Hypothetical Examples of How Ground-Water Systems Change in Response to Pumping

Consider a ground-water system in which the only natural source of inflow is areal recharge from precipitation. The amount of inflow is thus relatively fixed. Further consider that the primary sources of any water pumped from this ground-water system are removal from storage, decreased discharge to streams, and decreased transpiration by plants rooted near the water table.

If the above-described ground-water system can come to a new equilibrium after a period of removing water from storage, the amount of water consumed is balanced by less water flowing to surface-water bodies, and perhaps, less water available for transpiration by vegetation as the water table declines. If the consumptive use is so large that a new equilibrium cannot be achieved, water would continue to be removed from storage. In either case, less water will be available to surface-water users and the ecological resources dependent on streamflow. Depending upon the location of the water withdrawals, the headwaters of streams may begin to go dry. If the vegetation receives less water, the vegetative character of the area also might change. These various effects illustrate how the societal issue of what constitutes an undesired result enters into the determination of ground-water sustainability. The tradeoff between water for consumption and the effects of withdrawals on the environment often become the driving force in determining a good management scheme.

In most situations, withdrawals from ground-water systems are derived primarily from decreased ground-water discharge and decreased ground-water storage. These sources of water were thus emphasized in the previous example. Two special situations in which increased recharge can occur in response to ground-water withdrawals are noted here.

Pumping ground water can increase recharge by inducing flow from a stream into the ground-water system. When streams flowing across ground-water systems originate in areas outside these systems, the source of water being discharged by pumpage can be supplied in part by streamflow that originates upstream from the ground-water basin. In this case, the predevelopment water budget of the ground-water system does not account for a source of water outside the ground-water system that is potentially available as recharge from the stream.

Another potential source of increased recharge is the capture of recharge that was originally rejected because water levels were at or near land surface. As the water table declines in response to pumping, a storage capacity for infiltration of water becomes available in the unsaturated zone. As a result, some water that previously was rejected as surface runoff can recharge the aquifer and cause a net increase in recharge. This source of water to pumping wells is usually negligible, however, compared to other sources.

In summary, estimation of the amount of ground water that is available for use requires consideration of two key elements. First, the use of ground water and surface water must be evaluated together on a systemwide basis. This evaluation includes the amount of water available from changes in ground-water recharge, from changes in ground-water discharge, and from changes in storage for different levels of water consumption. Second, because any use of ground water changes the subsurface and surface environment (that is, the water must come from somewhere), the public should determine the tradeoff between ground-water use and changes to the environment and set a threshold at which the level of change becomes undesirable. This threshold can then be used in conjunction with a systemwide analysis of the ground-water and surface-water resources to determine appropriate limits for consumptive use.

Systemwide hydrologic analyses typically use simulations (that is, computer models) to aid in estimating water availability and the effects of extracting water on the ground-water and surface-water system. Computer models attempt to reproduce the most important features of an actual system with a mathematical representation. If constructed correctly, the model represents the complex relations among the inflows, outflows, changes in storage, movement of water in the system, and possibly other important features. As a mathematical representation of the system, the model can be used to estimate the response of the system to various development options and provide insight into appropriate management strategies. However, a computer model is a simplified representation of the actual system, and the judgment of water-management professionals is required to evaluate model simulation results and plan appropriate actions. We return to the use of models in the final chapter of this report, "Meeting the Challenges of Ground-Water Sustainability."

Because any use of ground water changes the subsurface and surface environment (that is, the water must come from somewhere), the public should determine the tradeoff between ground-water use and changes to the environment and set a threshold for what level of change becomes undesirable.

Field Examples of How Ground-Water Systems Change in Response to Pumping

LONG ISLAND, NEW YORK

Long Island is bounded on the north by Long Island Sound, on the east and south by the Atlantic Ocean, and on the west by New York Bay and the East River. Long Island is divided into four counties—Kings, Queens, Nassau, and Suffolk. The two western counties, Kings and Queens, are part of New York City.

Precipitation that infiltrates and percolates to the water table is Long Island's only natural source of freshwater because the ground-water system is bounded on the bottom by relatively impermeable bedrock and on the sides by saline ground water or saline bays and the ocean (Figure 9). About one-half the precipitation becomes recharge to the ground-water system; the rest flows as surface runoff to streams or is lost through evapotranspiration (Cohen and others, 1968). Much of the precipitation that reaches the uppermost unconfined aquifer moves laterally and discharges to streams and surrounding saltwater bodies; the remainder seeps downward to recharge the deeper aquifers. Water enters these deeper aquifers very slowly in areas where confining units are present but enters freely in other areas where confining units are absent. Water in the deeper aquifers also moves seaward and eventually seeps into overlying aquifers. Predevelopment water budgets for most of Nassau and Suffolk Counties on Long Island are shown in Figure 9.

Over the past three centuries, the island's ground water has been developed through three distinct phases. In the first, which began with the arrival of European settlers in the mid-17th century, virtually every house had its own shallow well, which tapped the uppermost unconsolidated geologic deposits, and also had its own cesspool, which returned wastewater to these same deposits. Because population was sparse, this mode of operation had little effect on the quantity and quality of shallow ground water. During the next two centuries, the population increased steadily, and, by the end of the 19th century, the individual wells in some areas had been abandoned in favor of shallow public-supply wells.

