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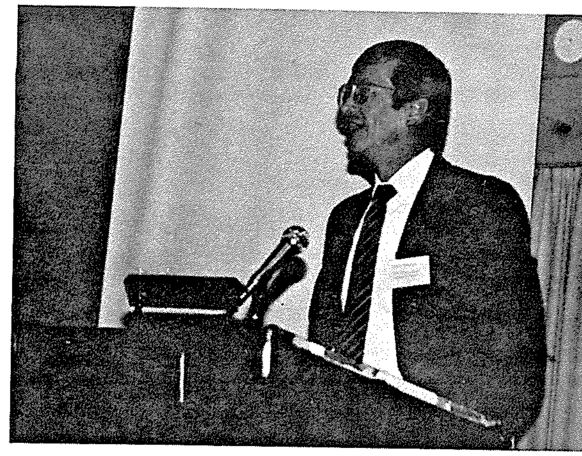

WHAT IS GROUNDWATER AND HOW DOES IT BEHAVE?

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WHAT IS GROUNDWATER?

" . . . groundwater is . . . subsurface water that occurs beneath the water table in soils and geologic formations that are fully saturated" (Freeze and Cherry 1979).

Figure 1 is a schematic diagram of an unconfined aquifer. "An aquifer is . . . a saturated permeable geologic unit that can transmit significant quantities of water under ordinary hydraulic gradients" (Freeze and Cherry 1979). The groundwater lies below the water table, or free water surface, designated by the inverted triangle in Figure 1. A hole drilled below the water table will fill with water to the same elevation as the water table if, as in Figure 1, the groundwater is unconfined. In situations where a confining layer exists within the saturated zone, the groundwater may be pressurized and can rise above the level in the aquifer.

The capillary fringe is a zone of saturation above the water table where the water is held by capillary forces at less than atmospheric pressure. Between the capillary fringe and the land surface lies the vadose zone, which contains air as well as water within the pore space. Perched groundwater may exist within the vadose zone due to the presence of low-permeability layers of soil or rock.

Groundwater occurs almost everywhere. Even in very arid climates, a small fraction of the rainfall manages to avoid evaporation and percolates downward. Eventually this percolating water usually encounters a layer of low permeability that hinders its downward mobility. The water builds up and a saturated zone develops. The water table may be as shallow as the land surface—in which case you have a lake, river or ocean—or may be many thousands of feet deep.

HOW DOES GROUNDWATER BEHAVE?

Groundwater obeys the same laws of physics as surface water. Thus, in Figure 2, we expect water in a tube to flow from the upper end of the

