Nassau County, New York—The response of an unconfined aquifer to stress in a humid climate that results from urban land-use practices is exemplified by the upper glacial aquifer on Long Island. It was noted previously that prior to installation of an extensive sewer system, a large proportion of the water pumped on Long Island for public supply and commercial use was returned to this unconfined aquifer by septic systems. After installation, water that formerly recharged the upper glacial aquifer from septic systems now was discharged directly into the ocean. This loss of recharge represented a significant change to the water budget of the ground-water system and resulted in a loss in storage of water in the upper glacial aquifer.

The effects of installation of the sewer system on aquifer storage in Long Island are reflected in the water-level record shown in Figure 18 for a well completed in the upper glacial aquifer in west-central Nassau County, an area where an extensive sewer system began operation in the early 1950's. The upper horizontal line in Figure 18 (water level equals 68 feet above sea

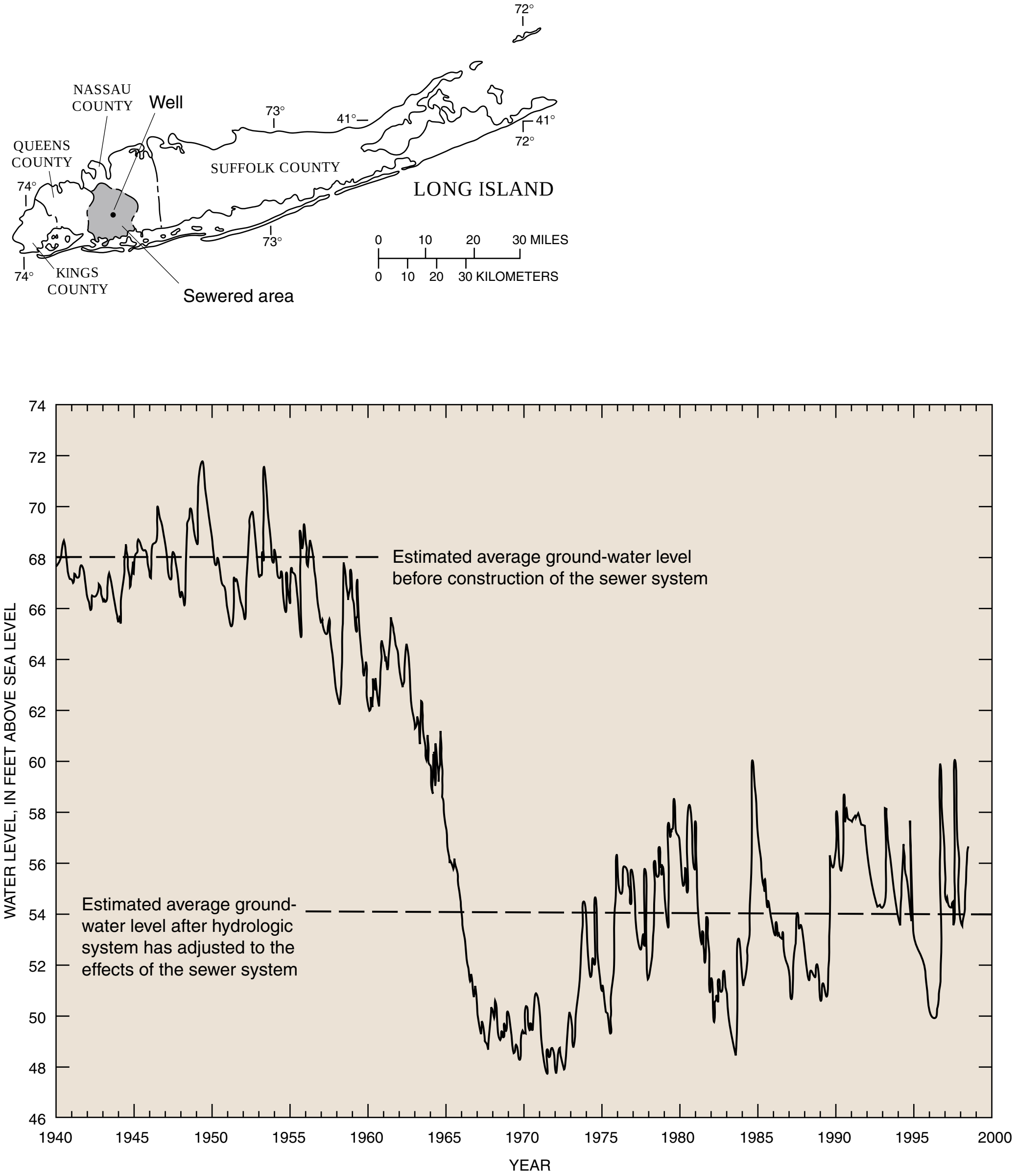
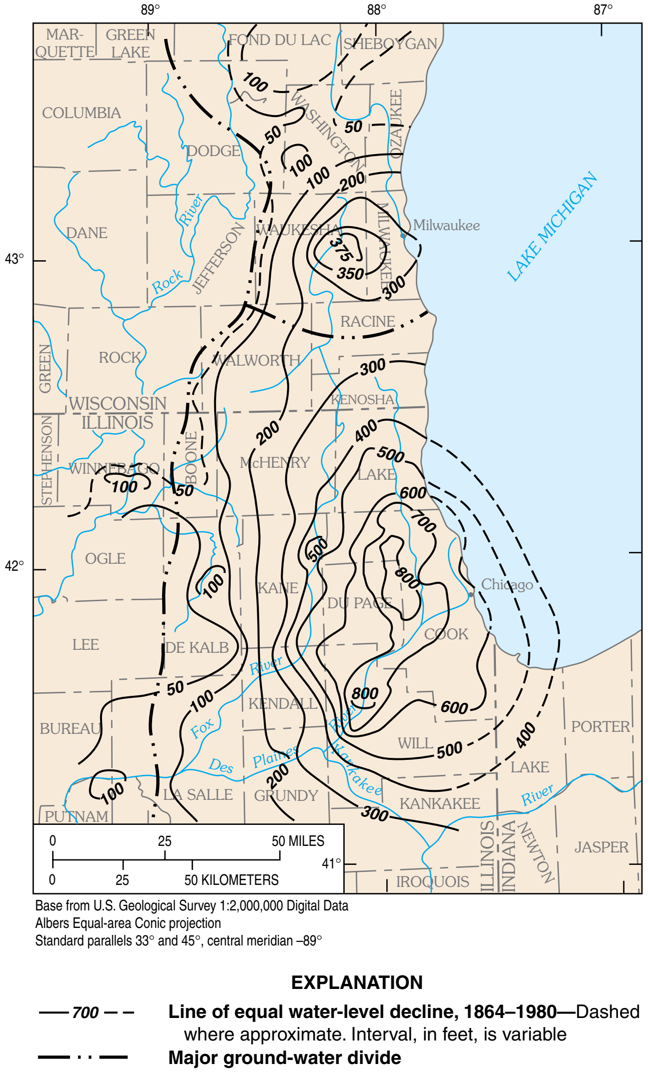