The second phase began with the rapid population growth and urban development that occurred during the first half of the 20th century. The high permeability of Long Island's deposits encouraged the widespread use of domestic wastewater-disposal systems, and the contamination resulting from increased wastewater discharge led to the eventual abandonment of many domestic wells and shallow public-supply wells in favor of deeper, high-capacity wells. In general, pumping these deep wells had only a small effect on the quantity of shallow ground water and related surface-water systems because most of the water was returned to the ground-water reservoir through domestic wastewater-disposal systems.

OVERALL PREDEVELOPMENT WATER-BUDGET ANALYSIS

INFLOW TO LONG ISLAND HYDROLOGIC SYSTEM	CUBIC FEET PER SECOND
1. Precipitation	2,475
OUTFLOW FROM LONG ISLAND HYDROLOGIC SYSTEM	
2. Evapotranspiration of precipitation	1,175
3. Ground-water discharge to sea	725
4. Streamflow discharge to sea	525
5. Evapotranspiration of ground water	25
6. Spring flow	25
Total outflow	2,475

GROUND-WATER PREDEVELOPMENT WATER-BUDGET ANALYSIS

INFLOW TO LONG ISLAND GROUND-WATER SYSTEM	CUBIC FEET PER SECOND
7. Ground-water recharge	1,275
OUTFLOW FROM LONG ISLAND GROUND-WATER SYSTEM	
8. Ground-water discharge to streams	500
9. Ground-water discharge to sea	725
10. Evapotranspiration of ground water	25
11. Spring flow	25
Total outflow	1,275

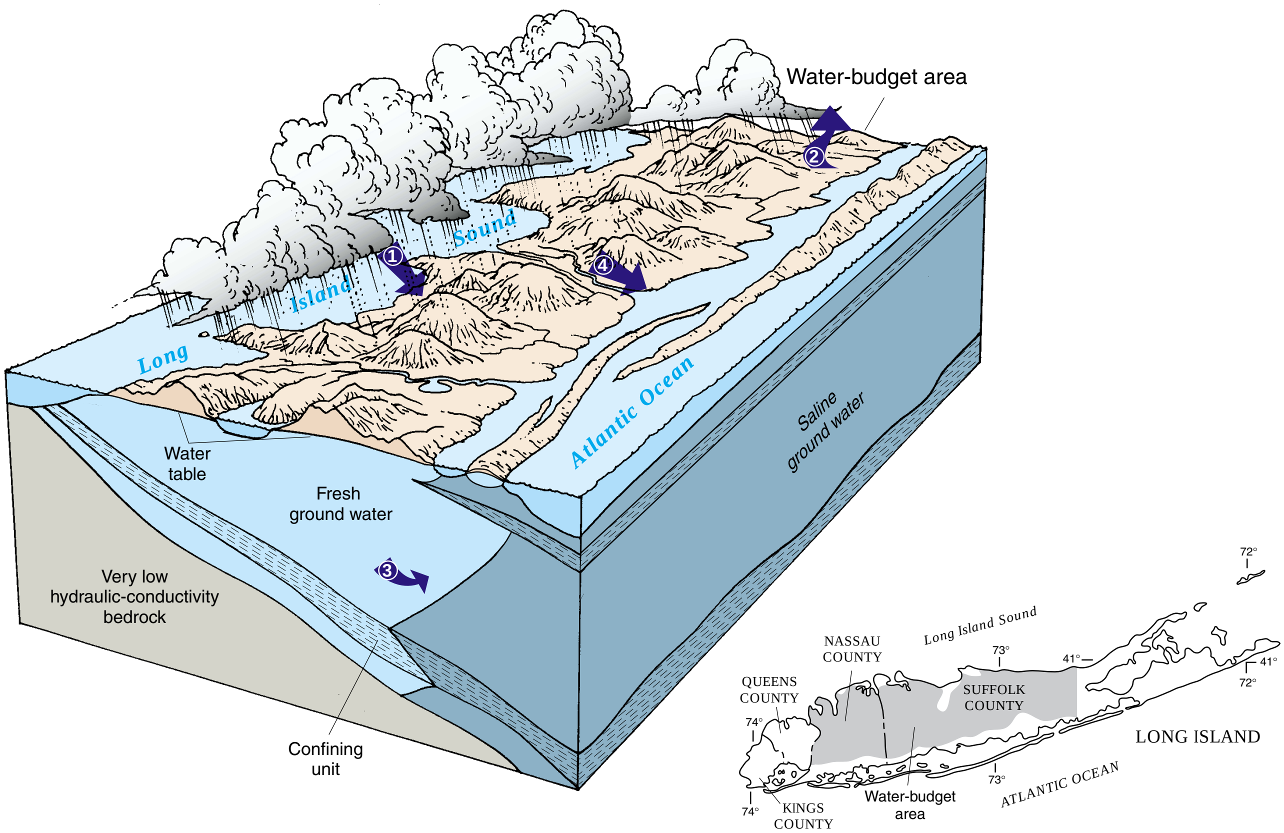


__Figure 9.__ Ground-water budget for part of Nassau and Suffolk Counties, Long Island, New York. (Modified from Cohen and others, 1968.)

