Key Topic #3: Understanding a variety of water quality indicators in different landscapes

Objective 1. Knowledge of water quality impacts such as agriculture practices, urban development, nitrates, toxic algae, etc.
Objective 2. Understand the indicators of water health, including physical, chemical and biological properties and its role in the hydrological system.

Resources: Please note the page numbers for # 9

1. Conservation Implications of Climate Change: Soil Erosion and Runoff from Cropland *(4 pages)*
2. The nitrate contamination concern *(6 pages)*
3. Soil Characteristics that influence nitrogen and water management *(6 pages)*
4. NET News: Nitrates a costly, persistent problem for small towns *(2 pages)*
5. Drinking Water: Nitrate-Nitrogen *(4 pages)*
6. Fact Sheet: Precautions and Facts Regarding Harmful Algal Blooms *(2 pages)*
7. Here's how Midwest Farmers are fighting agricultural water pollution *(4 pages)*
8. University of Nebraska Lincoln Urban Nonpoint Source Pollution *(2 pages)*
9. Groundwater and Surface Water: A Single Resource. USGS Circular 1139 - pages 61-66 and 77

(SCROLL DOWN for RESOURCES)



SOIL AND WATER CONSERVATION SOCIETY

CONSERVATION IMPLICATIONS OF CLIMATE CHANGE: SOIL EROSION AND RUNOFF FROM CROPLAND

A Report from the Soil and Water Conservation Society
January 2003

EXECUTIVE SUMMARY

A changing climate will affect soil and water resources on agricultural land in many ways, but will the effect of climate change on soil and water resources on agricultural land be large enough to warrant changes in U.S. conservation policy or practice? To answer this question, the Soil and Water Conservation Society (SWCS) reviewed the literature and engaged members of an expert panel in a discussion of quantitative estimates of the effects of climate change on soil and water resources in agricultural landscapes. We chose to focus on one climatic variable, precipitation; two primary conservation effects, soil erosion and runoff; and one type of agricultural land, cropland.

In the end, our answer to this question was an emphatic yes. Conservationists should be seriously concerned about the implications of climate change—as expressed by changes in precipitation patterns—for the conservation of soil and water resources in the United States. The magnitude and extent of increased rates of soil erosion and runoff that could occur under simulated future precipitation regimes are large. More importantly, analyses of the climate record in the United States show that changes in precipitation patterns are occurring now. In fact, the magnitude of observed trends in precipitation and the bias toward more extreme precipitation events are, in some cases, larger than simulated by global climate change models, particularly since 1970. Extrapolating those relationships to the changes in precipitation observed over the past century suggests increases in soil erosion ranging from 4 percent to 95 percent and increases in runoff from 6 percent to 100 percent could already be evident on cropland in some locations.

Unless additional protective measures are taken, such increases in soil erosion and runoff from cropland—if widespread—could reverse much of the progress that has been made in reducing soil degradation and water pollution from cropland in the United States.

The potential for climate change—as expressed in changed precipitation regimes—to increase the risk of soil erosion, surface runoff, and related environmental consequences is clear. The actual damage that would result from such a change is unclear. Regional, seasonal, and temporal variability in precipitation is large both in simulated climate regimes and in the existing climate record. Different landscapes vary greatly in their vulnerability to soil erosion and runoff. Timing of agricultural production practices creates even greater vulnerabilities to soil erosion and runoff during certain seasons. The effect of a particular storm event depends on the moisture content of the soil before the storm starts. These interactions between precipitation, landscape, and management mean the actual outcomes of any particular change in precipitation regime will be complex.

In sum, a change in precipitation regime also produces a change in the level of risk to which agricultural land is exposed. In general, a regime with greater annual precipitation—particularly if increased storm intensity changes more than storm frequency—heightens the risk of soil erosion, runoff, and related environmental and ecological damages. In general, the risk increases at a greater rate than precipitation amount or intensity increases. Whether that new, more risky baseline condition translates into greater soil degradation, pollution of surface water, pollution of groundwater, or a combination of all three outcomes is highly dependent on other factors.

We identified three particularly promising approaches to begin adapting soil and water conservation policies and practices to a changing precipitation regime.



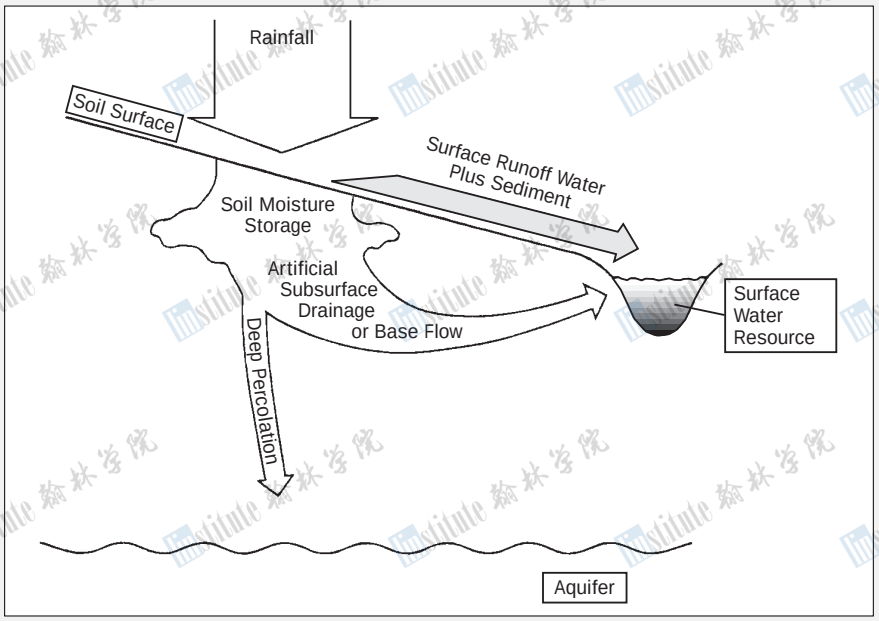
precipitation differed, depending on which simulation was used. Three ensembles of multiple simulations were used to make projections. An ensemble of simulations based on an idealized 1 percent per year compound increase of carbon dioxide resulted in projections of a global mean temperature increase of 1.1 degree Celsius to 3.1 degrees Celsius, with an average of 1.8 degrees and a standard deviation of 0.4 degree at the point when carbon dioxide concentrations doubled after 70 years. Use of the same ensemble resulted in projected changes in global mean precipitation ranging from –0.2 percent to 5.6 percent, with an average of 2.5 percent and a standard deviation of 1.5 percent. The relative agreement among models using the ensemble was much higher for projected changes in temperature than for changes in precipitation.

A second ensemble was constructed from simulations that use estimates of observed forcing during the 20th century to construct a baseline; future forcing from greenhouse gases and sulfate aerosols is projected from that baseline. Use of this ensemble projected an increase in global mean temperature of 1.3 degrees Celsius, with a range of 0.8 degree to 1.7 degrees. Global average precipitation was projected to increase by 1.5 percent, with a range from 0.5 percent to 3.3 percent. The points of comparison were 30-year averages—2021 to 2050 versus 1961 to 1990.