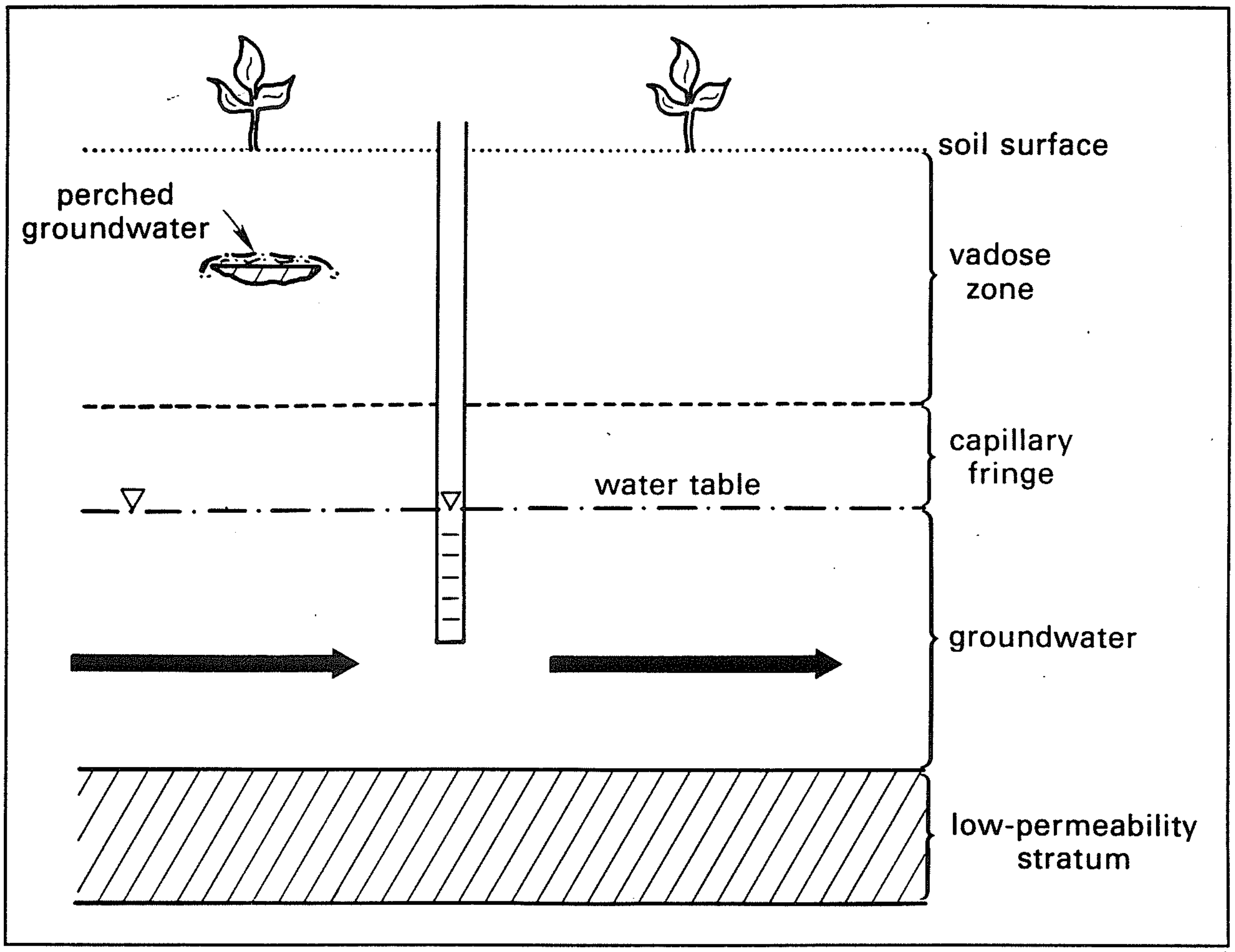

Figure 1. Cross section of the subsurface showing saturated zone and water table.

tube and out the lower end. Similarly, groundwater flows from regions of high potential energy (higher elevation in Figure 2) to regions of lower potential energy (lower elevation). If the water is pressurized and/or is moving, the pressure and the velocity, along with its elevation, determine the water's total energy at a given point.

Water moving from regions of higher energy to regions of lower energy results in interactions between surface water and groundwater. Thus, in Figure 3, water from a stream percolates through the stream channel to recharge underlying groundwater. In Figure 4, the water table is at a higher elevation than the stream channel, and groundwater is fed into the stream and discharged by surface flow. Figure 5 shows an example of an artesian system, where pressurized water formed by an upper confining layer comes to the surface downgradient through a well or a spring.

Groundwater pumping changes the water table's elevation in the vicinity of the well and alters the groundwater flow pattern. Thus in Figure 6, a "cone of depression" forms in the vicinity of the pumping well. If the well bore is too shallow, the well may "go dry" even though there is ample groundwater at greater depths. Pumping also alters the regional groundwater flow pattern, as shown in Figure 7. Some water in the vicinity of a well will be pumped into the well bore, while other water will escape the effects of the pumping and flow past the well. This pattern results in a "capture zone" for the well. Within the capture zone (defined by a given well configuration and pumping rate) all groundwater will ultimately be