Block diagram of Long Island, New York, and tables listing the overall water budget and ground-water budget under predevelopment conditions. Both water budgets assume equilibrium conditions with little or no change in storage.

The third and present phase of ground-water development on Long Island began in the early 1950's with the introduction of large-scale sewer systems in the more heavily populated areas. The purpose of the sewers was to prevent domestic wastewater from entering the aquifer system because contaminants from this source were being detected in deep public-supply wells. Even though the sewers protect the aquifers from further contamination, they also prevent the replenishment (recharge) that the wastewater had provided to the ground-water reservoir through the domestic wastewater-disposal systems. The wastewater is now diverted to sewage-treatment plants, whose effluent is discharged to the bays and oceans. The decrease in recharge has caused the water table in the sewered areas to be substantially lowered, the base flow of streams to be reduced or eliminated, and the length of perennial streams to be decreased.

In Nassau and Suffolk Counties, about 200 cubic feet per second of wastewater (ground water that has been pumped and used) was discharged in 1985 by the three major sewer districts to the surrounding saltwater bodies (Spinello and Simmons, 1992). As previously noted, the only source of freshwater to the system is precipitation. Therefore, the water required to balance the loss from the ground-water system must come primarily from decreases in ground-water discharge to streams and to surrounding saltwater bodies. Capture of ground-water evapotranspiration, spring flow, and some surface runoff are also possible, but each of these sources is limited to a maximum of approximately 25 cubic feet per second (Figure 9). As the flow to the streams decreases, the headwaters of the streams dry up and the streams become shorter. As the discharge of ground water to surrounding saltwater bodies decreases, saline ground water moves landward as saltwater intrusion. Thus, this case is an example in which the determination of sustainable yields cannot be based solely on predevelopment water budgets. The specific response of the ground-water system to development must be taken into account in determining the appropriate limits to set on ground-water use.

HIGH PLAINS AQUIFER

The High Plains is a 174,000-square-mile area of flat to gently rolling terrain that includes parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming. The area is characterized by moderate precipitation but generally has a low natural recharge rate to the ground-water system. Unconsolidated alluvial deposits that form a water-table aquifer called the High Plains aquifer (consisting largely of the Ogallala aquifer) underlie the region. Irrigation water pumped from the aquifer has made the High Plains one of the Nation's most important agricultural areas.

During the late 1800's, settlers and speculators moved to the plains, and farming became the major activity in the area. The drought of the 1930's gave rise to the use of irrigation and improved farming practices in the High Plains (Gutentag and others, 1984). Around 1940, a rapid expansion in the use of ground water for irrigation began. In 1949, about 480 million cubic feet per day of ground water was used for irrigation. By 1980, the use had more than quadrupled to about 2,150 million cubic feet per day (U.S. Geological Survey, 1984). Subsequently, it declined to about 1,870 million cubic feet per day in 1990 (McGuire and Sharpe, 1997). Not all of the water pumped for irrigation is consumed as evapotranspiration by crops; some seeps back into the ground and recharges the aquifer. Nevertheless, this intense use of ground water has caused major water-level declines (Figure 10*A*) and decreased the saturated thickness of the aquifer significantly in some areas (Figure 10*B*). These changes are particularly evident in the central and southern parts of the High Plains.

The southern part of the High Plains aquifer in Texas and New Mexico slopes gently from west to east, cut off from external sources of water upstream and downstream by river-carved escarpments, as shown in Figure 11*A*. Thus, ground-water recharge is due almost exclusively to areal recharge from precipitation. Although precipitation in the area is 15 to 20 inches per year, only a fraction of an inch recharges the aquifer due to high evapotranspiration from the soil zone. During predevelopment conditions, discharge as seeps and springs along the eastern escarpment equaled recharge. Today, the magnitude of natural recharge and discharge is small compared to withdrawals for irrigation.