The third ensemble of simulations used as an initial state the end of 20th century integrations; new forcing scenarios to the year 2100 were then used to project climate effects. The 30-year average temperature response (2071 to 2100 compared to 1961 to 1990) was an increase of 3.0 degrees Celsius or 2.2 degrees Celsius, depending on which of two forcing scenarios was used. Average global precipitation was projected to increase by 3.9 percent, with a range of 1.3 percent to 6.9 percent, or 3.3 percent, with a range of 1.2 percent to 6.1 percent, again depending on which forcing scenario was used.

The working group also reported that new results confirmed projections of precipitation events with increased intensities in a future climate with increased greenhouse gases—a finding that was among the earliest model results and remains a consistent result in a number of regions with improved, more detailed models. The percentage increase in extreme rainfall is greater than the percentage increase in mean rainfall, and the return period of extreme precipitation events is short-

Erosion, Runoff, and Water Pollution



There are four major pathways through which pollutants are delivered to surface water and groundwater from cropland. Sediment and sediment-adsorbed pollutants, such as phosphorus, ammonium, and strongly adsorbed pesticides, can be transported to surface water by erosion. Soluble pollutants, such as nitrates, soluble phosphorus, and highly soluble pesticides, can be transported to surface water dissolved in runoff water. Soluble pollutants also can be transported to surface water in subsurface flow through the soil profile. Finally, soluble pollutants can be transported to groundwater through subsurface flow to underlying aquifers.

The pathway precipitation follows through the soil system will significantly affect the quantities and types of pollutants delivered to surface water and groundwater. Partitioning of precipitation between infiltration into the soil and surface runoff is the most important factor in determining which of the four pathways dominates during a storm event.

Infiltration is the process of water entering the soil during a rainstorm event, snowmelt, or irrigation. Infiltration rate (quantity/unit time) is influenced by many soil physical and chemical properties. Under most conditions, however, infiltration rate decreases as the soil becomes more saturated. If the soil is dry, water is absorbed inside soil aggregates or adsorbed onto the surface of soil particles. As soil is wetted by rainfall, the cohesive forces (energy holding soil particles together) of the soil become less and less. As the soil approaches its saturation point, cohesive forces reach a minimum. Under these conditions, raindrop energy is dissipated on the soil surface, causing dislodgement and splashing of soil particles. These splashed soil particles return to the soil surface to fill in the low areas of the soil relief and plug soil pores, slowing infiltration. As the soil pores are plugged, forming a soil crust, infiltration rate decreases and soil cohesive forces again begin to increase. Soil particle splash decreases because more energy is required to dislodge the soil particles. Surface runoff increases proportionally to the decrease in infiltration rate.

Water is attracted to soil particles because of the di-polar nature of the water molecule. This attractive force of the soil particle on water molecules becomes less as the water film thickness on soil particles increases. Therefore, water can move downward by gravity more easily from soil particle to soil particle as soil water content increases. In large soil pores, the water films become so thick that water is not influenced by the attractive forces of the soil, and the water flows through vertical pores by gravity. This preferential flow can lead to large volumes of water transmitted through the soil profile rapidly, providing these pores extend to the soil surface and are continuous to deeper depths. Water flowing through large pores in this fashion also can carry dissolved pollutants to surface water via underground tile, or to groundwater.

In general, soil erosion and surface runoff are the dominant pathways affected by an increase in precipitation intensity. Delivery of sediment, sediment-absorbed pollutants, and soluble pollutants in runoff water will increase. The processes of erosion and runoff from cropland are described elsewhere in this paper.

Sediment transported to surface water by erosion tends to carry a higher concentration of pollutants than is contained in the topsoil generally. This is because the heavier particles of sand and silt in runoff fall out of suspension more easily than clay and organic matter particles. Because clay and organic matter have high specific surface area and a higher proportion of cation exchange sites, eroded sediment contains a higher proportion of nutrient ions, like phosphate and ammonium, relative to the bulk soil from which it eroded—a process called enrichment. Researchers have studied this process and calculated enrichment ratios for various sediment components and soil management conditions (Sharpley et al., 1995; Young et al., 1986). Young et al. 1986 evaluated nutrient enrichment ratios from soil erosion plots at three locations in the United States. He concluded that nutrient enrichment ratios varied with crop rotation, current crop, tillage system, soil mineralogy, and latitude.

An increase in the number of wet days with no increase in precipitation intensity will tend to emphasize subsurface flow to surface water and groundwater. Hatfield et al 1998, for example, found that delivery of nitrate increased linearly with cumulative weekly precipitation in a tile-drained watershed in Iowa.

period (spring). Thurman et al. 1991 documented the "spring flush" phenomenon of herbicide concentrations and frequency of detections of herbicides in the post-planting sampling dates of surface water in the midwestern United States. Squillace and Engberg 1998 hypothesized that surface water containing those elevated concentrations of herbicides may contribute significantly to alluvial aquifer contamination as a result of the reverse groundwater flow gradient (i.e. surface water from the stream flowing into the alluvial aquifer). A precipitation increase in Iowa after nitrogen has been applied in the spring will result in more nitrogen in streams than if a similar increase in precipitation occurs in August (Schuman et al., 1973).

If the seasonal distribution of precipitation changes so that more precipitation occurs during vulnerable periods, then the effects on soil degradation and water pollution will be magnified. Groisman et al. 2001 found that the largest linear trends in precipitation in the United States occurred in spring and autumn. The spring season is particularly vulnerable because of the lack of crop residues and/or a growing crop and the fact that fertilizers and pesticides have been applied to agricultural fields.

In sum, a change in precipitation regime also produces a change in the level of risk to which agricultural land is exposed. In general, a regime with greater annual precipitation—particularly if storm intensity increases more than storm frequency—heightens the risk of soil erosion, runoff, and related environmental and ecological damages. The actual damages that occur because of the new, more risky baseline conditions are highly dependent on additional factors.

Interactions with other components of climate change could mitigate or exacerbate the effects of changes in precipitation patterns. The effect of a change in precipitation on soil erosion and runoff and the consequent effects on the environment can be reduced or intensified by interactions with other factors. Biomass is a particularly influential factor. The increased risk to soil erosion and water pollution from an increase in annual precipitation could be mitigated by the increase in biomass expected from an increase in carbon dioxide concentrations in the atmosphere. Similarly, the reduced risk to soil erosion and water pollution from a decrease in annual precipitation could be negated by a reduction in biomass caused by a reduction in soil moisture.

Pruski and Nearing (in press) evaluated these interactions at eight U.S. locations. They found that biomass production, as affected by soil moisture, carbon dioxide concentration, temperature, and solar radiation, was a key factor that sometimes overshadowed the direct effects of rainfall increases or decreases on soil erosion and runoff. Different types of changes occurring in different periods of the year also complicated system responses. Overall, they found that these interactions tended to be more important when precipitation decreased than when precipitation increased. Significant increases in precipitation, they found, could be expected to lead to increased soil erosion. Decreases in precipitation could produce reductions or increases in soil erosion, depending on the interaction of plant biomass with erosion and runoff.