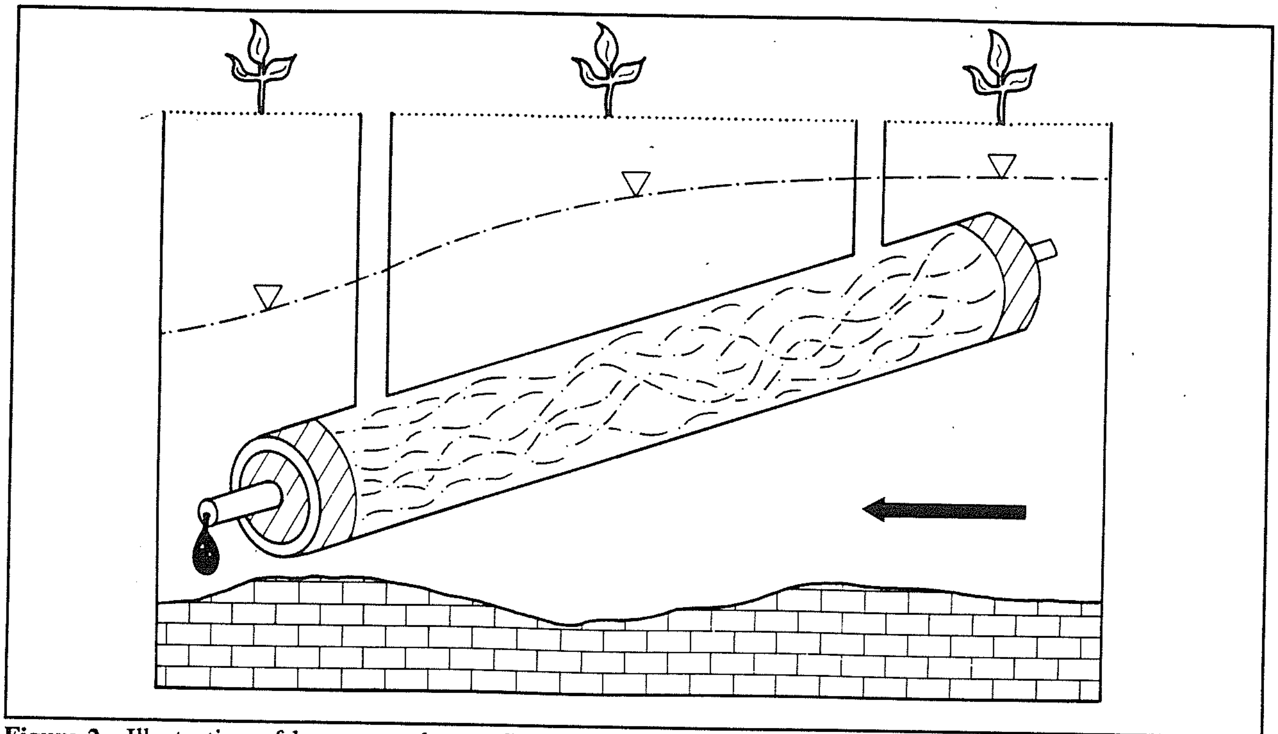

Figure 2. Illustration of how groundwater flows from region of high potential energy (elevation, in this case) to region of lower potential energy (after Freeze and Cherry 1979).

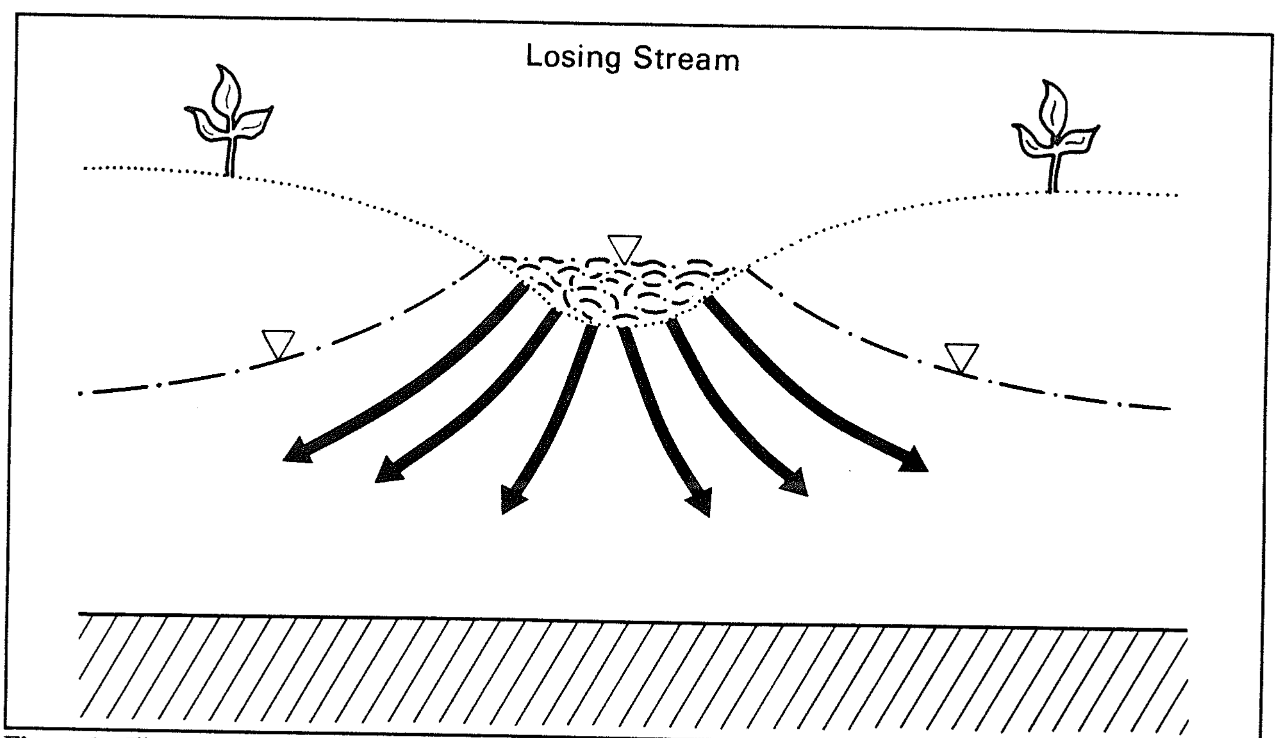

Figure 3. Illustration of a losing stream, where the groundwater elevation is lower than the stream elevation.