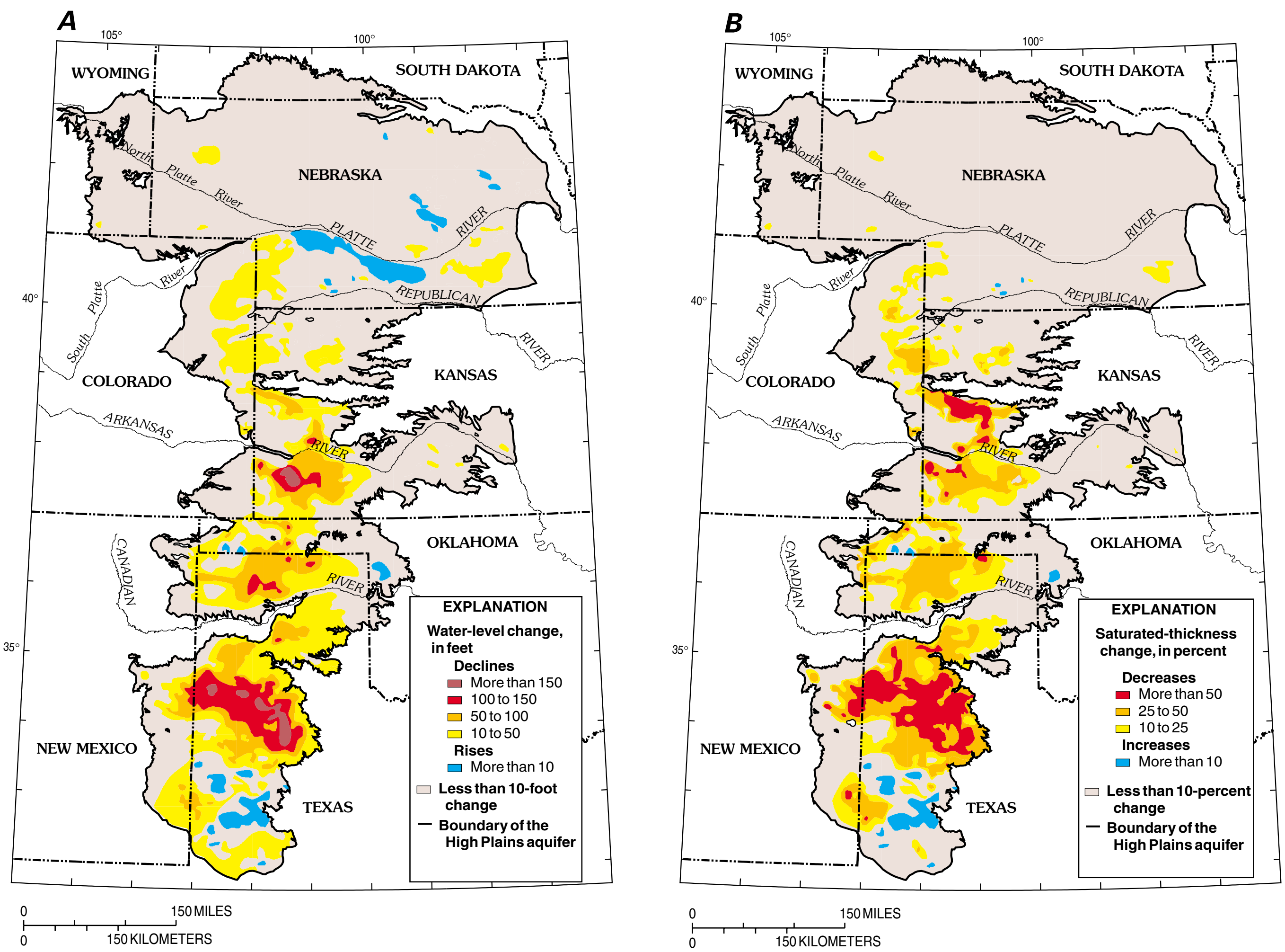


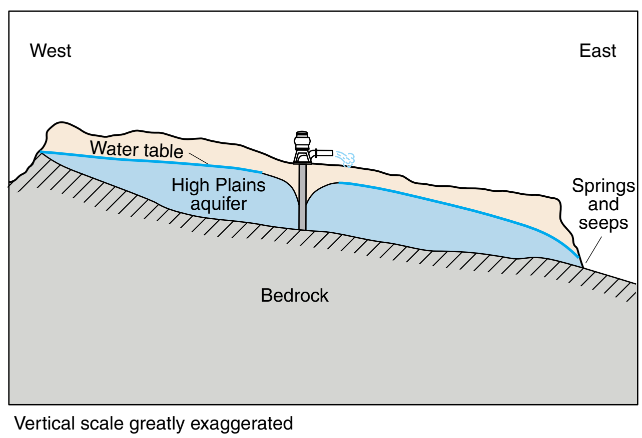
Figure 10. *Changes in (A) ground-water levels and (B) saturated thickness in the High Plains aquifer from predevelopment to 1997. (V.L. McGuire, U.S. Geological Survey, written commun., 1998.)*

Extensive pumping of ground water for irrigation has led to ground-water-level declines in excess of 100 feet in parts of the High Plains aquifer in Kansas, New Mexico, Oklahoma, and Texas. These large water-level declines have led to reductions in saturated thickness of the aquifer exceeding 50 percent of the predevelopment saturated thickness in some areas. Lower ground-water levels cause increases in pumping lifts. Decreases in saturated thickness result in declining well yields. Surface-water irrigation has resulted in water-level rises in some parts of the aquifer system, such as along the Platte River in Nebraska.

The predevelopment water budget and a water budget for average developed conditions in the southern High Plains aquifer during 1960–80 are shown in Figure 11*B*. Comparison of these water budgets shows that, due to irrigation return flow, recharge to the High Plains aquifer increased more than twentyfold from an estimated 24 million cubic feet per day during predevelopment to about 510 million cubic feet per day during 1960–80. This increase in recharge (about 486 million cubic feet per day) together with the decrease in storage (about 330 million cubic feet per day) accounts for over 98 percent of the total pumpage (about 830 million cubic feet per day). Less than 2 percent of the pumpage is accounted for by decreases in natural discharge (about 14 million cubic feet per day).

A long delay between pumping and its effects on natural discharge from the High Plains aquifer is caused by the large distance between many of the pumping wells and the location of the springs and seeps that discharge from the ground-water system. The southern High Plains is perhaps the best known example of significant, long-term nonequilibrium for a regional ground-water system in the United States. That is, water levels continue to decline without reaching a new balance (equilibrium) between recharge to and discharge from the ground-water system.

