Ground Water

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III. Well Hydraulics
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Glossary

Aquifer, aquitard, aquiclude Terms used to indicate the decreasing ability of a geologic material (or formation) to transmit significant amounts of water under normal conditions (forces, gradients)

Hydraulic conductivity Rate at which water can move through a soil or an aquifer under a unit hydraulic gradient

Soil root zone Biologically active zone extending from the soil surface to approximately 1 m depth

Storativity Volume of water that a unit volume of aquifer releases from storage when the hydraulic head is reduced by a unit length. For example, the specific storage of an aquifer that releases 0.1 m^3 of water from 1–m^3 of aquifer material after the hydraulic head is reduced 1 m is 0.1 m^{-1}

Transmissivity Rate at which water moves through an aquifer under a unit gradient; equivalent to the product of the hydraulic conductivity and the aquifer thickness

Vadose zone Aerated zone from approximately below the root zone to the upper-most aquifer

Water table Surface of an unconfined aquifer where the water pressure is atmospheric

Ground water is water located in the subsurface in fully saturated porous material. Ground water may occur in a geologic formation, which has confining zones (i.e., thick layers of clay or shale) above and below, where it is termed a confined aquifer, or it may have an unconfined upper boundary where it is called a phreatic or water table aquifer. It may be located above a layer of soil which inhibits downward movement of water. In this case, the water is perched in a region of porous material that is generally unsaturated. Generally, water moves from the soil surface through the soil-root zone (depth: 0 to approximately 1 m) into the vadose zone. The vadosc zone extends from just below the root zone to the ground-water table and is usually unsaturated, although local regions of saturation such as perched ground water may be located inside this zone. Separating the vadosc zone and a water table aquifer is the capillary fringe. This is a zone which is at saturation, but the water is under a negative potential as it is in unsaturated soil. The capillary fringe has properties which make it difficult to fit it in either of the vadosc or ground-water zones, as the capillary fringe is a transition between partially saturated porous media and fully saturated ground water. Ground water moves from high to low potential energy and from high to low elevation.

I. Importance of Ground Water to Agriculture

Over the past 40 years, the yields of agricultural commodities have risen dramatically. For example, harvests of wheat, soybean, and cotton have risen by as much as 50% and corn by up to 125%. These increases are due in part to improved farm operating procedures, management practices, new techniques for pest control, and more efficient use of water. In arid areas, a significant factor for increased crop yields is a steady supply of irrigation water. [See **WATER: CONTROL AND USE; WATER RESOURCES.**]

Although hydrologists generally focus on water movement in the subsurface, it is recognized that both ground- and surface-water supplies are important and inseparable parts of our water supply system. In arid

areas, lack of rainfall contributes to a reduced amount of surface water. Since surface water is often a source of recharge to ground water, the absence of surface water for a long period of time can cause lowering of ground-water tables and a reduction of ground-water supplies. In areas of abundant rainfall, ground water may feed into lakes and streams, keeping the water level in these surface water bodies relatively constant throughout the entire year. Abundant rainfall also provides water, through percolation, that keeps the ground-water level near the surface. It is important to recognize the interaction between ground and surface water when studying the use or contamination of ground water in agricultural areas.

For agriculture, there are two aspects of ground water which are of importance to those whose livelihood depend on growing crops. The first is ground-water quantity. In arid lands, profitability depends, in part, on sufficient amounts of relatively inexpensive water. In areas where there are no large quantities of surface water, ground water may be the principal source of water. To maintain crop yields over long time periods, however, ground water cannot be extracted at too great a rate: if the extraction rate far exceeds the rate of natural recharge, the ground-water resource will be depleted. This will have an effect on both agriculture and the people who live in agricultural areas, since without large surface-water sources nearby, ground water would also be the principal source of domestic drinking water.

The second issue of importance is ground-water quality. During the last 40 years, agriculture productivity has increased significantly, largely due to improvements in pesticides, seeds, fertilizers, equipment, and other management practices. Fertilizers and pesticides, in particular, can help to promote greater crop productivity relative to areas where they are not used. However, the detrimental effects from excessive pesticide and fertilizer use as well as other agricultural-induced effects can cause degradation of the quality of ground water. This can also have a negative effect on the persons using ground water for domestic drinking water. It has long been known that irrigation can cause accumulations of salts in soils, creating highly alkaline soils. Salinity now seriously affects productivity in about 20 to 30 million hectares or about 7% of the world's irrigated lands. The salinization of fertile croplands is between 1 and 1.5 million hectares per year. In the United States, it is estimated that 20 to 25% of all irrigated lands, about 4 million hectares, suffer from salinization. Salts are only one problem; toxic elements in agricultural return waters

can also pose extensive environmental problems. An example of this is the Kesterson Wildlife Refuge in California, where selenium concentrations have accumulated over time and have been detrimental to the fish and other aquatic wildlife. Therefore, management of our ground-water supplies requires the ability to determine quantities of water available for growing crops, the effects of extracting water from the ground-water supplies at the required rate, the cumulative effects on the ground water from pumping water throughout a basin, and determining the effects of agricultural management practices on ground-water quality.

