Groundwater
and
Wells

Second Edition

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Several problems can occur in attempting to determine a proper hydraulic conductivity with a permeameter. For example, trapped air within the sample can reduce the flow rate. In sophisticated permeameters, air may be driven out by passing carbon dioxide gas through the sample. Deaerated water is then allowed to enter the testing chamber. Any air that remains in the system is readily absorbed by the deaerated water, which also absorbs the carbon dioxide gas previously introduced. A combination of these two procedures assures that no air will remain in the sample chamber to impede the flow.

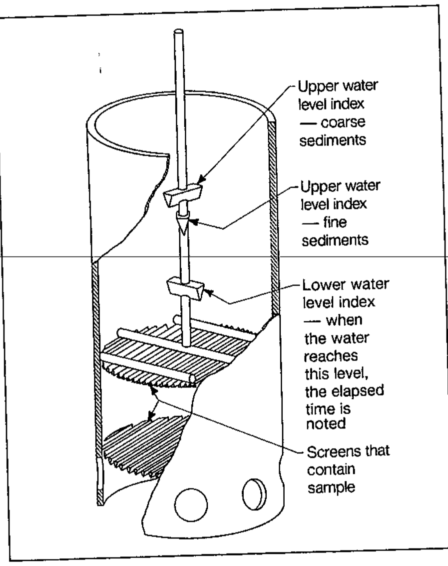


Figure 5.16. A field permeameter is based on the falling-head principle in which a certain volume of water is allowed to flow through a predetermined thickness of aquifer material. Once the time for the flow is known, an estimate of hydraulic conductivity can be made using Darcy's equation.

Packing of the grains presents a more difficult problem. When a sample is collected, the arrangement of individual grains is quite dense because component particles have settled together over tens of thousands or even tens of millions of years. Recent alluvial or late Pleistocene glaciofluvial sands and gravels, however, are not usually well packed and generally possess high porosities. Every sample becomes at least partly disaggregated during collection, transportation to the laboratory, and placement within the permeameter. The problem for the laboratory technician is clear: the original packing density must be reestablished if the measurements are to truly represent the percolation rates found in nature. Probably the best way to reestablish the original packing of a sample is by mechanical vibration; electrical vibrators are extremely useful for this purpose. Hand jarring or tamping also tends to reduce the bulk of the sample. In addition, it is possible to introduce water at a very slow rate into the sample chamber; as the water rises by capillarity, small particles are pulled downward into the voids.

Results obtained from properly built and operated permeameters may be quite accurate, provided that a sample has been returned to its field condition. Of course, a relatively undisturbed sample is best for testing.

FLOW NETS

Flow in an unconfined groundwater environment is controlled by impermeable geologic boundaries and the water table, which also acts as a boundary. Because no flow can cross these boundaries, the water must flow more or less parallel to them in what are called flow lines. Flow occurs because the potential energy head drives the water from areas of higher head to areas of lower head (that is, for example, from beneath a hill to a stream channel) (Figure 5.17a). Flow lines are perpendicular to lines of equal water-table elevations (potential head elevations) (Figure 5.17b).

The dotted lines in Figure 5.17b represent the potential head at those places on the groundwater table; these lines are called equipotential lines. Along each dotted line,