A



B

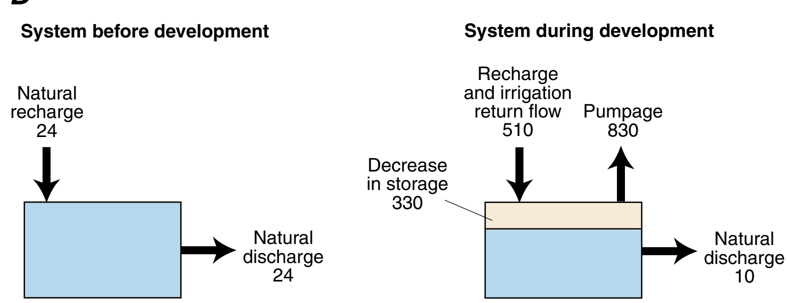


Figure 11. *The effects of ground-water withdrawals on the southern High Plains aquifer.*

Schematic cross section (A) of the southern High Plains aquifer illustrating that ground-water withdrawal in the middle of the southern High Plains aquifer has a negligible short-term effect on the discharge at the boundaries of the aquifer. (Modified from Lohman, 1972.) (B) Water budgets of the southern High Plains aquifer (all flows in million cubic feet per day) before development and during development. (Modified from Johnston, 1989; data from Luckey and others, 1986).

The preceding two field examples illustrate some of the complexities associated with the use of water budgets to determine the development potential of a ground-water system. Knowledge of the sources and discharges of water to and from the system and how they change with continuing development is needed to understand the response of ground-water systems to development, as well as to aid in determining appropriate management strategies and future use of the resource.

The examples discussed here and those in the following chapters illustrate several of the principles summarized by Bredehoeft and others (1982) in their article on the "water-budget myth" and earlier by Theis (1940):

- Some ground water must be removed from storage before the system can be brought into equilibrium.
- The time that is required to bring a hydrologic system into equilibrium depends on the rate at which the discharge can be captured.
- The rate at which discharge can be captured is a function of the characteristics of the aquifer system and the placement of pumping wells.
- Equilibrium is reached only when pumping is balanced by capture. In many circumstances, the dynamics of the ground-water system are such that long periods of time are necessary before even an approximate equilibrium condition can be reached.

In the next three chapters we discuss in more detail the effects of ground-water development on ground-water discharge to and recharge from surface-water bodies, the effects of ground-water development on ground-water storage, and water-quality factors affecting ground-water sustainability.

EFFECTS OF GROUND-WATER DEVELOPMENT ON GROUND-WATER FLOW TO AND FROM SURFACE-WATER BODIES

As development of land and water resources intensifies, it is increasingly apparent that development of either ground water or surface water affects the other (Winter and others, 1998). Some particular aspects of the interaction of ground water and surface water that affect the sustainable development of ground-water systems are discussed below for various types of surface-water features.

As development of land and water resources intensifies, it is increasingly apparent that development of either ground water or surface water affects the other.

Streams

Streams either gain water from inflow of ground water (gaining stream; Figure 12*A*) or lose water by outflow to ground water (losing stream; Figure 12*B*). Many streams do both, gaining in some reaches and losing in other reaches. Furthermore, the flow directions between ground water and surface water can change seasonally as the altitude of the ground-water table changes with respect to the stream-surface altitude or can change over shorter timeframes when rises in stream surfaces during storms cause recharge to the streambank. Under natural conditions, ground water makes some contribution to streamflow in most physiographic and climatic settings. Thus, even in settings where streams are primarily losing water to ground water, certain reaches may receive ground-water inflow during some seasons.

Losing streams can be connected to the ground-water system by a continuous saturated zone (Figure 12*B*) or can be disconnected from the ground-water system by an unsaturated zone (Figure 12*C*). An important feature of streams that are disconnected from ground water is that pumping of ground water near the stream does not affect the flow of the stream near the pumped well.

