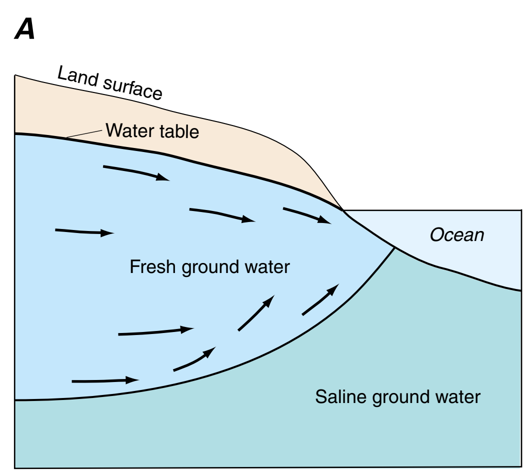
Saltwater Intrusion

The fresh ground-water resource of the United States is surrounded laterally and below by saline water. This is most evident along coastal areas where the fresh ground-water system comes into contact with the oceans, but it is also true in much of the interior of the country where deep saline water underlies the freshwater. The fresh ground-water resource being surrounded by saltwater is significant because, under some circumstances, the saltwater can move (or intrude) into the fresh ground-water system, making the water unpotable.

Freshwater is less dense than saline water and tends to flow on top of the surrounding or underlying saline ground water. Under natural conditions, the boundary between freshwater and saltwater maintains a stable equilibrium, as shown in Figure 25*A*. The boundary typically is not sharp and distinct as shown in Figure 25*A*, but rather is a gradation from fresh to saline water known as the zone of diffusion, zone of dispersion, or the transition zone. When water is pumped from an aquifer that contains or is near saline ground water, the saltwater / freshwater boundary will move in response to this pumping. That is, any pumpage will cause some movement in the boundary between the freshwater and the surrounding saltwater. If the boundary moves far enough, some wells become saline, thus contaminating the water supply. The location and magnitude of the ground-water withdrawals with respect to the location of the saltwater determines how quickly and by how much the saltwater moves. Even if the lateral regional movement of saltwater is negligible, individual wells located near the saltwater / freshwater boundary can become saline as a result of significant local drawdowns that cause underlying saltwater to "upcone" into the well (Figure 25*B*).



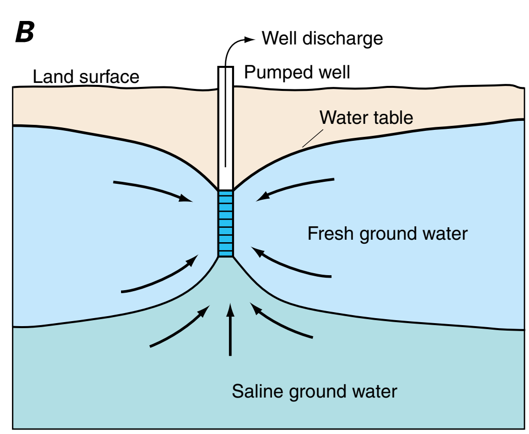


Figure 25. *Relation of fresh and saline ground water. (Modified from U.S. Geological Survey, 1984.)*

(A) In coastal areas, fresh ground water discharges to the surrounding saline surface-water bodies by flowing over the denser saline ground water. (B) In both coastal and inland areas, large drawdowns in an individual well can cause underlying saline water to migrate upward into the well and cause contamination of the water being discharged.

In 1969, the Task Committee on Saltwater Intrusion of the American Society of Civil Engineers (1969) indicated that saltwater intrusion of some type is an existing problem in nearly every State. Examples of saltwater intrusion are especially numerous along the coasts (U.S. Geological Survey, 1984). Some prominent examples follow.

Los Angeles and Orange Counties in California operate artificial-recharge programs to control saltwater intrusion caused by ground-water withdrawals. In Hawaii, several aquifers susceptible to saltwater intrusion underlie the island of Oahu. In Florida, saltwater intrusion occurs in the Jacksonville, Tampa, and Miami areas. Farther north on the Atlantic Coast, saltwater intrusion is occurring near Brunswick and Savannah, Georgia, and on Hilton Head Island, South Carolina. In New Jersey, aquifers underlying parts of Atlantic, Gloucester, Monmouth, Cape May, Ocean, and Salem Counties are being affected by saltwater intrusion. The threat of saltwater intrusion is always present on Long Island, New York, and Cape Cod, Massachusetts, because saltwater bodies surround both localities. A specific example of saltwater intrusion into the Old Bridge aquifer of New Jersey (Schaefer and Walker, 1981) is shown in Figure 26.