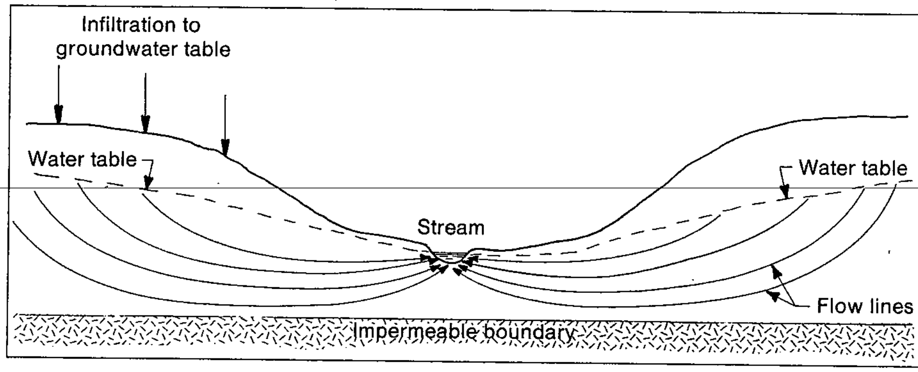


Figure 5.17a. Cross section through a stream valley showing flow lines in the groundwater system.

the potential energy head is the same. Flow lines can be easily drawn where the elevations of the water table are known because groundwater always flows perpendicular to these potentials in a down-gradient direction. This is strictly true only for isotropic aquifers where flow rates can be the same in all directions. The set of intersecting flow lines and equipotential lines is called a flow net. Figure 5.18 shows the arrangement of flow lines and equipotential lines around a pumping well in a homogeneous aquifer; the fault crossing the aquifer serves as an impermeable boundary.

Flow patterns and equipotential lines demonstrate how adjacent wells can have different water levels, depending on the hydraulic head at their intake points (Figure 5.19). This condition exists in many well fields but may be obscured because the elevation differences are minor or natural inhomogeneities of the aquifers cause distortion of the flow lines.

Knowing the direction of groundwater movement has become increasingly important because of the danger of contaminating groundwater supplies. Wells may become unsafe when sewage or other contaminants enter the ground at a higher head (gradient)

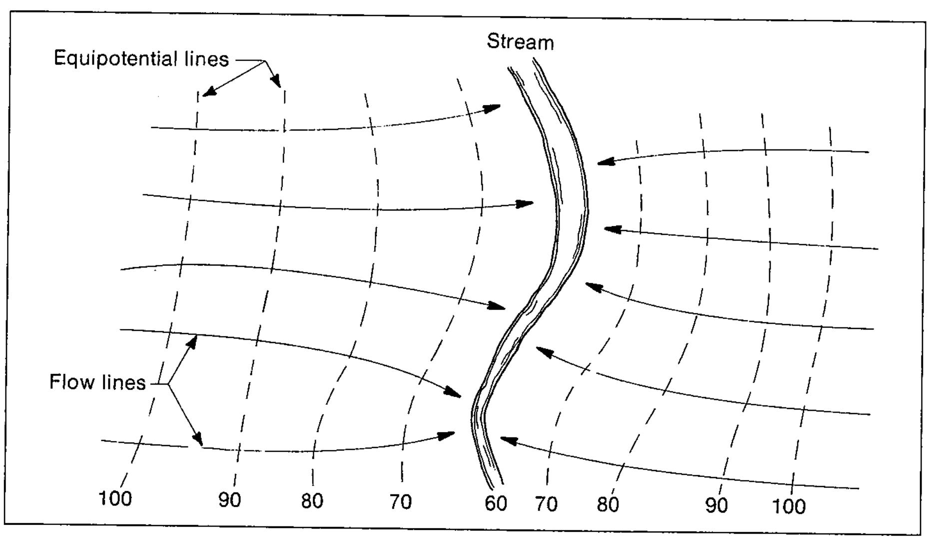


Figure 5.17b. Looking down on the stream valley from above with the water table exposed. The dotted lines represent points of equal groundwater elevation.