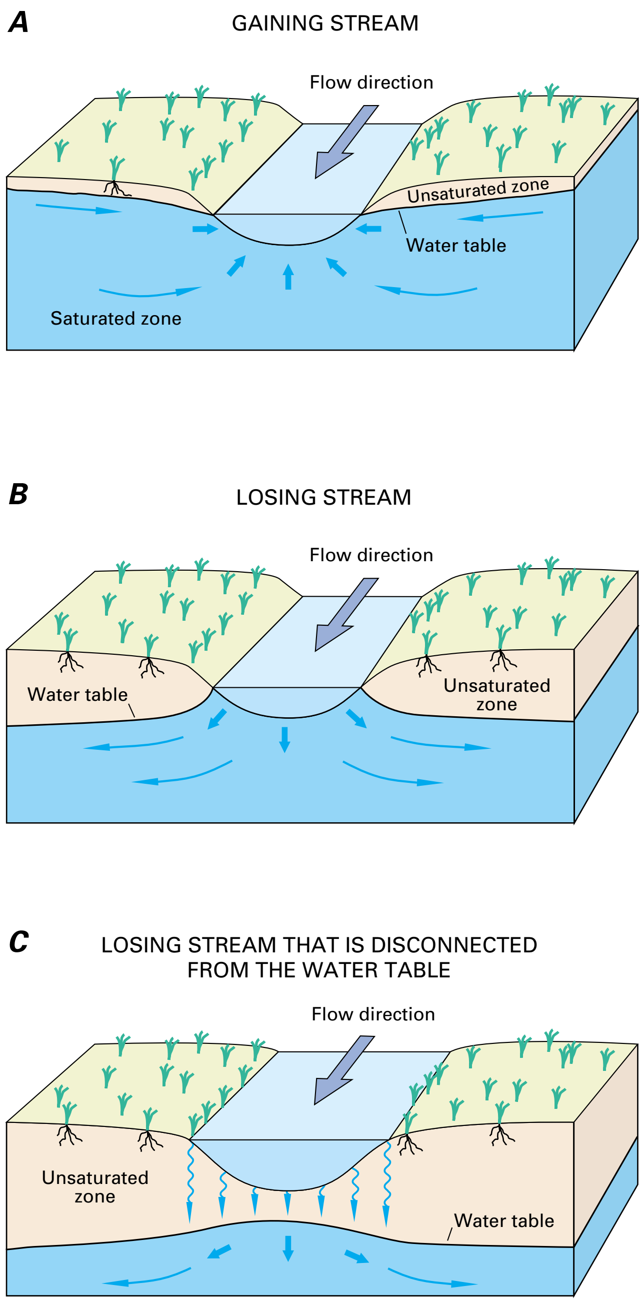


Figure 12. *Interaction of streams and ground water. (Modified from Winter and others, 1998.)*

Gaining streams (A) receive water from the ground-water system, whereas losing streams (B) lose water to the ground-water system. For ground water to discharge to a stream channel, the altitude of the water table in the vicinity of the stream must be higher than the altitude of the stream-water surface. Conversely, for surface water to seep to ground water, the altitude of the water table in the vicinity of the stream must be lower than the altitude of the stream surface. Some losing streams (C) are separated from the saturated ground-water system by an unsaturated zone.

A pumping well can change the quantity and direction of flow between an aquifer and stream in response to different rates of pumping. Figure 13 illustrates a simple case in which equilibrium is attained for a hypothetical stream-aquifer system and a single pumping well. The adjustments to pumping of an actual hydrologic system may take place over many years, depending upon the physical characteristics of the aquifer, degree of hydraulic connection between the stream and aquifer, and locations and pumping history of wells. Reductions of streamflow as a result of ground-water pumping are likely to be of greatest concern during periods of low flow, particularly when the reliability of surface-water supplies is threatened during droughts.

At the start of pumping, 100 percent of the water supplied to a well comes from ground-water storage. Over time, the dominant source of water to a well, particularly wells that are completed in an unconfined aquifer, commonly changes from ground-water storage to surface water. The surface-water source for purposes of discussion here is a stream, but it may be another surface-water body such as a lake or wetland. The source of water to a well from a stream can be either decreased discharge to the stream or increased recharge from the stream to the ground-water system. The streamflow reduction in either case is referred to as streamflow capture.

In the long term, the cumulative streamflow capture for many ground-water systems can approach the quantity of water pumped from the ground-water system. This is illustrated in Figure 14, which shows the time-varying percentage of ground-water pumpage derived from ground-water storage and the percentage derived from streamflow capture for the hypothetical stream-aquifer system shown in Figure 13. The time for the change from the dominance of withdrawal from ground-water storage to the dominance of streamflow capture can range from weeks to years to decades or longer.