A. **Ground Water as a Source of Potable Water**

Ground water is recognized as an important world-wide natural resource. In the United States, approximately 50% of the population and more than 90% of rural residents use ground water as their source of domestic drinking water. Ground water is the source for approximately 40% of the irrigation waters used in the United States and it is estimated that the total use of ground water for 1980 was approximately 90 billion gallons a day, triple the usage in 1950. As these figures indicate, ground water is a very important natural resource that will, without doubt, become more important in the future. Due to an extensive ground-water resource and the assumption that the soil would act as a perfect filter for percolating water, there was little concern for protecting the ground-water supply prior to the 1970s. More recently, however, there have been a large number of wells found to be contaminated, which has prompted more and more protective actions for our ground-water supplies. Recently documented problems from agricultural chemicals include nitrate and pesticide contamination of ground water.

II. **Equations Describing Ground-Water Flow**

Over the past several decades, there has been considerable work to develop a framework within which the ground water can be studied. This work has involved the development of methods for producing useful amounts of water as well as studying the effects of contaminant transport on the quality of ground water. A brief description of the important elements of ground-water flow follows.

It is difficult to study ground-water systems by direct observation. The cost of constructing wells to sample ground water is high. Therefore, mathematical models are used extensively to characterize the subsurface environment. This requires developing a framework in which the state of a ground-water system can be determined from the effects of anthropogenic or natural changes (e.g., due to pumping, transport of pollutants, global climate change, etc.). To achieve this, various relationships to describe the response of the groundwater system to changes in the forces acting upon it are needed.

Hydraulic potential is a way of expressing the energy status of water in porous media. It is easily recognized that water at the Earth's surface will move from higher to lower elevation in response to gravitational forces. This occurs because of differences in potential energy of the water at the higher elevation and movement will always occur from higher to lower potential energy in the same sense that a car with its engine off will roll down a hill. The same is true for ground water. Hydraulic head is a convenient way to express the potential energy of water, since the unit of hydraulic head is length and it can be determined by measuring the height of water above a datum (e.g., mean sea level). Hydraulic gradients represent the difference in the hydraulic potential over a given distance. The gradient indicates the direction and magnitude of the forces moving water.

Ground-water flow depends to a large extent on the local hydraulic conductivities. The hydraulic conductivity relates to the relative ease (or difficulty) with which water moves through the porous medium. Sandy soils are highly conductive, whereas clays have a very low conductivity. The hydraulic conductivity of porous material varies over many orders of magnitude (i.e., many factors of 10, such as from 10^{-10} to 10^{-2} cm/sec). This is a highly variable property of aquifers and this variability markedly affects the movement of water and contaminants contained within.

A. Darcy's Law

A fundamental relationship describing the movement of water is termed "Darcy's Law." Darcy's Law is an empirical description of the quantity of water that will move due to a difference in the hydraulic potential. In the original studies which led to Darcy's Law, a soil column was constructed to study the interaction between the hydraulic potential and the flow of water through a column. Darcy found that the flow of water

was proportional to the gradient of the hydraulic potential. He observed that for some soils water would pass through relatively quickly, for others much more slowly. For a given soil, however, a larger gradient would produce a proportionally larger flow. Doing this for many different soil types, Darcy found that a constant of proportionality could be introduced that would provide an equation that could be used to calculate the flow rate for a given soil type and hydraulic gradient. This constant proportionality is called the hydraulic conductivity and has the units of length per time. Further investigation with different liquids demonstrates that the hydraulic conductivity depends also on the type of liquid used. This relationship is of fundamental importance in characterizing the movement of water in soil and ground water. Darcy's Law is written as

$$q = -K\frac{dH}{dz,} \tag{1}$$

where q is the specific discharge (units length/time), which is the amount of water moving through a unit cross-sectional area of a column; K is the hydraulic conductivity (units length/time); and dH/dz is the gradient of the hydraulic potential (unitless).

