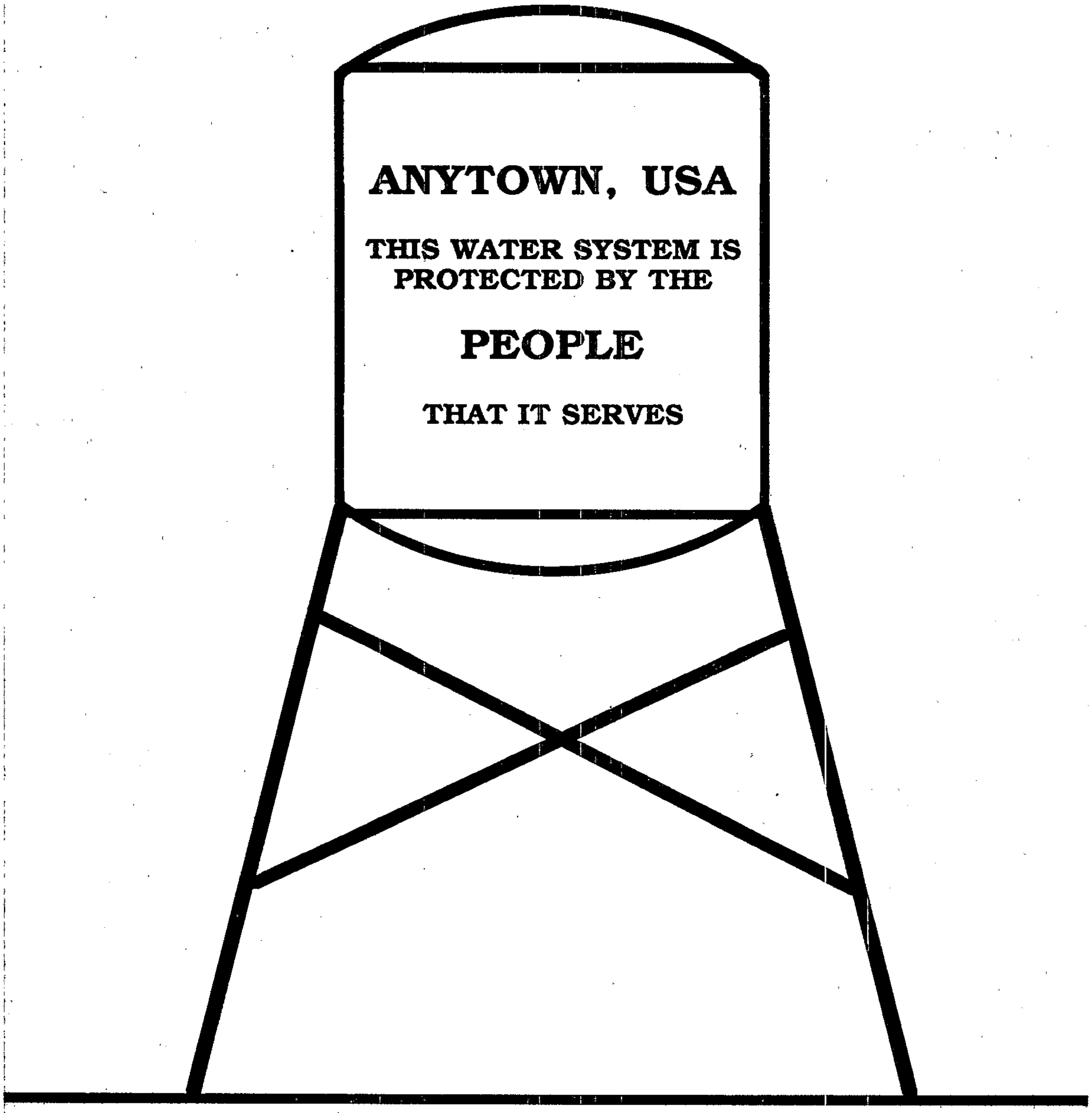
DEVELOPMENT OF A GROUND-WATER MANAGEMENT AQUIFER PROTECTION PLAN

A GUIDE TO CITIZEN PARTICIPATION



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SECTION 1

DEVELOPMENT OF A GROUND-WATER MANAGEMENT AND AQUIFER PROTECTION PLAN

Introduction

Communities smaller than 10,000 individuals that depend on wells as a source of water supply have special cause to develop a ground-water management and aquifer protection plan. Generally their tax base and other sources of income are small and they can ill afford an expensive and time consuming problem brought about by contamination of their well field. The best solution to the potential for contamination of a water supply is the timely development, monitoring, and enforcement of a plan that will protect the ground-water system. Prevention is far less costly than attempts, commonly futile, to restore an aquifer that has been contaminated through use, neglect, ignorance, or accident.

The 1986 Amendments to the Safe Drinking Water Act established a national program to protect ground-water resources that are used for public water supplies. The U.S. Environmental Protection Agency is attempting to achieve the goals of the Act by means of individual state Wellhead Protection Programs that "protect wellhead areas within their jurisdiction from contaminants which may have any adverse effect on the health of persons." The Wellhead Protection Program includes what is known as Wellhead Protection Areas, which are defined as "the surface and subsurface area surrounding a water well or wellfield, supplying a public water system, through which contaminants are reasonably likely to move toward and reach such a water well or wellfield."

It should be noted that although states are encouraged to develop a Wellhead Protection Program, the Environmental Protection Agency is not authorized to establish such a program in a state that does not wish to participate. The only impact on a state that does not so choose is the loss of grant funds. On the other hand, it makes good sense, both from a practical and monetary viewpoint, to develop and implement some type of plan to monitor and protect the water supply, the one resource that is absolutely essential to the survival and well being of every community.

The Wellhead Protection Program differs from a ground-water management and aquifer protection plan in that the former is concerned with public health and individual public water supply wells, while the latter encompasses a broader scope by dealing with the entire aquifer system, both as it presently exists and in the future. Furthermore, in many small communities a large percentage of the total water usage may be derived from private rather than public sources. The health of these users also needs to be protected as do the workers in plants and facilities that rely on private or semiprivate supplies. Likewise, water supplies used for industrial processing and the raising of livestock should meet certain chemical and biological criteria.

Contamination of ground-water supplies is generally the result of (1) selected past activities, (2) a problem(s) with the existing well or wellfield, including pumping, inadequate construction, operation, maintenance, or training of personnel, (3) waste disposal, (4) accidents, and (5) existing activities. Once recognized, each of these potential sources of contamination can be managed to reduce the likelihood of an adverse impact on the supply. For example, inadequacies of the public water supply system can be overcome with well construction codes, inspections, repairs and modifications, and operator training courses. Accidents can not be avoided, but they can be anticipated, at least as far as location is concerned, and a response plan that would have the least impact on ground-water can be formulated. Potential contamination brought about by waste disposal can be addressed by educational activities, by inventories, by municipal ordinances and zoning, by cleanup and restoration, and by organizing alternative means of disposal, such as collection stations.

The purpose of this report is to provide a number of ideas, guidelines, and techniques that can be used to formulate a ground-water management and aquifer protection plan with minimal cost. Of necessity, the report is generalized because each ground-water supply system is unique. Nonetheless, the concepts presented can be used to develop a general understanding of ground-water occurrence and movement so that a protection plan can be developed by a municipality.

Most likely the plan could be improved by hiring competent geological and engineering consultants, although this can be an expensive undertaking. In most states, a variety of local, state, or federal agency personnel, such as in health departments, the state and federal Environmental Protection Agency, or the state or federal geological survey, are more than willing to provide data and evaluations.

Any ground-water protection plan must consider potential sources of contamination, the geology of the area, and the local hydrogeology because they exert a major control on water quality. In addition, once a plan is developed there must be a move toward education of the public, monitoring, and enforcement. None of these activities need be expensive, although they can become time consuming. The municipality and responsible individuals must not be allowed to become complacent simply because no contamination events have occurred.

In some cases the implementation of a ground-water management and aquifer protection plan may be hindered by local politics and special interest groups, both of which work against the common good. A prime example is a small midwestern town with a population of about 1500. Nearly the entire income for the village is derived from the sale of water, which is pumped from shallow wells distributed through the corporation and on the flood plain of an adjacent river.

The wells produce from a mass of surficial sand that is particularly vulnerable to contamination from the surface. The city commission was very interested in an aquifer protection plan until they realized the various implications: a spill of liquid fertilizer at a local distribution plant that contaminated the ground water, a dry well at a slaughter house that receives blood and other wastes, a new landfill in a most inappropriate location, and an abundance of abandoned municipal wells. The spill, the dry well, and the landfill are all directly upgradient from one or more municipal wells; without corrective action, it is only a matter of time until some of the wells become contaminated. However, the owners of the bulk plant and the slaughter house are very influential citizens, the location of the new landfill represents a hard fought battle won by the commissioners, and it would be a relatively expensive undertaking to adequately plug all of the abandoned city wells. The ground-water management and aquifer protection plan was quickly tabled and, consequently, the citizens of the community will eventually suffer from the effects of poor government.

SECTION 2

INTRODUCTION TO GEOLOGY

A few basic principles of geology are essential for the development of an aquifer protection plan because ground water occurs in rocks and unconsolidated earth materials. Certain types of rocks are characteristic of various regions in the United States. Moreover, each rock type is sufficiently uniform, even in widely separated areas, so that some features can be generalized.

The crust of the earth is comprised of three types of rocks igneous, metamorphic, and sedimentary. Igneous rocks, such as granite,solidified from molten material either within the earth or on or near the surface. Metamorphic rocks, such as slate and marble, were formerly pre-existing rocks that have changed by an increase in temperature and pressure, and by chemically active fluids. Sedimentary rocks, examples being shale, sandstone, and limestone, are the result of weathering of pre-existing rocks, their subsequent erosion, and finally deposition.

Igneous and metamorphic rocks are generally very hard, crystalline, and fractured. For the most part they occur in the central part of old or existing mountain chains. They comprise but a small part of the land surface of the United States and occur notably in the Appalachian Mountains, New England, New York, Michigan, Wisconsin, Minnesota, and in several states west of the Rocky Mountain front (fig. 2.1).

For the most part, igneous and metamorphic rocks neither store nor transmit much water. Most, however, are fractured to some degree and can provide a modest amount of water to wells.

Although igneous and metamorphic rocks are generally poor sources of water, in several areas they are the only source. In places such as these, considerable care should be taken because a number of these water-bearing units can be easily contaminated. This vulnerability exists because the soil cover may be thin and fractures in the rocks may extend to land surface. The fractures may permit direct infiltration of precipitation, as well as contaminants, directly into the aquifer. There are few, if any, physical, chemical, or biological reactions available within the rock to attenuate the contaminant, other than dilution. Moreover, the contaminated water may flow rapidly in unanticipated directions.

Sedimentary rocks were deposited in a body of water or on the land surface by running water, by wind, or by glaciers. The most common sedimentary rocks are shale, siltstone, sandstone, limestone, and glacial till. Unconsolidated sedimentary deposits include sand, gravel, silt, and clay; they are changed to rock by the process of lithification.

Although sedimentary rocks appear (fig. 2.1) to be the dominant

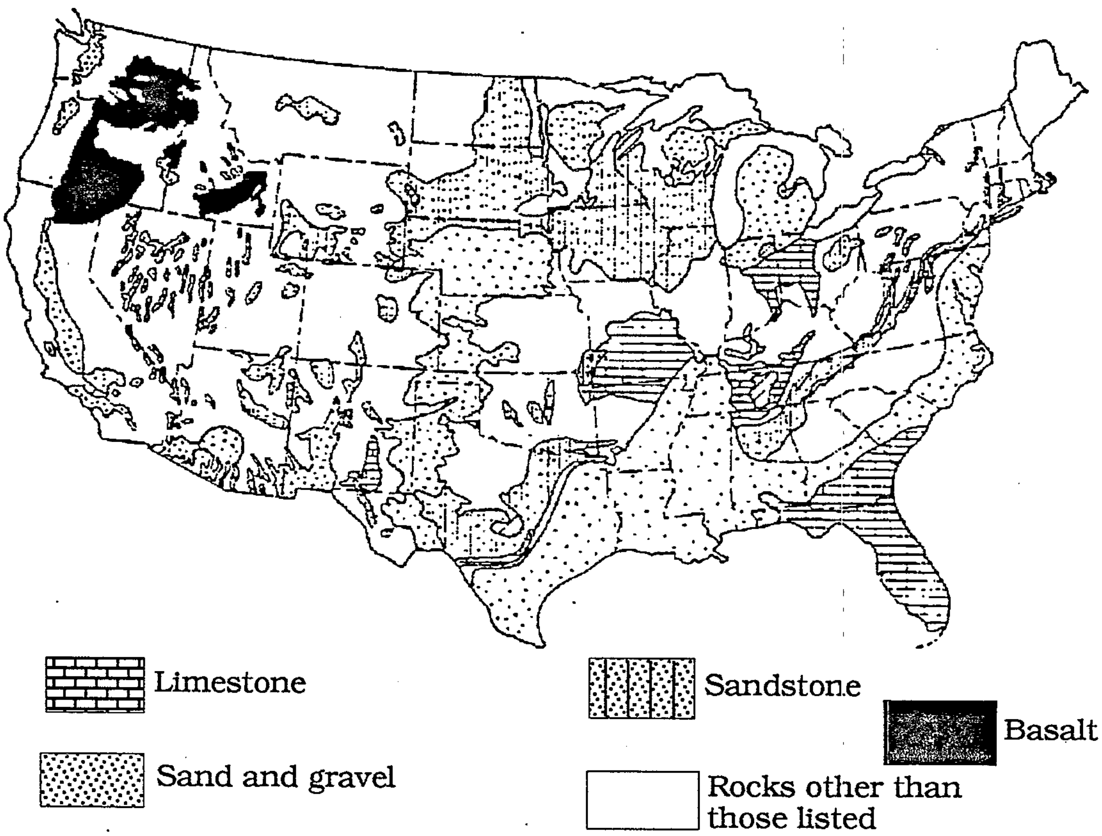


Figure 2.1 Distribution of major rock types.

type, in reality they make up but a small percentage of the earth. They do, however, form a thin veneer over much of the earth's surface, are the type most readily evident, and serve as the primary source of ground water.

Many sedimentary rocks store vast quantities of water, but some lack primary openings, such as many limestones and shales, and are poor sources of water. The latter serve as confining units because water does not easily move through them. Sedimentary rocks that form the best aquifers include sandstone and limestone that contains caves and other openings enlarged by solution of the rock. Regions typified by caves and solution openings are called karst areas. Karst areas are common in parts of Missouri, Indiana, and Kentucky, as well as many other regions underlain by limestone.

Limestone with solution openings and fractured sandstone also are subject to contamination in the same manner as the crystalline rocks. Karst areas are particularly troublesome, even though they can provide large quantities of water to wells and springs. Because of the pervasive nature of the openings in the rocks, it is usually difficult to trace the path of the contaminant, which may appear discharging from a spring miles away. In addition, the water may flow very rapidly, and there is no filtering action to degrade the waste. Not uncommonly in limestone areas, a well owner may be totally unaware that he is consuming or providing unsafe water. In fact, in several places sinkholes, disposal wells, or abandoned water wells have been used to dispose of wastewaters into limestone aquifers that also serve as sources of drinking water.

Sand and gravel deposits, particularly those found along major water courses, such as the Ohio, Mississippi, and Missouri Rivers and their tributaries, also are prolific suppliers of ground water. Likewise, the coarse-grained alluvial fill in the intermountain valleys of the west and southwest store vast quantities of water and provide significant yields to wells. It must be remembered, however, that coarse-grained, unconsolidated deposits not only provide large yields of ground water but that they also may be readily contaminated.

A few thousands of years ago, glaciers covered a vast area in North America, the southern boundary stretching from Montana, across the Dakotas, Nebraska, Kansas, and northern Missouri into Illinois, Indiana, Ohio, and New York (fig. 2.2). Although less widespread, glaciers also were present in the northwestern states. The remains include deposits of sand and gravel along streams and rivers, broad, relatively thin, sheet-like deposits of sand and gravel, called outwash, and

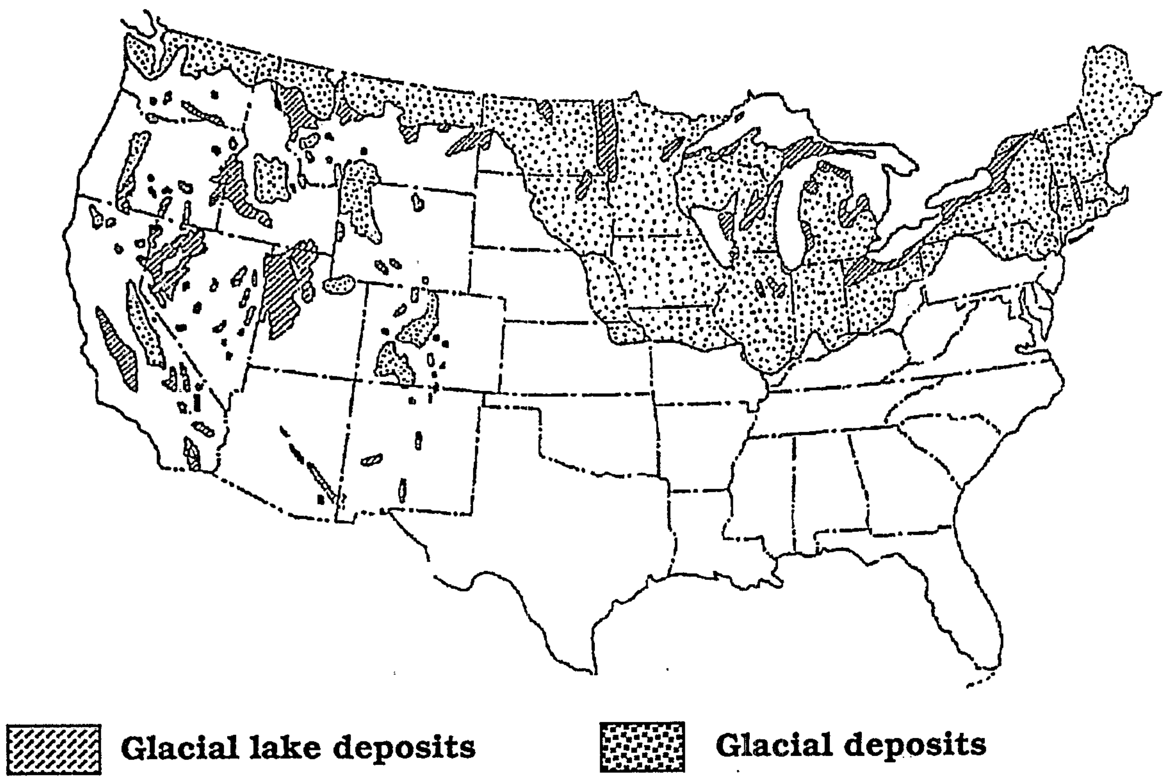


Figure 2.2 Distribution of glacial deposits.

glacial till, which in most places is a mixture of clay, sand, gravel, and boulders. The coarse-grained glacial deposits serve as major aquifers, while the till and clay act as confining layers.

Sedimentary rocks usually are deposited in a horizontal or nearly horizontal position, which is easily discernable because of bedding planes within the rock. The fact that many rocks are found overturned, displaced vertically or laterally, and squeezed into open or tight folds, clearly indicates that the crust of the earth is not at rest. There is a constant battle between the forces of destruction (erosion) and construction (earth movements).

Folded rocks are common in and adjacent to former or existing mountain ranges. Anticlines consist of rocks folded upward into an arch and their counterpart, synclines, are folded downward like a valley (fig. 2.3). Although the rocks may be dipping a few degrees or more, the land surface usually does not greatly reflect this structure.