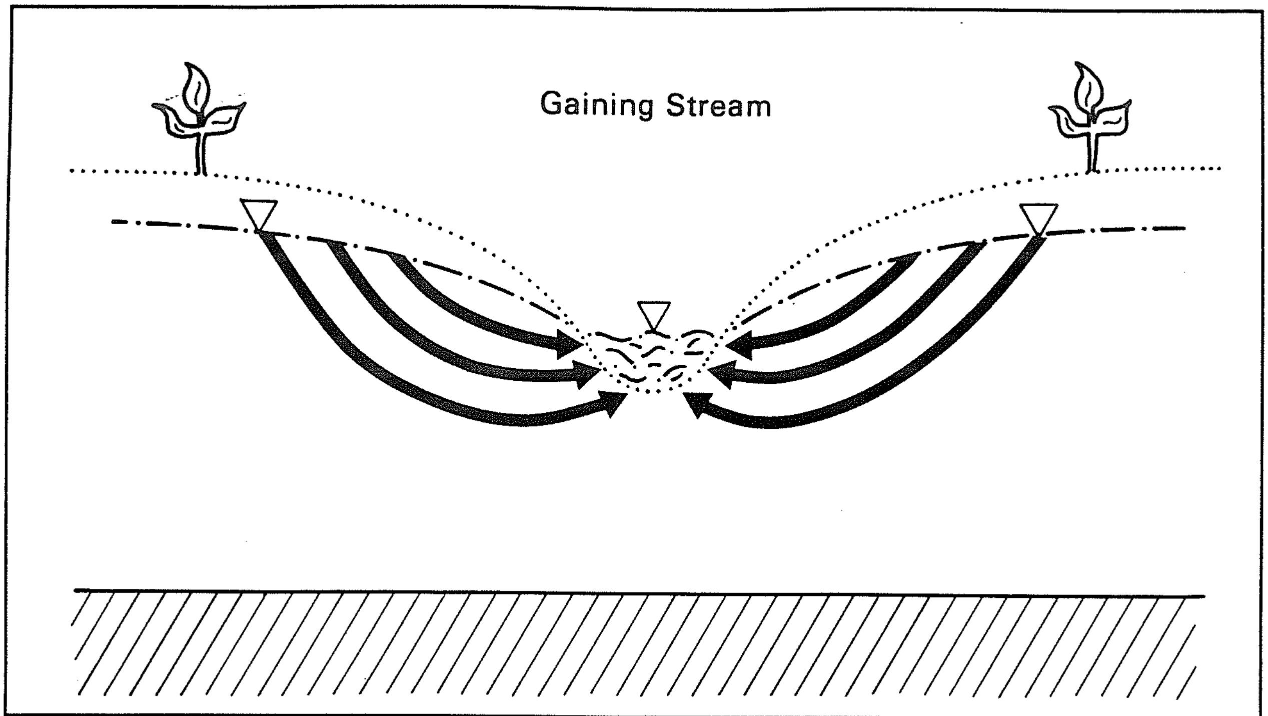

Figure 4. Illustration of a gaining stream, where the groundwater elevation is higher than the stream channel elevation.