Using Darcy's Law the specific discharge or the amount of water moving through the porous medium can be determined. Darcy's Law is not particularly useful, however, in determining the areal effects on a large aquifer since this relationship is based on flow through a relatively small "control" volume. Aquifers have a large areal extent, complex geologic features, layers, and boundaries, all of which preclude the use of such a simple relationship to fully characterize the movement of water. One can consider Darcy's Law as an expression relating flow in and through a "control" volume, which has a relatively small size such that the values for the gradient and conductivity are relatively uniform inside the volume and the flow rate is at steady state. An aquifer, on the other hand, is made up of many "control" volumes where locally Darcy's Law is valid. Also, an aquifer is rarely at steady state; therefore, the transient (time-dependent) nature of water movement must be considered. To fully describe the movement of water in an aquifer, a method is needed to combine the control volumes together in a consistent, mass-conserving manner.

B. Mass or Energy Conservation

To derive equations that would allow determining the areal effects on ground water from a pumping

water well requires the USC of a method for integrating the effects of all the control volumes while maintaining mass conservation. The basic statement of mass conservation is that the time rate of change of any physical quantity is equal to the amount that enters minus what leaves the control volume, minus what is lost from the control volume (i.e., from alteration or extraction), plus whatever is produced in the control volume (i.e., any sources). Generally, for ground-water systems, the only loss mechanism is from ground-water pumping; this could be stated more simply as: the change in storage of water is equal to the water that flows into the control volume minus the water that flows out of the control volume, minus any water pumped from the control volume. Incorporating Darcy's Law into the mass conservation equation produces a partial differential equation which can be solved using initial and boundary conditions to determine the effects of changes in the environmental conditions on ground-water flow:

$$S_s \frac{\partial H}{\partial t} = \frac{\partial}{\partial x}\left(K_x \frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial H}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial H}{\partial z}\right). \quad (2)$$

In Eq. (2), it has been assumed that the aquifer and water are both incompressible, that there are no other liquid phases present and that the ground water is under isothermal conditions.

To develop equations which can be used to solve problems, Eq. (2) must be integrated for a specific set of initial and boundary conditions. These conditions are determined by the physical configuration of the aquifer and its initial status. The integration process connects the control volumes together and produces an equation that describes the overall effects throughout the aquifer. A solution to Eq. (2) is said to be unique, that is, there is only one solution for a given set of assumptions (used to produce the governing equation) and initial and boundary conditions (from the physical system).

III. Well Hydraulics

One of the important methods for determining the effects on the ground-water supply from pumping is called the "Theis method." This equation provides a means for determining the draw-down of the potentiometric surface (i.e., the potential water-table level if no confining layer was present) in a confined aquifer due to extracting ground water. To use this equation, certain information such as the storage capacity of the

aquifer and the conductivity or the transmissivity of the aquifer must be known. Once this information has been obtained, the shape of the potential water-table profile can be estimated at any radial distance from the well to determine the effects on the potential water-table after pumping begins. The Theis method is a transient solution of the equation governing water flow; therefore, it provides information on the changes in the potential surface with time. This equation could be used to manage the ground-water supplies by limiting the amount of water pumped from ground water, so that excessive draw-downs do not occur. The Theis equation is one particular solution to the governing equation (Eq. (2)) of ground-water flow in aquifers. The Theis equation can be written as

$$h_o - h(r,t) = \frac{Q}{4\pi T}\int_u^\infty \frac{e^{-u}}{u}du = \frac{Q}{4\pi T}W(u) \quad (3)$$

with

$$u = \frac{r^2 S}{4Tt},$$

where $h_o - h(r,t)$ is the distance the potential water table has been lowered, (i.e., the draw-down), h_o is the potential ground-water surface before pumping begins, Q is the pumping rate, r is the radial distance away from the well, S is the aquifer storativity, T is the aquifer transmissivity, and t is the time after pumping begins. The techniques for obtaining this solution are beyond the scope of this discussion, but several assumptions concerning the aquifer configuration and ground-water flow are necessary to solve Eq. (2). It has been assumed that the flow of water is horizontal in the aquifer, the medium is homogeneous and isotropic, the thickness of the aquifer is a constant, the aquifer has infinite horizontal extent and no slope. The well is assumed to fully penetrate the aquifer and be open to the aquifer its entire extent and have an infinitesimal diameter.

Other solutions to the flow equation are available for different geometric configurations or initial and boundary conditions. For example, the Jacob's Straight-Line method can be used for larger times and situations where the confining layer is only partially impervious, and the Hantush-Jacob formula can be used for leaky aquifers with semi-impervious confining layers. Additional methods are available for cases where there is storage in the confining layer or where the well only partially penetrates the aquifer. Generally, as the initial and boundary conditions for the

problem become more complex, the equation describing draw-down becomes more complex. For water table aquifers, obtaining equations to determine draw-down are especially difficult. Given sufficiently strict assumptions, however, equations similar to the Theis equations can be developed to determine the draw-down. Another important use of the Theis and related equations is that they can be used to determine the aquifer parameters. To do this, measurements of the draw-down in several observation wells located at different distances from the pumping well are needed. The aquifer parameters are adjusted until the mathematical solution for the draw-down closely matches the observed draw-downs. The aquifer parameters which produce the best fit are retained. A reference containing a complete discussion of pump tests is given in the Bibliography.