Fractures in rocks are either joints or faults. A joint is a fracture along which no movement has taken place, but a fault implies movement. The movement, the primary cause of earthquakes, may range from a few inches to several tens of miles. Fractures, whether joints or faults, may exert a major control on ground-water movement because water can easily move through them unless they are filled with clay or mineral matter.

The difficulty of evaluating water and contaminant movement in fractured rocks is that the actual direction of movement may not be in the direction of the water-level gradient, but rather in some different though related direction. The problem is further compounded by the difficulty in locating the fractures.

In summary, ground water occurs in many types of rocks and unconsolidated sediments. From the point of view of contamination, regardless of the rock type, it is the permeability or interconnection of the openings in rocks that have the most sig-

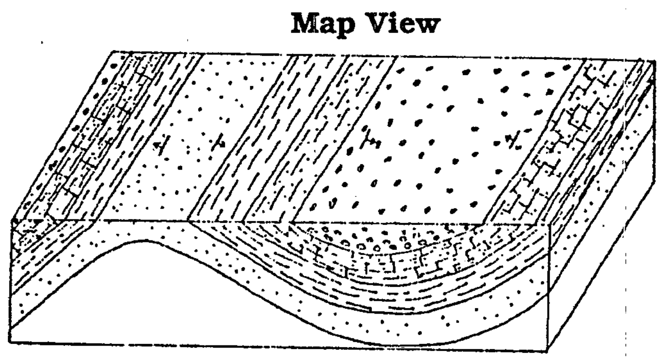


Figure 2.3 Sedimentary strata folded into an anticline and a syncline.

nificance. That is, permeable materials can readily allow the movement of contaminants into the ground-water system. Furthermore, permeable materials at or near the land surface are the most susceptible to contamination because they permit contaminants direct access to the water-bearing zone. It is ironic that shallow and surficial aquifers, which are commonly the most productive, the most readily recharged by precipitation, and the least costly for well construction, are those that are the most vulnerable to contamination to activities that occur on the land surface.

SECTION 3

FUNDAMENTALS OF GROUND-WATER OCCURRENCE AND MOVEMENT

The material in this section is designed to provide a general introduction to ground water, how it can be evaluated, and some of the controls on its storage and movement. It is not intended to be a definitive discussion. Sufficient material is included, however, for an individual or group of individuals to develop a generalized understanding of their ground-water system so that an aquifer protection plan can be developed.

If one were to dig a hole in the ground, the first few feet or so would probably be dry, but as the depth increased, the soil would become moist and eventually water would stand in the bottom of the hole. The surface of the water in the hole or well is called the water table. The relatively dry zone above the water table is the unsaturated zone, while below the water table lies the saturated zone, in which all of the open spaces are filled with ground water. The unsaturated zone is important because many physical, chemical, and biological reactions occur within it that tend to degrade waste materials and other contaminants. It is commonly called the "living filter" and the thicker it is, the more likely it will provide protection against contamination from surface or near surface sources.

The water table, in a general way, conforms to the contours of the land surface, although it lies at a greater depth under hills than it does beneath valleys. In humid and semiarid regions, the water table normally lies between 0 and 25 feet below the land surface. In some desert regions along mountain fronts the water table may occur at depths of hundreds of feet.

Below the water table, rocks serve either as confining units or aquifers. Confining units are characterized by low permeability and water does not readily pass through them, although they may store large quantities. Examples include shale, clay, and silt. An aquifer has sufficient permeability to permit water to flow through it with relative ease and, therefore, it will provide a usable quantity of water to a well or spring. The most common examples include sandstone, limestone, fractured crystalline rocks, and sand and gravel.

Water occurs in aquifers under two different conditions—unconfined and confined (fig. 3.1). An unconfined or water-table aquifer has a free water surface, which is the water table. The water table rises and falls in response to differences between inflow (recharge) of water to the aquifer and outflow (discharge) of water from it. As a general rule, unconfined aquifers are most subject to contamination from the surface and from shallow disposal wells.

A confined or artesian aquifer is overlain by a confining unit, such as clay, and the water in the aquifer is

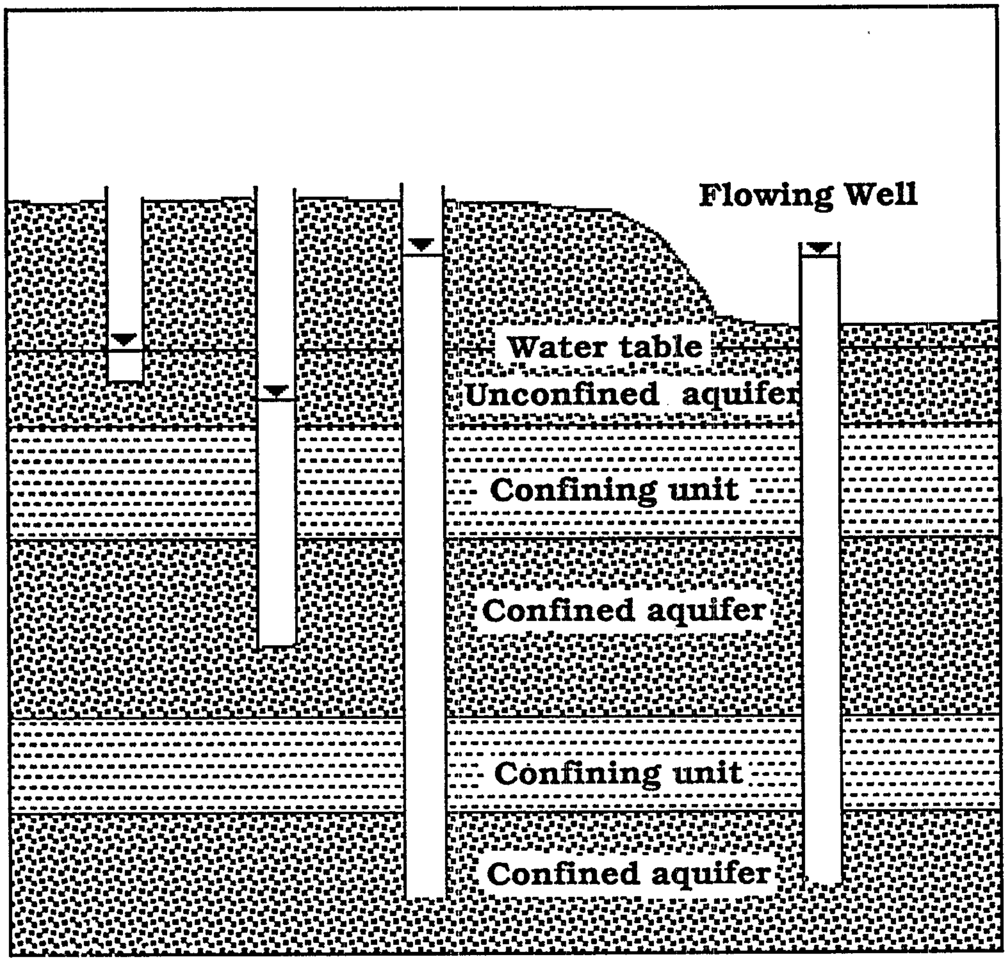


Figure 3.1 Major types of aquifer and confining units.

under sufficient pressure to rise above the base of the confining unit, if it is peetrated by a well. In some cases, the water is under enough pressure to flow from a well at the surface (fig. 3.1). These are called flowing artesian wells. The water level in a well tapping a confined aquifer is called the potentiometric or water-pressure surface. The confining unit that overlies the aquifer may provide a considerable degree of protection against the downward infiltration of contaminants.

Fresh ground water is derived largely by infiltration of precipitation, a process that is called recharge. Where the water table lies below a stream or canal, water may infiltrate from this source also. Interaquifer leakage, or flow from one aquifer to another, is probably the major source of water in deeper, confined aquifers.

An aquifer serves two functions, one as a conduit through which flow occurs, and the other as a storage reservoir. This is accomplished by means of openings in the rock. The openings include those between individual grains and those present as fractures, tunnels, and solution openings. The openings are primary if they were formed at the time the rock was deposited, or secondary if they developed after lithification. Examples of the latter include fractures and solution openings.

Porosity, expressed as a percentage or decimal fraction, is the ratio between the openings in the rock and the total volume of the rock. It defines the amount of water a saturated rock volume can contain. If a saturated rock is allowed to drain by gravity, not all of the water it contains will be released. The volume drained is called the specific yield, a percentage, and the volume retained is called the specific retention. It is the specific yield that is available to wells. Typical values for several rock types are listed in Table 3.1.

Material	Porosity %	Specific Yield	Specific Retention
Soil	55	40	15
Clay	50	2	48
Sand	25	22	3
Gravel	20	19	1
Limestone	20	18	2
Sandstone	11	6	5

Table 3.1 Selected values of porosity, specific yield, and specific retention

The term permeability (P) is used in a qualitative sense, while hydraulic conductivity (K) is a quantitative term. In this report they are expressed in units of gpd/ft^2 (gallons per day per square foot). Both terms refer to the ease with which water can pass through an aquifer, that is, they are expressions of the inteconnection of the openings in the rock. The hydraulic conductivity, which allows an aquifer to serve as a conduit, ranges between wide extremes from one rock type to another and even within the same rock. Typical values for most common water-bearing rocks are shown in Table 3.2.

Material	Hydraulic Conductivity* gpd/ft^2
Coarse sand	1500
Medium sand	1000
Mixed sand	500
Sandy gravel	2000
Clean gravel	4000
Limestone	2000

*Hydraulic conductivity is closely related to sorting and the size and number of fractures. These values are provided only as guidelines.

Table 3.2 Hydraulic conductivity of selected rocks.

The hydraulic gradient (I), the slope of the water table or potentiometric surface, is the change in water level per unit of distance along the direction of maximum water-level decline. It is determined by measuring the water level in two or more wells (fig. 3.2). A general impression of the hydraulic gradient of the water table can be obtained by examining a topographic map since the water table, in a subdued manner, tends to parallel the surface topography. The hydraulic gradient is the driving force that causes ground water to move. It is expressed in consistent units, such as feet per foot. For example, if the difference in

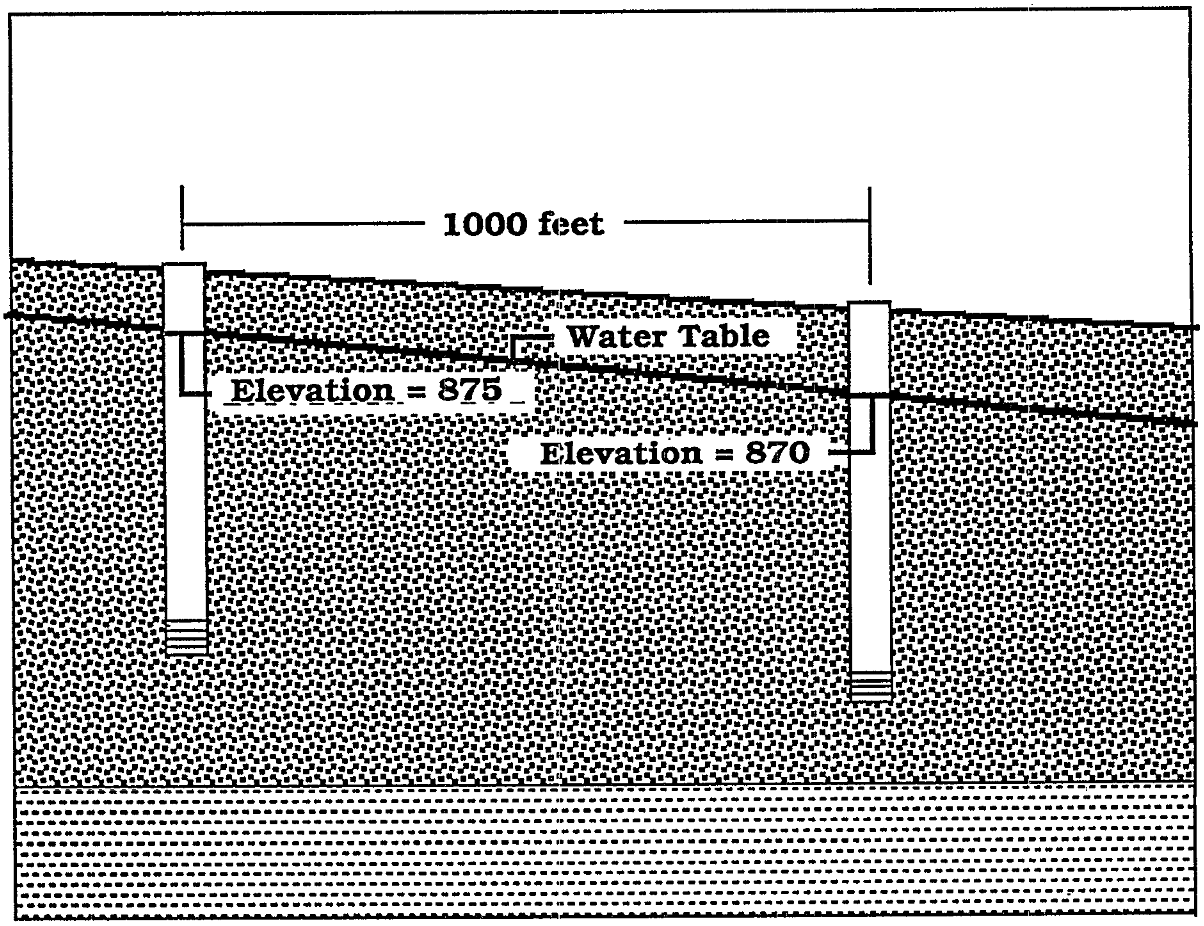


Figure 3.2 The hydraulic gradient (I) is the slope of the water table or potentiometric surface.

altitude of the water level in two wells 1000 feet apart is 5 feet, the gradient is 5/1000 or .002.

A water-level map is a graphical representation of the gradient. One can be prepared by plotting water-level measurements on a base map and then contouring them. An example is shown in Figure 3.3.

The direction of ground-water flow is determined by drawing a series of flow lines that intersect the water-level contours at a right angle. Flow lines are imaginary paths that would be followed by particles of water flowing through an aquifer (fig. 3.3).

Ground water moves both through aquifers and confining units, but it requires more energy to move water through fine-grained material than it does through coarse and, therefore, lateral flow in confining units is small when compared to aquifers, but vertical leakage through them can be significant.

The average velocity of ground water is generally much less than most individuals anticipate. In general it

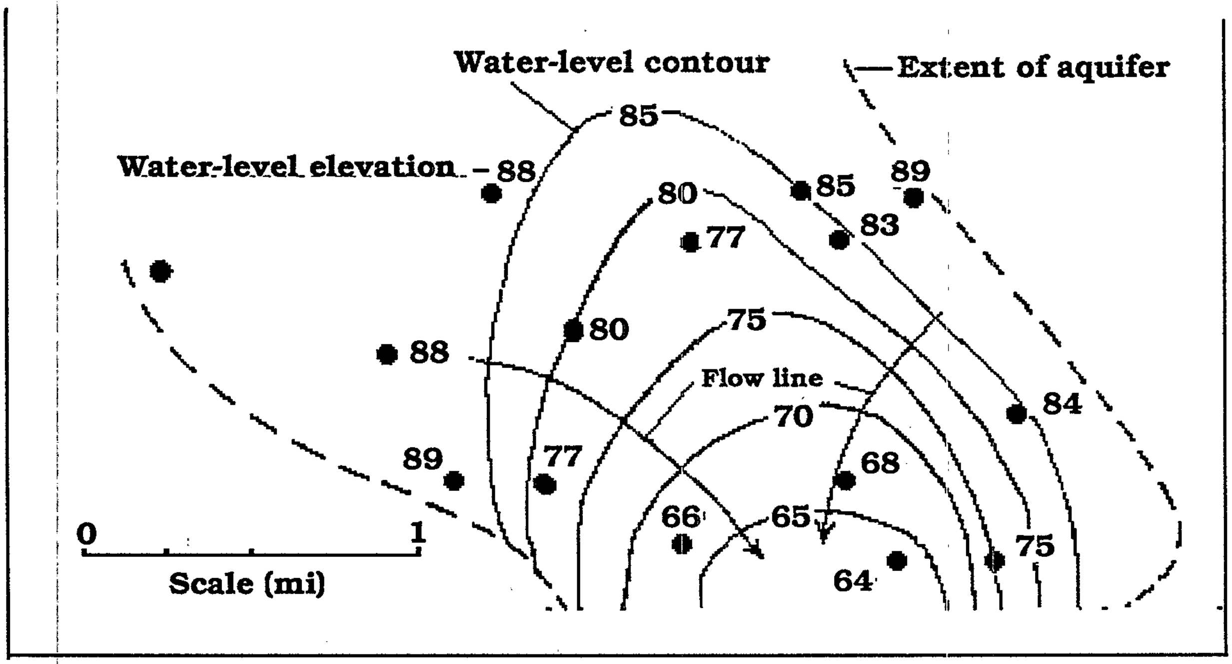


Figure 3.3 Water-level contour map and flow lines

ranges from less than 5 feet per year to more than 5 feet per day. The very slow movement is the major reason why ground water, once contaminated, can remain in an unusable or undesirable state for years or even decades. Ground-water velocity can be estimated by the following equation.

$$v = KI/7.48n$$

where v is the average velocity, in feet per day,
n is the specific yield,*
and the other terms are as previously defined.

For example, assume there is a spill of liquid fertilizer that flows through the unsaturated zone and quickly reaches a water-table aquifer. The aquifer consists of sand and gravel that has a hydraulic conductivity of 2000 gpd/ft² and a specific yield of .20 (see Tables 3.1 and 3.2). The water level in a well at the spill lies at an altitude of 825 feet and in a well 1000 feet directly down the hydraulic gradient the water level lies at an altitude of 815 feet. How long will it be before the second well is contaminated by fertilizer?

$$v = (2000\text{gpd/ft}^2)(10\text{ft}/1000\text{ft})/7.48 \times .20$$
$$= 13.4 \text{ ft/day}$$

* Actually effective porosity, which is slightly smaller than specific yield is the proper term, but it makes little difference in our analysis since we are only interested in rather broad generalizations.

Time = 1000ft/13.4 ft/day = 74.6 days or 2.5 months

Both the velocity and time of travel are only rather crude estimates, but they do provide a general impression of the rate of contaminant movement.

Hydrogeologists commonly use the term transmissivity (T) to describe an aquifer's capacity to transmit water. Transmissivity, described in units of gpd/ft (gallons per day per foot of aquifer thickness), is equal to the product of the aquifer thickness and hydraulic conductivity. That is:

$$T = Km$$

Another important term is storativity (S), which describes the quantity of water that an aquifer will release from or take into storage per unit surface area of the aquifer per unit change in water level. In unconfined aquifers the storativity is, for all practical purposes, equal to the specific yield and, therefore, it should range between about .01 and .3. The storativity of confined aquifers is substantially smaller because the water released from storage when the head declines comes from the expansion of water and compression of the aquifer, both of which are very small. For confined aquifers storativity generally ranges between .001 and .00001. The consequence of the small storativity of confined aquifers is that to obtain a sufficient supply from a well there must be a large pressure change throughout a wide area. This is not the case with unconfined aquifers because the water is derived from gravity drainage and dewatering of the aquifer.