Figure 18. *Water-level record for a well completed in the upper glacial aquifer in west-central Nassau County, Long Island, New York.*

level) represents an average water-table altitude at the well before installation of the sewer system. The fluctuations in water level around the average value represent a response to the annual cycle of recharge and evapotranspiration and the differences in this cycle from year to year. The sewer system achieved close to its maximum discharge by the mid-1960's for the existing population in the sewered area. The lower horizontal line (water level equals 54 feet above sea level) represents the average water level after the hydrologic system had adjusted to the effects of installation of the sewer system. The water-level fluctuations around the lower horizontal line again reflect annual recharge and evapotranspiration cycles.

Installation of the sewer system has resulted in an areally extensive (several tens of square miles) loss of storage in the unconfined aquifer. The most obvious undesirable effect of the lowered water-table elevations has been marked decreases in the flow and length of small, ground-water-fed streams in the area. The positive effect of installing the sewer system has been to reduce recharge of contaminated water from septic systems and thereby help maintain the quality of shallow ground water and the deeper ground water that is hydraulically connected to the shallow ground water.

Chicago/Milwaukee area—The long history of ground-water withdrawals from the Cambrian-Ordovician aquifer in the Chicago and Milwaukee areas is a well-documented example of the effects of heavy pumpage on heads in a confined aquifer. The first documented deep well in the Chicago area was drilled in 1864 to a depth of 711 feet and flowed at the land surface at a rate of 400 gallons per minute. During the next decades and into the 20th century as the Chicago metropolitan area grew, the number of wells, the areal extent of pumping, and the total withdrawals from this aquifer increased substantially. Maximum withdrawals, about 180 million gallons per day, and maximum declines in heads of about 800 feet for the Cambrian-Ordovician aquifer, occurred in the eight-county Chicago area in about 1980 (Figure 19). Since 1980, many public water suppliers in the Chicago area have shifted their source of water from ground water to additional withdrawals from Lake Michigan. This shift has resulted in a significant decrease in total withdrawals from the aquifer and a general recovery (increase) of heads in the areas of decreased withdrawal (Figure 20). Pumping continues in all parts of the Chicago and Milwaukee area, however, and may be increasing in some parts, so that heads in some localities may still be decreasing.



Base from U.S. Geological Survey 1:2,000,000 Digital Data
Albers Equal-area Conic projection
Standard parallels 33° and 45°, central meridian –89°

__Figure 19.__ Decline in heads (water levels) in the Cambrian-Ordovician confined aquifer, Chicago and Milwaukee areas, 1864-1980. (Modified from Avery, 1995.)

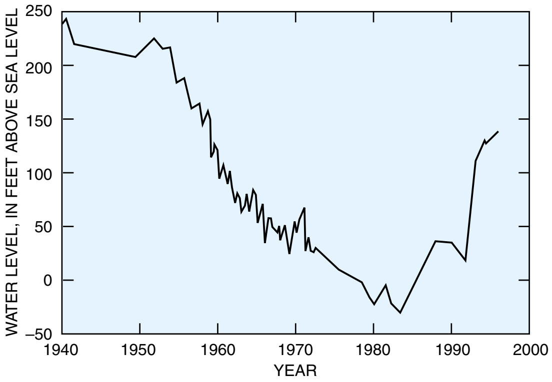


Figure 20. *Representative trend of water levels for a deep well in Cook County, Chicago area, since 1940. (From Visocky, 1997.)*

The volume of the cone of depression in the Chicago and Milwaukee area is large, even with the present decrease in withdrawal rates. A principal concern has been the possibility of beginning to dewater the confined aquifer and effectively convert it to an unconfined aquifer. This possibility was imminent at the center of the cone of depression in 1980 and was avoided by the subsequent decrease in withdrawal rates in this critical area.

The sustainability of confined aquifer systems like the Cambrian-Ordovician aquifer is typically controlled by the proximity of pumping centers to recharge and discharge areas or by the hydraulic connection with other aquifer systems. Walton (1964) defined the “practical sustained yield” of the Cambrian-Ordovician aquifer as the maximum amount of water that can be continuously withdrawn from existing pumping centers without eventually dewatering the most productive water-yielding formation. Using this definition, Walton estimated the practical sustained yield to be about 46 million gallons per day. He noted that with the existing distribution of pumping centers, the practical sustained yield was limited not by the rate of replenishment in recharge areas but by the rate at which water can move eastward through the aquifer from recharge areas. Walton estimated that the practical sustained yield could be increased more than 40 percent to about 65 million gallons per day by (1) increasing the number of pumping centers, (2) shifting centers of pumping toward the recharge area, and (3) spacing wells at greater distances.

In all but the deeply buried parts of the Cambrian-Ordovician aquifer in the Chicago and Milwaukee area, the water is chemically suited for all uses. Thus, water quality has not been a major factor affecting the use of this aquifer. Because of their greater depth, however, confined aquifers often contain saline water or are hydraulically connected to other aquifers and confining units that contain water with high dissolved-solids concentration. Declines in head in the confined aquifer can cause the movement of poor quality water from surrounding aquifers (or confining units), which may limit development of the aquifer more than declines in heads and aquifer storage.

Kings County, New York—The history of ground-water development in Kings County (Brooklyn), Long Island, New York since the early 1900's is a well-documented example of a complete cycle of intensive development with significant decreases in heads and reduction in storage in the unconfined aquifer accompanied by intrusion of saline ground water, followed by a decrease in total pumpage and a gradual recovery of heads. In 1903, total ground-water withdrawals in Kings County were about 30 million gallons per day. Available information on the altitude of the water table indicates no obvious cones of depression at this time (Figure 21). Total pumpage in Kings County peaked in the 1920's to early 1940's (maximum annual pumpage about 75 million gallons per day). As shown in Figure 21, water levels in 1936 were near or below sea level throughout Kings County, and the cone of depression extended into southwestern Queens County.