A. Draw-down

The simplest example of these concepts is draw-down in a confined aquifer due to pumping. Consider an aquifer, shown in Fig. I, that is fully confined by impermeable layers above and below the aquifer. The aquifer thickness is $b = 20$ m, it has a hydraulic conductivity of 8.64 m/day (therefore the transmissivity is $172.8 \ m^2/day$), a storativity of 0.001 (i.e., a specific yield of $5 \ x \ 10^{-5}$), and initial head of 50 m. After one day, consider the effects of several different rates of pumping: $Q = 100$, 500, and 1000 m^3/day. In Fig. 2, the potential water-table surface, h, is shown as a function of the radial distance, r, away from the well. Clearly, as the pumping rate, Q, increases, so does the draw-down.
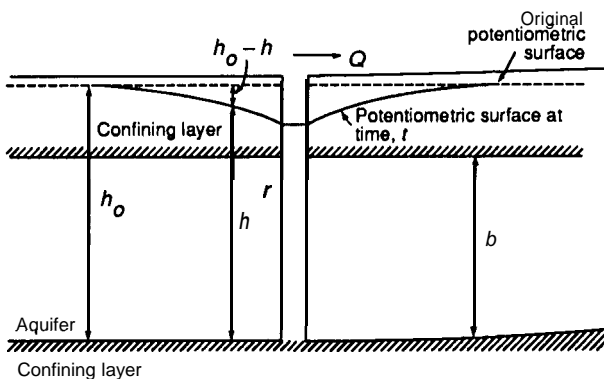

FIGURE 1 Fully penetrating well pumping from a confined aquifer. (Reprinted with the permission of Macmillan College Publishing Company from Applied *Hydrogeology,* 3/E by C. W. Fetter. Copyright © 1994 by Macmillan College Publishing Company, Inc.)
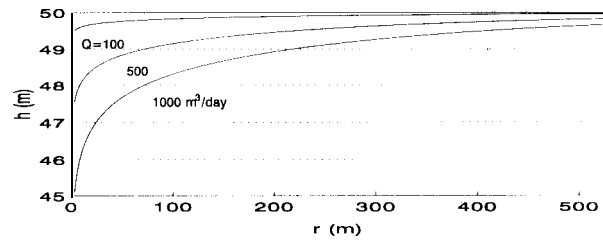

FIGURE 2 Potential water-table surface after pumping.

IV. Ground-Water Quality

Over the last 10 to 20 years, there has been more emphasis on protection of ground-water supplies from contamination than on developing new methods for optimizing ground-water yields. This is due, primarily, to the relatively advanced understanding of the principals of ground-water hydraulics, especially with regard to water extraction. The theory of transport of pollutants to and in ground water, however, is not nearly as advanced. This is due to the complex interactions between the contaminant and the subsurface environment.

Contamination of ground water from industrial and domestic pollutants has been recognized as a serious problem since the mid- to late 1970s. As ground-water monitoring programs have been initiated, more and more incidents of contamination have been reported. Results of EPA's survey of the quality of the nation's drinking water indicated that about 10% of community water system wells and 4% of rural domestic well water contained one or more pesticides; less than 1% of all wells were estimated to contain at least one pesticide in excess of the Maximum Contaminant Level (MCL) or Lifetime Health Advisory Level (HAL). There are several reasons for this. First, each year more waste products are being disposed of which increases the likelihood that contamination will occur. Second, chemical detection methods are constantly being refined which enable smaller and smaller amounts of a contaminant to be detected. For example, during the past few years, chemical analytical techniques were improved so that the concentration of certain chemicals could be detected at concentrations 100 million times lower than a few years before. Currently, some techniques are capable of detecting one part per quadrillion (ppq). This is roughly equivalent to locating a one-inch square stamp in the combined corn-belt states of Ohio, Indiana, Michigan, Illinois, and Wisconsin. Such large changes in the detection limit for a contaminant may give the percep-

tion that contamination is occurring more frequently when earlier monitoring studies may have had similar results if current technology had been available.

