GROUNDWATER MONITORING

1. Introduction

Groundwater monitoring is used to analyze the impact of a variety of surface and subsurface activities, including seawater intrusion, application of agricultural products such as herbicides (qv), pesticides, and fertilizers (qv), residential septic systems, and industrial waste ponds. Another focus of groundwater monitoring has been contamination associated with waste landfills and ruptured underground petroleum (qv) storage tanks (see TANKS AND PRESSURE VESSELS).

Groundwater monitoring is a necessary component in any investigation of subsurface contamination. A wide variety of information can be gleaned from the data including groundwater velocity and direction, and contaminant identification and concentration. These data can be combined with other observations to infer various characteristics of the contamination. Examples are source and timing of the release, and future location of the contaminant plume.

The design of a groundwater monitoring strategy requires a basic understanding of groundwater flow systems. The majority of groundwater flow occurs in formations known as aquifers. At least two types of data can be retrieved using groundwater wells, ie, groundwater pressure and groundwater quality. A monitoring well allows measurement of these properties at a specific point in an aquifer. *Monitoring wells* come in a variety of sizes and materials, but each is basically a pipe extending from the ground surface to a point in the aquifer at which the pressure or contaminant is to be assessed. Monitoring wells are functional only in the saturated zone of the subsurface. Within the unsaturated soil zone, tensiometers, soil moisture blocks, and psychrometers have been used to assess fluid pressures. Fluid samples are retrieved using suction cup lysimeters for subsequent quality analysis.

2. Aquifers

The *term aquifer* is used to denote an extensive region of saturated material. There are many types of aquifers. The primary distinction between types involves the boundaries that define the aquifer. An unconfined aquifer, also known as a phreatic or water table aquifer, is assumed to have an upper boundary of saturated soil at a pressure of zero gauge, or atmospheric pressure. A

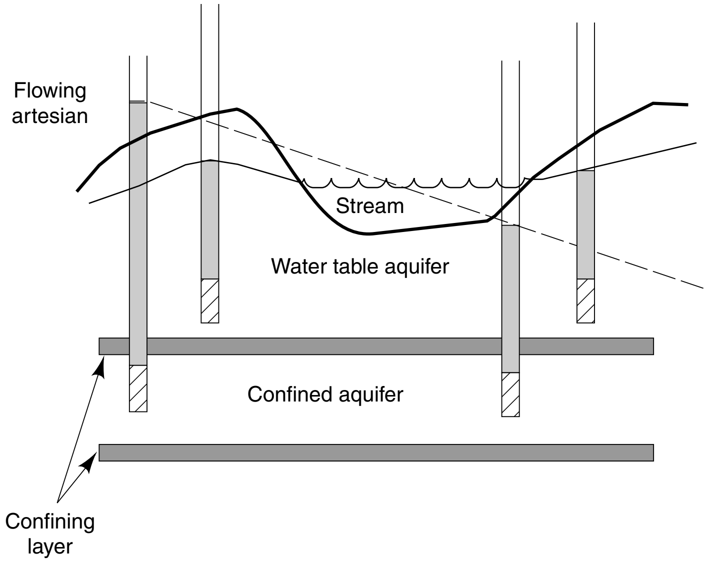

Fig. 1. Aquifers and monitoring wells where ▨ denotes the well screen and ■ the water-filled space in the monitoring well. (—) denotes the water table level, (- -), the potentiometric surface, and () the ground surface. Terms are discussed in text.

confined aquifer has a low permeability upper boundary that maintains the interstitial water within the aquifer at pressures greater than atmospheric. For both types of aquifers, the lower boundary is frequently a low permeability soil or rock formation. Further distinctions exist. An artesian aquifer is a confined aquifer for which the interstitial water pressure is sufficient to allow the aquifer water entering the monitoring well to rise above the local ground surface. Figure 1 identifies the primary types of aquifers.

Calculation of the flow in the saturated portion of the subsurface is generally much easier than that in the unsaturated zone, due to the fact that the hydraulic conductivity is a function of moisture content in the latter. However, calculation of flow in either requires a fundamental understanding of groundwater pressure and energy.