Ground-water levels fluctuate

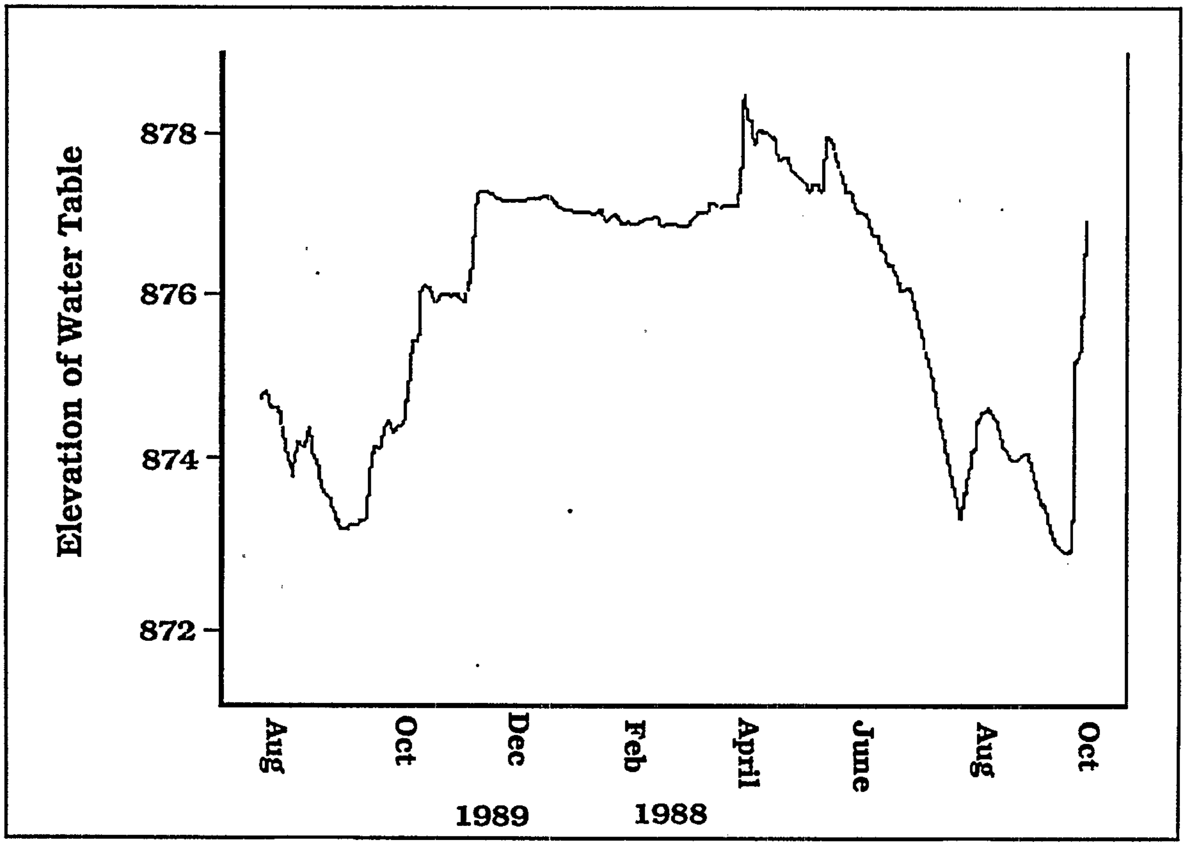


Figure 3.4 A hydrograph shows the fluctuation of the water level in a well.

throughout the year in response to natural changes in recharge and discharge, to changes in pressure, and to artificial stresses (fig. 3.4). Fluctuations that involve changes in storage are generally more long lived than those caused by pressure changes. Most ground-water recharge, which causes the water level to rise, takes place during the spring and fall. After these periods, which are a month or two long, the water level generally declines throughout the rest of the year because the ground water discharges into streams, springs, seeps, lakes, and wells, and is removed by plants where the water table lies at depths generally less than 15 feet.

When a well is pumped, the water level in its vicinity declines to provide a gradient to drive water toward the well. The gradient becomes steeper as the well is approached because the flow is converging from all directions and the area through which the flow is occurring becomes smaller. This results in a cone of depression in the water table or potentiometric surface around the well (fig. 3.5). Relatively speaking, the cone of depression around a well tapping an unconfined aquifer is small if compared to that around a well in a confined system. The former may be a few tens to a few hundreds of feet in diameter, while the latter may extend outward for miles.

Cones of depression from several pumping wells may overlap and, since their drawdown effects are additive, the water-level decline throughout the area of influence is greater than from a single cone. In ground-water studies, and particularly contamination problems, evaluation of the cone or cones of depression can be critical because they represent the area

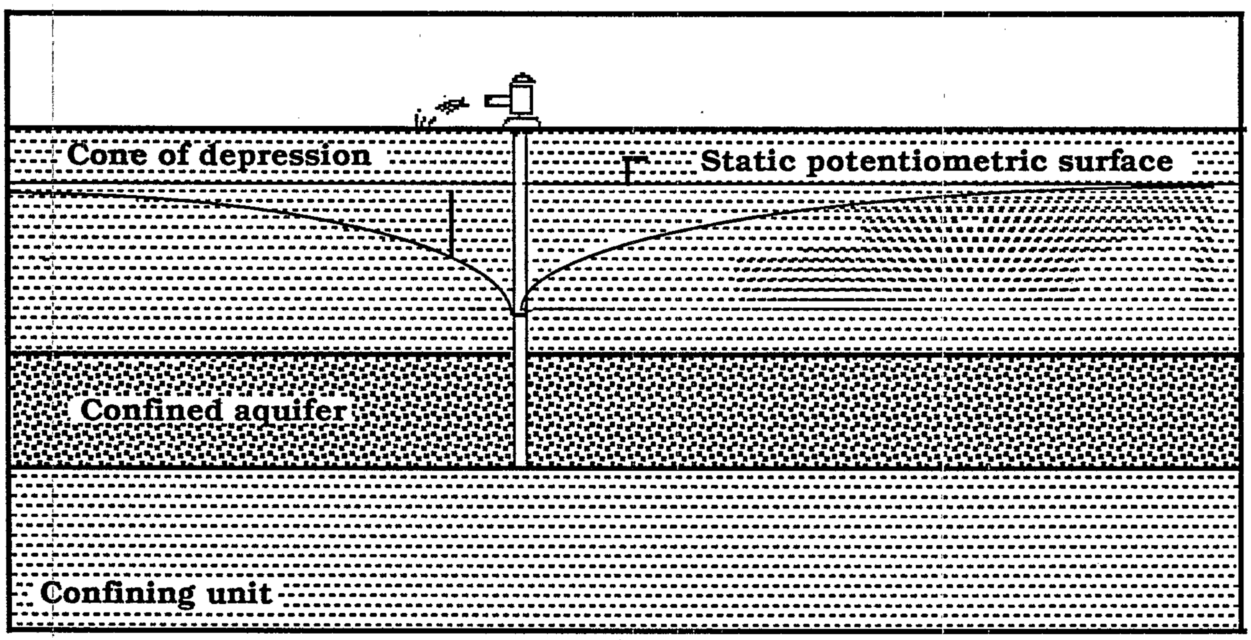


Figure 3.5 The cone of depression around a pumping well represents a steepening of the hydraulic gradient toward the well.

of capture of water and contaminants and the increase in the hydraulic gradient, controls ground-water velocity and direction of flow. In fact, properly spaced and pumped wells can be used to provide a mechanism to control the migration of contaminated ground water.

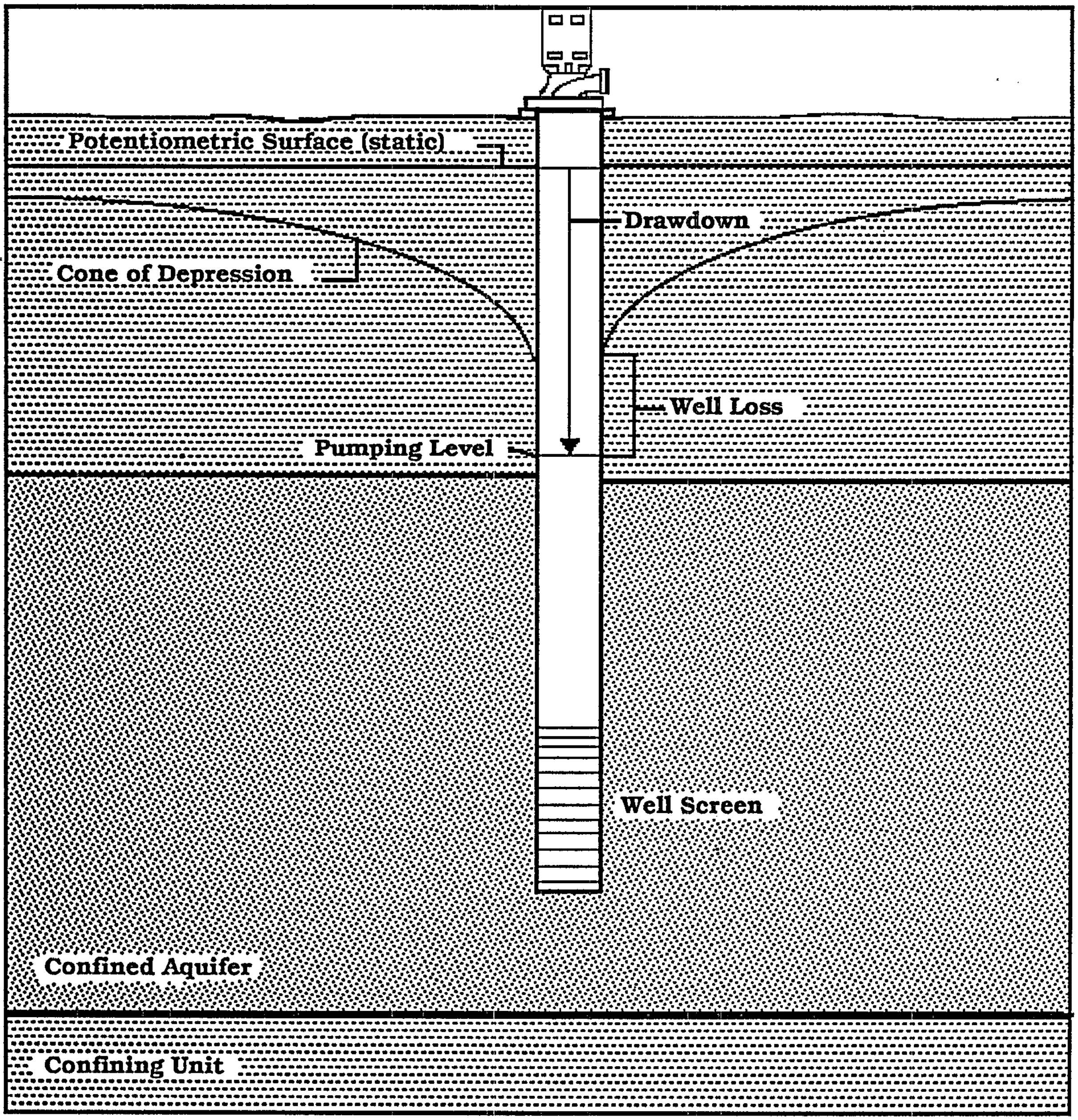


Figure 3.6 The water-level declined in and around a pumping well is called the drawdown.

The decline of the water level caused by a pumping well is called the drawdown and the pre-pumping level is the static level (fig. 3.6). The water level in a well that is pumping is called the pumping level. During pumping the drawdown or water level in the pumped well is greater than the drawdown adjacent to the casing. The difference is called well loss. Well loss is related to flow conditions in the vicinity of the screen and to the screen proper. As the screen becomes encrusted, as they generally do over time, the well loss increases. The discharge rate of the well divided by the difference between the static and the pumping level is called the specific capacity. The specific capacity indicates how much water the well will produce per foot of drawdown.

$$\text{Specific capacity} = Q/s$$

where Q is the discharge rate, in gpm, s is the drawdown, in feet.

For example, if a well produces 100 gpm and the drawdown is 8 feet, the well will produce 12.5 gallons per minute for each foot of available drawdown. One can rather crudely estimate the aquifer's transmissivity by multiplying the specific capacity by 2000. The transmissivity can then be divided by the thickness of the aquifer, as determined from well logs, to determine the hydraulic conductivity.

A Simple and Practical Approach To Estimate Velocity

The purpose of this generalized description of hydrogeology is to provide the reader with an impression of the manner in which ground water occurs and an aquifer functions. One of the purposes of the aquifer protection plan which follows is to indicate, in a generalized way, the manner in which contaminants might move in a ground-water system so that appropriate and timely steps can be taken to evaluate a potential problem. Here, the key word is "generalized", which means that the directions of flow, the velocity and rates, as well as the degree of natural protection are not absolute but rather are designed to provide only an impression. Keeping these restrictions in mind, it is not unreasonable to base some techniques on assumptions that are not entirely correct for every case, but yet are sufficiently near real values to be useful for their intended purpose.

Several field and laboratory methods are available to calculate hydraulic parameters, but rarely are time and funds available to a small municipality to conduct such tests. Nonetheless, it may be the responsibility of the water purveyor, city engineer, or other designated person, to estimate values in order to complete the aquifer protection plan. The following are four different approaches that can be used to estimate hydraulic conductivity and ground-water velocity.

The first method is to contact personnel in a state or federal agency, such as the state geological survey or the U.S. Geological Survey, and ask for their expert opinion. The second method is to compare the descriptions of the earth materials found in geologist's or driller's logs of the municipal wells with tables of information present in many textbooks. A third method is merely to guess, perhaps using the tables in this report. The final technique is to estimate hydraulic conductivity and velocity directly from easily obtainable measurements.

It is a good management practice to periodically determine the specific capacity (Q/s) of each well in a well field. When the specific capacity begins to decline, one needs to consider renovating the well because the decline is probably related to incrustation of the well screen. The greater drawdown caused by incrustation increases the cost of pumping the water.

Sample Calculation

Assume that the rate of discharge of a municipal well is 200 gpm (measured) and that after 8 hours the drawdown in the pumping well is 10 feet (measured). This means that the specific capacity of the well after 8 hours of pumping is 20 gpm/ft (200 gpm/10 ft of drawdown). In this case well loss is ignored.

As described previously, transmissivity is equal to the hydraulic conductivity (permeability) multiplied by the aquifer thickness and that an estimate of transmissivity can be obtained by multiplying specific capacity by 2000. Therefore:

$$K = \frac{2000\ Q/S}{\text{Aquifer thickness}}$$

Specific capacity can be measured at the well and the aquifer thickness can be estimated from the driller's log of the well. In this case, assume that the log of the well indicates a saturated thickness of 50 feet and, using the specific capacity (20 gpm/ft) calculated above:

$$K = \frac{2000 \times 20}{50} = 800$$

Next measure the hydraulic gradient, either by using the water-level difference between two wells or a water-level map. Assume that the difference in water lever between two wells is 20 feet and that the wells are a mile apart. That is:

$$I = 20/5280 = .004$$

The equation for ground-water velocity contains specific yield (effective porosity) in the denominator. Assume for all of the calculations that Specific yield is .15. The velocity equation can now be written in the form:

$$v = .9KI$$

Therefore, using the data calculated above:

$$v = .9 \times 800 \times .004 = 3 \text{ feet per day}$$

SECTION 4

SOURCES OF GROUND-WATER CONTAMINATION

Introduction

One of the starting points in a ground-water protection plan is to determine all of the potential sources of contamination, establish their locations, and become aware of the types of chemicals that might be present. Once this is done, each source can be evaluated relative to the vulnerability of the aquifer. This, in turn, will provide an indication of the degree of concern for each source.

Locating potential sources of contamination may not always be a simple process. Certainly the most obvious existing sources, such as abandoned gas stations, the city landfill, and various industrial works, are readily apparent, but two other areas also must be considered. The first consists of minor sources, such as the weekend auto repair shop, where brake and power steering fluid, as well as used oils, are dumped directly onto the ground behind the garage or in a dry well, or the part time photographer who disposes of spent developing chemicals out by the garbage cans (fig. 4.1).

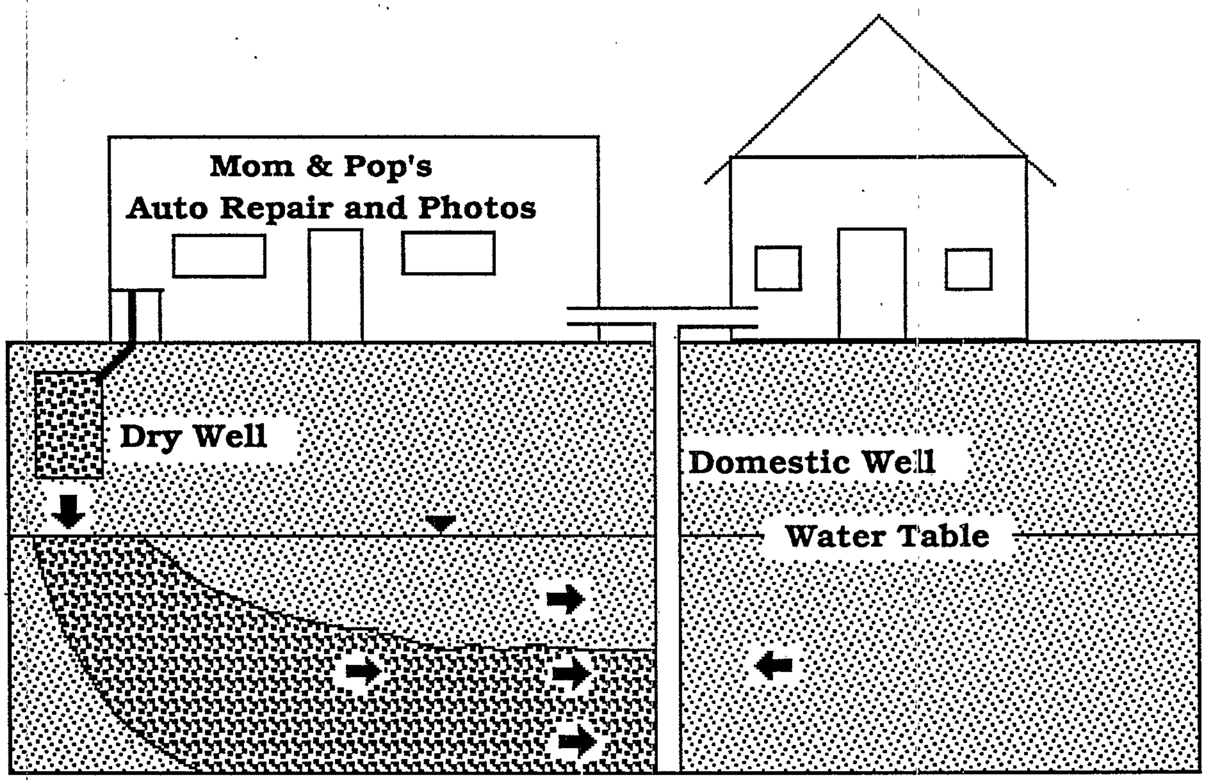


Figure 4.1 Minor sources of contamination, although difficult to locate, it may be of considerable importance in aquifer protection.

The second consideration represents those facilities and activities that have been gone for years or even decades. Where, for example, was the gasworks plant that burned in 1918, where was the city dump in 1923, the shingle factory that was torn down in the 1930's, or the military airfield that was abandoned in 1945? Records of facilities such as these may not be available, but one vast, largely untapped informational data base is at hand ... the senior citizens. In fact, senior citizens may be the only source of information.

As water moves from the land surface, into and through the soil, eventually reaching the water table, the quality changes. The changes may be either natural or man-influenced and it is often impossible or at least difficult to determine the origin of many water-quality problems. Although the chemical quality of water in surficial or shallow aquifers may range within fairly wide limits from one time to the next, deeper ground water maintains nearly constant chemical and physical properties where the aquifer is unstressed by pumping.

In most places the greatest potential for shallow ground-water contamination is by selected activities that occur on the land surface (table 4.1) and by what are known as Class V disposal wells (table 4.2).