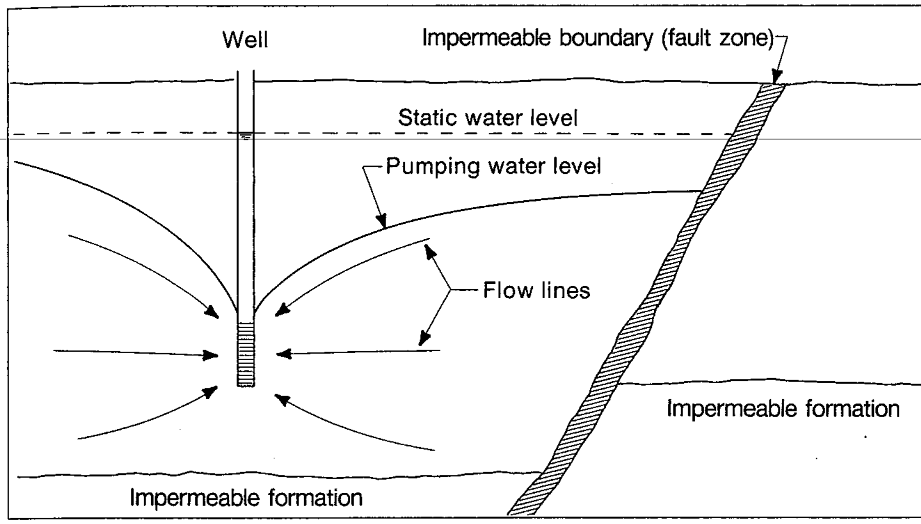


Figure 5.18a. Cross section near a pumping well showing the flow lines followed by water moving toward the well.

than exists in nearby shallow wells. The flow lines, or lines of water movement, can be determined by using water-elevation data from a minimum of three wells (Figure 5.20). The heavy solid line shown in Figure 5.20 shows the flowpath taken by water in the area. If sufficient information is available, flow lines may be drawn which indicate the general direction of groundwater flow in a specific area. Areas of recharge and discharge can also be defined by the use of a flow-net diagram. Flow lines diverge in areas of recharge and converge in areas of discharge.

GROUNDWATER FLOW VELOCITIES

Ordinarily, the rate of groundwater movement is of negligible interest to water well

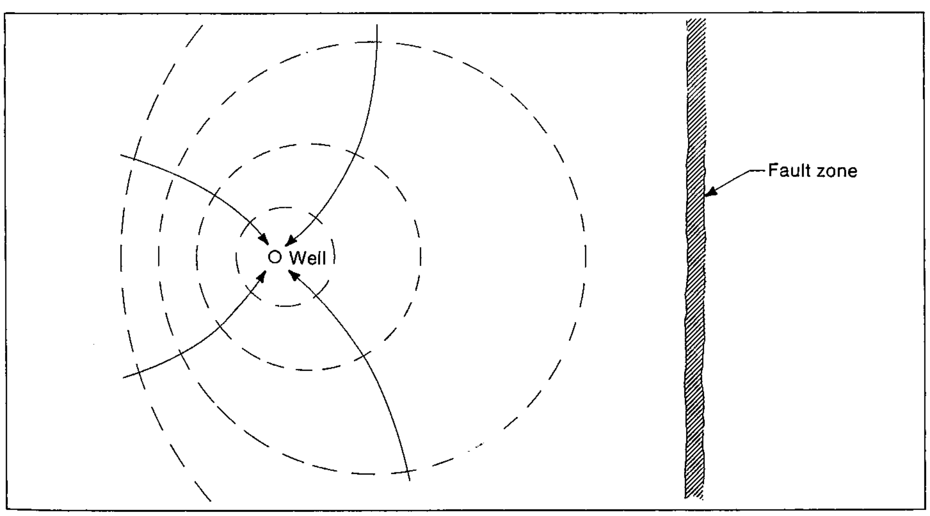


Figure 5.18b. Map of the potentiometric surface during long-term pumping shows that the impermeable boundary causes greater drawdown in the direction of the fault.