In 1947, public-supply pumpage ceased in Kings County. The source of water for public supply changed to the upstate surface-water system that supplies New York City through water tunnels. Furthermore, legislation was implemented during this period that required "wastewater" (including air-conditioning water) from some industrial/commercial uses be recharged to the aquifer system through wells. Concurrently, and partly as a result of these changes, industrial pumpage declined to a long-term stable rate of slightly less than 10 million gallons per day. These changes are reflected in the water-table map of 1965 shown in Figure 21 in which heads have risen throughout Kings County and are at or below sea level only in northern parts of the county. Subsequent maps show a small but continuing recovery of the water table.

Figure 21. *Water-table altitudes in Kings and part of Queens Counties, Long Island, New York in 1903, 1936, and 1965. (Modified from Franke and McClymonds, 1972.)*

The history of ground-water development in Kings County has been influenced considerably by the strong hydraulic connection between the unconfined ground-water system and the surrounding bodies of saline surface water. The decision to stop pumping for public supply and to recharge high-quality wastewater back to the aquifer system was driven in large measure by concerns about ongoing and continuing intrusion of saline ground water into the naturally fresh part of the aquifer system. On the other hand, an unforeseen and undesirable effect of decreased pumpage and the accompanying rise in the altitude of the water table in Kings County is that basements of major buildings constructed in the 1920's and 1930's now lie below the water table and require continuous pumping of dewatering systems to keep them dry.

Commonalities in the preceding four examples are noteworthy and include (1) the changes in storage resulted in observable changes in the ground-water system; (2) the changes in the ground-water system generally were viewed by local stakeholders as undesirable, at least to some extent; and (3) in at least three of the four examples, some response to mitigate the perceived undesirable effects of the change in storage was initiated. In examples such as the southern High Plains aquifer in Texas and New Mexico, and the unconfined aquifer in Brooklyn, New York, the long-term sustainability of the ground-water resource was perceived to be in jeopardy.

Subsidence

Land subsidence, which is a decline in land-surface elevation caused by removal of subsurface support, can result from a variety of human activities (Galloway and others, in press). Subsidence can severely damage structures such as wells, buildings, and highways, and creates problems in the design and operation of facilities for drainage, flood protection, and water conveyance. Human activities related to ground water cause land subsidence by three basic mechanisms: compaction of aquifer systems, dissolution and collapse of rocks that are relatively soluble in water (for example, limestone, dolomite, and evaporites such as salt and gypsum), and dewatering of organic soils.

Compaction of aquifer systems as a result of ground-water withdrawals and accompanying land subsidence is most common in heavily pumped alluvial aquifer systems that include clay and silt layers. As heads in the aquifer system decline due to pumping, some of the support for the overlying material previously provided by the pressurized water filling the sediment pore space shifts to the granular skeleton of the aquifer system, increasing the intergranular pressure (load). Because sand and gravel deposits are relatively incompressible, the increased intergranular load has a negligible effect on these aquifer materials. However, clay and silt layers comprising confining units and interbeds can be very compressible as water is squeezed from these layers in response to the hydraulic gradient caused by pumping.

So long as the intergranular load remains less than any previous maximum load, the deformation of the aquifer system is reversible. However, when long-term declines in head increase the intergranular load beyond the previous maximum load, the structure of clay and silt layers may undergo significant rearrangement, resulting in irreversible aquifer system compaction and land subsidence. The amount of compaction is a function of the thickness and vertical hydraulic conductivity of the clay and silt layers, and the type and structure of the clays and silts. Because of the low hydraulic conductivity of clay and silt layers, the compaction of these layers can continue for months or years after water levels stabilize in the aquifer. In confined aquifer systems that contain significant clay and silt layers and are subject to large-scale ground-water withdrawals, the volume of water derived from irreversible compaction commonly can range from 10 to 30 percent of the total volume of water pumped (Galloway and others, in press). This represents a one-time mining of stored ground water and a permanent reduction in the storage capacity of the aquifer system.

The first recognized land subsidence in the United States from aquifer compaction as a response to ground-water withdrawals was in the area now known as “Silicon Valley” in California. Other areas experiencing significant land subsidence from ground-water withdrawals include the San Joaquin Valley of California (see Box B), the alluvial basins of south-central Arizona (Figure 22), Las Vegas Valley in Nevada, the Houston-Galveston area of Texas, and the Lancaster area near Los Angeles, California.