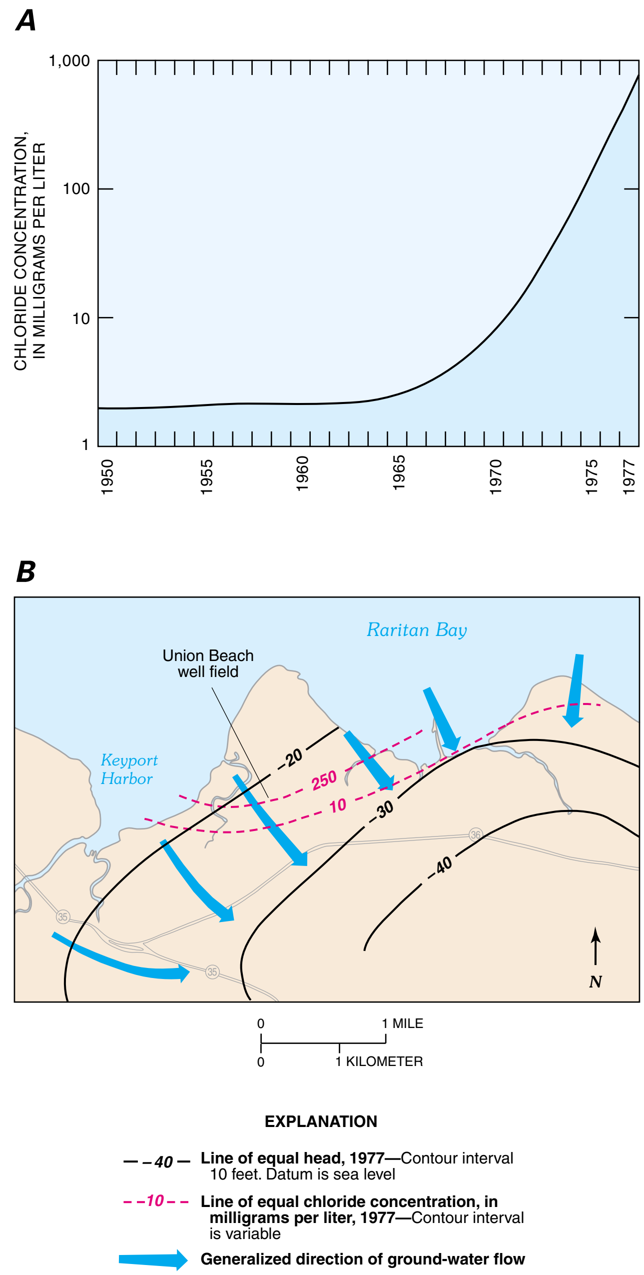


Figure 26. *Saltwater intrusion into the Old Bridge aquifer, New Jersey. (Modified from Schaefer and Walker, 1981.)*

(A) A composite graph of chloride concentration in water samples from wells screened at about the same depth in the Union Beach Borough well field. Chloride concentration in water samples from the Union Beach well field increased significantly above background levels beginning in about 1970 and increased steadily after that time. (B) As pumping in the area caused water levels to decline below sea level, saline ground water moved landward and caused the increase in chloride (and dissolved solids) in wells near the shore. Because of the increasing chloride and dissolved solids, pumpage was curtailed in the 1980's, and the well field was abandoned in the early 1990's and replaced by wells farther inland.

An inland area where saltwater intrusion is an important issue is the Mississippi River alluvial plain in Arkansas. For example, ground-water withdrawals from the alluvial aquifer for irrigation near Brinkley, Arkansas, have caused upward movement of saline water from the underlying Sparta aquifer into the alluvial aquifer (Morris and Bush, 1986). A confining unit separating the aquifers is discontinuous, and the intrusion appears to occur mainly where the confining unit is absent.

Many of the deeper aquifers in the central part of the United States contain saline water. Withdrawals from the overlying aquifers in these areas increase the potential for saltwater intrusion from below.

In summary, the intrusion of saltwater or mixing of fresh ground water with the surrounding saltwater, caused by withdrawals of freshwater from the ground-water system, can make the resource unsuitable for use. Thus, ground-water development plans should take into account potential changes in water quality that might occur because of saltwater intrusion.

MEETING THE CHALLENGES OF GROUND-WATER SUSTAINABILITY

As we have seen, the sustainability of ground-water resources is a function of many factors, including decreases in ground-water storage, reductions in streamflow and lake levels, loss of wetland and riparian ecosystems, land subsidence, saltwater intrusion, and changes in ground-water quality. Each ground-water system and development situation is unique and requires an analysis adjusted to the nature of the water issues faced, including the social, economic, and legal constraints that must be taken into account. A key challenge for achieving ground-water sustainability is to frame the hydrologic implications of various alternative management strategies in such a way that they can be properly evaluated.

Ground-water scientists have developed an expanding capability to address issues associated with the development and sustainability of ground-water resources. Early efforts focused on methods of evaluating the effects of ground-water pumping on an aquifer's long-term capacity to yield water to wells. Subsequently, methods were applied to evaluate various effects of ground-water development on surface-water bodies, land subsidence, and saltwater intrusion. Starting in the late 1970's, increasing concerns about contamination of ground water by human activities led to an awareness of the great difficulty and expense of cleaning up contaminated aquifers and drew attention to the importance of prevention of ground-water contamination. With time, it has become clear that the chemical, biological, and physical aspects of ground-water systems are interrelated and require an integrated analysis, and that many issues involving the quantity, quality, and ecological aspects of surface water are interrelated with ground water. Thus, ground-water hydrologists are challenged continually by the need to provide greater refinement to their analyses and to address new problems and issues as they arise.