Ground-Water Quality Problems that Originate on the Land Surface
1. Infiltration of contaminated surface water
2. Land disposal of liquid and solid waste
3. Stockpiles
4. Dumps
5. Disposal of sewage and water-treatment plant sludge
6. Deicing salt usage and storage
7. Animal feedlots
8. Fertilizers and pesticides
9. Accidental spills
10. Particulate matter from air borne sources
Ground-Water Quality Problems that Originate in the Ground Above the Water Table
1. Septic tanks, cesspools, and privies
2. Holding ponds and lagoons
3. Sanitary landfills
4. Waste disposal in excavations
5. Leakage from underground storage tanks
6. Leakage from underground pipelines
7. Artificial recharge
8. Sumps and dry wells
Ground-Water Quality Problems that Originate in the Ground Below the Water Table
1. Waste disposal in wet excava tions
2. Drainage wells and canals
3. Well disposal of wastes
4. Underground storage
5. Mines
6. Exploration wells
7. Abandoned wells
8. Water-supply wells
9. Ground-water development

Table 4.1
Generalized sources of ground-water quality degradation.

Drainage Wells (dry wells): agricultural drainage wells, storm water drainage wells, improved sinkholes, industrial drainage wells, special drainage wells.
Domestic Wastewater Disposal Wells: untreated sewage disposal wells, cesspools, septic systems (undifferentiated), septic systems (well disposal method), septic system (drainfield disposal method), domestic wastewater treatment plant effluent disposal wells.
Industrial/Commercial/Utility Disposal Wells: cooling water return flow wells, industrial process water and waste disposal wells, automobile service station disposal wells.
Recharge Wells: aquifer recharge wells, saline water intrusion barrier wells, subsidence control wells.
Mineral and Fossil Fuel Recovery Related Wells: mining, sand, or other backfill wells, solution mining wells, in-situ fossil fuel recovery wells, spent-brine return flow wells.
Geothermal Reinjection Wells: electric power reinjection wells, direct heat reinjection wells, heat pump/air conditioning return flow wells, ground-water aquacultural return flow wells.
Miscellaneous Wells: Radioactive waste disposal wells, experimental technology wells, aquifer remediation related wells, abandoned drinking water wells.

Table 4.2
Generalized listing of Class V wells.

Class V disposal wells, which likely exceed a half million units, include a diverse array of facilities, ranging from grease pits and industrial septic tank systems to storm runoff collectors, that are used to inject a broad range of waste waters into the subsurface. Most of these disposal facilities are shallow, extending into the unsaturated zone or a few feet into a shallow or surficial aquifer that has sufficient permeability to accept the waste. Although attempts are being made at state and federal levels to inventory and control their siting and use, few individuals are fully aware of the potential of the exceedingly high adverse impact of many Class V wells on underground sources of drinking water in the United States. In addition, even fewer are sufficiently knowledgeable about the vulnerability of the aquifers that provide their water supply.

Water Quality Problems Related to Septic Systems

Probably the major cause of ground-water contamination in the United States is effluent from septic tanks, cesspools, and privies (fig. 4.2). Individually of little significance, these devices are important in the aggregate because they are so abundant and occur in every area not served by municipal or privately owned sewage treatment systems. The area that each point source affects is generally small, since the quantity of effluent is small, but in some limestone areas effluents may travel long distances in subterranean cavern systems. Residential or

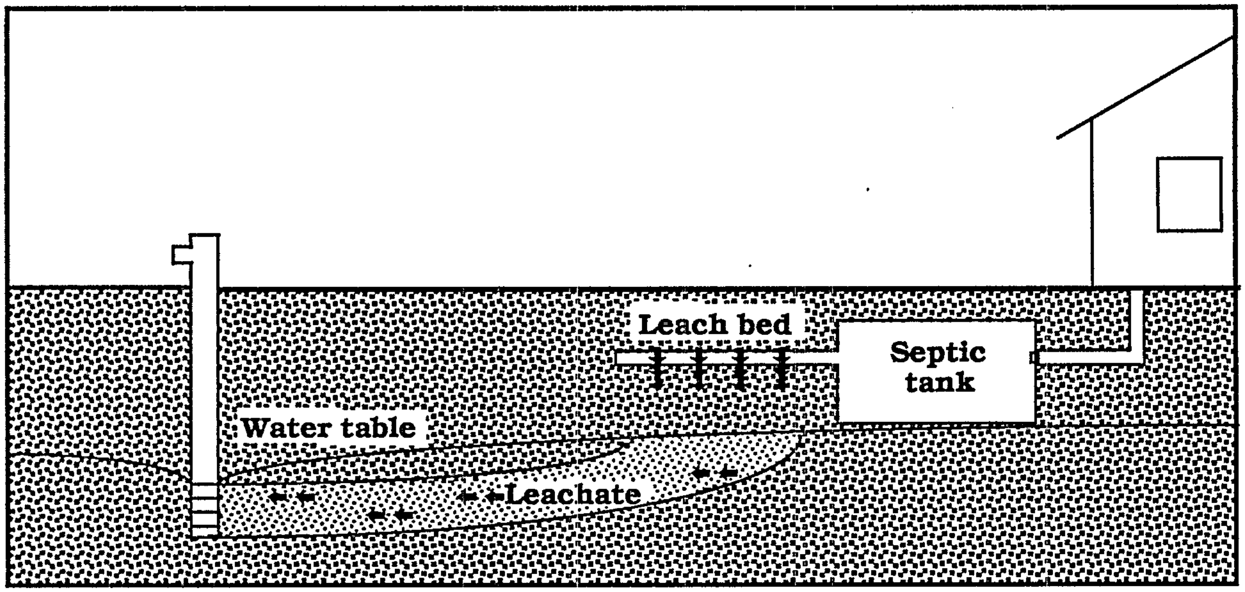


Figure 4.2 The cone of depression surrounding a water-supply well may cause septic tank effluent to migrate to the well.

commercial septic systems serving 20 or more people are included in the Class V well category.

Artificial Ground-Water Recharge

Artificial recharge includes a variety of techniques used to increase the amount of water infiltrating to an aquifer. It consists of spreading the water over the land or placing it in pits, ponds, or wells from which the water will seep into the ground.

Waters used for artificial recharge consist of storm runoff, irrigation return flows, stream water, cooling water, and treated sewage effluent, among others. Obviously the quality of water artificially recharged can have a major effect on the water in the ground.

Water Quality Problems Related To Dry Wells

Dry wells may locally cause some contamination problems and in places where these structures are adjacent to a stream, bay, lake, or estuary, they may pollute such surface water bodies and lead to a proliferation of the growth of algae and water weeds. These structures are commonly used to collect runoff or spilled liquids, which will infiltrate through the well (fig. 4.3). Dry wells are typically installed to solve surface drainage problems, so they may transmit to ground water whatever pollutants are flushed into the well.

Where surficial materials consist of heavy clay, flat-lying land may be poorly drained and contain an abundance of marshes and ponds. Drainage of this type of land is generally accomplished with field tiles and drainage wells. A drainage well is

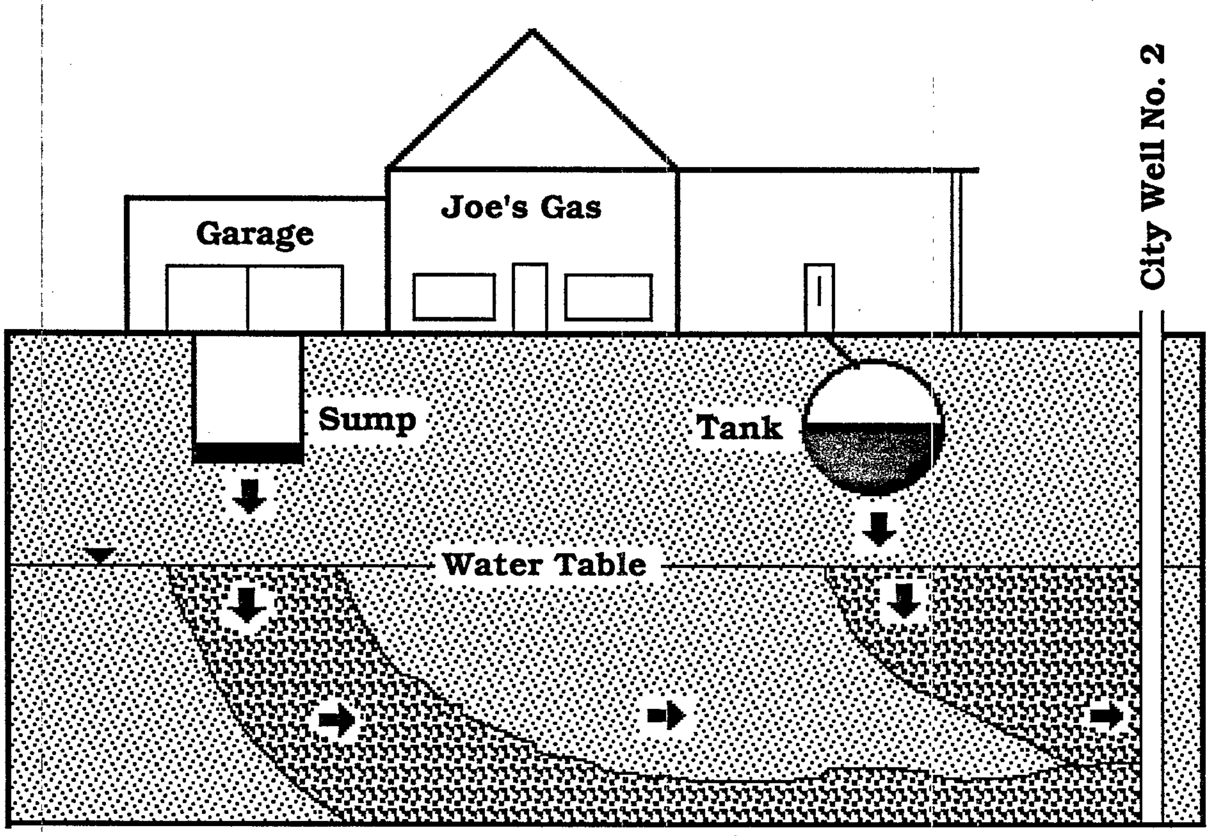


Figure 4.3 Sumps dry wells, and underground storage tanks are potential sources of ground-water contamination.

merely a vertical, cased hole in the ground or in the bottom of a pond that allows the water to drain into deeper, more permeable materials (fig. 4.4). The pond water may be highly mineralized which, in turn, leads to deterioration of water quality in the receiving aquifer.

Hazardous Waste Injection Wells

For decades, man has disposed of liquid wastes by pumping them into wells. The wells are called Class I if used to inject hazardous (and nonhazardous) waste below the lowermost underground source of drinking water. Since World War II, a considerable number of Class I wells have come into existence, usually at industrial sites. These wells typically are several hundred to several thousand feet deep. In the past, injection of highly toxic wastes into some of these wells has led to contamination of fresh water due to direct injection into the aquifer, as well as leakage from the well head, through the casing, along the outside of the casing, or through fractures in confining beds.

It should be noted that wells used for oil-field brine, injection are class II wells. Exclusive of oil-field brine, most deep-well injection (class I) operations are tied to the chemical industry. Well depths range from 1,000 to 9,000 feet and average 4,000. The

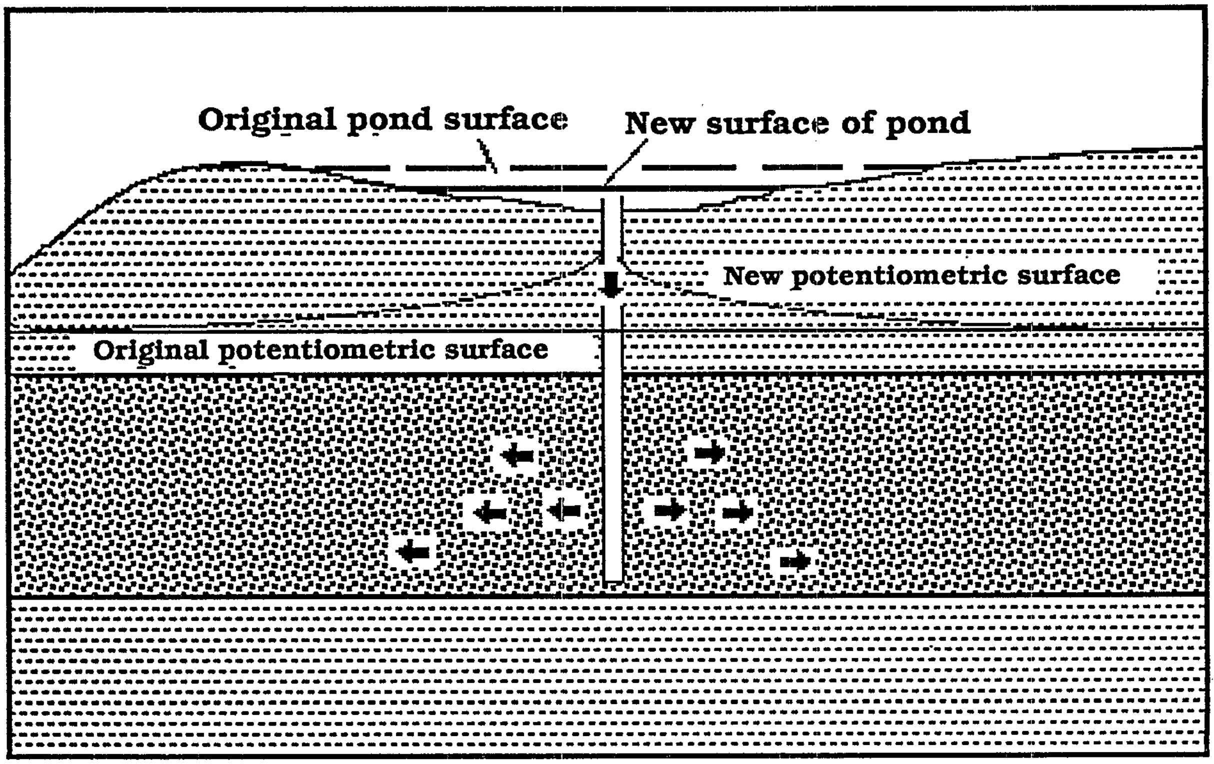


Figure 4.4 Drainage wells are designed to permit direct infiltration of surface water into the subsurface.

deepest wells are found in Texas and Mississippi.

Properly managed and designed deep-well disposal systems can be effectively used for storage of wastes deep underground and may permit recovery of the waste in the future. Before deep well disposal of wastes is permitted, however, extensive evaluations of the well system, the waste fluids, and the rocks in the vicinity of the proposed disposal well, are required and strictly enforced by state and federal regulatory agencies.

Note that wells injecting hazardous or radioactive waste into or above an underground source of drinking water is classified as a Class IV injection well; these wells are prohibited.

Water Quality Problems Related to Pumping/Well Construction

The yield of many wells tapping streamside aquifers is sustained by infiltration of surface water. In fact, more than half of the well yield may be derived directly from induced recharge from a nearby stream (fig. 4.5). If the water in the stream is of undesirable quality, it may seep into the ground and degrade the drinking water supply. In some coastal areas, particularly in Florida, the construction of extensive channel networks has permitted tidal waters to flow considerable distances inland. The salty tidal waters infiltrate, increasing the salt

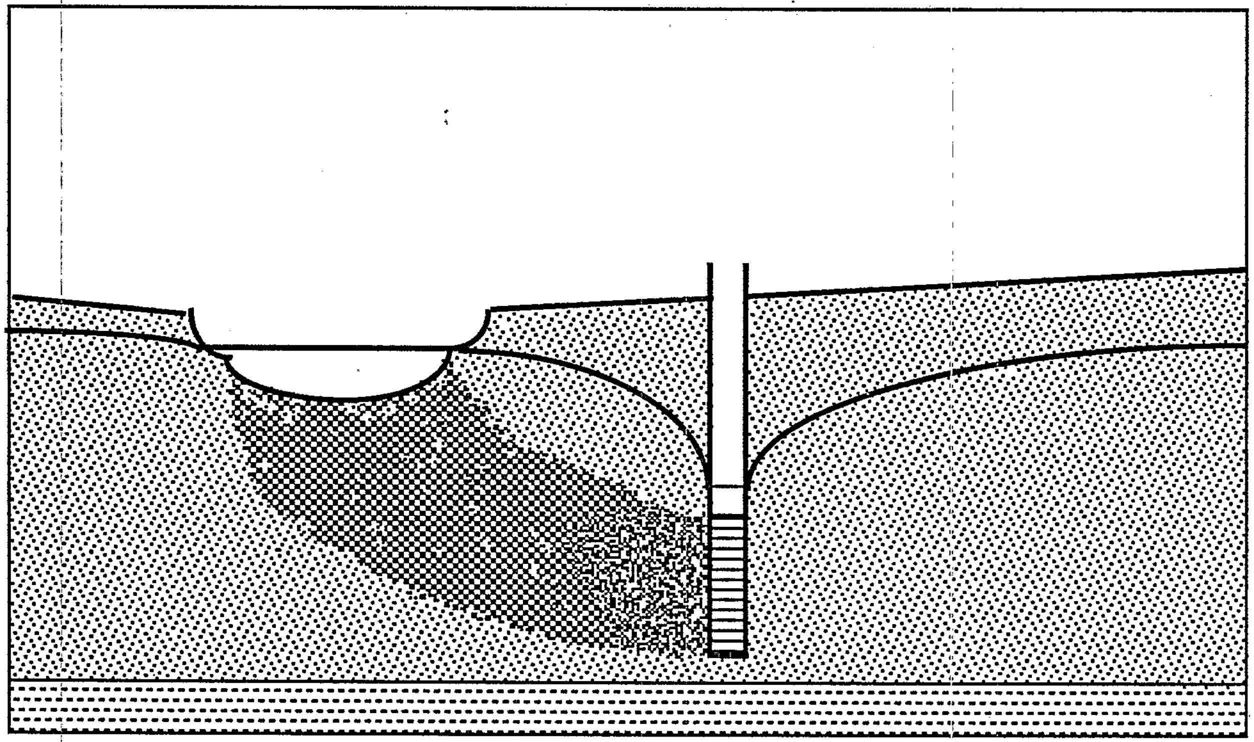


Figure 4.5 A cone of depression that intersects a body of surface water will cause the surface water to flow into the ground.

content of the ground water in the vicinity of the canal.

For reasons such as these, it is important that streams not be allowed to become contaminated. Municipal officials must carefully monitor all activities within each stream watershed, particularly upstream of a well field, in order to protect supplies that depend on induced infiltration.

In certain situations pumping of ground water can cause significant changes in ground-water quality. The principal reasons include interaquifer leakage, induced infiltration, and, in coastal areas, landward migration of sea water. In these cases the lowering of the hydrostatic head in the fresh water aquifer leads to migration of more highly mineralized water toward the well. Undeveloped coastal aquifers are commonly full, the hydraulic gradient slopes towards the sea, and fresh water discharges from them through springs and seeps into the ocean. Extensive pumping lowers the fresh water potentiometric surface, allowing sea water to migrate toward the pumping center. A similar predicament occurs in inland areas where saline water is induced to flow upward, downward, or laterally into a fresh water aquifer due to the decreased head (pressure) in the vicinity of a pumping well (fig. 4.6).