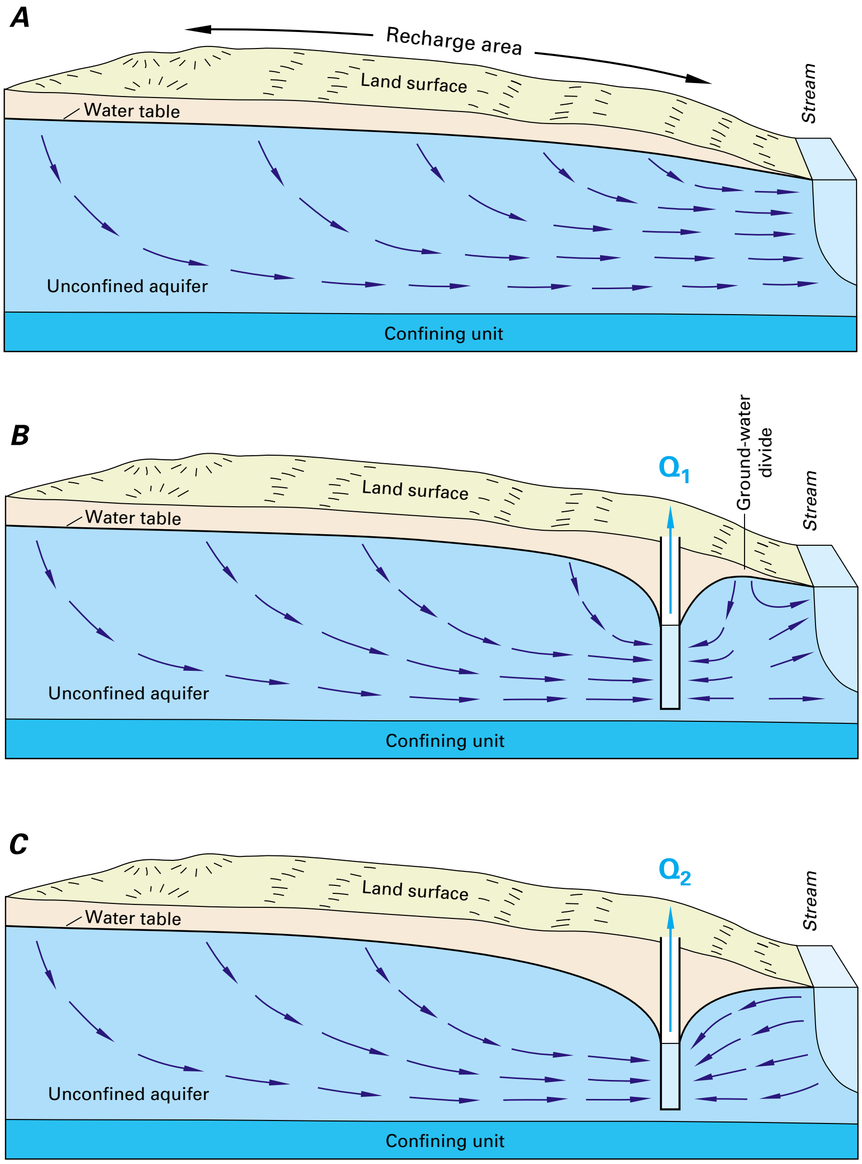


Figure 13. *Effects of pumping from a hypothetical ground-water system that discharges to a stream. (Modified from Heath, 1983.)*

Under natural conditions (A), recharge at the water table is equal to ground-water discharge to the stream. Assume a well is installed and is pumped continuously at a rate, Q_1, as in (B). After a new state of dynamic equilibrium is achieved, inflow to the ground-water system from recharge will equal outflow to the stream plus the withdrawal from the well. In this new equilibrium, some of the ground water that would have discharged to the stream is intercepted by the well, and a ground-water divide, which is a line separating directions of flow, is established locally between the well and the stream. If the well is pumped at a higher rate, Q_2, a different equilibrium is reached, as shown in (C). Under this condition, the ground-water divide between the well and the stream is no longer present, and withdrawals from the well induce movement of water from the stream into the aquifer. Thus, pumping reverses the hydrologic condition of the stream in this reach from ground-water discharge to ground-water recharge. Note that in the hydrologic system depicted in (A) and (B), the quality of the stream water generally will have little effect on the quality of ground water. In the case of the well pumping at the higher rate in (C), however, the quality of the stream water can affect the quality of ground water between the well and the stream, as well as the quality of the water withdrawn from the well. Although a stream is used in this example, the general concepts apply to all surface-water bodies, including lakes, reservoirs, wetlands, and estuaries.

From a sustainability perspective, the key point is that pumping decisions today will affect surface-water availability; however, these effects may not be fully realized for many years.

Most ground-water development is much more complex than implied in Figure 13; for example, it may comprise many wells pumping from an aquifer at varying pumping rates and at different locations within the ground-water-flow system. Computer models commonly are needed to evaluate the time scale and time-varying response of surface-water bodies to such complex patterns of ground-water development. From a sustainability perspective, the key point is that pumping decisions today will affect surface-water availability; however, these effects may not be fully realized for many years.

The eventual reduction in surface-water supply as a result of ground-water development complicates the administration of water rights. Traditionally, water laws did not recognize the physical connection of ground water and surface water. Today, in parts of the Western United States, ground-water development and use are restricted because of their effects on surface-water rights. Accounting for the effects of ground-water development on surface-water rights can be difficult. For example, in the case of water withdrawn to irrigate a field, some of the water will be lost from the local hydrologic system due to evaporation and use by crops, while some may percolate to the ground-water system and ultimately be returned to the stream. Related questions that arise include: how much surface water will be captured, which surface-water bodies will be affected, and over what period will the effects occur? Some of these issues are illustrated further in Box C.

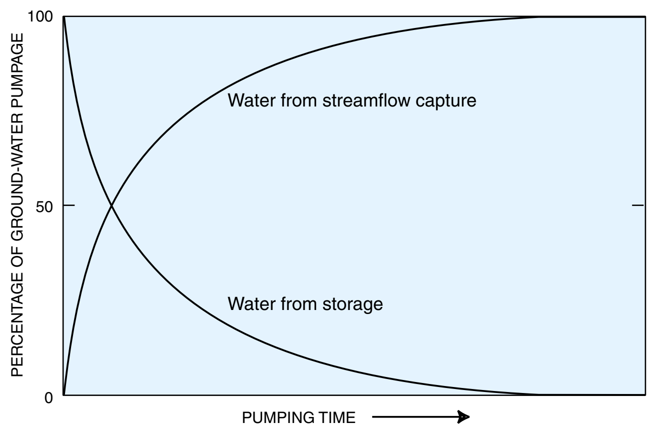
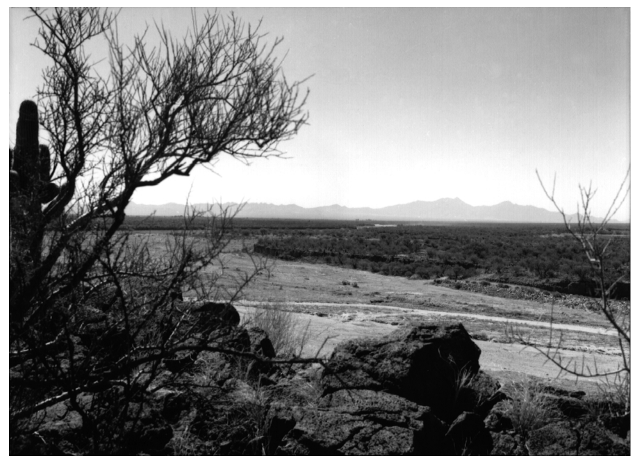