3. Groundwater Pressure and Energy

The energy state of soil water can be defined with respect to the Bernoulli equation, neglecting thermal and osmotic energy as

$$E = z + P/\gamma + v^2/2g \qquad (1)$$

where E is the energy per unit weight (L), P the pressure (F/L^2), γ the specific weight (F/L^3), z the elevation (L), and v the average velocity (L/T). The three energy terms represented by the right-hand side of the equation are pressure energy, potential energy, and kinetic energy, respectively. In most groundwater applications, the kinetic energy term is much less significant than the other two and is neglected. Thermal gradients cause moisture to migrate toward colder regions. However, thermal energy has been neglected in the present formulation and the equation cannot be used to simulate problems where there is a significant temperature gradient present. The osmotic energy has been neglected as variations in the osmotic energy status are considered negligible compared to the other energy terms.

When the energy terms are expressed as energy per unit weight, the term head is often used. Therefore, the total head, $h(L)$, is equal to the elevation head, z, plus the pressure head, P/γ:

$$h = z + \frac{P}{\gamma} \tag{2}$$

The total head is also often denoted as ψ. For a saturated soil having no vertical component of acceleration, the pore water pressure is calculated using basic hydrostatic principles, and the depth below the free surface defines the fluid pressure. This depth is evaluated using a monitoring well. Water passes through the screened portion of the well and rises in the casing until it reaches an elevation associated with the energy status of the fluid at the screened elevation. A variety of means can be used to determine the elevation of the fluid in the monitoring well, including electrical depth devices, sonar techniques, or steel tape and chalk (1).

In the unsaturated zone, measurement of the fluid head is a bit more complex, because the fluid pressures are less than atmospheric, and therefore, fluid does not rise above the point of measurement in a monitoring well, ie, ψ is negative. Instead, a tensiometer such as that shown in Figure 2 may be used to determine the soil water suction. A tensiometer consists of an airtight, water-filled

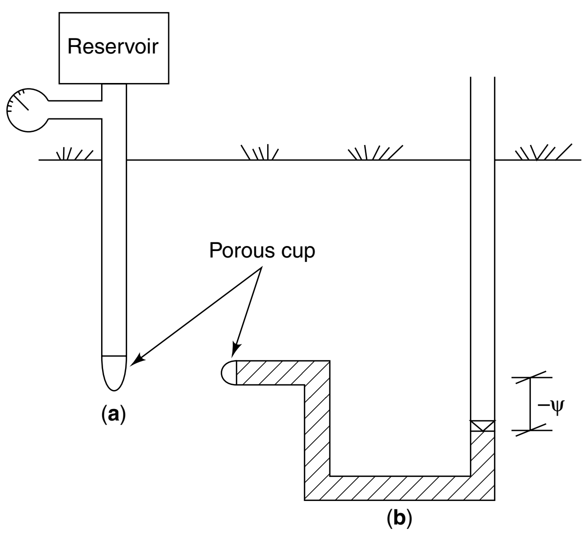

Fig. 2. (**a**) Schematic of a tensiometer and (**b**) a hydraulic analogy showing the negative value of the total head, ψ.

tube having a porous cup at the base. After insertion into the soil, moisture exits the tensiometer while hydraulic equilibration is achieved with the surrounding unsaturated soil. As moisture exits, a vacuum is created in the evacuated space at the upper portion of the tensiometer. When the suction created in the tensiometer is equivalent to the negative pressure head in the surrounding soil, equilibration has been achieved and the corresponding pressure can be read on the tensiometer gauge. Other setups that may be used to indirectly evaluate the pore fluid pressure in the unsaturated zone include soil moisture blocks, thermocouple psychrometers, γ-ray attenuation, and nuclear moisture logging (1–3).

4. Calculation of Groundwater Flow

The framework for the solution of porous media flow problems was established by the experiments of Henri Darcy in the 1800s. The relationship between fluid volumetric flow rate, Q, hydraulic gradient, and cross-sectional area, A, of flow is given by the Darcy formula:

$$Q = KA\frac{h_1 - h_2}{\Delta l} \tag{3}$$

Here h_z represents the hydraulic head at location z, whereas Δl is the hydraulic length between points 1 and 2. A is an area perpendicular to the discharge vector. The constant $K(L/\mathrm{T})$, which maintains the equality, has been termed the hydraulic conductivity, permeability, or simply conductivity. Most aquifers exhibit significant variation in permeability from point to point in the aquifer. This space-dependent nature is termed "heterogeneity". Often, however, a representative value of permeability is used to describe the field behavior of the aquifer in a specific region. This representative value can be determined using a field test with a combination of one, two, or multiple pumps (2–4).