Improperly constructed water wells may either contaminate an aquifer or produce contaminated water. Dug wells, generally of large diameter

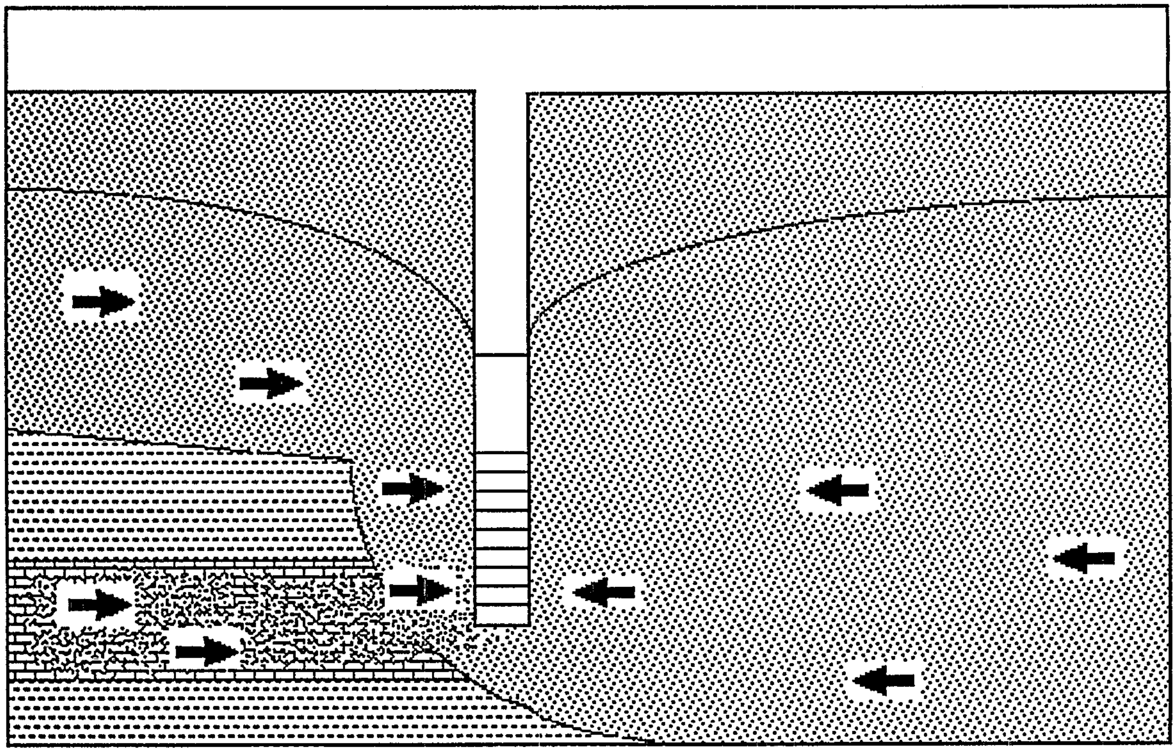


Figure 4.6 Pumping may induce water of undesirable quality to flow from one rock formation into another

and shallow depth, and typically poorly protected, are commonly contaminated by surface runoff flowing into the well. Other contamination situations have been caused by infiltration of water through polluted fill around a well, through the gravel pack, and still others by barnyard, feedlot, septic tank, or cesspool effluent draining directly into the well.

Although construction of public water-supply systems is presently controlled by well construction codes and standards, this is not necessarily the case with private supplies. Furthermore, many public and municipal wells were installed long before construction standards were established and, consequently, they may have little or no grout above the gravel pack, an inadequate concrete pad surrounding the well, and no sanitary well seal.

Water Quality Problems Related To Abandoned Wells And Test Holes

Literally hundreds of thousands of abandoned exploratory wells dot the country side. Many were drilled to determine the presence of underground mineral resources (seismic shot holes, coal, salt, oil, gas, etc.). The open holes permit water to migrate freely from one aquifer to another. A fresh water aquifer could thus be joined with a deeper saline aquifer, or mineralized surface water could drain into fresh water zones.

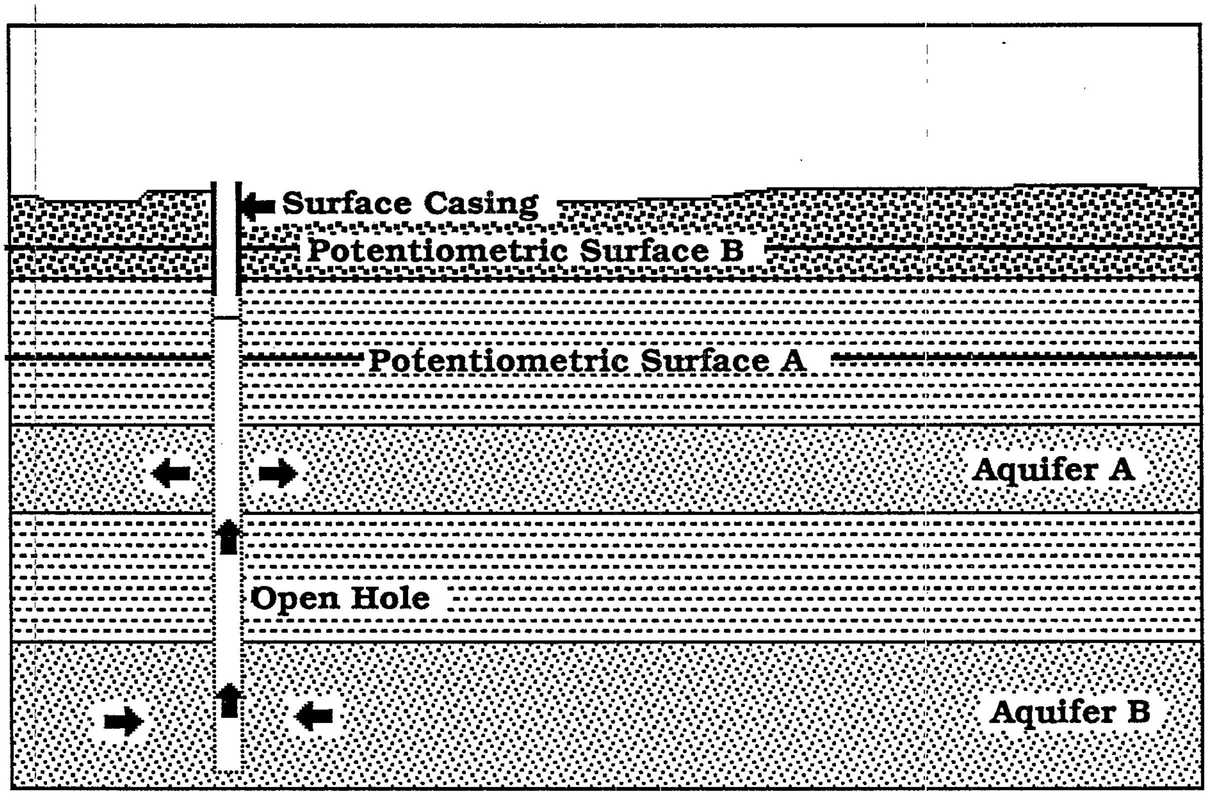


Figure 4.7 Wells without casing may permit the movement of water from one aquifer to another.

Another major cause of ground-water contamination is the migration of mineralized fluids through abandoned wells (fig. 4.7). Many times when a well is abandoned, the casing is pulled (if there was one) or eventually the casing may become so corroded that holes develop. This permits ready access for fluids under higher pressure to migrate either upward or downward through the abandoned well to adjacent aquifers. In other cases, improperly cased wells may allow high-pressure artesian saline water to spread from an uncased or partly cased hole into shallower, lower-pressure aquifers, resulting in widespread salt intrusion.

Finally, upon well abandonment, many individuals remove the pump and leave an open hole with neither a protective cover nor any indication of its presence. In addition to the likelyhood of contaminants entering the well, they can provide an imminent danger to humans, particularly children, and wild or domestic animals, as several recent cases have so clearly shown.

Water Quality Problems Related To Mining Activities

Following the removal of clay, limestone, sand and gravel, or other material, the remaining excavations are commonly left unattended. Many eventually fill with water, and often they are used as unregulated dumps into which are placed both solid and liquid wastes. The quantity and variety of materials placed in them are

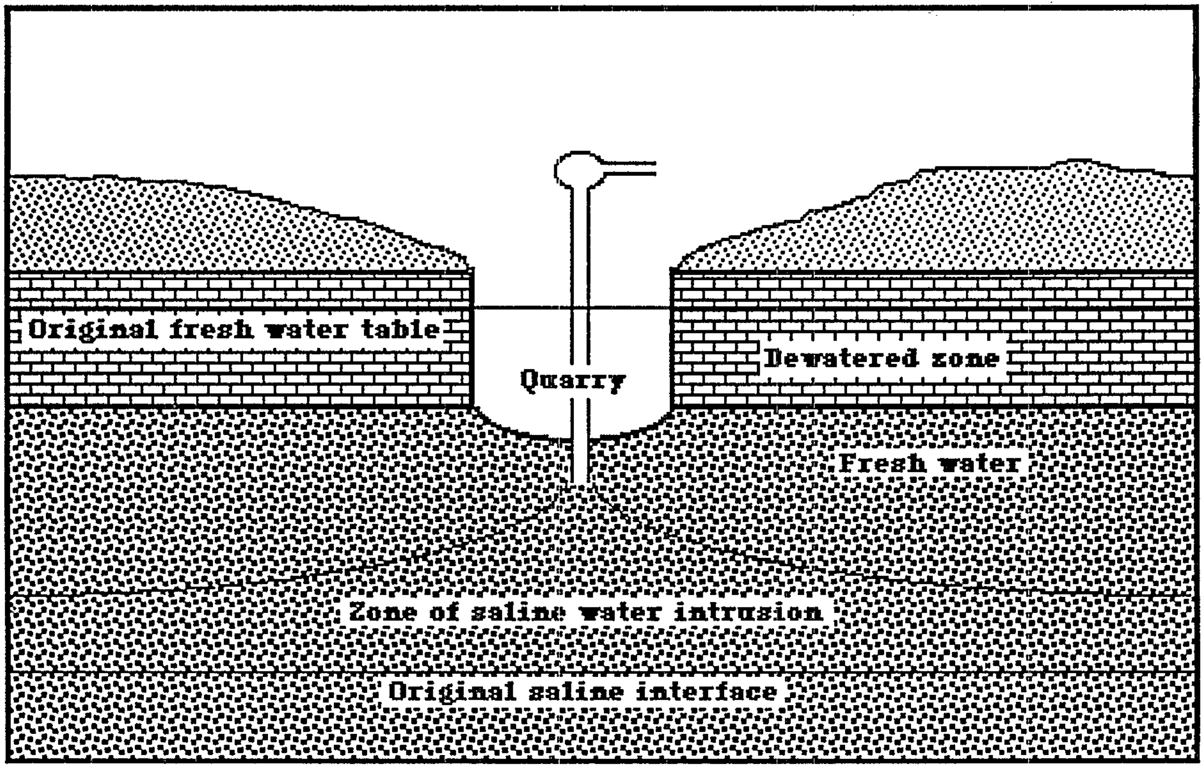


Figure 4.8 Dewatering may cause upward migration of salty water.

almost limitless. The wastes may be in direct connection with an aquifer.

Excavations also have been used for the disposal of liquid wastes, such as oil-field brines and spent acids from steel mills. Many others serve as disposal sites for snow removed from surrounding streets and roads—snow that commonly contains a large amount of deicing salt.

Mining has led to a number of problems brought about by pumping mine waters to the surface, by leaching of the spoil material, by waters naturally discharging through the mine, and by milling wastes, among others. Literally thousands of miles of stream and hundreds of acres of aquifers have been contaminated by highly corrosive mineralized waters originating in coal mines and dumps in Appalachia. In many western states, mill wastes and leachates have seriously affected both surface water and ground water.

Many mines are deeper than the water table, and in order to keep them dry, large quantities of water are pumped to waste. If salt water lies at relatively shallow depths, the pumping of fresh water for dewatering purposes may cause an upward migration of the salt water, which may be intercepted by wells (fig. 4.8). The mineralized water most commonly is discharged into a surface stream.

Water Quality Problems Related To Product/Waste Storage

Another major cause of ground-

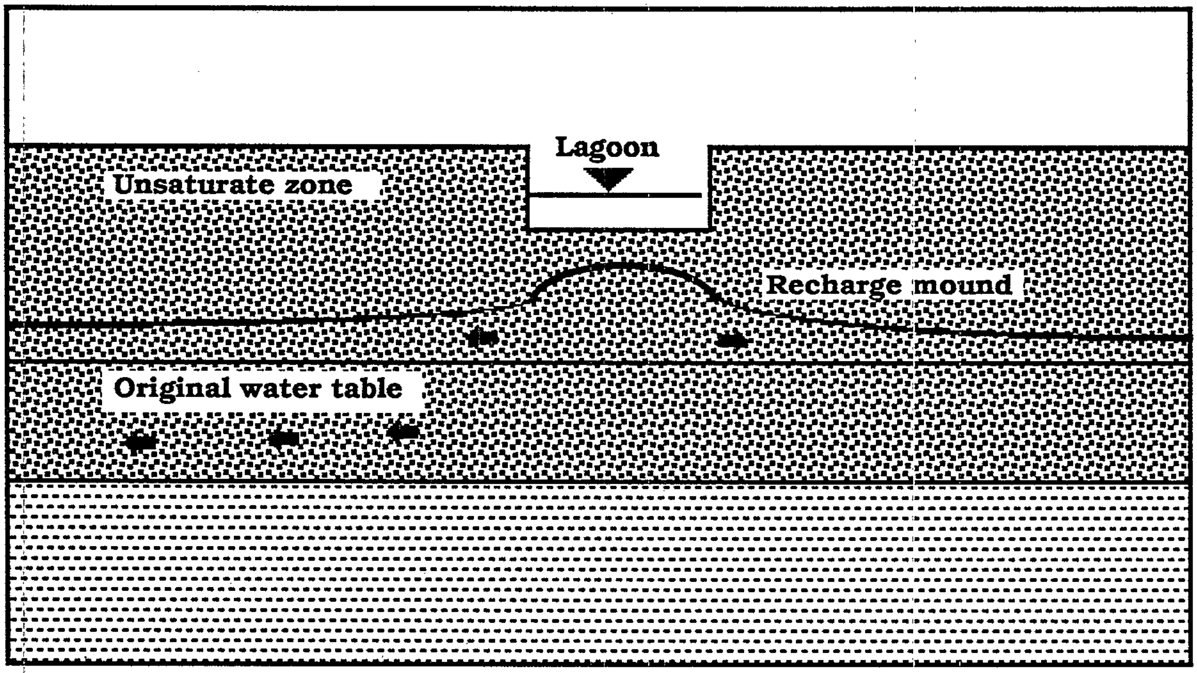


Figure 4.9 Leakage from holding ponds and lagoons may form a water mound that causes to flow in unanticipated directions.

water contamination is the storage of certain materials and the disposal of waste matter directly onto the land surface. Examples include deicing salt (sodium and calcium chloride), treated lumber, manure, sludges, garbage, industrial wastes, dumps, septic tank wastes, etc. The material may occur in individual units or it may be spread over the land. If the substance contains soluble products, they may cause ground-water contamination.

Water Quality Problems Related To Agricultural Activities

An increasing amount of fertilizers and pesticides are being used each year. Many of these substances are highly toxic, their long term health effects are largely unknown, and some are quite mobile in the subsurface. In many heavily fertilized areas, the infiltration of nitrate, a decomposition product of ammonia fertilizer, has contaminated ground water. The consumption of nitrate-rich water may cause a disease in infants known as "blue babies" (methemoglobinemia). Furthermore, many types of pesticides have been found in ground water within the past few years. In Iowa, for example, where atrazine is the compound most commonly detected, the estimated number of individuals exposed to pesticides in ground water is believed to exceed 25 percent of the population.

In rural communities pesticide/fertilizer bulk plants and spraying operations are a very real concern. Spills are the rule rather than the exception at loading stations. In addition, individual as well as commercial pesticide spraying operators commonly rinse their tanks, allowing the pesticide-enriched wash waters to flow freely onto the ground where much of it can infiltrate.

Animal feedlots, which cover relatively small areas, provide a huge volume of waste. These wastes have polluted both surface and ground water with large concentrations of nitrate and other chemicals. Even small feedlots have created local but significant problems.

Water Quality Problems Related To Holding Ponds And Lagoons

Holding ponds and lagoons consist of relatively shallow excavations that range in area from a few square feet to many acres (fig. 4.9). They are used to store municipal sewage as well as large quantities of other wastes, including industrial chemicals.

Special problems develop with holding ponds and lagoons in limestone terrain where extensive near-surface solution openings have developed. In Florida, Alabama, Missouri, and elsewhere municipal sewage lagoons have collapsed into sinkholes draining raw effluent into widespread underground openings. In some cases the sewage has reappeared in springs and streams several miles away. Wells producing from the caverns could easily become contaminated, leading to epidemics of water-borne disease.

Oil-field brines, consisting of highly mineralized salt solutions, are particularly noxious and they likley have locally polluted both surface and ground water in every state that produces oil. The brine, an unwanted by-product, is produced with the oil. In many states (in the past) it was stored or disposed of by placing it in holding ponds from which it infiltrated. Not uncommonly the oil well was long abandoned before it becomes apparent that the adjacent ground water was contaminated.

Water Quality Problems Related To Landfills

Sanitary landfills generally are constructed by placing wastes in excavations and covering the material daily with soil. Even though a landfill is covered, however, leachate may be generated by the infiltration of precipitation. Fortunately many substances are removed from the leachate as it filters through the unsaturated zone, but leachate may pollute ground water and even streams if it discharges at the surface as springs and seeps.

Water Quality Problems Related To Underground Storage Tanks And Transmission Lines

Many toxic materials are transported throughout the country by truck, rail, and aircraft and stored in above or below ground tanks; accidental spills of these materials are not uncommon. There are virtually no methods that can be used to quickly and adequately clean up an accidental spill or spills caused by explosion or fires. Furthermore, immediately following an accident the usual procedure is to spray the area with water and, of course, firefighters use great quantities of water to control fires. The resulting fluid may then either flow into a stream or infiltrate. In some places the accepted prodedure is to impound the fluids by dikes, which leads to an even greater potential for infiltration.

A growing problem of substantial consequence is leakage from storage tanks and pipelines leading to such tanks. Gasoline leakage has caused sever pollution problems throught the nation. Gasoline, bein g less dense, floats on the ground-water surface and leaks into basements, sewers, wells, and springs, causing noxious odors, explosions, and fires. A single wall steel tank has a life expectancy of only about 18 years and costs about $1 per gallon to replace. A cleanup operation will generally exceed $70,000 and some have cost millions of dollars.

SECTION 5

GROUND-WATER MANAGEMENT AND AQUIFER PROTECTION PLAN

Introduction

Just because a water quality problem is not known to exist at the present time does not mean that one may not appear tomorrow or at some other time in the future. Contingency plans should be developed so that sufficient time is available for rational decisions and planning should a problem occur. Several approaches can be followed, any of which must be dictated by the particular political, economic, and technical situations that exist. The contingency plans need not be expensive nor should they necessarily follow traditional methods. Some of the best ideas are generated by individuals with little or no scientific training, but these same people are characterized by a great deal of common sense and a need to quickly and inexpensively solve a problem.

Although any ground-water protection plan must be flexible, a number of steps can be followed that should make the plan easier to follow. Certainly not inclusive , at least the following steps could be taken: (1) determine where the supply originates and what problems might be associated with it, (2) learn the system, (3) locate potential sources of contamination, (4) develop a system of situation monitoring, (5) consider alternate sources of supply, (6) locate and evaluate existing germane laws and regulations, (7) develop an aquifer sensitivity/vulnerability model, (8) determine background chemical quality of the supply, (9) develop an organization structure, and (10) initiate an educational program.

Where Does The Supply Originate

A short distance from its border with Kansas, Oklahoma's Cimarron River contains more than 50,000 mg/l of dissolved solids during dry weather. Scores of miles down stream near its confluence with the Arkansas River, the Cimarron still contains more than 2000 mg/l of dissolved solids despite the dilution from several major tributaries. The source for the calcium sulfate and sodium chloride in the river is natural, bring derived from a series of saline springs and seeps.

In this case any wells drilled in the flood plain that are dependent on induced infiltration soon would be contaminated as the river water flows into the aquifer. On the other hand, if the discharge of the wells was reduced or they were constructed farther from the river, their cones of depression would not intercept the river and there would be no induced infiltration.