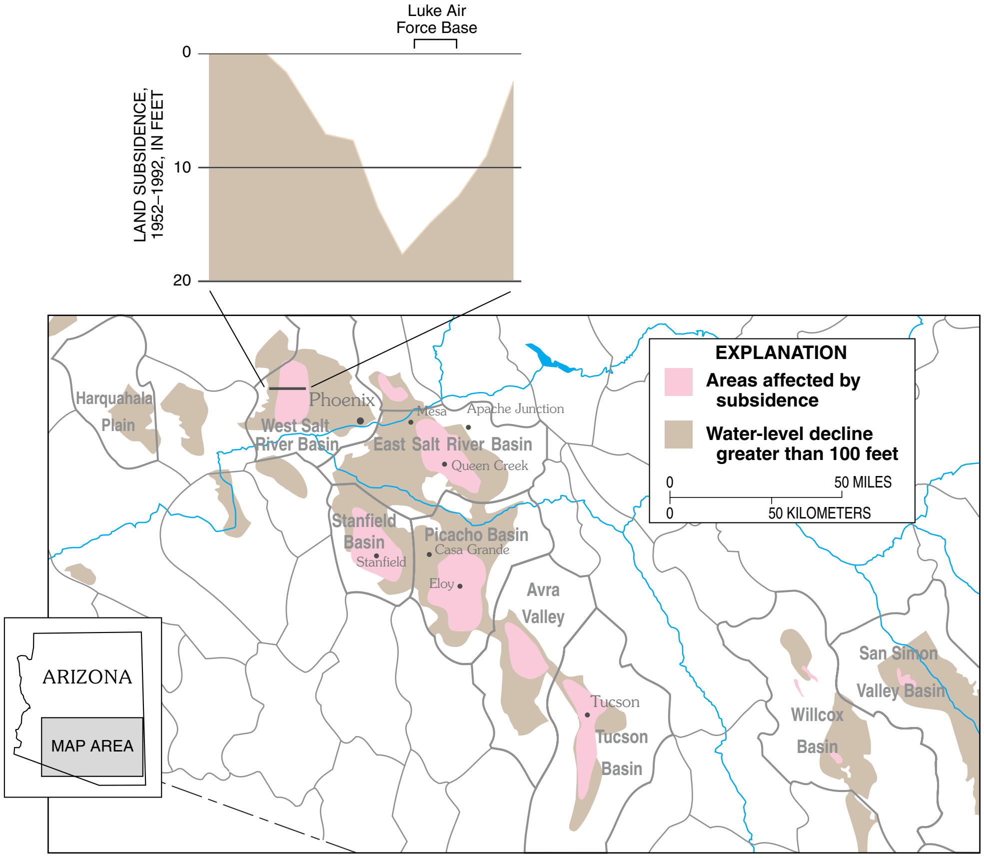


Figure 22. *Land subsidence in south-central Arizona. (Modified from Carpenter, in press.)*

Ground-water development for agriculture in the basin-fill aquifers of south-central Arizona began in the late 1800's, and by the 1940's many of the basins had undergone intensive ground-water development. Ground-water depletion has been widespread over these basins, and locally, water-level declines have exceeded 300 feet. These water-level declines have resulted in regional subsidence, exceeding 10 feet in some areas. A profile near Luke Air Force Base illustrates that subsidence is greater near the center of basins, where the aggregate thickness of the fine-grained sediments is generally greater. In conjunction with widespread subsidence, numerous earth fissures have formed at and near the margins of subsiding basins or near exposed or shallow buried bedrock.

In many areas of the arid Southwest, earth fissures are associated with land subsidence. Earth fissures are caused by horizontal movement of sediment that occurs during compaction. These features start out as narrow cracks, an inch or less in width. They intercept surface drainage and can erode to widths of tens of feet at the surface and may extend more than 100 feet below the land surface. Fissures may be a few hundred feet to miles in length. One extraordinary fissure in the Picacho Basin, northwest of Tucson, Arizona, is 10 miles long.

Sign warning motorists of subsidence hazard was erected after an earth fissure damaged a road in Pima County, Arizona (left photograph). Earth fissure near Picacho, Arizona (right photograph). (Photographs by S.R. Anderson, U.S. Geological Survey.)