Feedback mechanisms could magnify the long-term effects of a change in precipitation regime. Over time, the soil's capacity to resist the effects of extreme or, in some cases, mean events can be reduced. In some cases, this loss in resilience or resistance can happen suddenly in response to a particularly damaging event. Runoff from an infrequent but large-magnitude event, for example, can destabilize gully sidewalls, increasing the soil's vulnerability to future, much smaller runoff events (Toy et al., 2002). An extreme erosion episode that removes a large portion of the organic matter-rich topsoil likely would decrease the rate water infiltrates into the damaged soil, leading to accelerated surface runoff, less biomass production, less soil cover and greater risk of erosion in future events of a smaller magnitude.

Such losses in resistance or resilience leave soils and landscapes more vulnerable to subsequent events. In the worst case, this can lead to a downward spiral characterized by accelerated degradation of soil and related water resources (Seybold et al., 1999). Degradation of soil, stream channels, and other watershed features can lead to a similar downward spiral in watershed functions.

CONSERVATION IMPLICATIONS

The key findings from our review of (1) simulated and observed changes in precipitation regime and (2) quantitative estimates of the effect of changes in precipitation on soil erosion and runoff formed the factual basis for discussion and debate among our expert panel and staff. We also relied on the professional judgment of the panel and SWCS staff to answer our primary question: Are the effects of changing precipitation regimes on soil erosion and runoff from cropland likely to be large enough to warrant changes in U.S. conservation policy or practice?

Our answer was, emphatically, yes. Conservationists should be concerned. That answer led to further discussion about how conservationists should respond to the risk posed by climate change in the form of an altered precipitation regime.

Conservationists Should Be Concerned

Conservationists should be seriously concerned about the implications of climate change—as expressed by changes in precipitation patterns—for the conservation of soil and water resources in the United States. The magnitude and extent of increased rates of soil erosion and runoff that could occur under simulated future precipitation regimes are large. More importantly, analyses of the climate record in the United States show that changes in precipitation patterns are occurring now. In fact, the magnitude of observed trends in precipitation and the bias toward more extreme precipitation events are, in some cases, larger than simulated by global climate change models, particularly since 1970. The soil degradation, water pollution, and other environmental effects noted in Figure 1 that could occur as a result of the more pronounced increases in precipitation amounts and intensities would be severe enough that conservation policies and practices would need to change and adapt to the increased risk of soil erosion and surface runoff.

Pruski and Nearing 2002, for example, quantified the relationship between a 1 percent change in precipitation and the resulting change in soil erosion and runoff, depending on whether precipitation increased in frequency, intensity, or a combination of both. Extrapolating those relationships to the changes in precipitation observed over the past century suggests increases in soil erosion rang-

ing from 4 percent to 95 percent and increases in runoff from 6 percent to 100 percent could already be evident in some locations (Table 4).

Unless additional protective measures are taken, such increases in soil erosion on cropland—if widespread—could reverse much of the progress that has been made in reducing soil degradation on cropland in the United States.

Changes of this magnitude in soil erosion and runoff likely would have profound effects on water resources, although published estimates are few. Nicks 1993 estimated that a 16 percent average annual increase in precipitation, using mean monthly precipitation quantities from global climate change model estimates, would produce a 128 percent or 103 percent increase in sediment yield and a 70 percent or 73 percent increase in water yield within an Oklahoma watershed depending on what method was used to estimate montly precipitation trends . Favis-Mortlock and Guerra 1999 used mean monthly precipitation outputs from three global climate models for 2050 to estimate changes in sediment yield in Sorriso, Brazil. They reported an increase in sediment yield of 27 percent under the first model in which change in mean monthly precipitation ranged from –10 percent to 38 percent, a decrease in sediment yield of 9 percent under the second model in which change in mean monthly precipitation ranged from –20 percent to 4 percent, and an increase in sediment yield of 55 percent under the third model in which change in mean monthly precipitation ranged from –5 percent to 95 percent. Transport of soluble pollutants, such as nitrates, some pesticides, and salts, could be accelerated by changes in precipitation patterns that are significantly smaller than those needed to induce accelerated erosion. Hatfield et al. 1998, for example, reported that monitoring of subsurface drainage in an Iowa watershed indicates that 67 percent of the nitrate loadings could be accounted for by considering the effects of precipitation patterns in the watershed.

The potential for climate change—as expressed in changed precipitation regimes—to increase the risk of soil erosion, surface runoff, and related environmental consequences is clear. The actual damage that would result from such a change is unclear. That uncertainty is largely the result of variability in precipitation patterns and variability in the landscape features and management that ultimately determine the outcome of a change in a precipitation regime.

Table 4. Potential effects on soil erosion and runoff from cropland of observed changes in precipitation.

	Increase in Mean Annual Precipitation			
	5%	10%	20%	40%
Change in Erosion				
Increase only frequency of precipitation	4%	9%	17%	34%
Increase only intensity of precipitation	12%	24%	48%	95%
Increase frequency and intensity equally	8%	17%	33%	66%
Change in Runoff				
Increase only frequency of precipitation	6%	13%	26%	51%
Increase only intensity of precipitation	13%	25%	50%	100%
Increase frequency and intensity equally	10%	20%	39%	79%

Source: Derived from Pruski and Nearing 2002.

Regional, seasonal, and temporal variability in precipitation is large in both simulated climate regimes and the existing climate record. Different landscapes vary greatly in their vulnerability to soil erosion and runoff. Timing of biomass production and harvest, tillage operations, and applications of nutrients and pesticides combine to create greater vulnerabilities to soil erosion and runoff during certain seasons. The effect of a particular storm event depends on the moisture content of the soil before the storm starts and, therefore, on the amounts and intensities of previous storm events. These interactions between precipitation, landscape, and management mean the actual outcomes from any particular change in precipitation regime will be complex.

In sum, a change in precipitation regime also produces a change in the level of risk to which agricultural land is exposed. In general, a regime with greater annual precipitation—particularly if increased storm intensity changes more than storm frequency—heightens the risk of soil erosion, runoff, and related environmental and ecological damages. In general, the risk increases at a greater rate than precipitation amount or intensity increases. Whether that new, more risky baseline condition translates into greater soil degradation, pollution of surface water, pollution of groundwater or a combination of all three outcomes is highly dependent on interactions among precipitation patterns, landscape features, and management.

We focused our work on the effects of increased precipitation amounts and intensities on soil erosion and runoff from cropland. It is important to note, however, that increases in the amount and intensity of precipitation are not the only—and in some cases probably not the most important—risks posed by climate change. Decreases in precipitation, for example, can accelerate erosion as much as increases in precipitation because of reduced biomass production. Pruski and Nearing (in press) reported that soil erosion increased in about half of the cases in which a decrease in total precipitation was simulated. More importantly, change in the seasonal distribution of precipitation, coupled with increased minimum temperatures, could have profound effects on water budgets in the western United States. Those effects could be more important than effects on erosion, runoff, and related environmental endpoints. Similarly, a change in precipitation regimes in arid areas could lead to major shifts in plant communities on rangeland. Such shifts could have profound effects on the environment and on the sustainability of agricultural production in those regions. We did not attempt to assess the magnitude of such changes, but such an assessment would likely increase the reasons conservationists should be concerned about climate change.