$$Q = -KA\frac{\partial h}{\partial l} \tag{4}$$

The gradient, $\frac{\delta h}{\delta l}$, is often denoted i for simplicity. It is often convenient to analyze the discharge for a unit area using the specific discharge, q. The specific discharge represents the volumetric discharge divided by the total cross-sectional area, ie,

$$q = -Ki \tag{5}$$

In terms of fluid velocity,

$$v = \frac{Q}{An} \tag{6}$$

or

$$v = -K\frac{i}{n} \tag{7}$$

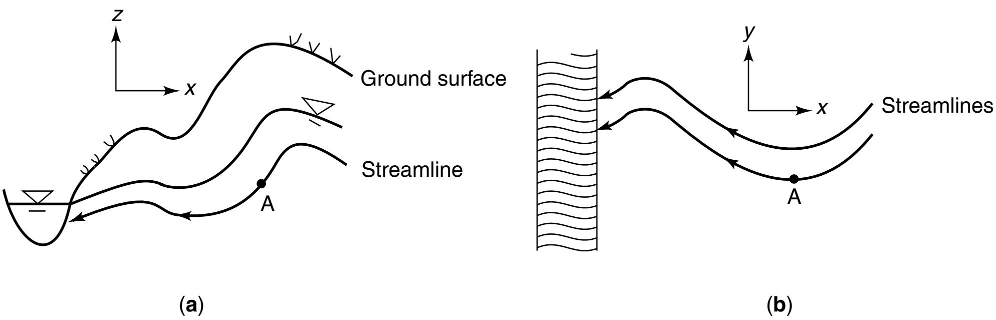

Fig. 3. Three-dimensional flow for stream recharge via a water table aquifer where (**a**) is the elevation view and (**b**) is the plan view.

The porosity, n, represents the ratio of pore volume to total soil volume. It appears in the denominator of the right-hand side of the equality owing to the dependence of velocity on the *available* flow area, which is reduced from the total cross-sectional area by the factor n.

This form of Darcy's law is applicable only to saturated flow. As discussed earlier, there are distinctions between the state of soil water in the saturated and unsaturated regions. These distinctions lead to an alternative form of Darcy's law for the case of unsaturated flow (2,5).

Application of equation 5 requires caution. In this simplistic form, the equation can be used to find only one component of fluid velocity, namely that defined by the direction over which the gradient is measured, ie, the line between two monitoring wells. In general, however, the direction of groundwater flow at a point is fully characterized by assignment of values in three mutually orthogonal directions. Figure 3 provides an example of such a situation.

The vertical component of flow can be determined if a well is screened at two different elevations as shown in Figure 1. Frequently, nested wells are used instead of a single well and multiple screenings to determine the vertical component of flow (2). Nested wells must be situated close enough to one another so horizontal gradients do not become a factor.

Nested wells can also be used to analyze multilayer aquifer flow. There are many situations involving interaquifer transport owing to leaky boundaries between the aquifers. The primary case of interest involves the vertical transport of fluid across a horizontal semipermeable boundary between two or more aquifers. Figure 4 sets out the details of this type of problem. Unit 1 is a phraetic aquifer, bound from below by two confined aquifers, having semipermeable formations at each interface.

Judging from the hydraulic heads, the vertical flow across the semipermeable interface 1 is in a downward direction, whereas across the semipermeable interface 2 it is in an upward direction. Therefore, unit 2 is being fed by fluid from the phraetic aquifer above it and the confined aquifer below.

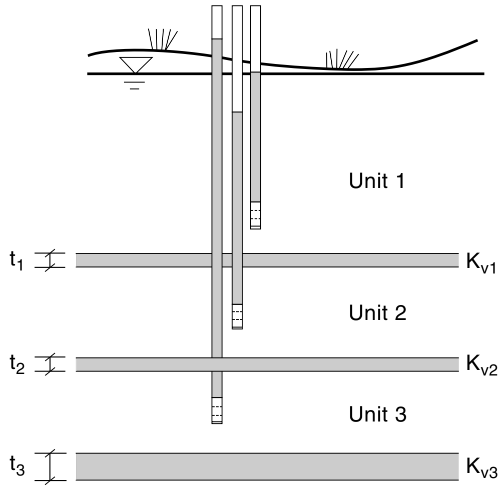

Fig. 4. Multilayered aquifer flow where *t* represents thickness of confining layers between units 1, 2, and 3.