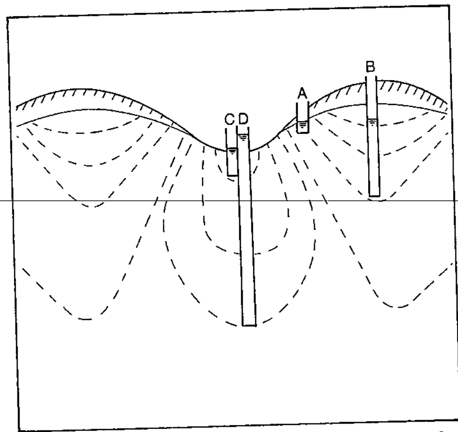


Figure 5.19. Water level in a well rises to the elevation of the hydraulic head represented by the potential at the intake end of the well. The water level in wells A and B is the same because both wells terminate on the same equipotential line. *(From APPLIED HYDROGEOLOGY, by C. W. Fetter, Jr., © 1980 Merrill Publishing Company, Columbus, Ohio)*

contractors or others concerned primarily with yields from wells. Yields are directly affected by flow velocities, of course, but velocity in an aquifer is difficult to study. Determination of the groundwater flow rate, however, has become more important as underground contamination problems multiply. The ability to predict the rate at which a plume of contaminated water may move downgradient from a source of pollution has become a vital water management objective.

The average groundwater flow rate is easily determined by combining Darcy's equation with the standard continuity equation of hydraulics. The continuity equation simply states that whatever goes into a system must come out. In Darcy's equation, the hydraulic conductivity has the dimensional units of velocity. When the conductivity is expressed as cubic feet (meters) per day passing through one square foot (meter) of aquifer, this is the same as expressing the flow rate in terms of feet (meters) per day under the defined hydraulic gradient of one. Multiplying this flow rate by the actual hydraulic gradient in the aquifer gives the velocity of groundwater movement in that aquifer.

Thus, using Darcy's equation:

$$Q = \frac{KA\,(h_1 - h_2)}{L} \tag{5.14}$$

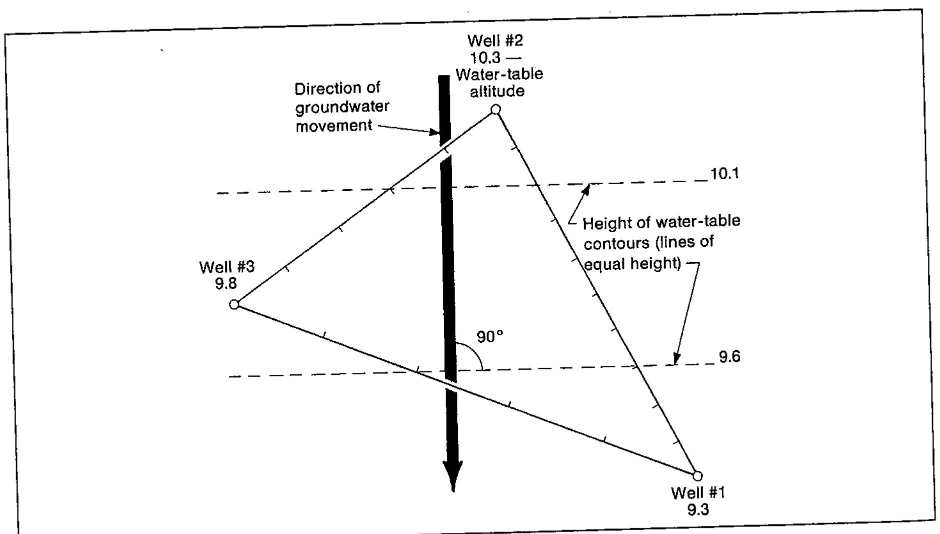


Figure 5.20. The direction of groundwater flow can be calculated by connecting a triangle linking the known potentiometric levels of three wells.