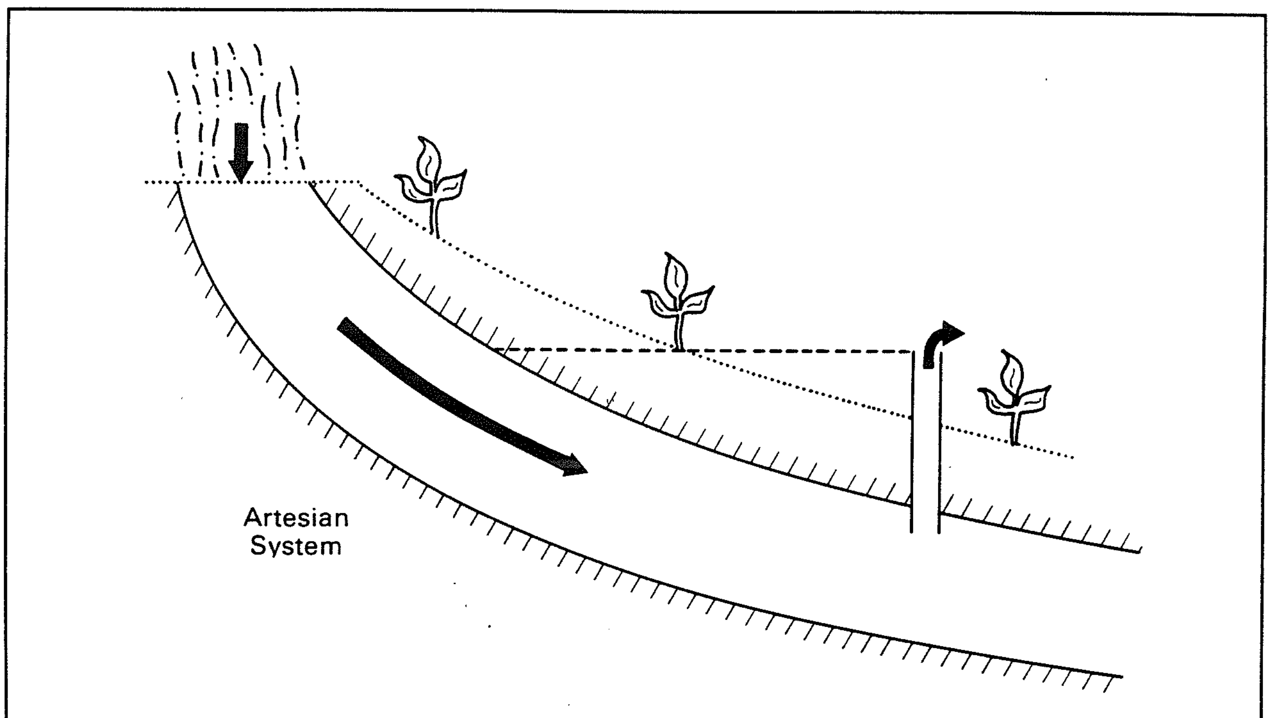

Figure 5. Example of an artesian well resulting from a confined aquifer.

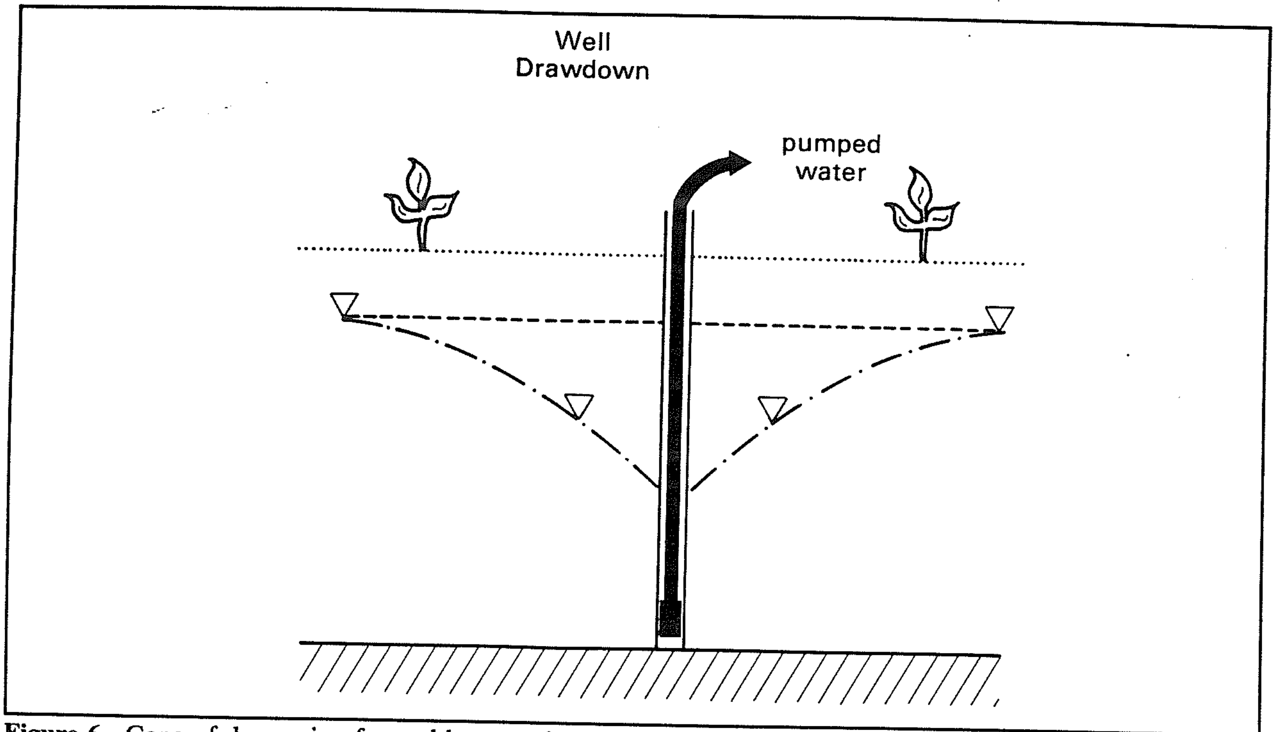

Figure 6. Cone of depression formed by pumping a well in an unconfined aquifer.