5. Monitoring Well Design for Contaminant Transport Studies

There are a variety of contaminant problems that may prompt the development of a groundwater monitoring program. The specific details of the program depend on the situation prompting such monitoring. For example, groundwater monitoring may be required in the vicinity of a new or existing landfill, and would serve the purposes of clarifying groundwater flow conditions, identifying background water quality, and leak detection. Groundwater monitoring in the vicinity of known contamination is used to delineate the spatial extent of the contamination as well as to verify the chemicals present. Groundwater monitoring may be required in association with real estate transactions to verify the existence of a pristine water source for well development.

Monitoring wells are installed by first completing a soil boring to the approximate depth of groundwater measurements. Drilling methods for the borehole include auger, mud rotary, cable tool, jetted wells, and driven wells (1,6). During the drilling, a boring log is prepared that records details of the subsurface materials encountered as the depth progresses. A well casing is installed in the borehole with a well screen at or near the bottom of the borehole. The annular space between the borehole and the casing must be filled properly to allow free passage of groundwater from the monitored zone to the well screen and to preclude passage of moisture from the surface vertically along the sides of the casing. In the vicinity of the well screen, a filter pack of natural, ie, typically sand or pea gravel, or synthetic materials is used to preclude clogging of the well screen. The specific design of the filter pack must take into consideration details of the aquifer soil. Often, a secondary filter pack consisting of finer materials is placed above the primary filter. Above this is the virtually impermeable bentonite seal. A neat cement grout above this layer extends to the ground surface. Figure 5 illustrates the primary components of a monitoring well.

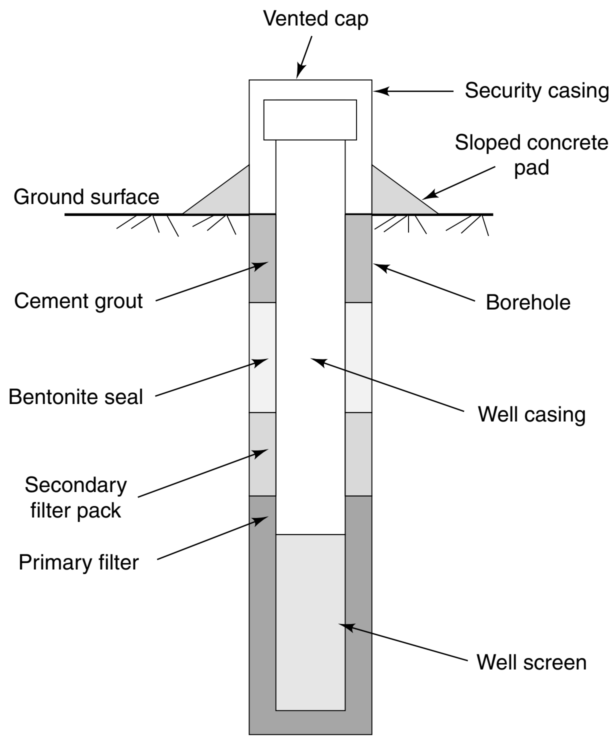

Fig. 5. Schematic of a monitoring well.

A variety of techniques can be used to retrieve the groundwater sample once the well is in place. Pumps, bailers, and syringes are among the devices used to draw the sample to the surface. Typically, the well is purged of 3–10 casing volumes of fluid prior to retrieval of the sample, to ensure standing water is not being analyzed (1,6,7). Care must be taken during sampling and delivery to the lab. The characteristics of the sample may be altered if protocols are not followed. Volatile gas stripping, oxidation, and pH shifts are examples of modifications that may occur owing to the introduction of oxygen or other gases to the samples (7).

It is often important to quantify the contamination of pore fluid in the unsaturated soil zone, where monitoring wells are ineffective. In this region, suction cup lysimeters are useful (7). These samplers consist of a porous cup, typically ceramic, having two access tubes what are usually Teflon. One access tube provides a pressure-vacuum, the other discharges the sampled fluid to the surface. The porous cup, typically between 2 and 5 cm in diameter, is attached to a poly(-vinyl chloride) (PVC) sample accumulation chamber.