At Minot, North Dakota two municipal wells produce water that contains higher concentrations of chloride than do the other wells in the field. The two wells are also about 50 feet deeper than the average. In this location a buried interglacial river valley trends through the center of town; it had cut several tens of feet into the underlying bedrock. One of the bedrock formations that subcrops along the buried valley walls contains salty water. Pumping the deeper municipal wells causes salty water to flow from the bedrock, mix with the fresher water in the sand and gravel, and eventually reach the municipal wells. This problem also is related to natural conditions and perhaps the most practical control is to reduce the rate of pumping from the two wells or to blend the water with that from other wells.

Several years ago in an industrialized city in Michigan a plant water manager decided to dredge the adjacent river in order to increase the yield from their induced infiltration supply wells. Not realizing the river contained high concentrations of industrial wastes, the river was dredged and within days the chemical quality of the well water deteriorated dramatically. It was then recognized that waste papermill products had sealed the river bottom, providing a last line of defense between the contaminated river and the well field.

It is evident from the above that a knowledge of the source of the water supply can serve as a starting point in the development of management alternatives.

Learn The System

For the most part, geologic and hydrologic evaluations of the subsurface are based on an analysis of logs of wells and test holes. These data can be used to construct a number of maps and cross sections of the aquifer system. Cross sections should provide an idea of how much protection the aquifer and confining units provide against contamination.

As illustrated in Figure 5.1, the shallow or surficial aquifer, which consists entirely of permeable material that extends from land surface to the base of the water-bearing zone (aquifer A), is highly vulnerable to contamination from the surface and other shallow sources. The aquifer has practically no natural protection other than the unsaturated zone where sorption and biological degradation will partly attenuate the contaminant. It could be easily contaminated by a spill or nearly any type of waste disposal scheme.

On the other hand, aquifer B is overlain by a layer of clay of low permeability, one that might require years for a contaminant to penetrate. Contaminants from the surface would be required to migrate through the unsaturated zone, where some degradation would occur, through the surficial aquifer, where additional dilution and sorption would occur, and then through the clay layer where not only would more sorption occur, but the rate of movement would be considerably reduced. Moreover, if aquifer B were confined and its water level was above the clay layer, then water movement would be upward through the confining layer and there would be little or no danger from surface spills. Therefore, the deeper aquifer has some degree of natural protection and, in the case of a spill, time likely would be available to develop plans to overcome a potential contamination problem.

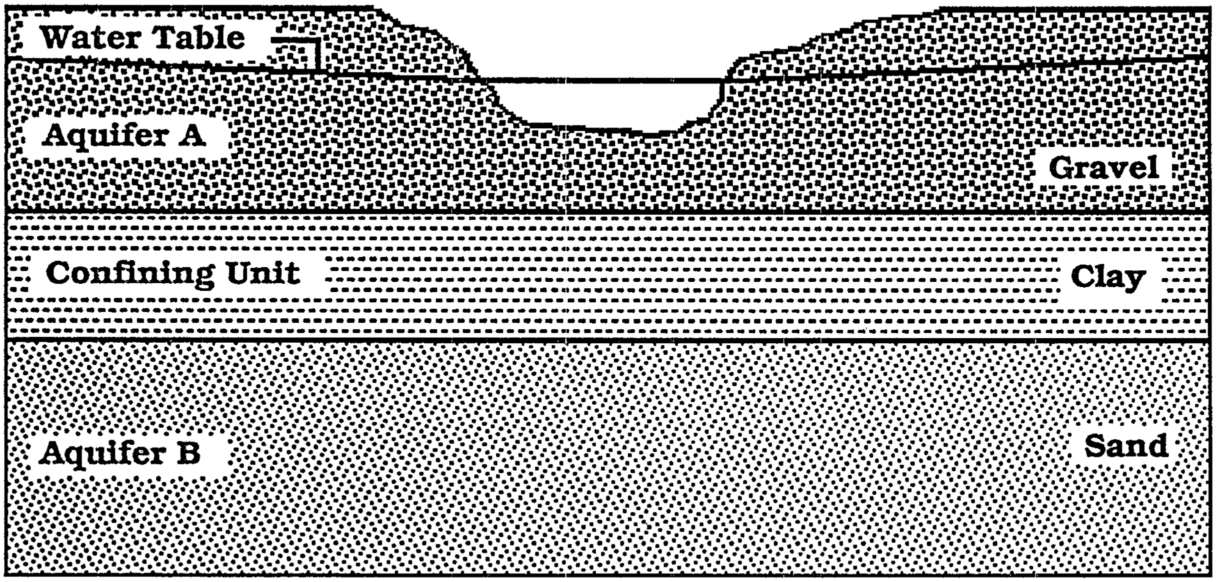


Figure 5.1 Aquifer A is readily subject to contamination from the surface while aquifer B has a degree of natural protection because of the overlying confining unit.

Unfortunately, the well logs that are required to obtained geologic data commonly are not readily available. Experience has shown, however, that the logs of municipal wells and test holes, as well as the logs of industrial and domestic wells, are likely to be stored in a file some place, perhaps in the city engineers office, at the water plant, or in the city managers office. If they can not be found, it might be possible to obtain copies from the original driller, contractor, or consultant, or they might be available from a state or federal agency. Along the same line, well construction details, such as depth, length of screen, etc, also can be of considerable value.

Nearly as important as geologic information are records of well discharge and water-level fluctuations, the latter indicating how the aquifer acts under stress. Generally a new well is tested by pumping before it is accepted by a municipality. During the test, the discharge rate and water level are measured in the pumping well and, sometimes, in one or more observation wells during a period that commonly exceeds eight hours. These data routinely are used to determine how the well reacts, but they also can be used to evaluate an aquifer's hydraulic conductivity, transmissivity, and storativity.

Of particular concern is the size of the cone of depression around a pumping well. As described previously, the radius of the cone of depression is controlled by the aquifer properties and the discharge rate of the well. In an unconfined aquifer, the radius of the cone may be in the order of a few tens or a few hundred feet, but in a confined aquifer it may extend outward for miles. Furthermore, the drawdown caused by overlapping cones of depression is greater than that caused by a single well. Additionally, horizontal and vertical variations in aquifer properties, pumping schedules and rates, and well interference will tend to distort the shape of the composite cone of depression in a well field.

The shape and areal extent of the cone of depression are important in contamination studies for two major reasons. First, the cone represents a change in the hydraulic gradient, which steepens as it approaches the well. This, in turn, increases the velocity of ground-water flow. Secondly, contaminants that reach the aquifer and are within a cone will migrate toward the pumping well. Therefore, what ever happens within the radius of influence of a well is of concern to the water manager.

Likewise, the size of the area of influence of a well field is important because this is the area that should be protected. Although the area of influence might well exceed several square miles, the velocity of the ground water near the outer margin should be relatively low, as compared to that in the vicinity of a well. Resultingly, if the aquifer were contaminated in this region, it might require several months or even years for the contaminant to appear at a well. In the meantime, the contaminant might be diluted or degraded to such an extent that it would not be of concern to the plant operator.

Locating Potential Sources Of Contamination

In order to develop an aquifer protection plan, local sources or potential sources of contamination must be known. These include, in addition to the more obvious ones discussed previously, such things as the location of railroads, major highways, streams and rivers, shallow waste disposal and drainage wells and sumps, gasoline stations, and small industrial or service plants, particularly those small concerns that might be operated in someone's garage, basement, or outbuilding. The latter are not likely to be well known to regulatory agencies nor are they likely to have discharge permits.

In order to develop a data base for potential sources of ground-water pollution, several waste surveys could be conducted. These should include (1) an industrial waste survey, (2) a municipal waste survey, and (3) a state and federal property survey. The surveys themselves could be as simple as examining a map to locate highways, railroads, industrial sites, disposal sites, etc, to actual interviews. Surveys of this nature could become both time consuming and expensive.

One approach, which could be both comprehensive and inexpensive, would be to contact a number of local service clubs, such as the Lion's Club, and request their members to provide information. Other than the obvious advantages of this method, one important consideration is that the members of local service clubs represent a wide spectrum of the population that, as a whole, might well have a detailed knowledge of the area. Resultingly, the data base that could be developed would be comprehensive, inexpensive, and flavored with community pride.

A second and probably essential approach would be the development of contacts with senior citizens, either through local groups or the Senior Citizen Center. Not only do these individuals have a great deal to offer in the way of time and experience, they may well be the only source of information concerning past activities within the municipality.

Once the location of potential sources of contamination are located, it will then be possible to estimate the time required for a contaminant to migrate to a well. It must be remembered, however, that what ever method is used to predict travel time, it will be only an estimate.

Situation Monitoring

Situation monitoring concerns keeping ones finger on the pulse of the community, that is, what has happened in the past, what is happening at the present time, and what might happen in the future. Situation monitoring should cover two main categories—(1) monitoring of the existing water supply system and plant and (2) monitoring of other local situations. The former can and should be accomplished by water utility personnel, while the latter can be carried out by interviews, the news media, and local agencies.

It is surprising that so few operators, particularly those involved with small water systems, are aware of the chemical quality of their supplies. Even if routine chemical analyses are carried out periodically, it is unlikely that samples will be scanned for the more exotic compounds, such as heavy metals or organic compounds. This is understandable in view of the cost. On the other hand, without background data it is commonly difficult if not impossible to detect many contaminants or locate a source, especially if proof is required in a legal action. Nonetheless, the costs of chemical analyses must be accepted by the operator as a part of the normal business practice.

Another part of the survey that should be conducted by the water utility personnel includes an examination of their facilities addressing such items as: possibility of back siphonage, cross-connection, distribution system deficiencies, and poor well construction or location. Are there, for example, potential sources of contamination, such as fuel tanks or sewer lines, adjacent to the well or well house?

The second part of situation monitoring involves the collection and evaluation of information in the community or area within the influence of the cone of depression of the well field. For example, have there been any fires that might have resulted in the release of chemicals that could reach the aquifer? Have there been any spills from truck or train wrecks? Might new construction produce a hazard? Are plans being developed for the placement of hazardous waste storage or disposal sites, or the construction of a new golf course over a sensitive part of the aquifer? In other words, the purpose of this type of monitoring, which must be continuous, is to keep in touch with the community.

Alternate Sources of Supply

A common solution to a water quantity problem is to deepen a well and to a contamination event is to offset and drill another well. Unfortunately, such potential solutions, although simple, are rarely available. It may not be possible to deepen a well and merely offsetting a contaminated well may only solve the problem for a few hours or days. It appears that human nature is such that we tend to procrastinate, hoping that life will continue uninterrupted. The far thinking individual, however, will consider alternatives, formulate cost estimates, and develop plans, both for design and obtaining the necessary funds for construction, for other sources of supply.

When addressing potential alternate sources of either a surface water supply (table 5.1) or a well field (table 5.2), a number of questions should be asked, looked into, and answers formulated. Is there a source of surface water sufficiently nearby that will meet water quality standards after treatment? If so, is a site available and what are the potential costs of constructing intake structures and conveyance facilities, of treating the water, and how much time would it require to actually provide the water? Is the supply dependable, or contaminated, or can water rights be obtained?

1. Is a practical source available?
2. Can water rights be obtained?
3. Is the supply sufficient for the needs?
4. Is it of acceptable quality?
5. Will treatment be necessary?
6. How much time will be required to actually provide wa ter from the new source?
7. How can the property be obtained?
8. What is the cost to develop the supply?
    a. Pipeline
    b. Treatment (costs, how, where)
    c. Source design/construction
9. Funding?
    a. How much time to obtain?
    b. How much will it cost?

Table 5.1 Considerations for alternate sources of surface water supply

1. Are other ground-water sources available?
2. What is the potential yield?
3. What is the chemical quality?
4. Is land available?
5. What are costs of construction for
    a. Wells
    b. Pipeline(s)
    c. Treatment facilities
6. What kind of treatment & where?
7. How much time to put online?
8. Funding
    a. How much?
    b. How to obtain?
    c. How long will it take?
9. Are the site characteristics adequate for future development
10. Is the site vulnerable to future contamination?

Table 5.2 Considerations for alternate sources of supply from ground water

Construction plans, either for a surface or ground-water supply, can be drawn and funding mechanisms addressed when it is convenient. The plans can be filed with the hope and expectation that they will never be required. But if they are ever needed, the preplanning may save several days or months of work during a period when time may be of the essence. Furthermore, the plans might consider an entire supply, a supplemental supply, or a temporary supply.

Sometimes it might be possible to use nontraditional concepts to develop a water supply. One method might be collection galleries, particularly if the available streams are small. In this case a ditch could be cut across a stream into which is placed a gravel bed (fig. 5.2). A well screen attached to a suction line can be placed on the bed and the ditch filled with gravel. This is virtually a horizontal well whose supply depends on infiltration of surface water through the gravel pack. Although the filter pack might well reduce turbidity, it would have little or no effect on many chemicals. Nonetheless, this technique offers a simple and relatively inexpensive alternative.

Along the same line is the subsurface dam. The village of Glenburn in north-central North Dakota had a difficult time supplying sufficient water for their needs. They overcame this deficiency with an unusual and inexpensive design. Most of the surficial rocks in the Glenburn area consist of clay, but near the edge of town is a stream channel, about 30 to 40 feet wide, that is usually dry. The channel contains 7 to 8 feet of coarse gravel and sand. Upstream the deposit widens and a half mile or so from the village there is an abandoned gravel pit.

During the spring runoff a considerable amount of water infiltrates the gravel and the water table rises dramatically. Because the deposits are very permeable, however, the ground water flows down gradient quickly and the water table declines as the aquifer is drained. The gravel channel has a considerable capacity for storage but no control to limit or prohibit rapid drainage.

This problem was solved with almost no cost by a volunteer work force, representing nearly the entire community, by excavating a ditch, 4 or 5 feet wide, across the channel and entirely through the gravel deposit. The excavation was backfilled with clay, which formed a subsurface dam (fig. 5.3). Perforated culvert, serving as a well, was installed on the upstream side of the dam. Farther upstream a diversion ditch was excavated from the intermittent stream channel to the abandoned gravel pit. During periods of runoff, some of the surface water is diverted into the gravel pit, where it infiltrates and part of the remainder infiltrates along the stream bottom. Thus, during wet periods a considerable amount of water is collected in the underground storage reservoir. The subsurface dam impedes the flow of the ground water down the gravel-filled channel and the water table remains at a high level, permitting increased water usage and a sustained supply.

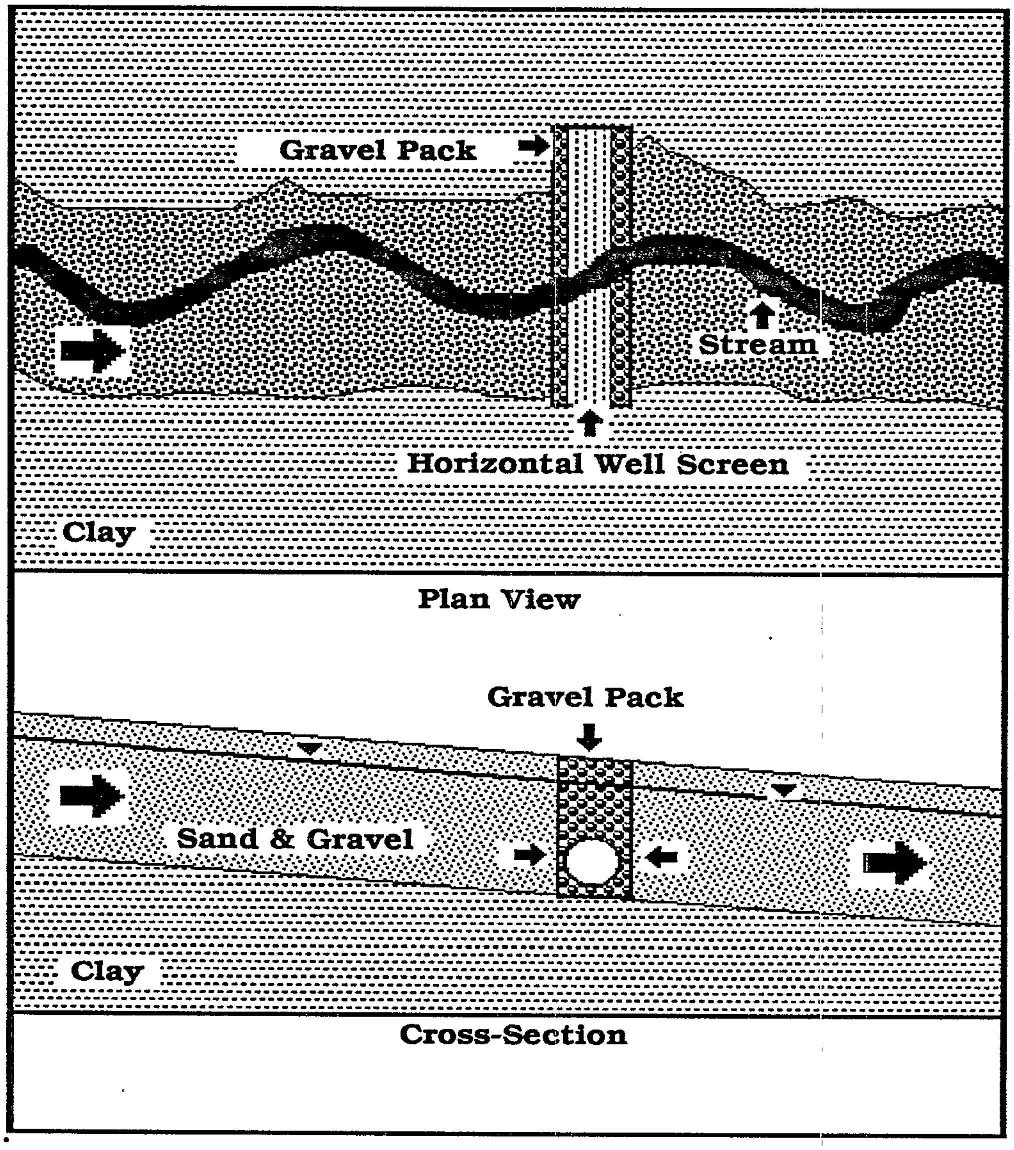


Figure 5.2 Plan view and cross-section of an infiltration gallery.

Water supply problems in arid regions are particularly vexing because of scanty rainfall and the high rate of evaporation. In some situations, it may be possible to augment supplies by constructing artificial aquifers. Artificial aquifers, by necessity, can store only modest quantities of water, but they are labor intensive and, therefore, can be built with a minimal equipment cost.

At the Santa Clara Indian Reservation, New Mexico, a small gully, several yards wide, was cleared of vegetation, deepened, and sloped. Spoil material was used to construct an earthen dam across the gully. A trench was cut adjacent to and parallel with the dam into which was installed a slotted plastic pipe. The slotted pipe was connected, at a right angle, to a second pipe, extending through the dam in the low point of the gully. The second or discharge pipe was laid on a slight downslope grade (fig. 5.4) and installed prior to dam construction.

Once the gully was shaped, the pipes installed, and the dam built, plastic lining was placed in the floor of the excavation which was then back-filled with uniform sand (gravel could be used) and topped off with gravel mulch.