Figure 14. *The principal source of water to a well can change with time from ground-water storage to capture of streamflow.*

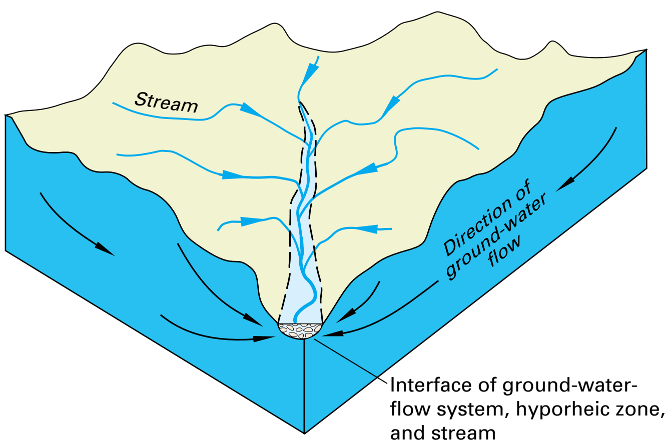
The percentage of ground-water pumpage derived from ground-water storage and capture of streamflow (decrease in ground-water discharge to the stream or increase in ground-water recharge from the stream) is shown as a function of time for the hypothetical stream-aquifer system shown in Figure 13. A constant pumping rate of the well is assumed. For this simple system, water derived from storage plus streamflow capture must equal 100 percent. The time scale of the curves shown depends on the hydraulic characteristics of the aquifer and the distance of the well from the stream.

Ground-water pumping can affect not only water supply for human consumption but also the maintenance of instream-flow requirements for fish habitat and other environmental needs. Long-term reductions in streamflow can affect vegetation along streams (riparian zones) that serve critical roles in maintaining wildlife habitat and in enhancing the quality of surface water. Pumping-induced changes in the flow direction to and from streams may affect temperature, oxygen levels, and nutrient concentrations in the stream, which may in turn affect aquatic life in the stream.



Perennial streams, springs, and wetlands in the Southwestern United States are highly valued as a source of water for humans and for the plant and animal species they support. Development of ground-water resources since the late 1800's has resulted in the elimination or alteration of many perennial stream reaches, wetlands, and associated riparian ecosystems. As an example, a 1942 photograph of a reach of the Santa Cruz River south of Tucson, Ariz., at Martinez Hill shows stands of mesquite and cottonwood trees along the river (left photograph). A replicate photograph of the same site in 1989 shows that the riparian trees have largely disappeared (right photograph). Data from two nearby wells indicate that the water table has declined more than 100 feet due to pumping, and this pumping appears to be the principal reason for the decrease in vegetation. (Photographs provided by Robert H. Webb, U.S. Geological Survey.)

In gaining and in losing streams, water and dissolved chemicals can move repeatedly over short distances between the stream and the shallow subsurface below the streambed. The resulting subsurface environments, which contain variable proportions of water from ground water and surface water, are referred to as hyporheic zones (see Figure 15). Hyporheic zones can be active sites for aquatic life. For example, the spawning success of fish may be greater where flow from the stream brings oxygen into contact with eggs that were deposited within the coarse bottom sediment or where stream temperatures are modulated by ground-water inflow. The effects of ground-water pumping on hyporheic zones and the resulting effects on aquatic life are not well known.



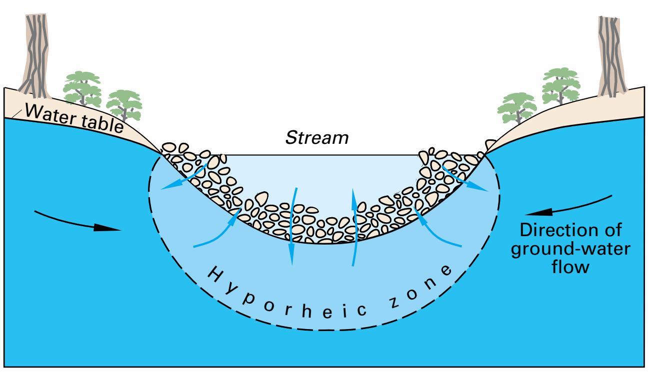


Figure 15. *The dynamic interface between ground water and streams. (Modified from Winter and others, 1998.)*

Streambeds are unique environments where ground water that drains much of the subsurface of landscapes interacts with surface water that drains much of the surface of landscapes. Mixing of surface water and ground water takes place in the hyporheic zone where microbial activity and chemical transformations commonly are enhanced.