A key challenge for achieving ground-water sustainability is to frame the hydrologic implications of various alternative management strategies in such a way that they can be properly evaluated.

The Importance of Ground-Water Data

The foundation of any good ground-water analysis, including those analyses whose objective is to propose and evaluate alternative management strategies, is the availability of high-quality data. Principal types of data commonly required are listed in Table 2. Some, such as precipitation data, are generally available and relatively easy to obtain at the time of a hydrologic analysis. Other data and information, such as geologic and hydrogeologic maps, can require years to develop. Still other data, such as a history of water levels in different parts of ground-water systems, require foresight in order to obtain measurements over time, if they are to be available at all. Thus, a key starting point for assuring a sustainable future for any ground-water system is development of a comprehensive hydrogeologic data base over time. As examples, these data would include depths and thicknesses of hydrogeologic units from lithologic and geophysical well logs, water-level measurements to allow construction of predevelopment water-level maps for major aquifers as well as water-level maps at various times during development, ground-water sampling to document pre- and post-development water quality, and simultaneous measurements of streamflow and stream quality during low flows to indicate possible contributions of discharging ground water to surface-water quality. Many of the types of data and data compilations listed in Table 2 need to be viewed on maps. Thus, Geographic Information Systems (GIS) typically are an integral part of the data-base system to assist in organizing, storing, and displaying the substantial array of needed information.

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***Table 2.**—Principal types of data and data compilations required for analysis of ground-water systems*

Physical Framework
Topographic maps showing the stream drainage network, surface-water bodies, landforms, cultural features, and locations of structures and activities related to water
Geologic maps of surficial deposits and bedrock
Hydrogeologic maps showing extent and boundaries of aquifers and confining units
Maps of tops and bottoms of aquifers and confining units
Saturated-thickness maps of unconfined (water-table) and confined aquifers
Average hydraulic conductivity maps for aquifers and confining units and transmissivity maps for aquifers
Maps showing variations in storage coefficient for aquifers
Estimates of age of ground water at selected locations in aquifers
Hydrologic Budgets and Stresses
Precipitation data
Evaporation data
Streamflow data, including measurements of gain and loss of streamflow between gaging stations
Maps of the stream drainage network showing extent of normally perennial flow, normally dry channels, and normally seasonal flow
Estimates of total ground-water discharge to streams
Measurements of spring discharge
Measurements of surface-water diversions and return flows
Quantities and locations of interbasin diversions
History and spatial distribution of pumping rates in aquifers
Amount of ground water consumed for each type of use and spatial distribution of return flows
Well hydrographs and historical head (water-level) maps for aquifers
Location of recharge areas (areal recharge from precipitation, losing streams, irrigated areas, recharge basins, and recharge wells), and estimates of recharge
Chemical Framework
Geochemical characteristics of earth materials and naturally occurring ground water in aquifers and confining units
Spatial distribution of water quality in aquifers, both areally and with depth
Temporal changes in water quality, particularly for contaminated or potentially vulnerable unconfined aquifers
Sources and types of potential contaminants
Chemical characteristics of artificially introduced waters or waste liquids
Maps of land cover/land use at different scales, depending on study needs
Streamflow quality (water-quality sampling in space and time), particularly during periods of low flow

Use of Ground-Water Computer Models

During the past several decades, computer simulation models for analyzing flow and solute transport in ground-water and surface-water systems have played an increasing role in the evaluation of alternative approaches to ground-water development and management. The use of these models has somewhat paralleled advances in computing systems. Ground-water models are an attempt to represent the essential features of the actual ground-water system by means of a mathematical counterpart. The underlying philosophy is that an understanding of the basic laws of physics, chemistry, and biology that describe ground-water flow and transport and an accurate description of the specific system under study will enable a quantitative representation of the cause and effect relationships for that system. Quantitative understanding of cause and effect relationships enables forecasts to be made for any defined set of conditions. However, such forecasts, which usually are outside the range of observed conditions, typically are limited by uncertainties due to sparse and inaccurate data, poor definition of stresses acting on the system, and errors in system conceptualization (Konikow and Bredehoeft, 1992). Although forecasts of future events that are based on model simulations are imprecise, they nevertheless may represent the best available decision-making information at a given time. Because of the usefulness of computer simulation for decision making, the basic construction of computer simulation models, as well as model forecasts, need to be updated periodically as the actual ground-water system continues to respond to the physical and chemical stresses imposed upon it and as new information on the ground-water system becomes available.

Although forecasts of future events that are based on model simulations are imprecise, they nevertheless may represent the best available decision-making information at a given time.