Subsidence also occurs from local sinkhole collapse in areas underlain by limestone, dolomite, and other soluble rocks. Areas susceptible to sinkhole collapse are particularly common in the humid Eastern United States. Sinkhole development occurs naturally but may be enhanced by human activities, such as diversion and impoundment of surface water and pumping of ground water. Ground-water pumping can induce sinkholes by reducing the buoyant support of cavity walls and ceilings or by reducing the cohesion of loose, unconsolidated materials overlying preexisting sinkholes. The effects of ground-water pumping on sinkhole development can result from long-term declines in water levels or in response to rapid fluctuations of water levels caused by pumping wells. Some notable examples of rapid sinkhole development have occurred in the Southeastern United States. Though the collapse features tend to be highly localized, their effects can extend well beyond the collapse zone as a result of the introduction of contaminants from the land surface to the ground-water systems.

Finally, land subsidence can occur when organic soils are drained for agriculture or other purposes. Causes include compaction, desiccation, wind erosion, and oxidation of drained organic soil layers. These effects commonly are associated with the purposeful draining of the land surface but also may occur as a result of ground-water pumping near wetlands and other poorly drained areas. Subsidence at rates of an inch or more per year as a result of drainage has been observed over large areas such as the Sacramento-San Joaquin Delta in California and the Florida Everglades (Galloway and others, in press).

Development of a new irrigation well in west-central Florida triggered hundreds of sinkholes over a 20-acre area. The sinkholes ranged in size from less than 1 foot to more than 150 feet in diameter. (Photograph by Ann B. Tihansky, U.S. Geological Survey; see person in center for scale.)

WATER-QUALITY FACTORS AFFECTING GROUND-WATER SUSTAINABILITY

Previous chapters have discussed quantities of water recharging, flowing through, and discharging from the ground-water system and quantities of water stored in the system. This brief discussion of ground-water quality adds a further dimension to ground-water resource sustainability; namely, the question of the suitability of ground water for different uses. Various measures of water quality such as taste and odor, microbial content, and dissolved concentrations of naturally occurring and manufactured chemical constituents define the suitability of water for different uses.

The availability of ground water and the suitability of its quality for different uses are inextricably intertwined. To take an extreme example, salt brines having very high dissolved-solids concentrations occur adjacent to fresh ground water almost everywhere. Although brines represent huge volumes of ground water in storage, these brines are not included in most inventories of available ground water because of their inherent unsuitability for almost all uses. Ground waters having somewhat lower dissolved-solids concentrations may be suitable for some uses but not for others. For example, some cattle can tolerate a higher dissolved-solids concentration in their drinking water than humans.

A key consideration in managing a ground-water resource is its vulnerability to sources of contamination that are located primarily at and near the land surface. Because of generally low ground-water velocities, once contaminants have reached the water table, their movement to nearby surface-water discharge areas or to deeper parts of the ground-water-flow system is slow. For the same reason, once parts of an aquifer are contaminated, the time required for a return to better water-quality conditions as a result of natural processes is long, even after the original sources of contamination are no longer active. Ground-water-quality remediation projects generally are very expensive and commonly are only partly successful. In some settings, steep gradients caused by ground-water pumping can greatly increase the rate at which contaminants move to deeper ground water. For these reasons, State and Federal environmental

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The availability of ground water and the suitability of its quality for different uses are inextricably intertwined.

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agencies seek to protect the ground-water resource by stressing regulatory efforts to prevent ground-water contamination.

Contamination of ground water is not always a result of the introduction of contaminants by human activities. Possible natural contaminants include trace elements such as arsenic and selenium, radionuclides such as radon, and high concentrations of commonly occurring dissolved constituents.

The first two subsections below involve two of the most significant linkages in hydrology—the land-surface / water-table connection and the ground-water / surface-water connection. The third subsection, saltwater intrusion, involves movement of naturally occurring, highly saline ground water into parts of adjacent aquifers that contain less saline water. Pumping of the less saline (commonly potable) ground water generally causes this movement.