Table 21.7. Decontamination Solutions

Name of solution	Remarks
Sodium bicarbonate	Effective for acids and bases, amphoteric, 5-15 percent aqueous solution
Sodium carbonate	Effective for inorganic acids, good water softener, 10-20 percent aqueous solution
Trisodium phosphate	Good rinsing solution or detergent, 10 percent aqueous solution
Calcium hypochlorite	Excellent disinfectant, bleaching and oxidizing agent, 10 percent aqueous solution

(Richter and Collentine, 1983)

itoring wells should be in a sterile and contaminant-free condition when placed in the ground. Some manufacturers ship their products in this condition, but handling in the field requires a final wash with detergent or other solution. Table 21.7 lists typical decontamination solutions. Some form of steam cleaning, or high-pressure water-spraying technique combined with a low-sudsing soap or detergent, is recommended (Richter and Collentine, 1983). In addition, acetone and hexane are used to clean drilling tools and sampling equipment at hazardous waste sites. Working components of the drilling rig (drill pipe, subs, collars, kelly, and all parts of the rig chassis near the borehole) should also be cleaned. These cleaning operations should be verified by the driller in the well log.

The method of joining screens to casing and of assembling the casing string must also be done so as to prevent contamination of the samples. In general, no solvent

Table 21.8. Fitting Types

Type	Advantages	Disadvantages
Plain square ends (no fittings to weld)	• Readily available in pipe and screen • No need to purchase threads and couplings	• Special equipment and skills needed to field-weld metals • Plastics are welded using solvent cement which causes the following problems: — Cementing procedures are very temperature and moisture sensitive — Cements must be cured after application — Cements may interfere with groundwater quality analysis Time spent welding may cause this type of fitting to actually cost more than threads
Threads and couplings	• No solvents needed • Lengths of pipe and screen joined quickly • Readily available • Reasonably priced	• May be difficult to get filter pack and/or grout past the lip of couplings • May need to wrap threads with Teflon tape to make connections watertight
Flush threads	• No solvents needed • No couplings needed; filter packing and grouting simplified • Lengths of pipe and screen joined quickly • Readily available • Reasonably priced	• May need to wrap threads with Teflon tape to make connections watertight • Threads generally not compatible from manufacturer to manufacturer

welds are recommended; all plastic screens and casing should be joined by threads and couplings or flush threads. The joints are made watertight by wrapping with Teflon tape or by placing a Teflon or Viton (Viton is a registered trademark of E.I. DuPont DeNemours and Co., Inc.) o-ring in the joint (Table 21.8).

A primary objective of monitoring well construction is to make sure that contaminated groundwater does not enter contaminant-free geologic formations. Although some minor amount of cross-contamination may occur during drilling and well installation, the integrity of individual formations must be protected thereafter. This is usually accomplished by placing either bentonite or cement grout in the borehole above the filter pack in both single- and multiple-screen wells. Drill cuttings should not be placed in any open borehole annulus. To prevent downward migration of the bentonite or cement into the screen, the filter pack is extended at least 2 to 10 ft (0.6 to 3 m) above the top of the screen. The filter pack should not extend into an overlying formation, because this would permit downward vertical seepage in the pack and either dilute or add to the contamination of the water being monitored. See Table 21.9 for a comparison of bentonite and cement grouts. Polymeric fluids are not recommended as an alternative to bentonite or cement because they contain so few solids. See Chapter 10 for grout placement procedures.

For monitoring wells drilled by cable tool rigs, contaminant migration in the borehole can be eliminated by the well design shown in Figure 21.9. The 6-in (152-mm) casing is first installed into the clay layer. After flushing the casing and changing the drilling fluid, the borehole is extended using 4-in (102-mm) casing. A 2-in (51.8-mm) monitoring well is then installed and filter packed. Before installing the pack, the well bore should be thoroughly flushed. As the 4-in temporary casing is extracted, cement or bentonite grout is placed as shown in Figure 21.9. A protective surface casing with a locking cap is installed before the cement has hardened. Normally the locking cap will be vented. The well should then be developed as thoroughly as possible.