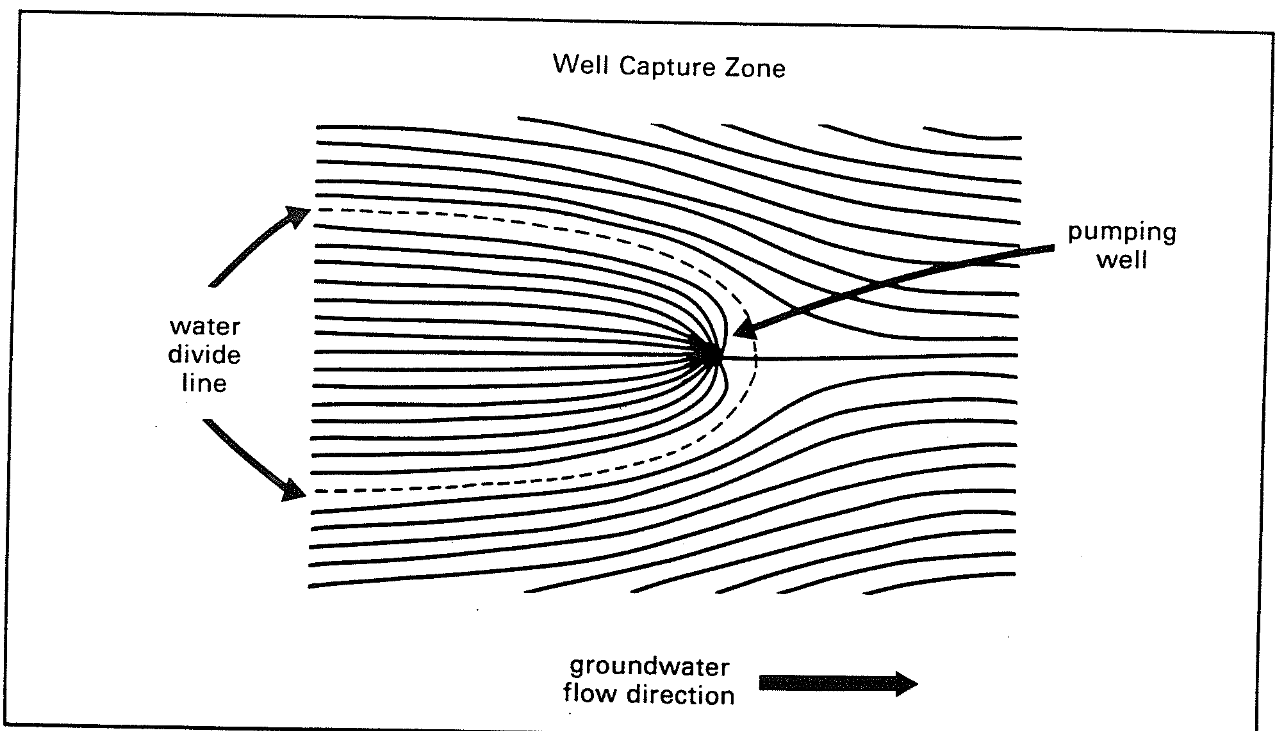

Figure 7. Illustration of a capture zone in the vicinity of a pumping well.

delivered to the well. Delineating capture zones is important to prevent activities within them which might lead to groundwater quality degradation.

GROUNDWATER CONTAMINATION

Almost any human activity can contribute to groundwater contamination. Waste disposal, industrial activities, and agricultural inputs immediately come to mind when we think of potential sources of groundwater pollution. More subtle activities such as changes in land use can result in mobilization and transformation of potential pollutants naturally present in the environment. The selenium groundwater contamination in California, resulting from irrigation of formerly low-water input desert land, is a good example.

Groundwater pollution may be chemical or microbial. In the United States and other developed countries, microbial water pollution has been largely controlled, and the main concern is with chemical contamination. In less-developed countries, microbial contamination is usually a greater problem.

There are many factors controlling the ability of a chemical contaminant to move from the land surface, through the vadose zone, and ultimately to groundwater. These include the specific properties of the chemical, the subsurface geology, and environmental conditions. Often the contaminant's mobility is highly correlated with its solubility in water. Thus, as shown in Figure 8, high-solubility species such as nitrate can migrate rapidly to groundwater, while lower-solubility chemicals such as pesticides are less mobile. This is why in agricultural areas the appearance of nitrates from fertilizer or animal wastes is often the first evidence of groundwater contamination. The nitrate may be followed later by the appearance of slower-moving chemicals.

Chemicals only partially miscible with water represent special groundwater pollution problems. These chemicals, usually fuels or solvents, can exist as separate liquid phases in the subsurface environment. If the liquid is less dense than water, as are most fuels and oils, a situation such as depicted in Figure 9 can result. After leaking out of its storage container, gravity moves the oil downward. Some of the oil is trapped in the vadose zone. If