Work to identify the most effective ways in which soil and water conservation policies and practices can be adapted to a changing precipitation regime should, therefore, be undertaken with some urgency.

How Should Conservationists Respond?

The primary objective of this project was to answer one question: Are the effects of changing precipitation regimes on soil erosion and runoff from cropland likely to be large enough to warrant changes in U.S. conservation policy or practice? Our answer was, emphatically, yes. Conservationists should be concerned. In the process of coming to that conclusion, we developed ideas regarding the most promising responses to the risk posed by an altered precipitation regime. Three particularly promising responses include:

1. Immediately update climatic parameters in critical conservation planning tools.

2. Undertake targeted investigations to firm up estimates of the damage that would likely occur under simulated or observed climate regimes.

Section A

The nitrate contamination concern

In 1974, the U.S. Congress passed the Safe Drinking Water Act (SDWA). This law required the Environmental Protection Agency (EPA) to determine the level of contaminants in drinking water at which no adverse health effects were likely to occur. Contaminants were defined as any physical, chemical, biological, or radiological substances or matter in water. One of the **contaminants** on the EPA list is nitrate (NO_3). The EPA has set the enforceable regulation for nitrate, referred to as the **maximum contaminant level** (MCL) at **10 mg/L or 10 ppm NO_3-N**.

Contaminants are any physical, chemical, matter, biological, or radiological substances in water.

Maximum Contaminant Level (MCL) is an enforceable regulation that establishes the level of a contaminant at which no adverse health effects are likely to occur.

Nitrate (NO_3) is a naturally occurring inorganic ion and a **nitrogen**-oxygen combination which readily reacts with various organic and inorganic compounds.

Groundwater is water contained in pores of geologic materials that make up the earth's crust.

Methemoglobinemia or "blue baby syndrome" is caused when water or food containing nitrates are ingested and bacteria in the human digestive system convert the nitrate to nitrite. Nitrite reacts with iron in hemoglobin to form methemoglobin which has a reduced oxygen carrying capacity.

Nitrate is a naturally occurring form of nitrogen found in most soils. Nitrate is a colorless, odorless, and tasteless compound and is also one of the most common groundwater contaminants in Nebraska. Though nitrate occurs naturally in some **groundwater**, in most cases levels above 3 ppm result from human activities. Nitrates form when microorganisms break down ammonium fertilizers, decaying plants, manures, or other organic residues involved in crop production systems. Sources of nitrate in water include fertilizers, septic systems, wastewater treatment effluent, animal wastes, mineralization of organic matter, industrial wastes, and food processing wastes. Usually plants take up these nitrates, but sometimes precipitation or irrigation water can leach nitrates out of the crop root zone and into the groundwater.

Health concerns

Several health concerns may be related to the consumption of high nitrate water. The acute health hazard associated with drinking water having elevated levels of nitrate occurs when bacteria in the human digestive system transform nitrate to nitrite. The nitrite reacts with iron in the hemoglobin of red blood cells to form methemoglobin, which lacks the oxygen-carrying ability of hemoglobin. This creates the condition known as **methemoglobinemia** (sometimes referred to as "blue baby syndrome"), in which blood lacks the ability to carry sufficient oxygen to individual body cells.

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The current 10 ppm standard was set to prevent the occurrence of methemoglobinemia in infants under six months of age. Infants are particularly susceptible if fed formula, due to the volume of water intake relative to their body weight. A much greater question is whether consuming water with various levels of nitrate can have chronic health impacts for adults. While research is limited, correlations have been found between long-term ingestion of water with nitrate and increased incidence of certain diseases and cancers.

Figure A-1 shows the location of wells where nitrate-nitrogen concentrations were documented above 10 ppm, in a recent compilation of sampling results across the state. The Platte Valley stands out, as well as northern Holt County, where most intensive corn production is on sandy soils. However, many wells in South Central Nebraska, as well as a smaller but growing number in other locations, are also beginning to show increasing nitrate-nitrogen concentrations.

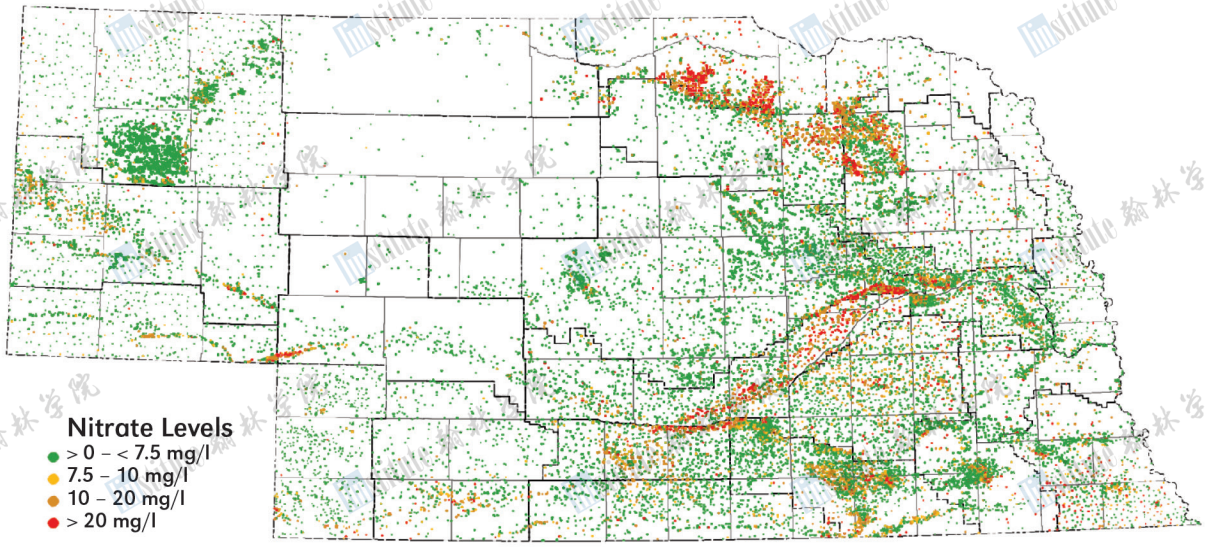


Figure A-1. **Nebraska map presenting recorded concentration of nitrate from 1974 - 2012. (Source: Quality-Assessed Agrichemical Database for Nebraska Groundwater, 2013). Empty areas indicate no data reported, not the absence of nitrate in groundwater.**

Groundwater sampling programs conducted by local NRDs across the state indicate that groundwater nitrate concentrations continue to rise (*Figure A-2*). However, data for the last 30 years of using nitrogen and irrigation best management practices show signs that some areas in the Platte Valley are seeing nitrate levels plateau or beginning to decline.