Table 21.9. Grouting Materials for Monitoring Wells

Type	Advantages	Disadvantages
Bentonite	• Readily available • Inexpensive	• May produce chemical interference with water-quality analysis • May not provide a complete seal because: — There is a limit (14 percent) to the amount of solids that can be pumped in a slurry. Thus, there are few solids in the seal; should wait for liquid to bleed off so solids will settle — During installation, bentonite pellets may hydrate before reaching proper depth, thereby sticking to formation or casing and causing bridging — Cannot determine how effectively material has been placed — Cannot assure complete bond to casing
Cement	• Readily available • Inexpensive • Can use sand and/or gravel filter • Possible to determine how well the cement has been placed by temperature logs or acoustic bond logs	• May cause chemical interferences with water-quality analysis • Requires mixer, pump, and tremie line; generally more cleanup than with bentonite • Shrinks when it sets; complete bond to formation and casing not assured

If the well is drilled by rotary methods, a 4-in (102-mm) casing can be grouted in an 8-in (203-mm) borehole that is drilled through the contaminated aquifer into an underlying impermeable layer. After the grout has hardened, the borehole is continued inside the 4-in casing to the desired depth. A 2-in (51-mm) casing and screen is filter packed and then grouted in the 4-in casing.

In saline environments, a Dowell seal ring gasket (manufactured by Dow Chemical) may be used in place of bentonite, because bentonite will not hydrate in a highly saline environment (Senger and Perpich, 1983). These gaskets can be made in variable lengths and mounted on the casing just prior to the installation of the screen. They are suitable for use in regularly shaped boreholes and where the organic and inorganic compounds in the gasket do not interfere with the chemical analysis of the water in the well. Cement can be placed above the gaskets to complete the seal.

A cement seal around the top of the well bore is recommended even if the annular seal is carried to the surface. The cement seal is shaped so that surface water flows away from the casing. If plastic casing is used, a short section of metal surface casing should be installed around the top section of the plastic pipe and extended 3 to 5 ft (0.9 to 1.5 m) into the ground. The metal casing prevents accidental damage to the plastic pipe. The top of the casing should be fitted with a locking cap.

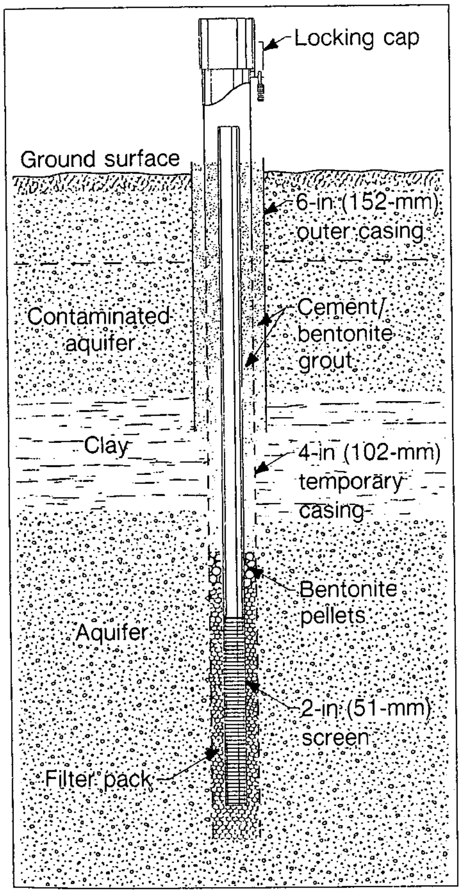


Figure 21.9. Intraborehole contamination can be prevented by proper well design and construction techniques.

Frost heaving can be a major problem for small-diameter PVC monitoring wells installed in cold climates. As the soil freezes during the winter, it expands upward, occasionally pulling the casing apart. Damage caused by frost heaving can be minimized by placing a metal surface casing to a depth of 5 to 10 ft (1.5 to 3 m). A steeply inclined cement cap should be placed around the surface casing. If frost action exerts pressure on the cement, the surface casing can rise without disturbing the monitoring well casing.