Generally, the source of the contamination can be classified as originating from a point in space or from a relatively uniform source over a large area; the latter is often termed nonpoint source pollution. Industrial pollutants such as from landfills, containment ponds, leaky storage tanks, injection wells, etc., are considered to be point sources. Agricultural fertilizers and pesticides that are used over large land areas and find their way into surface and/or ground water are classified as nonpoint sources of pollution. The use of agricultural chemicals is one of the most pervasive nonpoint sources of ground-water contamination. Each year approximately 661 million pounds of pesticides (active ingredients; 3.5 billion pounds of formulated pesticides) are used in agriculture. The first reported instances of ground-water contamination by pesticides occurred in 1979 where dibromochloropropane (DBCP) was detected in California and aldicarb in New York. Subsequently, monitoring found DBCP in four additional states. By 1983, ethylene dibromide (EDB) was found in wells located in 16 counties of California, Florida, Georgia, and Hawaii; this prompted suspension of the use of EDB in the United States. Fertilizers are also a large contributors to ground-water pollution: it is estimated that 20.5 million tons of fertilizers were applied to crops during 1988-1989.

Other nonpoint sources of pollution result from household septic-tank systems. Although each septic tank can be considered a point source, when aggregated over a community they have the characteristics of a nonpoint source. Because of the large number (greater than 22 million tanks with more than 1 trillion gallons of waste/year) of septic tanks used in the United States, disease outbreaks caused by these systems and elevated levels of nitrate in ground water caused by septic systems are of great concern.

There are large costs associated with environmental contamination. First, it is very difficult to accurately determine how and to what extent contamination injures an individual's health. Increased numbers of cancers due to exposure to low levels of pesticides have been reported but often it is difficult to determine whether pesticide exposure is the true source of the increased occurrence of cancers. Next, the costs associated with the degradation of the public's health arc difficult to determine since it is often unclear whether an illness would have occurred anyway. The costs to remediate contaminated soils and ground water arc

extremely high. In the case of ground water, remediation may not be technologically feasible or economical. It may be more cost effective to install water purification systems for potable supplies rather than attempting to rcmcdiate the contaminated ground water supply in *situ.*

The problem is exacerbated by the large number of chemicals currently in use in the United States and the approximately 1000 new chemicals that are put into use each year. Pesticides, in particular (which include insecticides, herbicides, fungicides, nematicidcs, rodenticides, fumigants, desiccants, defoliants, growth regulators, and miticides), are composed of between 1200 and 1400 active ingredients, which make up about 50,000 end-use products. Given this number, and the fact that new pesticides are developed every year, it is very unlikely that adequate hazard evaluation will be made on more than few of these. [See PEST MANAGEMENT, CHEMICAL CONTROL.]

There are few studies on the economic impact of ground-water contamination. The few that do exist tend to concentrate on the direct costs of cleanup and neglect confounding issues such as how to put a value on ground water and whether this value is adequately reflected in the market place. It is difficult to determine associated costs such as the short- and long-term health effects, and to evaluate the lost value of the contaminated ground water or the increased cost (i.e., cost to those that must purchase it) of replacement sources of ground water. The Office of Technology Assessment has provided some estimates of the economic costs of contaminated ground water. Their simplified economic analysis included the costs due to losing a well, extension of water supply lines, lost plumbing, lost profits, cost of new well construction, or purchase of water. Even so, the reported losses ranged from l 40,000 to 31 million dollars per year. It is likely that the costs would bc considerably higher had additional direct and indirect costs been included in the economic analysis.

A. Physical Processes Affecting Solute Transport in Ground Water

Contaminants can enter aquifers by several different avenues. Contamination can occur as water containing contaminants percolates downward from a surface source or from sources in the shallow subsurface, or possibly directly from wells, which may result from a spilling or back-siphoning during chemigation or from pesticide cleaning or handing. Movement

from the land surface to ground water can occur through preferential flow paths, such as biochannels (rootholes and wormholes), cracks, joints, and solution channels in the vadose zone. These may bc the predominant pathways affecting ground-water contamination in many instances by providing a direct and rapid path to ground water. In some locations, the potential exists for water in contaminated shallow aquifers to move to deeper aquifers through existing improperly sealed or abandoned wells. Also, cross-contamination of adjacent aquifers might take place through the wcllbore or outside the well casing in an unscaled annulus. It is difficult to incorporate many of these rapid-pathway mechanisms into models of transport, because of their localized nature, and to develop process models and supporting data for these processes and/or a lack of understanding of the mechanisms involved.

Contaminants in water can be transported great distances to public drinking water supplies or to discharge zones. The processes that affect transport of contaminants arc highly complex, and many of them are not clearly understood. The processes can be divided into two groups: those responsible for producing the **flux** of materials that move through an aquifer and other mechanisms, often compound-specific, that either affect the rate of movement (i.e., adsorption) or reduce the contaminant level (i.e., degradation). *Advection* is one of the primary processes characterizing the movement of contaminants in ground water. Under advective conditions, the contamination is transported along with the ground water moving in the flow system and, in general, the contaminant can be considered to move in the same direction and at the same velocity as the ground water. This may not be true for materials that have vastly different density compared to water, where the vertical movement may bc considerably different than water.