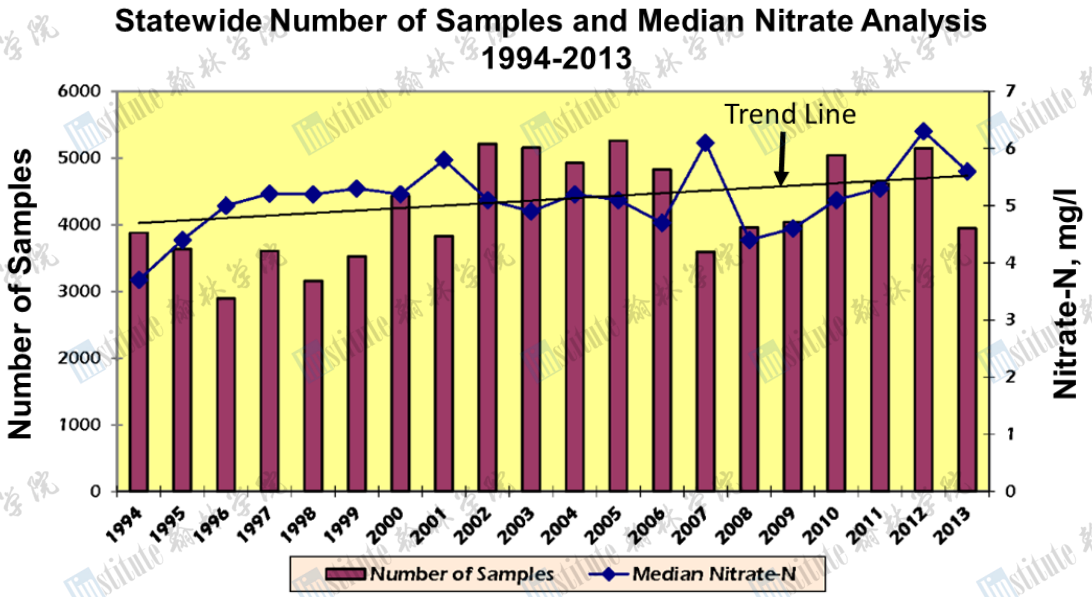


Figure A-2. Water laboratory analyses and median **nitrate-nitrogen** levels for 102,386 samples collected across Nebraska between 1994 and 2013. (See 2014 Nebraska Groundwater Quality Monitoring Report, NDEQ.)

Impacts on town and rural water supplies

Today, residents of cities, small towns, and rural areas deal with excess nitrate concentration in their water supplies. In Nebraska, much (but certainly not all) of the groundwater nitrate is the result of **nonpoint source contamination** coming from intensive production of irrigated corn. Nitrogen leaching loss from applied fertilizer and the spreading of manure is increased by excessive applications of irrigation water. With improper management of nitrogen sources, non-irrigated crop production can also contribute to the problem. In some cases urban sources of contamination, including **nitrate leaching** from areas such as lawns and golf courses, contribute to the nitrate contamination levels. *Figure A-3* depicts the number of cities and towns that have issues with nitrate contamination of their water supplies.

Nitrate-nitrogen (NO_3-N) is one chemical formulation used by the EPA to establish the U.S. drinking water maximum contaminant level for nitrates. 1.0 ppm NO_3-N = 4.5 ppm NO_3.

Nonpoint Source Contamination (NPS) is contamination discharged over a wide land area. Typically the exact source of the contamination is difficult to identify. Leaching of fertilizer from a corn field or surface runoff from a large land area are examples of NPS.

Nitrogen leaching is the passage of nitrogen vertically through the soil to a position where the nitrogen effectively becomes unavailable to the crop.

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Figure A-3 shows that at least 12 small towns and villages had to find alternative drinking water supplies and are treating their water to meet the 10 ppm standard. Although the users of private wells are not required to meet the EPA nitrate MCL, they should monitor nitrate levels in the water supply. If nitrate levels are excessive, they should identify an alternative water supply or treat their water to assure it is safe to drink especially if babies will be present.

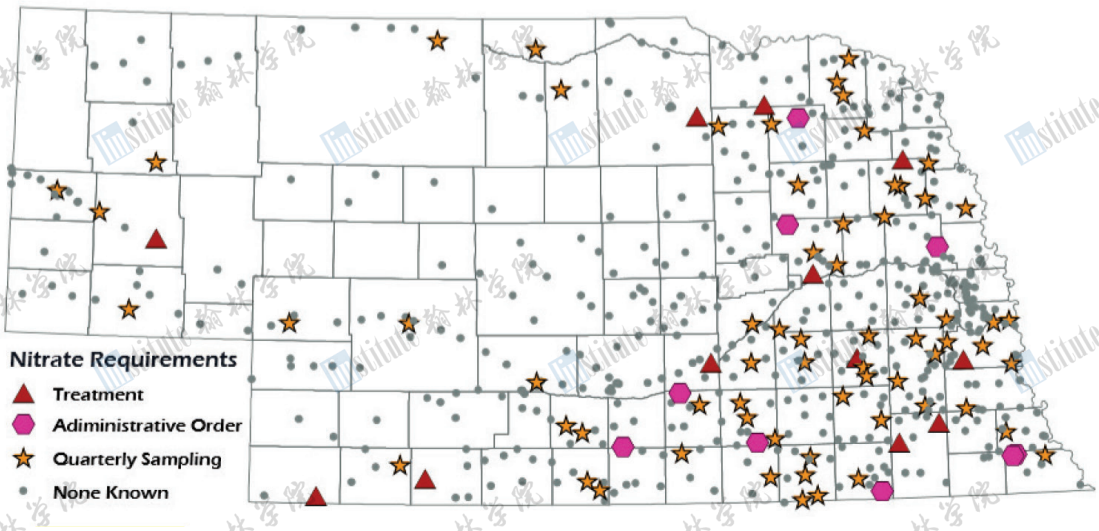


Figure A-3. 2013 map of community and public water supply systems with nitrate contamination issues. (Source: Department of Health and Human Services).

How does nitrate contamination of groundwater happen?

Nitrate contamination happens when water moves through the soil profile that contains excess nitrate (*Figure A-4*). When nitrogen fertilizer, manure, or some other nitrogen source is added to the soil, microorganisms gradually convert the various nitrogen forms to nitrate-nitrogen. Nitrate-nitrogen is highly soluble in water and since soil is a porous system, water passing through the soil will carry some nitrate with it to the groundwater.

One factor is that crops are unable to remove all available nitrogen from the root zone. Even if the crop is under-fertilized, there will be some residual nitrate-nitrogen in the root zone at the end of the growing season. During the off-season, part of the excess nitrate-nitrogen can be leached by excess precipitation. Similarly, early spring precipitation events can move available nitrate-nitrogen from the root zone.