During the rainy season, water flows down the gully and infiltrates through the gravel mulch to the artificial aquifer. (In some cases it might be necessary to construct a spillway to

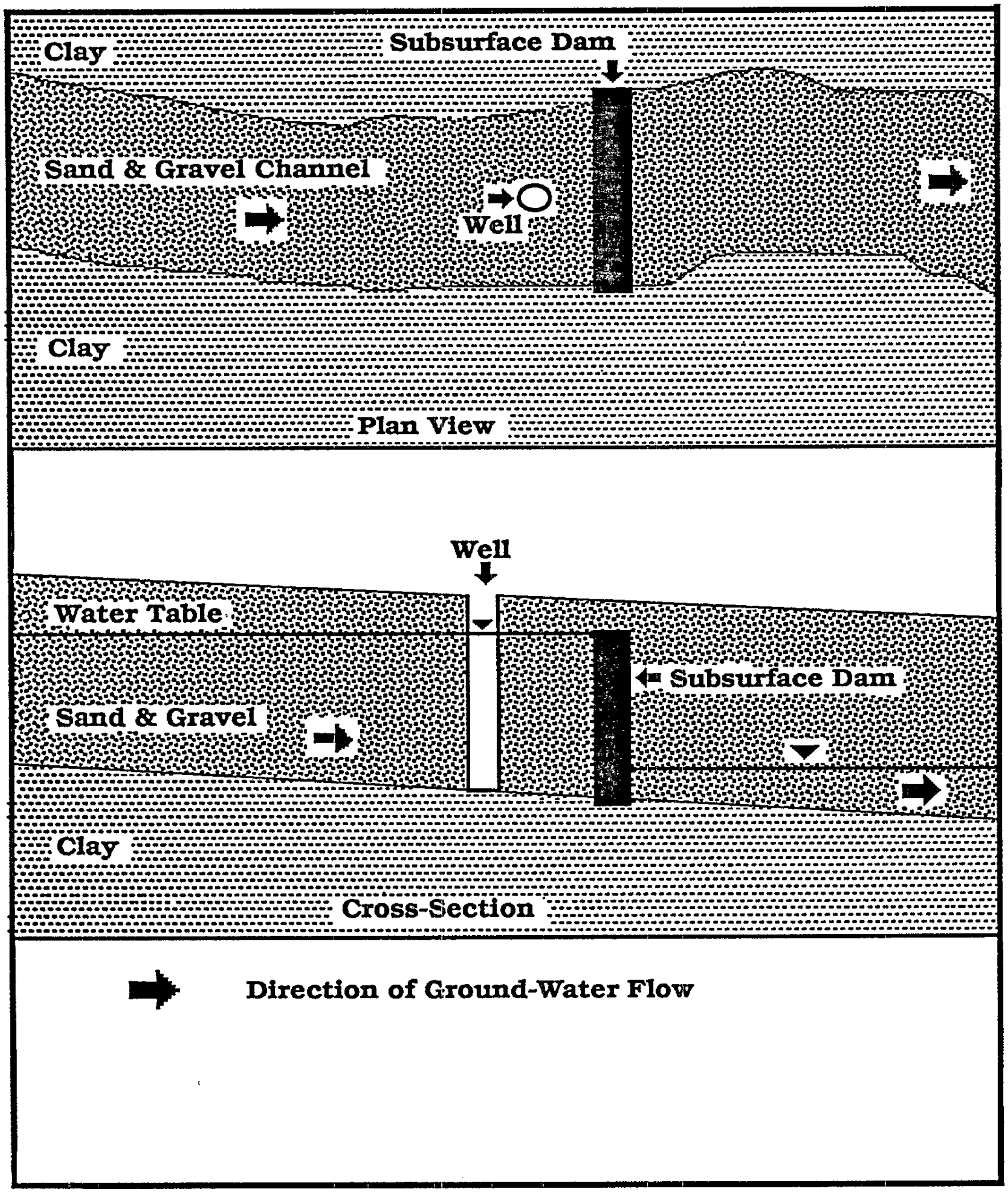


Figure 5.3 Plan view and cross-section of a subsurface dam.

avoid excessive erosion of the dam.) Water is removed from the reservoir by gravity through the discharge pipe, the rate being controlled by a valve.

Another management alternative might be to consider developing another aquifer or a different part of a contaminated aquifer. In the latter case, care would be required in the well field design to insure that the new system would not be contaminated due to changing hydraulic gradients.

Generally new well fields require considerable time and financing in order to achieve a proper design and adequate construction. The first question to be addressed should be "is there an aquifer available that will supply the required needs and what are its characteristics?" If one is available, what is the quality of the water it contains and what is an estimate of the treatment requirements and costs? How many wells will be required and how much will they cost?

Periodically various regions suffer from prolonged droughts, streamflow decreases or may even cease, and water rationing becomes the rule. In many of these areas it is only the surface water supply that is decreasing, while billions of gallons of ground water remain untapped in naturally occurring underground reservoirs that remain hidden from view.

Legal Controls On Waste Disposal

A variety of laws, regulations, and rules exist to control waste disposal. In addition to the often quoted federal laws are those established by state legislatures and the regulations formulated by state agencies. Local zoning ordinances may play an impor-

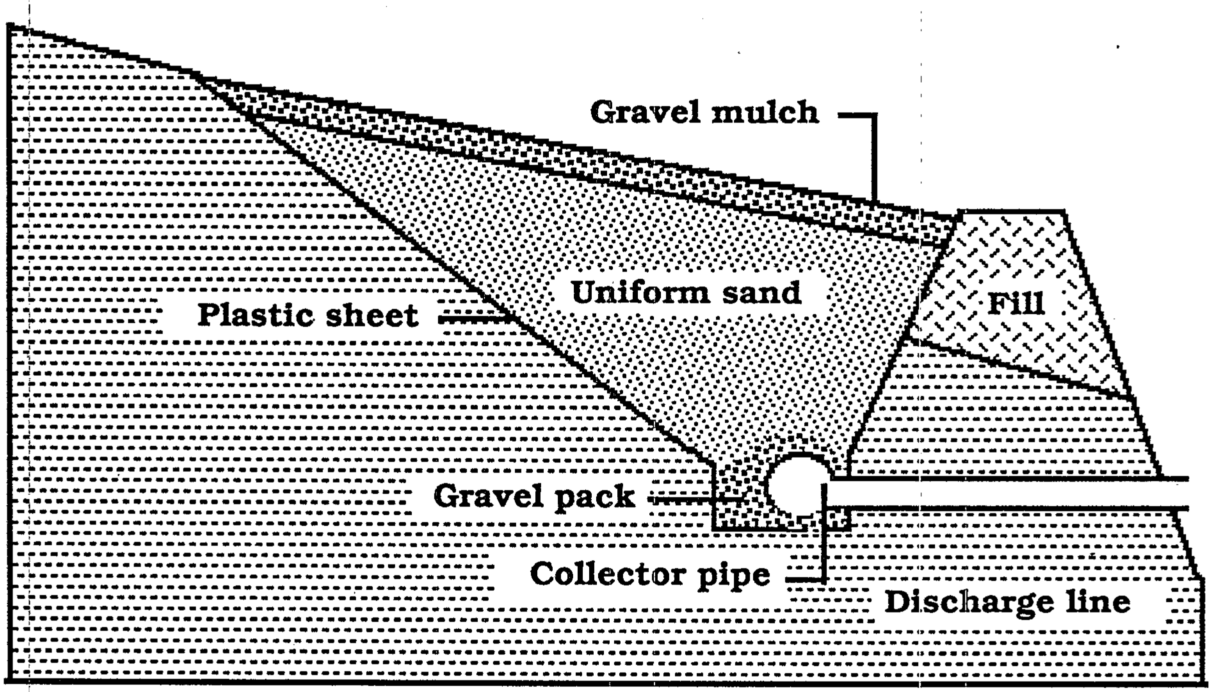


Figure 5.4 Cross-section of an artifical aquifer.

tant role in developing and maintaining an aquifer protection program. These need to be researched, understood, and modified as the need arises.

Development Of A Ground-Water Protection Plan

The basis of a ground-water protection plan is at least a general knowledge of the aquifer system and the manner in which it functions. Where are the inherent weaknesses of the physical system, where are the strong points, and where is a contamination problem most likely to occur? These questions can best be answered or at least evaluated by means of a series of maps. Once the maps have been prepared, the next step is to make a number of simple calculation and estimates of ground-water velocity and potential contaminant travel time from a source to a well.

The key features of a ground-water protection plan include an aquifer sensitivity map, a water-level map, a map of potential contamination sources, estimates of ground-water velocity and travel time from a potential source to a well, and finally an organizational structure and educational program. These requirements can be achieved through a logical series of 11 steps (table 5.3). The steps do not need to be followed in sequence and several can be carried out at the same time.

Step 1.	Schedule all wells in area
Step 2.	Plot well locations on basemap
Step 3.	Map potential sources of contamination
Step. 4	Construct aquifer sensitivity map
Step 5.	Measure water levels in wells
Step 6.	Draw water-level map
Step 7.	Estimate permeability, specific yield, and velocity
Step 8.	Calculate travel time to wells
Step 9.	Collect water samples for chemical analyses
Step 10.	Develop organizational structure
Step 11.	Develop educational program

Table 5.3 Steps in the development of an aquifer protection plan

The following is an explanation of each step and an example of the type of data that should be collected. These data will be used to develop an aquifer sensitivity map and protection plan.

Step 1.

Schedule all wells in the area. A well schedule describes specific information concerning a particular well. The schedule should include the exact well location (a generalized map could be drawn on the reverse side of the form), water-level notations or measurements, well construction details, availability of a driller's or geologist's log, and chemical quality information. The well inventory should include all well (municipal, industrial, and domestic) as well as test and exploration holes. This survey could be conducted by municipal workers, service clubs, or senior citizens.

Very likely all of these data will not be readily available and a search will be required. This should include an examination of municipal files, contacts with contractors, consultants, and local well drillers, as well as a visit to the state or federal geological survey.

Step 2.

On a base map of the area, plot the location of all wells and test holes. Use a variety of symbols to show the type of information that exists for each well.

Step 3.

Prepare a map showing the location of all potential sources of contamination, including roads, railroads, streams, dumps, and landfills, as well as industrial sites.

Step 4.

Using the well logs obtained in Step 1, construct an aquifer sensitivity map. The purpose of the sensitivity map is to determine how much natural protection the aquifer has, where it is, and its characteristics. Some care must be taken here because drillers commonly use different terminology to describe rock types. For example a geologic or driller's log may use the term "sandy clay", which in reality may be a fine sand with minor amounts of silt and clay that is substantially more permeable than the log implies. The general rule here is to assume that the material is more permeable than it would appear from the log. In addition, when constructing the sensitivity map all sources of information should be checked, including the location of gravel and borrow pits, excavations, mines, building foundations, pipeline excavations, and even stream channels.

Step 5.

Measure the water level in as many wells as possible. The water levels should be measured while the well is pumping, if feasible, because this will be the time of maximum drawdown. Plot the altitude of the water surface on the well location base map.

Step 6.

Draw a water-level elevation map using the data collected in Step 5. On another map reproduce the water-level contours and plot all of the potential sources of contamination as determined in Step 3. Construct flowlines that originate at each potential source and continue them to the nearest well, keeping in mind that the flow lines must cross the water-level contours at a right angle.

Step 7.

From specific capacity data, well logs, tests, or tables, calculate or estimate the hydraulic conductivity and specific yield of the aquifer. Estimate ground-water velocity.

Step 8.

Calculate the estimated time of travel from each potential pollutant source to the nearest well by dividing the distance, measured along a flow line, between the source and the well by the ground-water velocity.

Step 9.

Collect water samples from municipal wells and test holes for routine chemical analysis. Although expensive it would be prudent to analyze for characteristic organic compounds for those wells that are in a sensitive area and relatively near (1500 feet or so) a potential source of contamination that contains organic compounds. The purpose of these analyses is twofold. First to determine if there is presently contamination and second to establish background concentrations. The latter is essential to prove subsequent contamination in a legal action.

Step 10.

Develop an organizational structure and chain of responsibility. Ultimately, someone must be in charge of the program. This needs to be an individual who has the authority to assign duties and act as a clearing house for information. Depending on the community organization, this individual might be the city manager, fire-chief, chief of police, city engineer, or a senior citizen experienced in technical matters.

Step 11.

The long term success or failure

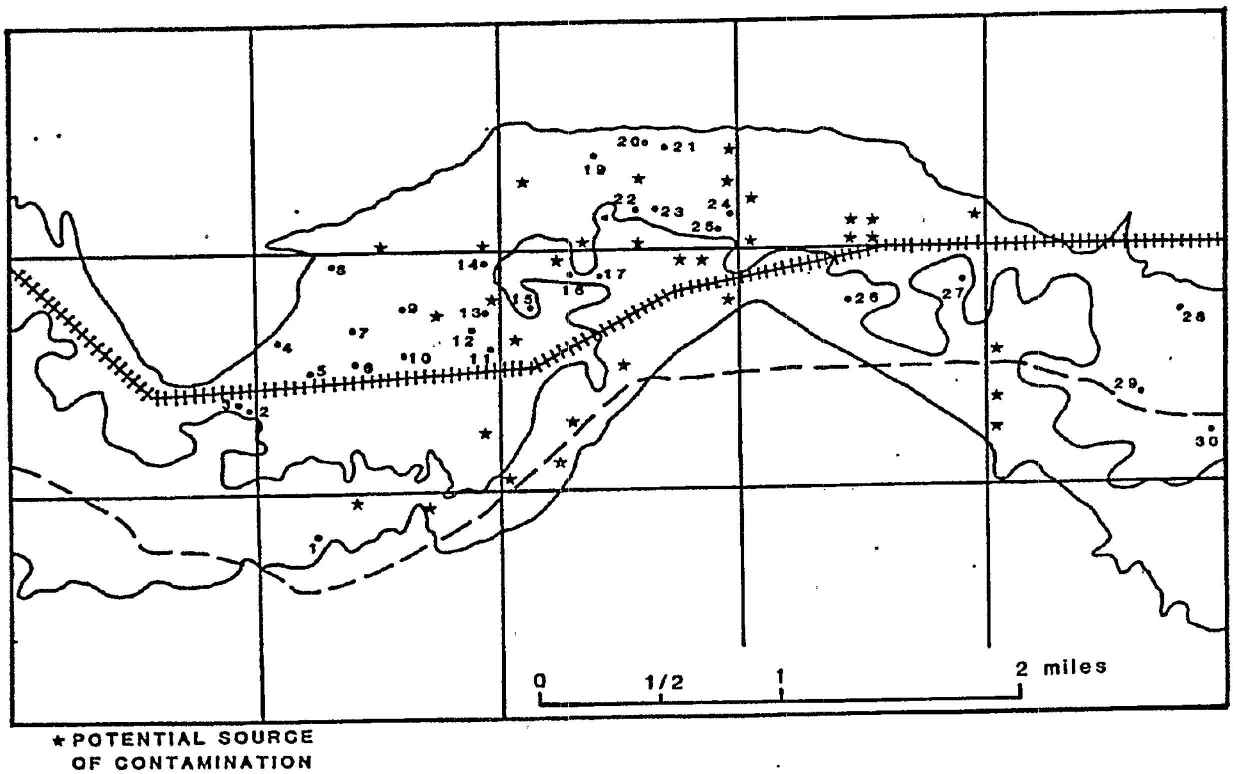


Figure 5.5 Map showing location of all wells and test holes and potential sources of contamination.

of an aquifer protection plan, to a large extent, depends on the citizens of the community, both young and old. They need to know why various things should be done and what are the possible consequences if they are done incorrectly or not done at all. Education is the key. Again, this might be accomplished through educational programs provided to service clubs, garden clubs, senior citizen centers, the Boy Scouts and Girl Scouts, and in schools. This method of public awareness also leads to community pride. A great many pamphlets and reports , as well as speakers, are available, free of charge, from county extension agents, health departments, and state and federal agencies, as well as a variety of associations.

Another advantage of public education and activity is peer pressure. The owner of an abandoned gasoline station might be reluctant to remove old underground tanks, which might be a source of contamination. Once his neighbors and colleagues are aware of his reluctance they might well bring to his attention that he is endangering their lives and property values.

Example of a Ground-Water Protection Plan

The following example is based on data obtained from a city in the Northern Great Plains. The region was glaciated and the earth materials consist largely of glacial till and sand and gravel that overlie nearly flat lying sedimentary rocks that consist of alternating layers of sand, shale, and lignite.

A topographic map of the area shows that the city lies both within the flood plain of a river and on the adjacent upland, which is about 200 feet higher. The major aquifer is confined to the river valley and consists of deposits of sand and gravel that are interbedded with and locally overlain by glacial till. A base map was constructed from the topographic map.

Steps 1 and 2

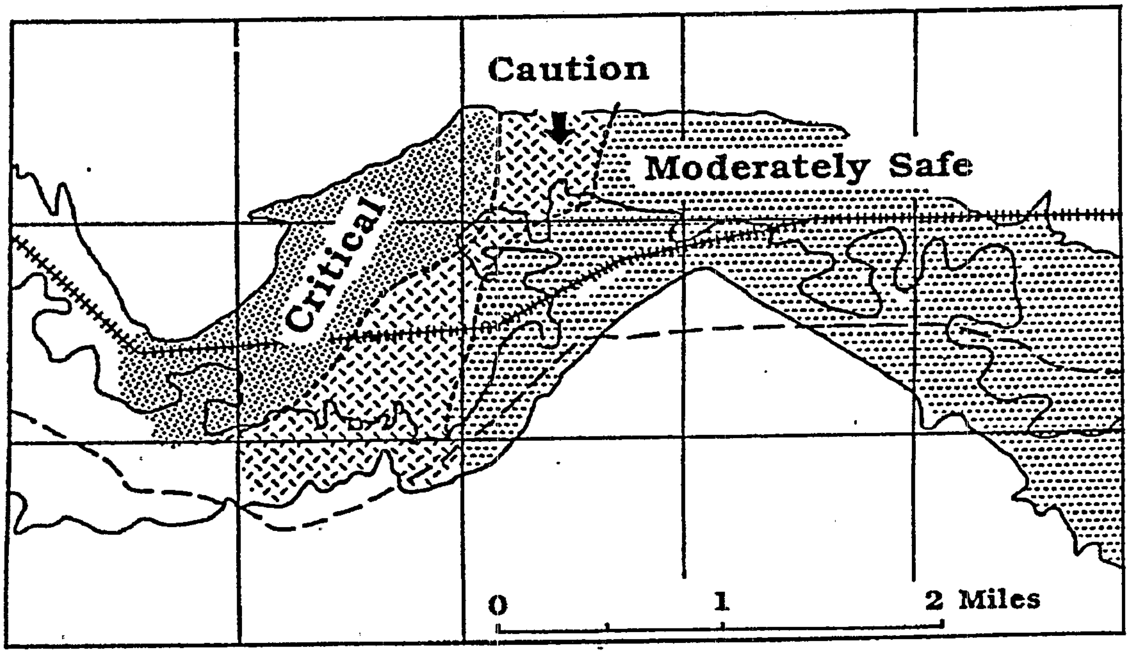
All of the wells within the valley were scheduled and their locations plotted on the base map with a sequential numbering system (fig. 5.5).

Step 3

Using data from the waste surveys, the location of all potential sources of contamination were plotted on a base map (fig. 5.5). These include the river, railroad tracks, and major highways.

Step 4

An aquifer sensitivity map was prepared on the basis of the well logs obtained in Step 1 (Appendix). In this case a total of 30 logs were available and they were divided into Potential Contamination Classes. It was assumed in this study that if the log indicated that sand or sand and gravel extended, more or less uninterrupted, from land surface to the bottom of the well that the aquifer was very sensitive to contamination from the surface (Class 1). If the log indicated that there was a total of 25 to 45 feet of clay



Critical: less than 25 feet of overlying clay
Caution: 25 to 45 feet of overlying clay
Moderately Safe: more than 45 feet of overlying clay

Figure 5.6 Map showing aquifer sensitivity

between the surface and the aquifer, the site was considered to be only questionably safe from surface contamination (Class 2). Where more than 45 feet of clay separated the surface from the aquifer, it was assumed the aquifer is moderately safe from contamination from the surface (Class 3).