Hydrodynamic dispersion is a process that characterizes the spreading of a solute moving through porous material. There are three factors that contribute to the overall dispersion. At low ground-water velocities, the molecular diffusion can be important in the spreading process. At higher velocities, molecular diffusion also occurs but produces a small effect compared to mechanical mixing. At the pore scale, there is a variation in solute velocity depending on the location in the pore; a parabolic velocity distribution forms due to drag exerted on the fluid adjacent to the particle surfaces. Mechanical mixing causes a reduced concentration locally due to mixing of solute and the

adjacent carrier fluid as the solute diverges and converges around particles making the porous medium. This occurs since a mass of water that splits and diverges as it moves around soil particles does not converge to the same orientation on the other side of the particles, thus causing the solute to spread. This can be seen in Fig. 3. Dispersion occurs both in the direction that water is flowing as well as transverse to that direction. Dispersion and advection are considered to be interrelated, where the dispersion is related to the variance of the velocity distribution. A consequence of ignoring the velocity distribution is the observance that the dispersion process appears to increase with increasing measurement scale. Even so, because of a lack ofinformation, many times dispersion is assumed to be a constant for a given porous medium. Procedures for including scale-dependent dispersion in current models for simulating contamination transport at field-scale arc generally recognized as a limiting factor of current models. There arc many possible means for describing the scale-dependent dispersion process but, to date, there is no consensus on the best approach for doing this.

B. Other Contaminant-Specific Factors Affecting Ground-Water Quality

1. Pesticides

When assessing a pesticide's potential to contaminate ground water, both the mobility and the persistence of the pesticide must be considered. If a pesticide is very mobile, and is active for a long period of time, it has a high potential to contaminate ground water. On the other hand, if it is not mobile, and only persists for a short period of time, the potential for ground-water contamination is low (although it may be a candidate to contaminate surface water through runoff).

One of the most important factors determining the mobility of a pesticide is its solubility in water. When a pesticide enters the soil, it will adhere to the soil particles through a process called adsorption, and some will mix with the water that is present in the pores between the soil particles. The solubility of the pesticide determines the amount that will be present in the soil water, and thus be available for leaching. Solubility and adsorption are usually inversely related; therefore, pesticides that have a high solubility will be present in the soil water at a relatively high concentration compared to the amount that is adsorbed onto the soil particles. The affinity of a pesticide to adsorb to the soil can be expressed using the soil adsorption

Mixing in individual pores

Mixing by molecular diffusion

Mixing of pore channels
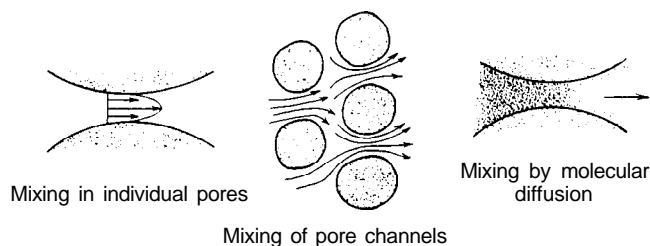
FIGURE 3 Processes of dispersion on a microscopic scale. (R. Allan Freeze/John A. Cherry, GROUNDWATER, © 1979, p. 76. Reprinted by permission of Prentice Hall, En&wood Cliffs, New Jersey.)

coefficient, K_{oc}. The smaller the K_{oc} value, the smaller the amount of pesticide adsorbed to the soil and the larger the amount in the water. Pesticides with small K_{oc} values are more likely to be leached through the soil than those with large K_{oc} values.

The persistence of a pesticide is generally expressed in terms of its half-life, sometimes written $t_{1/2}$. One half-life is the amount of time required for one-half of the mass of the pesticide to be degraded. After two half-lives, three-fourths of the pesticide will have been degraded; after three half-lives, seven-eighths will have been degraded, and so on. Pesticides can be degraded by many mechanisms, including chemical, physical, and biological processes. The half-life of a pesticide is reported in such a way as to reflect the process used to calculate that half-life. Examples include hydrolysis half-life (degradation by the chemical process of splitting the pesticide with water) and aerobic soil metabolism half-life (degradation by oxygen-requiring soil bacteria). The larger the half-life value, the greater the possibility that the pesticide can persist long enough to leach through the entire soil profile and reach the ground water.