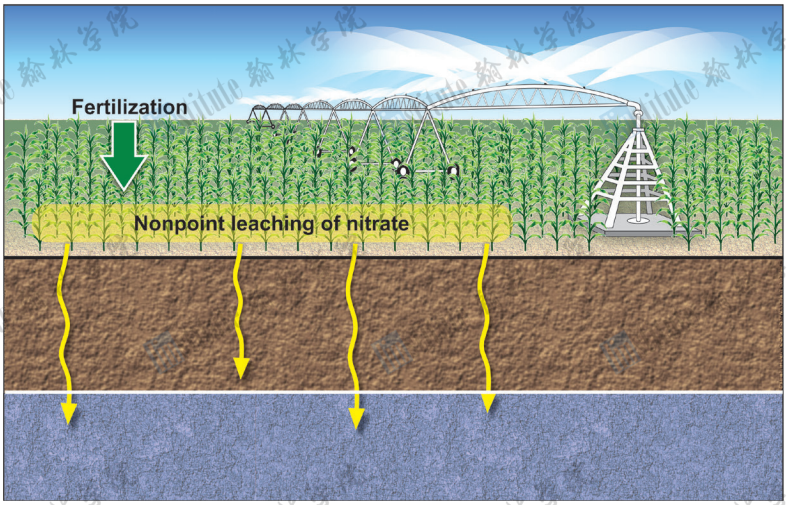


Figure A-4. Nonpoint source nitrate contamination of groundwater can come from intensive production of irrigated corn.

At some point, **nitrate leaching** occurs under all corn fields that receive nitrogen fertilizer whether the field is irrigated or not. However, *Figure A-5* shows significant difference in nitrogen leaching potential due to the type of system used to apply irrigation water. *Figure A-5* also shows that nitrate loss cannot be entirely stopped, but it can be reduced with good management. Two major advantages of the surge and sprinkler irrigation systems are that the depth and uniformity of water applied can be more precisely controlled by the irrigator. Center pivots provide the greatest level of control of these two factors. For a traditional furrow irrigation system, the field conditions such as soil texture, cropping practices, and furrow length can contribute greatly to how much water infiltrates into the soil, and thus how uniform the water can be applied along the furrow length.

Nitrate leaching loss rates range from 5 to 10 lb/ac-in of deep percolation or drainage, which is why over-irrigation needs to be avoided.

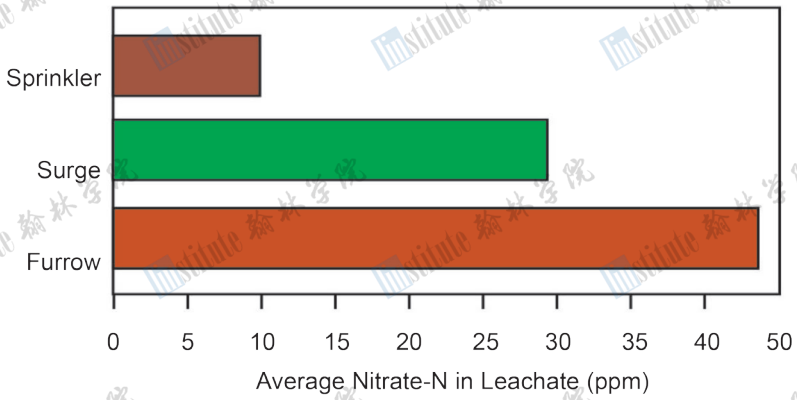


Figure A-5. Average nitrate-nitrogen concentrations in leachate water below corn fields irrigated by sprinkler, surge flow, and traditional furrow irrigated fields in the Platte Valley. (See Spalding, et al., 2001).

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Annual nitrate leaching losses

University of Nebraska researchers measured water and nitrogen loss from the root zone in a deep, silt loam soils, and sandy soils. Yearly average concentrations of nitrate-nitrogen in the drainage often ranged from 22 to 44 ppm. They found annual nitrate-nitrogen losses ranging from 40 to 80 lb/acre. This occurred with an average of 8 in/yr of drainage from the bottom of the root zone. This amounts to 5 to 10 lb/acre of nitrogen loss per inch of drainage. This rate of drainage is typical under continuous corn production, when following recommended nitrogen and irrigation water management programs. Thus, losses are greater where irrigation and nitrogen applications are not well managed during the growing season.

Aquifer is a water-bearing geological formation capable of yielding water in sufficient quantity to support a well.

Transit time is the length of time required for contaminants to move from the bottom of the root zone to groundwater. Transit times range between a few weeks to decades depending on the depth and texture of the soil.

How long does it take for nitrate contamination of an aquifer to occur?

The time it takes soil nitrate to reach the groundwater **aquifer** after it moves below the root zone is called the **transit time**. Depending on the geology of the area and the depth of drainage loss, nitrate-nitrogen can reach the top of a shallow aquifer in a matter of weeks, or at most, a few months. Today the nitrate problem is appearing in areas where the water table is 100 ft or more below the surface and is covered almost entirely with fine-textured soil material. Some people thought that the depth to groundwater conditions would prevent aquifer contamination. However, nitrate-nitrogen moves slowly in such materials, too. In this case the travel time from the root zone to the water table may be more than 30 years. Some areas in Nebraska have subsoil conditions that greatly limit the movement of nitrate to the aquifer. Groundwater in these areas is not significantly affected by farming practices.

See these publications for additional information:

EC91-735, The impact of nitrogen and irrigation management and vadose zone conditions on groundwater contamination by nitrate-nitrogen (archived publication)

RP189, Agricultural nitrogen management for water quality protection in the midwest

For More Information

Nebraska Department of Environmental Quality. 2014. 2014 Nebraska groundwater quality monitoring report. Prepared Pursuant to Nebraska Rev. Stat. §46-1304.

Spalding, R. F., D. G. Watts, J.S. Schepers, M. E. Burbach, and M. E. Exner. 2001. Controlling nitrate leaching in irrigated agriculture. Journal of Environmental Quality 30: 1184-1194.

Section C

Soil characteristics that influence nitrogen and water management

Soil characteristics vary across the landscape

Soils vary from one field to another, and often within the same field. Soil differences certainly affect yield potential from one part of a field to another, and also impact how water and fertilizer must be managed to maintain good production levels. Some important characteristics that change across a landscape include soil texture, **organic matter** content of the top 6 to 8 inches, pH, and the thickness and density of the clay accumulation horizon.

Organic Matter is that fraction of the soil composed of anything that once lived, including microbes, and plant and animal remains.

Parent Material is the geologic material from which soil horizons form. As an example: wind-blown loess over glacial till.

Soils are formed by climate acting on "**parent material**" over long periods of time. The parent material can be rock that has weathered in place, or material that has been deposited by the wind, laid down by water, or brought in by glaciers. An area of soil that has the same parent material and has similar characteristics throughout is called a soil series. Different soils develop in a region as slope, drainage, vegetation, and parent materials change (*Figure C-1*).