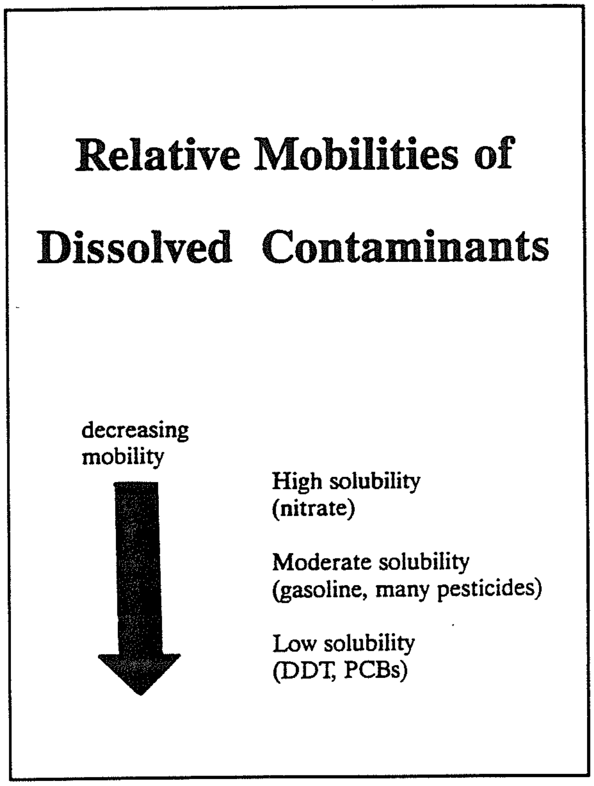

Figure 8.

there is enough oil, eventually it reaches the water table and floats downgradient on the water surface. The oil slowly dissolves into the water until it is fully dissolved or dissipated due to other processes such as volatilization or degradation. Free oil phase trapped in the vadose zone (and in the saturated zone as well) remains as a contaminant source which may be difficult or impossible to reclaim or displace.

Figure 10 shows a similar situation for an organic liquid having a density greater than that of water. Chlorinated solvents such a carbon tetrachloride or trichloroethylene (TCE) are examples of this liquid type. Again the fluid leaks downward, leaving some residual material in the vadose zone. When it hits the water table, however, this dense fluid continues to migrate downward until it encounters a low-permeability layer. Depending upon the slope direction of this layer, the polluting liquid may then proceed to migrate in a direction unrelated to the groundwater flow direction, while continuing to dissolve into and pollute the water.

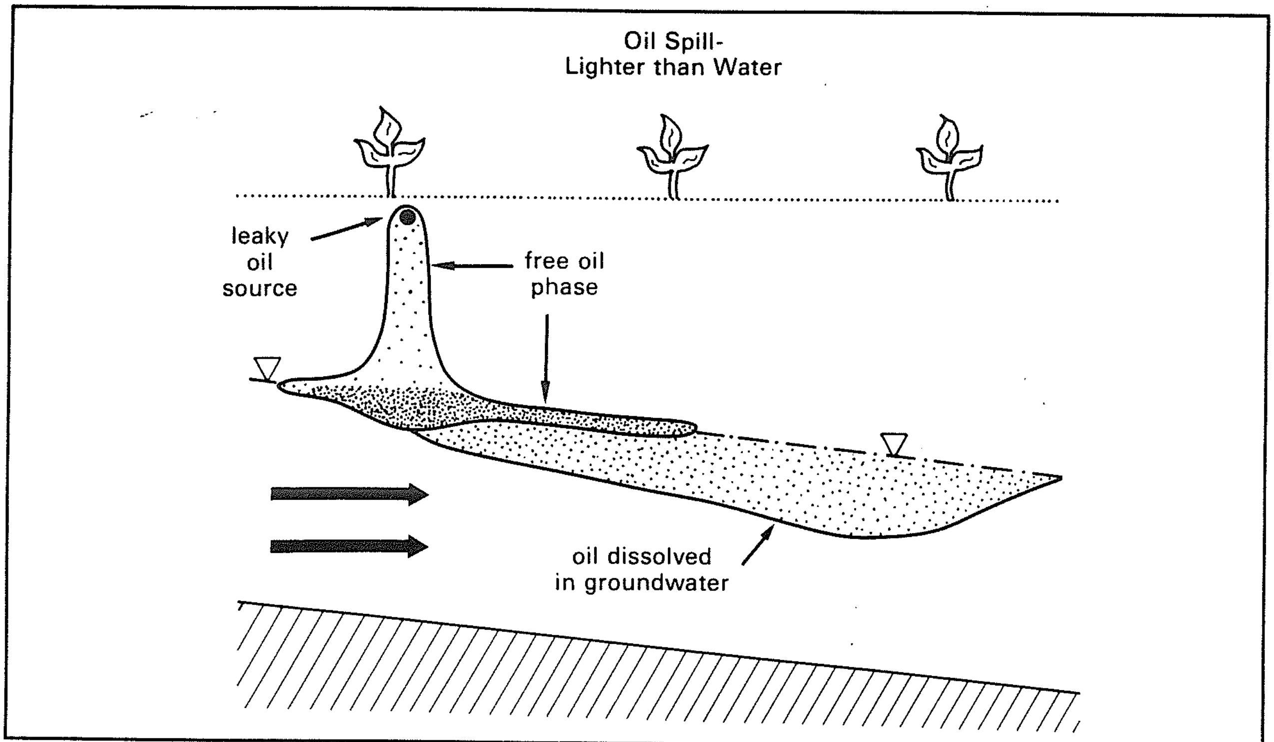

Figure 9. Schematic diagram of a spill of oil which is less dense than water (after Schwille 1984).