Land-Surface /Water-Table Connection

In principle, virtually any human activity at and near the land surface can be a source of contaminants to ground water as long as water and possibly other fluids move from the land surface to the water table. Sources of chemicals introduced to ground water in this way include fertilizers, manure, and pesticides applied to agricultural lands; landfills; industrial-discharge lagoons; leaking gasoline storage tanks; cesspools and septic tanks; and domestically used chemicals. These sources commonly are classified as “point” or “nonpoint” sources. For example, industrial lagoons, leaking storage tanks, and landfills are considered to be point sources. A considerable number of these sources and associated contaminant plumes have undergone intensive studies followed by a remediation program. Many of the chemicals associated with point sources—for example, gasoline and other manufactured organic chemicals—even at very low concentrations, render the contaminated ground water highly undesirable or useless as a source of domestic or public supply.

Croplands are a primary nonpoint source of contamination because of their large areal extent and significant applications per unit area of possible contaminants (fertilizers and pesticides) to ground water. Irrigated agriculture also has noteworthy effects on ground-water (and surface-water) quality. Increased areal recharge from excess irrigation-water applications results in the potential for increased transport of contaminants from the land surface to ground water. Also, a marked increase in dissolved-solids concentrations in soil water and shallow ground water may result from evaporation of irrigation water during delivery of the water to the crops and from transpiration of the applied water by the crops. In addition to cropland, agricultural activities include numerous point sources such as animal feedlots, waste lagoons, and storage sheds for agricultural chemicals.

Although the area occupied by urban land is small compared to the total area of the Nation, the diverse activities in urban areas provide innumerable point sources of contamination that can affect the quality of shallow ground water. From a regional perspective, urban land can be considered as a nonpoint source that exhibits a wide range in water quality. These effects on ground-water quality are particularly important from a water-management viewpoint if the water-table aquifer beneath urban land is used or could be used as a source of water supply.

A noteworthy effort to protect ground-water quality and the sustainability of the local ground-water resource, specifically to protect the quality of ground water that is pumped from public-supply wells, is the wellhead protection programs undertaken by the U.S. Environmental Protection Agency and the States. The approach of these programs is to estimate areas at the water table that contribute recharge to public-supply wells (Figure 23) and then to implement ground-water protection practices on the overlying land surface. Because many uncertainties exist in estimating areas contributing recharge to pumping wells (particularly for well-screen placements at some distance below the water table), and because areas contributing recharge may be located a considerable distance from the pumped wells, implementing ground-water protection practices at the land surface often poses considerable challenges.

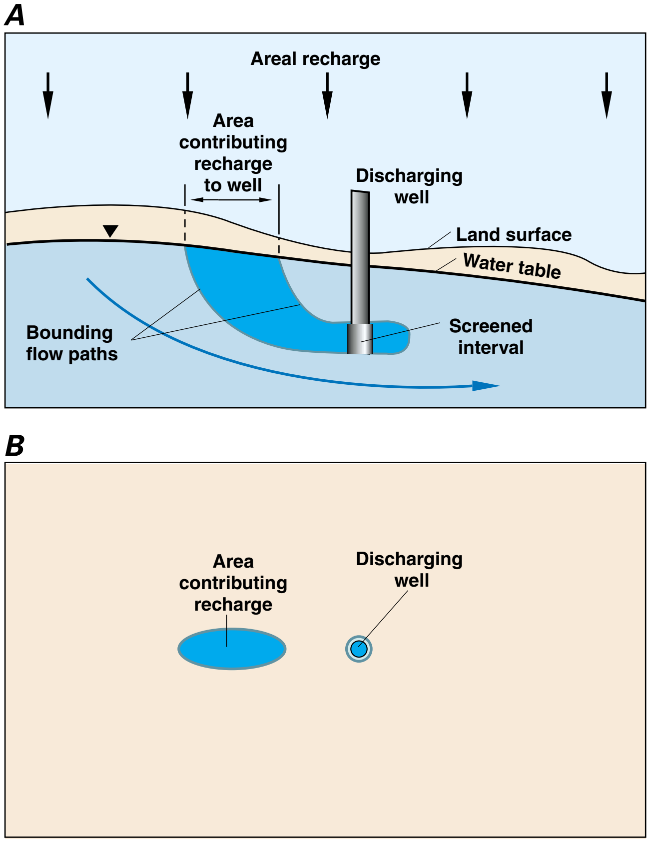

Figure 23. *Area contributing recharge to a single discharging well in a simplified hypothetical ground-water system: (A) cross-sectional view, and (B) map view. (Modified from Reilly and Pollock, 1993.)*

The area contributing recharge to a pumping well can be defined as the surface area at the water table where water entering the ground-water system eventually flows to the well. If the system is at equilibrium, this area must provide an amount of recharge that balances the amount of water being discharged from the well. Thus, lower areal recharge rates result in larger contributing areas of wells. If a nearby surface-water body also contributes water to the discharging well, the area contributing recharge is reduced and is a function not only of the areal recharge rate but also of the amount of water obtained from the surface-water body. Depending on factors that describe the three-dimensional flow system and the placement of the well, the area contributing recharge to a well does not necessarily have to include the location of the well itself.