The development of the sensitivity map, which is quite subjective, is dependent on a reasonable evaluation of existing well logs. Consequently, one needs to be conservative in the evaluation. The logs are not greatly detailed and, therefore, some interpretation is required. As an example, many of the logs refer to a "sandy clay", but this description does not clearly indicate if this geologic unit consists of clay with admixed sand, if it is predominantly sand with some clay, or if it is actually layers of sand and clay. The permeability of the three possible types could differ significantly. Here the key is to be conservative. The estimated total thickness of fine-grained material, largely clay or shale, overlying the aquifer is shown on each log in the Appendix.

Once the logs were evaluated, the thickness or Potential Contamination Class of each log was plotted on the base map and the specific classes were incorporated as units.

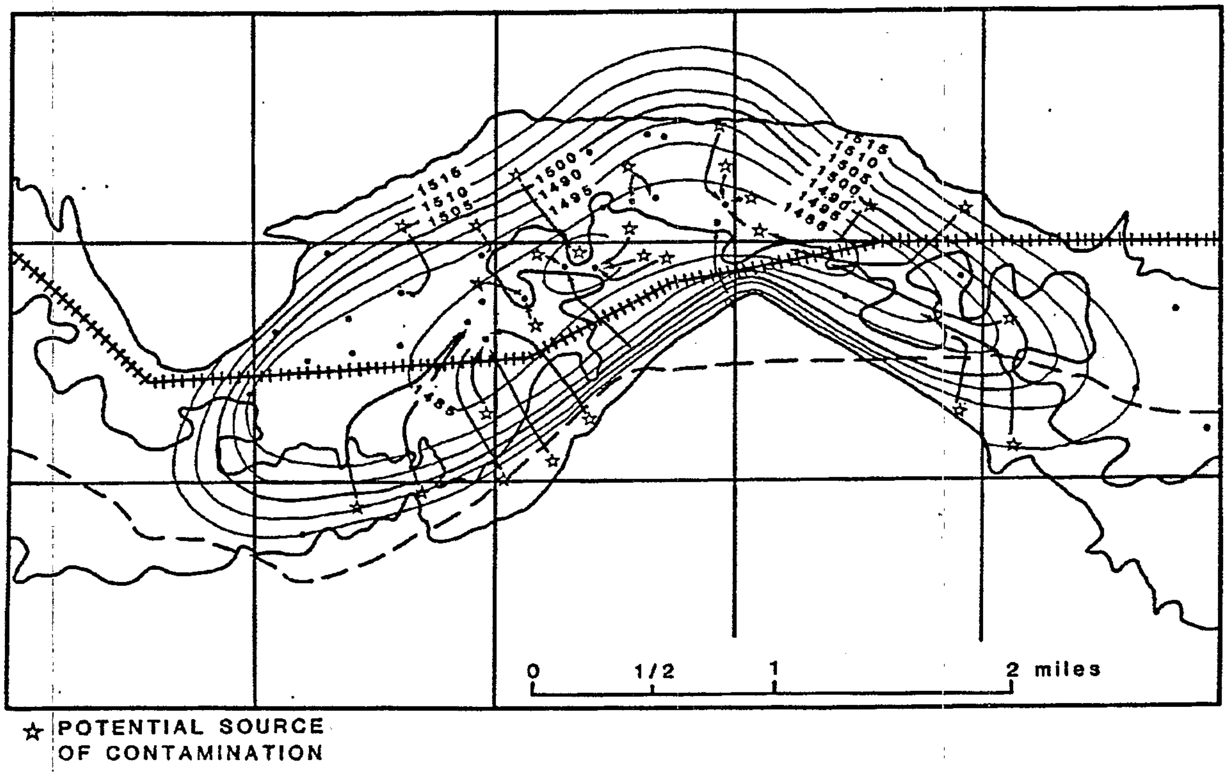


Figure 5.7 Map showing water-level contours, potential sources of contamination, and flow lines extending from potential sources nearest dow-gradient well.

The degree of natural protection afforded the aquifer is outlined in Figure 5.6. The map indicates that the eastern part of the valley-fill aquifer is protected by a considerable thickness of clay through which contaminants originating on the surface are not likely to flow (Class 3). To the west, however, the valley fill consists of sand and gravel that extends from land surface to bedrock, a distance of more than 100 feet (Class 1). Any contaminants entering the ground here could reach the aquifer. In the central part of the aquifer the major water-bearing zone has some overlying protection in the form of alternating layers of clay and sand (Class 2). Although a contaminant eventually might reach the aquifer in this area, it would require a substantial amount of time and probably the contaminant would be degraded or sorbed to some extent and certainly diluted as it migrated through 25 to 45 feet of fine-grained material.

The sensitivity map rather clearly indicates those areas of most and least concern. The eastern part of the aquifer is moderately safe, caution should be exercised in the central part, and the western part should be carefully protected and monitored (fig. 5.6). The latter critical area should be brought to the attention of city officials and an attempt made to protect it by local

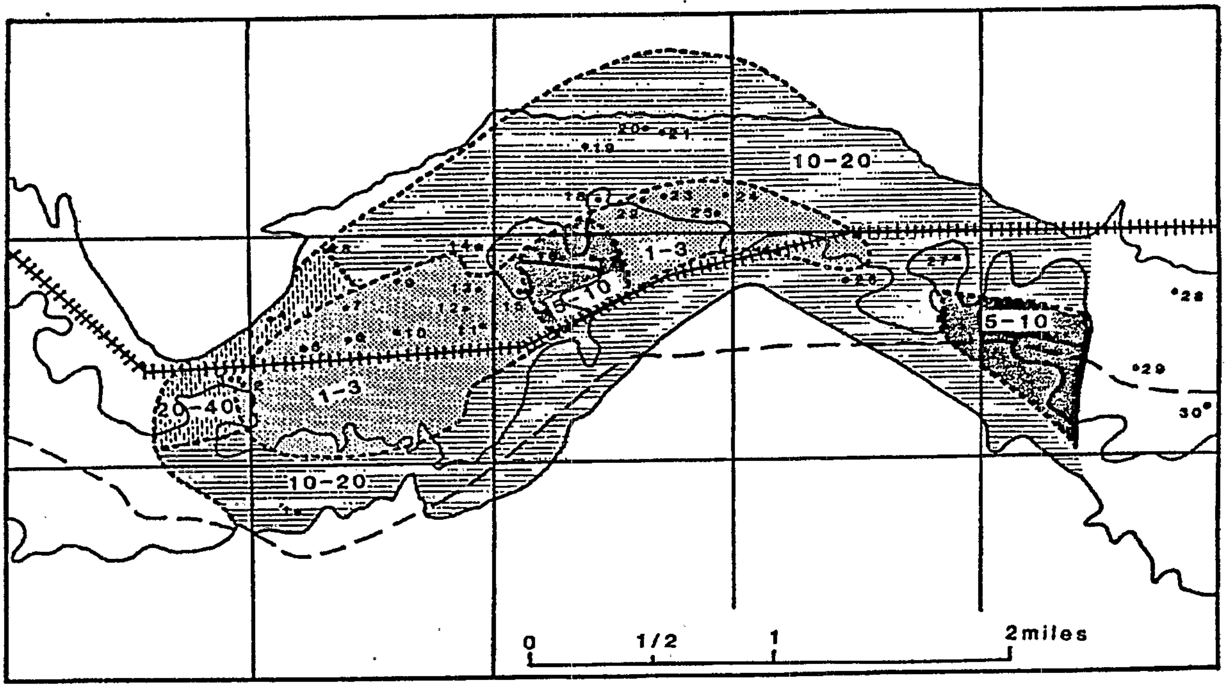


Figure 5.8 Map showing general range in ground-water velocity. Numbers are velocity in feet per day.

zoning ordinances.

Steps 5 and 6

The next step was the measurement of water levels in all available wells. The elevation of each well was determined, either by estimation from a topographic map or by actual surveys. Added to the elevation of the well house floor was the distance from the floor to the top of the casing or whatever point was used for the measuring point. The depth to water in the well was subtracted from the elevation of the measuring point and the difference was recorded as the elevation of the water-level surface (table 5.4). These elevations were plotted on a base map and contours or lines of equal water-level elevation were constructed (fig. 5.7. Next, flow lines were extended from each potential contamination source to the nearest well (fig. 5.7).

The map in Figure 5.7 shows a large cone of depression around a well field and the arrows indicate the general direction of ground-water flow. Notice that the contours indicate that water is flowing into the pumping center from all directions. Consequently, a large area should be protected or at least monitored because contaminants reaching the aquifer in any part of the area of pumping influence could eventually reach a well.

Step 7

As is evident from the well logs, the material that forms the aquifer ranges considerably in thickness and grain size. Using specific capacity data tually reach a well.

Step 7

As is evident from the well logs, the material that forms the aquifer ranges considerably in thickness and grain size. Using specific capacity data and an estimation of the aquifer thickness, as implied by the logs of wells and water-level measurements, the generalized range in velocity of ground water was calculated (fig. 5.8). The estimates may be quite wrong, but they are not likely to be incorrect by a factor of more than 2 or 3. Furthermore, the purpose of this analysis is to develop only a general impression of the manner in which the aquifer functions.

Step 8

The travel time from a potential contaminant source to the nearest well was calculated by dividing the distance between the source and the well, measured along a flow line, by the ground-water velocity.

Step 9

The next step in this analysis was the collection of water samples for chemical analysis from all wells. In this case there are no analyses for organic compounds, which are the most pervasive and hazardous of all the possible contaminants. The recommendation was to collect well water samples specifically for the purpose of evaluating the presence of potential organic contaminants in order to determine the existing load, if any, in the aquifer and to establish a background concentration.

Step 10

An organizational structure was established in cooperation with the city council.

Step 11

An educational program was developed and presented throughout the city.

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Appendix

WELL 1 (DOMESTIC)

	Thickness (feet)	Depth (feet)	
Hard clay	18	18	
Sand	9	27	
Yellow sand	11	38	*
Dark clay	24	62	
Dark gravel and sand	13	75	*
Coal and sandy clay	5	80	
Coal and clay	5	85	
Blue clay	6	91	
Coal and water	3	94	*

WELL 2 (TEST HOLE)

Fine yellow sand and silt, some gravel streaks	24	24	
Sand, gravel, some clay	4	28	
Clay, gravel	24	52	
Sand, gravel	2	54	*
Sand, gravel, boulders, some clay lenses last 10 feet	44	98	*
Dirty sand, gravel	3	101	*
Clay, some gravel	13	114	

WELL 3 (MUNICIPAL)

Fine yellow sand and silt, some gravel streaks	24	24	
Sand, gravel, clay	4	28	
Clay and gravel	24	52	
Sand, gravel, boulders	46	98	*
Sand, gravel, boulders, with clay traces	3	101	*
Clay with gravel	13	114	

WELL 4 (TEST HOLE)

Gravel, medium to coarse; rougr drilling	11	11
Gravel, coarse; boulders, rough drilling, lost circulation, abandoned hole	9	20

* Major water-bearing zone

WELL 5 (MUNICIPAL)

Dirty sand	10	10
Sandy	16	26
Coarse gravel	46	72 *
Fine gravel	8	80 *
Fine gravel and sand	5	85 *
Gravel with traces of clay	4	89 *
Hard clay	2	91

WELL 6 (MUNICIPAL)

Silt, sand, and clay	8	8
Sand and gravel	32	40 *
Small boulders, sand, and gravel	14	85 *
Coarse gravel, boulders	26	111 *
Clay and gravel	10	121

WELL 7 (TEST HOLE)

Silt and sand	8	8
Sand and gravel	32	40 *
Small boulders, sand, and gravel	14	54 *
Sand and gravel	31	85 *
Course gravel and boulders	26	111 *
Clay and gravel	10	121

WELL 8 (TEST HOLE)

Clean, fine sand	70	70 *
Sand, gravel, and boulders	10	80 *
Sandy clay, blue in color	13	93

WELL 9 (MUNICIPAL)

Sandy, some silt	20	20
Dirty sand	30	50*
Clean sand	5	55*
Sand and gravel	5	60*
Coarse gravel	55	115 *
Clay	2	117

WELL 10 (MUNICIPAL)

Sandy clay, silt	11	11	
Very fine sand, some clay and silt	27	38	
Mostly clay, some sand layers	16	54	
Sand (dirty)	3	57	*
Clean coarse sand	15	72	*
Clean sand, gravel	18	90	*
Dirty (clay) sand, gravel	7	97	*
Sandy clay, clay	14	111	

WELL 11 (INDUSTRIAL)

Gumbo	2	2	
Sandy clay	13	15	
Sand and clay layers	15	30	
Gravel, muddy water	7	37	*
Fine sand and muddy water	43	80	*
Clay and sand	10	90	*
Sand and watet	6	96	*

WELL 12 (MUNICIPAL)

Sandy clay	25	25	
Blue clay	50	75	
Sand and gravel	5	80	*
Gravel	9	89	*
Coarse gravel and boulders	25	114	*
Sand	7	121	*
Clay with gravel	2	123	*

WELL 13 (MUNICIPAL)

Clay, silty, some thin, fine sand layers	46	46	
Dirty, medium to fine sand, some lignite	22	68	*
Some clean sand, clay lenses, lignite	10	78	*
Clean, coarse sand and gravel	7	85	*
Mostly coarse gravel, rough drilling	9	94	*

Very coarse gravel, boulders, some sand	17	111	*
Sand, gravel and boulders	9	120	*
Gray clay	20	140	

WELL 14 (TEST HOLE)

Sand, very fine to fine, brown	15	15	*
Sand, very fine to coarse; minor amount of fine gravel, pelecypod valves	2.5	17.5	*
Sand, medium to very coarse, gray; minor amount of fine gravel	7.5	25	*
Sand, very fine to medium	5	30	*
Sand, medium to coarse; minor amount of fine gravel	5	35	*
Gravel, fine; sand, fine to coarse; thin layer of clay	5	40	*
Sand, fine to coarse; gravel, very fine; scattered lignite grains; boulder at 85 feet; lost circulation	60	100	*

WELL 15 (MUNICIPAL)

Black soil	3	3	
Sandy clay	81	84	
Clay, some sand	6	90	
Dirty sand	9	99	*
Coal	3	102	*
Coarse sand	2	104	*
Coarse gravel	21	125	*
Gravel and fine sand	5	130	*

WELL 16 (MUNICIPAL)

Topsoil	2	2	
Sand and clay	6	8	
Sand	13	21	
Clay	42	63	
Sand and clay streaks	7	70	
Clay	20	90	
Muddy sand	10	100	*

Sand	18	118	*
Gravel and coarse sand	15	133	*

WELL 17 (MUNICIPAL)

Fill and topsoil	4	4	
Sandy clay	4	8	
Sand	8	16	
Clay	70	86	
Sand	4	90	*
Coarse sand	10	100	*
Fine sand	10	110	*
Gravel	5	115	*
Medium sand	7	122	*
Sand and gravel	3	125	*

WELL 18 (MUNICIPAL)

Sand	40	40	
Clay, sandy; gravel	13	53	
Clay, boulders	2	55	
Clay, sandy	18	73	
Sand, fine	17	90	*
Sand, fine; traces of lignite	29	119	*
Sand, fine; gravel	16	135	*
Sand; boulders	4	139	*

WELL 19 (INDUSTRIAL)

Yellow sandy clay	5	5	
Hard sand and clay	3	8	
Yellow sandy clay	22	30	
Hard sand	2	32	
Yellow sandy clay	2	34	
Hard sand	4	38	
Sand and gravel	3	41	*
Sandy blue clay	11	52	
Black sandy clay	11	63	
Sand, gravel, and clay, mixed	23	86	*
Sand	3	89	*
Coarse sand	2	91	*
Blue clay	5	96	
Rock	1	97	
Sand and clay	6	103	
Blue clay and sand	5	108	

Clay, sand and gravel mixed	3	111	*
Sand and gravel, water	7	118	*

WELL 20 (INDUSTRIAL)

Topsoil	0.5	0.5	
Gravelly yellow clay	5.5	6	
Sandy yellow clay	32	38	
Very sandy soft yellow clay	7	45	
Sandy gray clay, some very sandy with a little water	47	92	
Muddy sand and gravel, yellow	4	96	*
Fine muddy sand, yellow	12	108	*

WELL 21 (TEST HOLE)

Soil, black	2	2	
Sand, very fine, clayey	3	5	
Clay, silty and sandy, yellowish-brown	8	13	
Gravel, fine to coarse; sand, medium to coarse	4	17	
Clay, silty, olive-gray; thin layers of sand and gravel; lignite fragements	33	72	
Sand, fine to medium; minor amount of clay	11	83	*
Gravel, fine to coarse	3	86	*
Clay, silty, olive-gray, pebbles	8	94	
Gravel, fine to coarse	2	96	*
Clay, silty, olive-gray	6	102	
Clay, sandy, ovlive-gray; abundance of lignite fragments	43	145	
Gravel, fine to medium; sand, coarse	27	172	*
Clay, silty, olive-gray; lignite fragments and thin layers between 240 and 273 feet	100	272	
Gravel, fine to coarse, rough drilling	6	278	*
Sand, clayey, greenish-gray	15	293	

WELL 22 (TEST HOLE)

Topsoil and clay	10	10	
Clay; streak of sand	10	20	
Clay and sand interbedded	10	30	
Clay; streak of sand	35	65	
Sand; trace of clay	5	70	*

Sand, fine	64	134	*
Rocky, trace of hard clay	1	135	
Rocky and clay, hard	5	140	
Shale	1	141	

WELL 23 (MUNICIPAL)

Clay, hard and soft	67	67	
Sand, "clean"	81	148	*
Sand; rocky	7	155	*
Sandy and clay	2	157	
Clay, "blue"	5	162	

WELL 24 (MUNICIPAL)

Fill	4	4	
Clay and streaks of sand	107	111	
Coarse gravel and boulders	36	147	*

WELL 25 (MUNICIPAL)

Fill	6	6	
Gumbo	2	8	
Sand	6	14	
Clay	68	82	
Mud, sticks and sea shells	5	87	
Clay	10	97	
Muddy sand and clay	13	110	
Clay and big gravel	3	113	
Big gravel	26	139	*

WELL 26 (INDUSTRIAL)

Fill	4	4	
Yellow clay	12	16	
Sandy gray clay	24	40	
Hard pan, rocks	8	48	
Gravel	19	67	*
Clayey sand and gravel	4	71	*
Sand and gravel	11	82	*

WELL 27 (TEST HOLE)

Soil, black	1	1	

Clay, yellowish-gray	3	4	
Sand, very fine to fine	4	8	
Sand, very fine to very coarse; abundance of pelecypod valves	8	16	
Clay, silty, dark-greenish-gray	57	73	
Clay, sandy, brownish-gray	5	78	
Sand, fine to coarse; abundance of lignite fragements; many fragement of pelecypod valves	11	89	*
Gravel, fine to very coarse; lost circulation from 100 to 128 feet; used 41 bags of bentonite; abondoned at 128 feet	39	128	*

WELL 28 (INDUSTRIAL)

Clay	10	10	
Shale, dark (small amount of water)	2	12	
Clay blue	22	34	
Shale, dark (Small amount of water)	2	36	
Clay, blue	51	87	
Clay, gray	162	249	
Hard material	2	251	
Shale (water)	3	254	*
Clay, blue	2	256	

WELL 29 (TEST HOLE)

Soil, black	1	1	
Clay, silty to sandy , yellow to olive brown	9	10	
Sand, meidum to coarse; gravel, fine, clayey	22	32	
Clay, sandy, dark-greenish-gray	7	39	
Clay, dark-greenish-gray; alternating with sand, very fine to fine	33	72	
Gravel, fineto medium; sand, coarse; gastropodand pelecypod fragments	35	107	*
Sand, very fine, light-greenish-gray clayey	19	126	

WELL 30 (DOMESTIC)

Brown clay	26	26	
Quicksand	2	28	*
Sandy clay	6	34	

Blue clay	19	53
Soft blue clay	11	64
Sandy blue clay	1	65
Blue Clay	15	80
Sandy clay	4	84