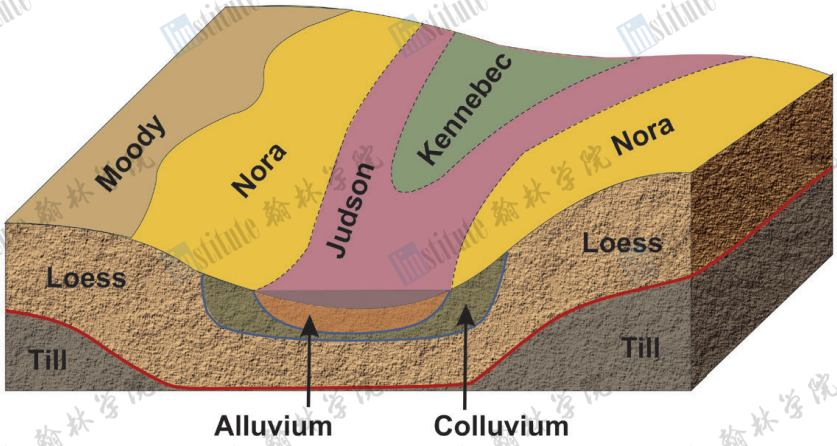


Figure C-1. Different soil series form based on their position on field topography. Note that the soil series changes from the top of the hill to the bottom land areas.

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Some important features of a soil profile are shown in *Figure C-2*. Two features are particularly important to nitrogen management.

- The organic matter in the top few inches is a vast storehouse of organic nitrogen, which soil microbes slowly mineralize into a form of nitrogen that crops can use. The organic matter, together with the clay particles in the surface horizon, holds many nutrients essential for plant growth. The amount of organic matter in the surface horizon also greatly improves the soil structure and tilth.
- The clay accumulation horizon slows the rate of water drainage and nutrient loss from the upper root zone. This horizon can also limit root zone expansion if it is thick and/or compacted.

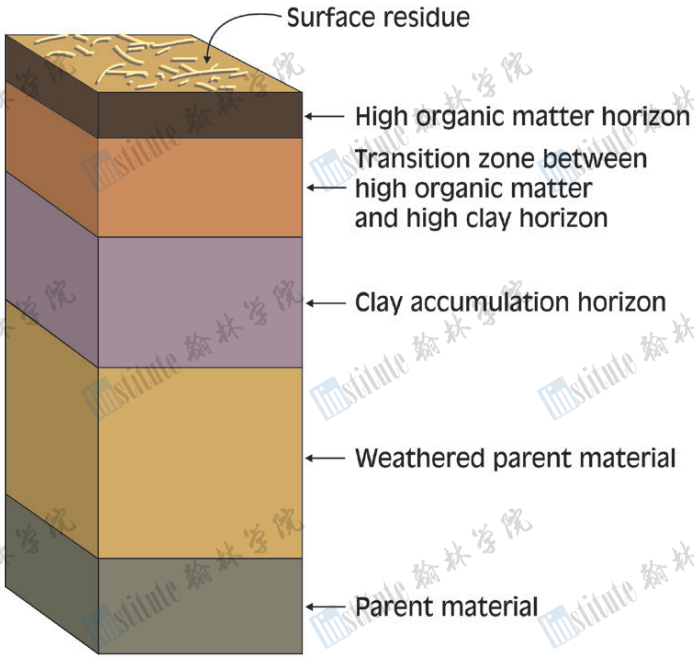


Figure C-2. A typical soil profile depicting important textural features.

Soils vary dramatically from east to west across Nebraska due to the wide range in parent materials and precipitation levels. Thus, not all soils show the characteristics shown in *Figure C-2* to the same degree. Even within the same county, parent material and soil age often require different management practices to reduce nitrate leaching. For example, a silty clay loam formed from fine-textured, wind-deposited material has a thick, high organic matter horizon, and a thick dense clay accumulation horizon. This means that a silty clay loam soil has slow internal drainage, thus nitrate leaching occurs slowly. The high organic matter means that a silty clay loam provides substantial amounts of nitrate from mineralization of organic matter over the growing season.

With all the differences between soil series and even within a soil series, in any field there can be variability in water intake, water movement and storage, and available nutrients within very short distances. If nitrate leaching losses from the root zone are to be held to a minimum, the characteristics of different soils and soil variability within fields have to be considered when planning fertilizer and water management programs.

Nitrate Leaching: Nitrogen Leaching is the passage of nitrogen through the soil profile and downward beyond where crop roots can access the nitrogen (*Figure D-8*). When making the decision on when and how to apply N fertilizers, consider the **4Rs** of nutrient management; **R**ight time of application, **R**ight fertilizer type, **R**ight placement, and **R**ight application rate. Research has shown that fall applications of N fertilizer are less efficient than applications during the growing season. Corn uses N more efficiently when applied as close as possible to when the plant needs it. As stated previously N is a very mobile nutrient that is easily lost from the soil through leaching and denitrification. Significant quantities of N applied in the fall can be lost during the off-season.

Residual N is the N remaining in the soil at the end of a cropping season. This is the leftover N that was not used by the crop during the growing season. The amount of residual N is related to nitrogen fertilizer management practices, irrigation management practices, crop yield (plant N uptake), and environmental conditions such as precipitation and temperature that affect mineralization. The majority of residual N is dissolved in water held in the pore space between the soil particles. Nitrate is very mobile and when the water moves in the soil, the N moves as well (*Figure D-8*).

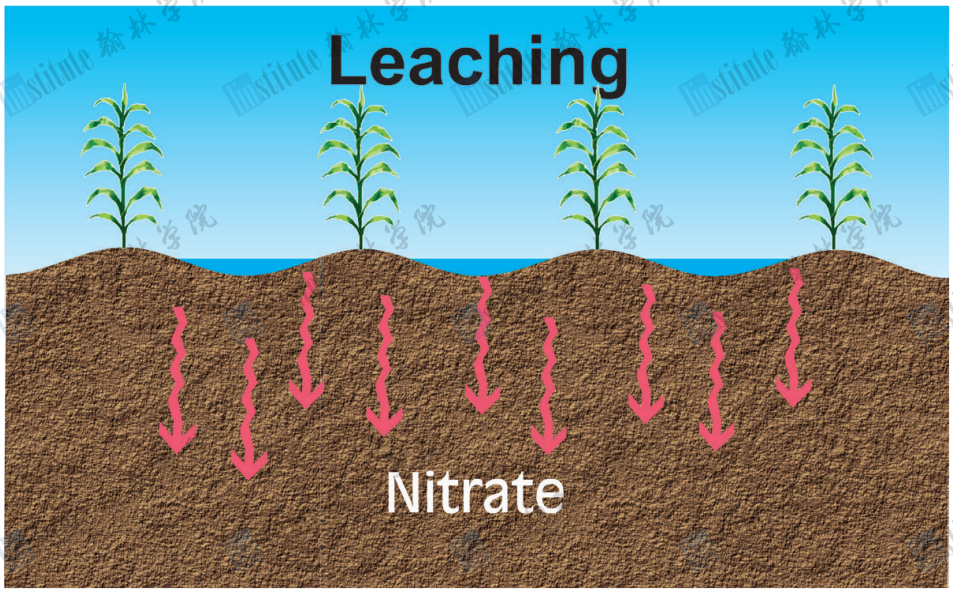


Figure D-8. Depiction of nitrate-nitrogen being leached due to excessive water application via irrigation or precipitation.