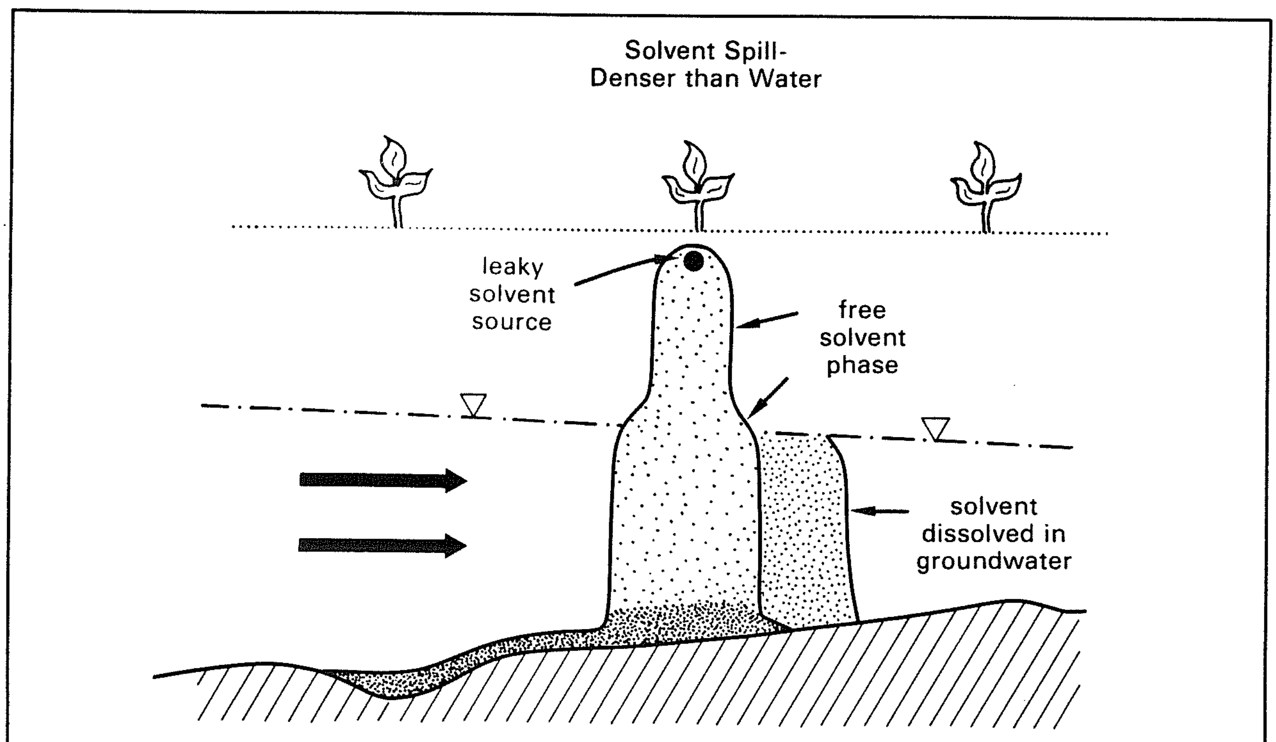

Figure 10. Schematic diagram of a spill of oil which is more dense than water (after Schwille 1984).

Locating the fluid source and remediation of an aquifer contaminated in this manner is very difficult.

PROTECTION OF GROUNDWATER RESOURCES

Although groundwater behavior follows simple laws, the complexity of subsurface geology makes predicting groundwater movement a difficult problem. Chemical migration in groundwater is even harder to predict. While as recently as 100 years ago most groundwater was essentially pristine, today we find ourselves with many aquifers contaminated with anthropogenic chemicals (whether these chemicals represent significant health hazards is a separate but related issue.) This isn't surprising, given the small amount of chemical required to contaminate a large volume of water. For instance, the drinking water standard for TCE is 5 ppb (parts per billion.) One gallon of TCE is enough to contaminate 293 million gallons (900 acre-feet) of water to this level. The costs associated with pumping and remediation of such large volumes of water are almost always prohibitive. Contamination prevention by better source control and the use of chemicals which break down rapidly in the environment are the only viable alternatives for long-term groundwater quality preservation.

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Schwille, F. 1984. Migration of organic fluids immiscible with water in the unsaturated zone. In *Pollutants in porous media.* Edited by B. Yaron, G. Dagan, and J. Goldshmid. Ecological study series 47. Springer-Verlag, Berlin.