The installation of the probes should ensure good contact between the suction cup portion of the sampler and the surrounding soil, and minimize side leakage of liquid along the hole that has been cored for the sampler and access tube lines. Typically a clay plug of bentonite is used to prevent leakage down the core hole. A silica–sand filter provides good contact with the suction cup and prevents

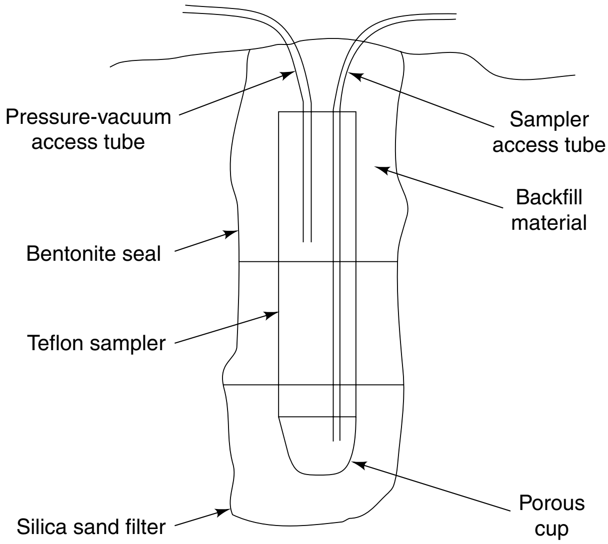

Fig. 6. Schematic of a pressure-vacuum sampler.

clogging of the cup. To retrieve a sample, the sample tube is clamped and suction is applied to the lysimeter through the air tube, which is then clamped. Moisture enters the accumulation chamber through the porous cup. The suction is released and pressure is applied, forcing the sample to the surface through the sample collection tube. Figure 6 shows a sample installation.

Design of a groundwater monitoring program minimally includes consideration of materials, location, indicator parameters, and timing. Material selection is important for both the well casing and screen. Materials of construction must be inert to the fluid being tested and to the ambient soil. The material must not release any type of chemical that could be interpreted, as present in the groundwater. Typical inert materials include Teflon, polypropylene, PVC, and stainless steel (3,8,9). Material durability is also an issue, especially because many monitoring systems must be utilized for 50 years or more. The screens should also be evaluated regarding the potential for clogging, either via the porous media or biological activity.

Locational considerations include both surficial location and screened interval, ie, the sampling depth. The surficial location is selected based on whether the sample is to represent background quality or quality at the location of contamination, or potential leak location. In selecting the surficial location, the groundwater flow parameters, velocity and direction, are assumed to be known from other monitoring wells or borings already completed. The sampling depth is selected based on the type of contaminant monitored, ie, light or heavy, aqueous or nonaqueous, and/or the groundwater depth of interest (10,11). For example, if unit 2 of Figure 4 is used for groundwater well development as a drinking source, it is likely that a monitoring well is screened within that depth interval to assess water quality in that zone. Because it is possible for contaminants to migrate vertically, other zones may also be monitored. Evaluation of nonaqueous phase liquids (NAPLs) is very difficult, owing to the complexities associated with locating their position, and therefore sampling the appropriate region of the aquifer (4). The location and placement of monitoring wells may also take into consideration future use of the wells for pump-and-treat remediation efforts, as suggested by EPA's Superfund Accelerated Clean-up Model.

Indicator parameters are those chemicals for which the water sample is analyzed. Often it is a simple matter to select the indicator parameter, if one suspects a discharge of a particular chemical. However, the situation is often much more complex. If monitoring wells are used to assess the occurrence of leachate leaks below a landfill, selection of the indicator parameters should be based on the expected chemical composition of the landfill leachate. In addition, the indicator parameters should be distinct from chemicals known to exist in the background groundwater (6). If the monitoring program is used for leak detection, the indicator parameter should be one that is expected to have an early arrival at the monitoring well, eg, the material having negligible adsorption.

Groundwater monitoring programs typically employ a routine schedule of sampling. Depending on the application, samples may be retrieved for analysis at weekly, monthly, quarterly, or other appropriate intervals. When the monitoring program serves the purpose of leak detection, as around the periphery of a landfill, wells are sampled quarterly. If contamination of an aquifer is known to exist, and monitoring wells are used to track movement of contaminants or the effectiveness of remediation efforts, sampling may occur more frequently. If monitoring wells are used in combination with a tracer test (4,6) to analyze flow characteristics, continuous sampling may be required.

Data analysis is aided by a variety of statistical techniques to assess significance, highlight trends, and form mathematical models of any correlations developed (12). It is never possible to design a groundwater monitoring program that samples an aquifer completely. Many pockets of unknown quality remain. A geostatistical technique, such as kriging (12), can, however, be used to determine an optimized estimate of groundwater quality at such an unsampled location using observed data from surrounding sampled locations.

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