In addition to the characteristics of the pesticide, soil properties are very important when determining the vulnerability of a site to ground-water contamination by a pesticide or other contaminant. The soil texture (i.e., the percentage sand, silt, and clay) affects pesticide leaching in two ways. Water, and any materials it contains, moves more slowly through clay soil than through soils with a high sand content. Clay particles also act to slow the movement of some pesticides by providing adsorption sites. Therefore, all other factors being equal, there tends to be less of a concern for ground-water contamination at sites with clayey soils than sandy soils. Also, soils with a high permeability lose applied water quickly through leaching. Pesticides applied to very permeable soils have a greater potential to contaminate ground water than if they are applied to less permeable soils. How-

ever, soils with low permeability have more problems with surface runoff that can lead to surface-water contamination by pesticides.

The organic matter content of soil is positively correlated with the adsorption of pesticides. Soils with high organic matter content would be less vulnerable to leaching than would soils with low organic matter content. Another benefit associated with high organic matter soils is that organic matter is required for microbial growth. Soil microorganisms are important in the degradation of many pesticides.

2. Nitrates

Nitrogen is an essential plant nutrient; thus, its use in agriculture is widespread. Since the 1940s, fertilizer application in the United States has increased from 1.8 million tons per year to approximately 20 million tons per year. Approximately 9 to 12 million tons of nitrogen is contained in the applied fertilizer. Nitrogen can exist in several different forms in the soil: as ammonia, as organic nitrogen, as nitrogen gas (which generally volatilizes out of the soil and into the atmosphere), and as nitrate. Nitrate is the soluble form of nitrogen, and it readily moves through the soil with percolating water. Under aerobic conditions, nitrogen in the soil is converted to the nitrate form. Any nitrogen that is applied in excess of the plant requirements and leaches below the root zone so that it is no longer available to plants has the potential to contaminate the underlying ground water with nitrate.

There are several sources of nitrogen to the soil in addition to agricultural fertilizer application. In certain areas, the geologic deposits are naturally high in nitrate. For example, nitrate-nitrogen concentrations as high as 300 mg liter^{-1} have been measured in the glacial till in the Great Plains of Alberta, Canada. Atmospheric deposition of nitrogen may be as high as 10 to 14 kg ha^{-1} year in some areas. The disposal of waste (human, animal, and crop residue) has been

estimated to add 15 million tons of nitrogen to the soil every year in the United States.

The concerns over nitrate contamination of ground water are primarily focused on the susceptibility of very young infants (under the age of 6 months) to high concentrations of nitrate. The stomach of an infant is not as acidic as that of older individuals; thus, certain bacterial species that convert nitrate to nitrite proliferate. Hemoglobin is the molecule in the blood that carries oxygen. In the presence of nitrate, the iron in hemoglobin is oxidized from Fe^{+2} to Fe^{+3}, forming a molecule known as methemoglobin. Methemoglobin is not capable of binding oxygen; thus, oxygen cannot be carried throughout the body. Over time, the skin of the infant turns blue due to the lack of oxygen, thus the term "blue-baby syndrome" or methemoglobinemia. This condition can be fatal without proper medical treatment.

There arc other concerns related to high nitrate and high nitrite waters. These concerns are based on the reactions between the nitrogen compounds and secondary or tertiary amines in foods to form nitrosamines. There have been studies in animals that suggest that there may be adverse effects (e.g., cancers, birth defects, reproductive toxicity) associated with exposure to nitrosamines. However, to this date, none of the studies has conclusively demonstrated a link between the consumption of high nitrate waters and these effects in humans.

The U.S. Environmental Protection Agency (EPA) regulates the concentration of nitrate in public drinking water supplies. A maximum contaminant level of 10 mg $liter^{-1}$ nitrate-nitrogen has been established; this level is enforced by either the state or the EPA.

3. Salinity and Drainage

Water management for salinity and sodicity control is very important in agriculture. Salt can affect plant growth from three mechanisms: osmotic effects which result from the total dissolved concentration of salts in the water and soil in the root zone; specific ion toxicity which results from a concentration of an individual ion above a threshold that causes harm to the plants; and poor soil physical conditions such as soil dispersion which result from high sodium or low salinity levels. These effects cause reduced yields of crops and therefore are highly undesirable. One method for controlling these kinds of effects is by flushing relativity clean water through the soil to carry the salts down below the root zone. Continued USC of this type of flushing will have a negative effect on the ground water as the salts are flushed down toward the water table. Even with water of relatively low salinity, salt accumulation occurs over time, since a portion of water applied to the soil surface is evaporated, leaving behind a higher concentration of salt in the remaining water. Over a season, the build-up of salts may increase to a point where extra water is needed to flush the salts below the root zone. As a consequence, over numerous seasons large amounts of salts and toxic ions can be leached to ground water.