Development is especially important for monitoring wells, because drilling fluid residues remaining in the borehole will affect the chemistry of the water samples (Walker, 1983). Figure 21.10 shows that the presence of bentonite affects the chemical analyses of samples for at least 90 days after completion of the well. More thorough development shortens the time the bentonite will affect water quality. In some cases, the impact of drilling fluid additives on sampling chemistry can last for 1 to 2 years (Walker, 1983).

Residual amounts of polymeric drilling

fluid additives can also cause chemical effects; see Appendix 21.C for a list of the chemical constituents of a commonly used polymer. If any of these constituents are found in the first few water samples taken from a monitoring well drilled with the polymeric additive, they are ignored. As in the case of bentonite, the chemical effects of polymeric drilling fluids tend to disappear over time, although they will disappear faster if a breakdown chemical is added to the drilling fluid as the well is developed (Figure 21.11).

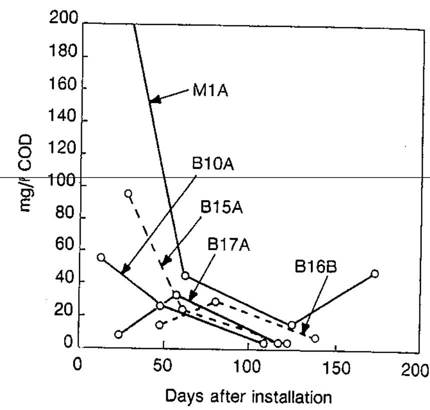


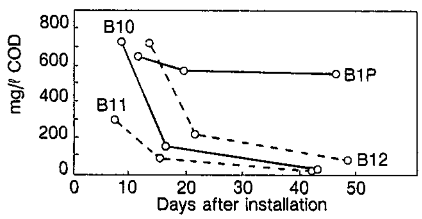
Figure 21.10. Inorganic residues of bentonite remain in the well after development. These residues will affect chemical oxygen demand (COD) of samples for 90 to 100 days after the well has been completed. *(R. Brobst, personal communication)*

It should be stressed that all monitoring wells must be developed as thoroughly as possible, not only to remove all traces of the drilling fluid from the formation, but also to increase the yield so that reliable samples can be collected in the shortest time. Development is also important to assure that the ambient water quality is maintained in the sample container until the water can be analyzed. Any sediment in the sample container, for example, can react with the water, thereby altering the actual chemical quality.

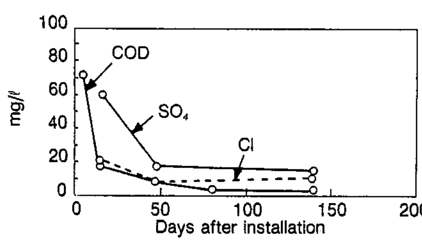
SAMPLING MONITORING WELLS

Sampling of monitoring wells will usually be done by field personnel from the testing laboratory or by groundwater consultants. Nevertheless, drilling contractors should have an appreciation of the difficulties in sampling protocol. In general, a sample is taken only after the pH, electrical conductivity, and temperature of the water being pumped from the well have stabilized (Wood, 1976). The methodology used in the sampling procedure is critically important if the true chemical nature of the groundwater contamination at that site is to be determined. Samples may not be representative of groundwater conditions for the following reasons:

1. The sample was taken from stagnant water in the well, which is usually different chemically from water in the ground near the well bore. The transmissivity of the aquifer should be determined so that the consultant can estimate the time required to remove enough water to obtain a reliable sample. In most wells, a sample



(a) These wells were not developed; the organic residues in the drilling fluid were allowed to break down naturally.



(b) These wells were developed using a breakdown chemical to reduce the viscosity of the drilling fluid.

Figure 21.11. Organic drilling fluid (Revert) residues will affect water-quality data for a certain length of time depending on whether the well is developed. *(R. Brobst, personal communication)*