Ground-Water/Surface-Water Connection

The movement of water in both directions between ground-water systems and surface-water bodies has been discussed previously in this report. Chemical constituents are transported along with the moving water. Thus, contaminants in surface water can be transported into adjacent ground-water systems, and contaminants in ground water can be transported into adjacent surface-water bodies.

Because ground water commonly is a major component of streamflow, the quality of discharging ground water potentially can affect the quality of the receiving stream in many hydrologic settings (Figure 24). Because the proportion of streamflow contributed by ground water can vary greatly throughout the year, seasonal variations in the effects of ground-water quality on stream-water quality can occur.

Reductions in the quantity of ground water discharged to a stream as a result of pumping may have significant consequences where this discharge significantly dilutes the concentration of contaminants introduced to streams from point sources and surface runoff. In such situations, streamflow capture by pumping wells may reduce the contaminant-dilution capacity of the stream during periods of low flow below the dilution capacity assumed in setting discharge permits for the stream.

Contributing areas to wells often include surface-water bodies, and increasing attention is being placed on surface water as a potential source of contamination to wells. Possible contamination by induced infiltration of surface water adds several dimensions to the protection of ground water. These include consideration of the upstream drainage basin as part of the "contributing area" to the well and greater consideration of microbial contamination. Contaminated surface water may have a significant effect on the sustainable development of ground water near streams or on the need for treatment of ground water prior to use. Among the settings of greatest concern for contamination of ground water by streams are karst terrains where aquifers are hydraulically connected by sinkholes or other conduits that can channel river water directly into an aquifer with little or no filtration (see Box E).

In many aquifers, large changes in chemical oxidation conditions, organic-matter content, and microbial activity occur within a relatively thin (a few feet or even inches) zone or interface between ground water and surface water. Thus, conditions near the interface between ground water and surface water can significantly affect the transport and fate of nutrients, metals, organic compounds, and other contaminants between the two resources. Reactions at this interface commonly decrease the concentrations that might be transported between surface water and ground water (Winter and others, 1998).

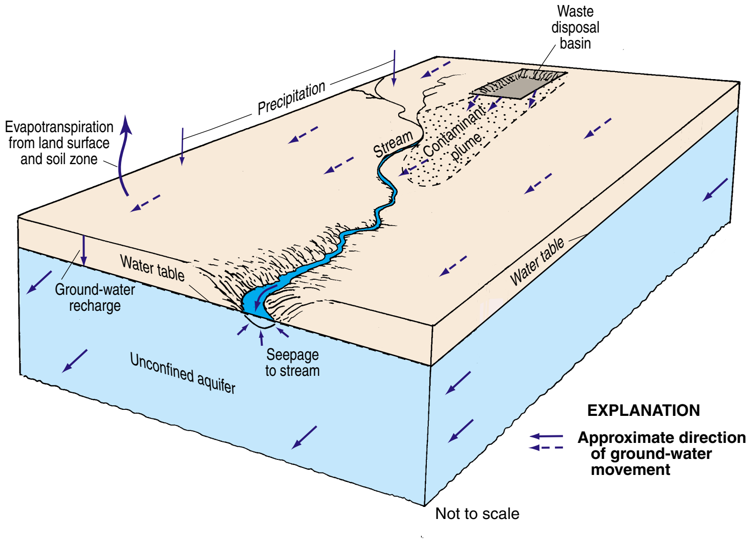

***Figure 24.** Simplified representation of a contaminant plume in ground water.*

In this hypothetical example, sufficient time has elapsed for part of the plume of contaminated ground water to reach and discharge into a nearby stream. As shown, the stream intercepts the plume as it reaches the stream. In some situations, depending upon the geometry of the ground-water-flow system and the location of the plume in the flow system, part or all of the plume may flow under the stream and contaminate ground water on the other side of the stream.