dense tropical rainforest and rainfall, and yield information that can be used to produce a geological map for use in groundwater exploration (Engman and Gurney, 1991). Radar imagery has been used successfully to reveal previously unchartered network of valleys and smaller channels buried by the desert sands (McCauley and others, 1986).

A comprehensive state-of-the-art review of remote-sensing applications to groundwater (Meijerink in Schultz and Engman, 2000) as well as references to a number of specific applications are included in the list of references and further reading below.

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