For locations where the ground-water table is too close to the soil surface, the presence of a high water table can be harmful to crops growing on the soil surface. When this situation occurs, it may be necessary to install drains to lower the water table to a depth sufficient for the plants to have an aerated soil zone. Many factors affect the need for the use of drains, such as how much rainfall occurs, whether there arc impermeable zones, or hard pans, in the soil which restrict water movement out of the root zone.

4. Microorganisms

Microorganisms that can cause disease in humans may be introduced into the subsurface environment in a variety of ways. In general, any practice that involves the application of domestic waste water to the soil has the potential to cause microbiological contamination of ground water. This is due to the fact that the treatment processes to which the waste water are subjected do not effect complete removal or inactivation of the discasc-causing microorganisms present. For example, viruses have been detected in the ground water beneath cropland being irrigated with sewage effluent.

Another source of microorganisms to the subsurface is municipal sludge. Land application of municipal sludge is becoming a more common practice as alternatives are sought for the disposal of the ever-increasing amounts of sludge produced in this country. The sludge that is produced during the process of treating domestic sewage contains high levels of nitrogen and other nutrients that are required by plant materials. However, it may also contain pathogenic microorganisms at concentrations sufficient to cause disease in exposed individuals (Table I). Several studies conducted in the late 1970s suggested that viruses are tightly bound to sewage solids and arc not easily released into the soil. In a more recent study, viruses were detected in a 3-m-deep well at a site where anaerobically digested sludge was applied to a sandy soil 11 weeks after sludge application (Table II).

The EPA has recently promulgated new standards for the disposal of sewage sludge. Two classes of

TABLE I

Concentrations of Microorganisms in Digested Sludge

Organism	Type of stabilization	
	Anaerobic	Aerobic
	(No. per g dry weight)	
Enteroviruses	0.2-210	O-260
Rotaviruses	14-485	ND[a]
Salmonella	3- 10'	3
Total coliforms	$10^2-10"$	10^5-10^6
Fecal coliforms	$10^2-10"$	10^5-10^6
Shigella sp.	20	ND
Yersinia enterocolitica	10	ND
Ascaris	4^b	
Trichuris	1.3^b	
Toxocara	$0.4"$	

Source: Adapted from Gcrba (1988).
[a] ND, no data
[b] Average of att types of digested sludge, percentage viable.

sludge are defined based on the pathogen reduction requirements. The crop and access limitations to the land are dependent on the class of sludge applied, with the strictest controls on land receiving the least treated sludge.

Another practice regulated by many states is the reuse of treated sewage effluent for the purpose of crop irrigation. In general, the restrictions on the method of irrigation and the crops which can be irrigated arc stricter for the use of effluent that has not been highly treated, and less strict for effluent which has been extensively treated.

Some examples of pathogen detection in ground water at sites where domestic waste was applied to the land arc shown in Table II.

5. Management Practices

The pesticide, fertilizer, and domestic waste application practices and the irrigation practices at the site

TABLE II

Viruses in Ground Water following Land Application of Waste

Researchers	Site
Goyal *et al.*	27.5 m below cropland irrigated with secondary sewage effluent
Jorgensen and Lund	3 m below sludge application site 11 weeks after application
Vaughn and Landry	402 m down gradient from a sanitary landfill
Wellings *et al.*	12.2 m below a septic tank at a well 32.8 m away

are very important in determining the potential for contamination of ground water. Contaminants that would not be considered to be leachers by virtue of their chemical and physical properties may leach to ground water if the proper management techniques arc not used. Conversely, good management practices may result in preventing ground-water contamination by compound that arc considered lcachcrs. Following the label directions and using common sense when applying chemicals or domestic waste can help to minimize the potential for ground-water contamination. Irrigation management is also very important, because in general, the more water applied, the more the contaminant will move into and through the soil. Only the amount of water required by the plants should be applied; overwatering is costly and could contribute to contamination of surface or ground water. l'rcventing contamination of ground water is less cxpcnsivc and much easier than trying to remediatc contaminated sites or closing wells that exceed standards and drilling new ones.

Optimizing management practices to reduce pollution involves balancing opposing forces. There is inccntivc to reduce water needed to grow crops. This has led to the development of new techniques to increase irrigation efficiency. Along with new irrigation methods there is a need to determine how these new tcchniqucs affect the leaching of contaminants below the root zone. Once the important characteristics arc identified, management strategies can be devised that minimize the pollution potential of agrichemicals and other contaminants. For example, trickle irrigation can virtually eliminate leaching of water from the root zone. It has been suggested that this will reduce the movement of contaminants to ground water. If over time, however, salt build-up occurs, a large pulse of water will be required to reduce the salt to appropriate lcvcls. During this leaching period, the accumulated contaminants may be transported out of the root zone at a much higher concentration compared to a situation where some lcaching occurs continually. The overall effect of these practices on environmental quality needs to be determined.

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