In the fall, if the distribution of residual N looks like the graph shown in *Figure D-9A*, there either was a crop failure due to insufficient water or storm damage, or the N application rate was too high for the grain yield level. The relatively high concentration of N in the surface 24 inches of soil leaves a lot of N in a high-leaching potential. If excess precipitation is recorded, the nitrate will move deeper in the soil during the offseason.

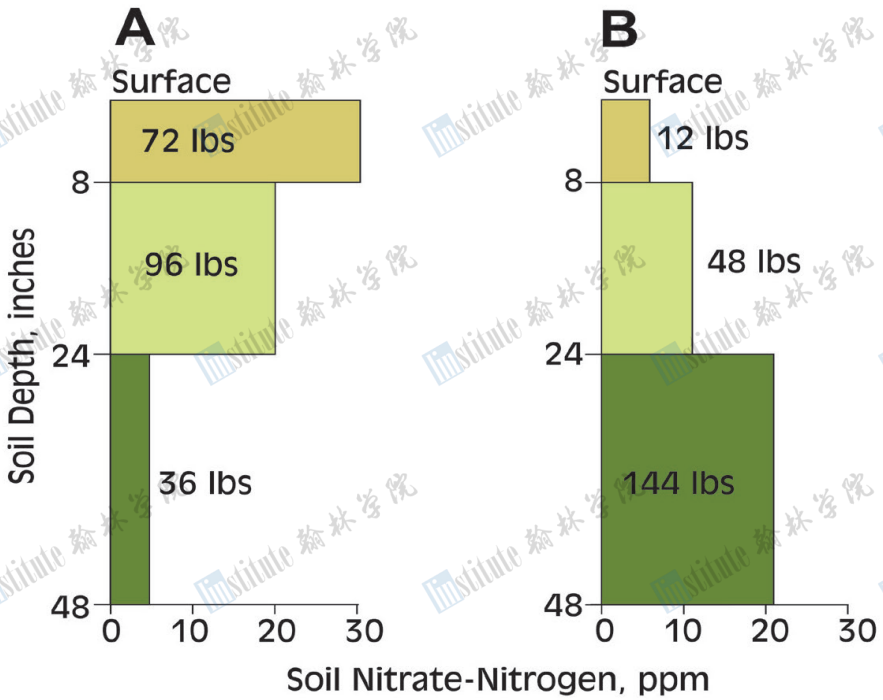


Figure D-9. **Summary of two sets of soil samples: A) taken from soil that was sprinkler irrigated; and B) taken from soil that was irrigated by a furrow irrigation system.**

The distribution of residual N in the soil profile at harvest depends greatly on the method of irrigation (furrow, drip, or sprinkler) and the care taken to manage the water correctly during the growing season. Under furrow irrigation, it is likely that N will be moved deeper in the profile during the growing season because the depth of water applied with each irrigation is typically more than is required to refill the root zone. So the scenario depicted in *Figure D-9B* may represent the position of soil N at the end of the season. With a furrow system that is well-designed, well-maintained, and well-managed, there is a chance that the N will remain in the crop root zone and accessible to crop roots.

Well-managed sprinkler irrigation systems should result in zero deep percolation so that most of the N applied remains in the crop root zone. Under sub-surface drip irrigation, the dynamics of N movement changes depending on the N application method. Surface applied N can create high N levels near the soil surface because N movement will be controlled by amount of precipitation and the soil's water holding capacity. If N is injected into the sub-surface drip system it is possible to move N much deeper into the profile as the nitrate will move with the water.

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The way water is applied affects how both water and nitrate move down through the soil. When the application rate is less than the soil intake rate (such as from a gentle rain or a well-managed sprinkler system), water tends to move downward in a relatively uniform manner. For example, *Figure D-10* shows a band of nitrate that has formed from a previous application of anhydrous ammonia. A wetting front is moving down under precipitation. When the wetting front reaches the band, the nitrate tends to spread mainly downward (*Figure D-11*).

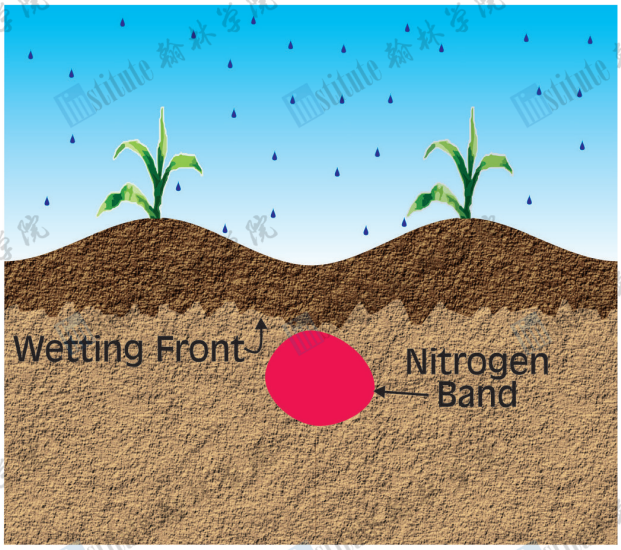


Figure D-10. Depiction of a nitrate band resulting from application of liquid urea ammonium nitrate or anhydrous ammonia using a knife applicator.

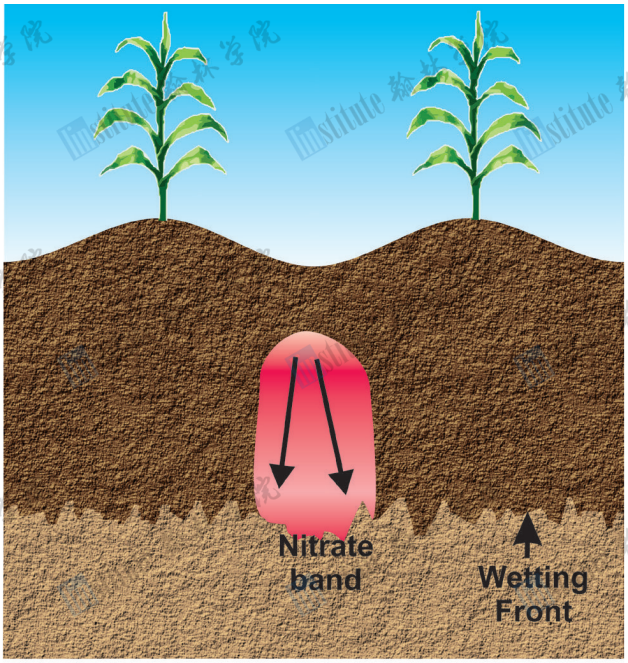


Figure D-11. Depiction of the downward vertical movement from a concentrated band of nitrogen application following excessive precipitation or sprinkler irrigation.

Under furrow irrigation, only part of the surface is completely saturated. This allows the water to flow through the largest pores. There is a faster and more uneven wetting of the soil profile. Also, the depth of water applied with each irrigation event is greater than under sprinkler irrigation. Under these conditions, a nitrate band will tend to spread further, both vertically and horizontally (*Figure D-12*). Excess irrigation will move the nitrate even deeper.

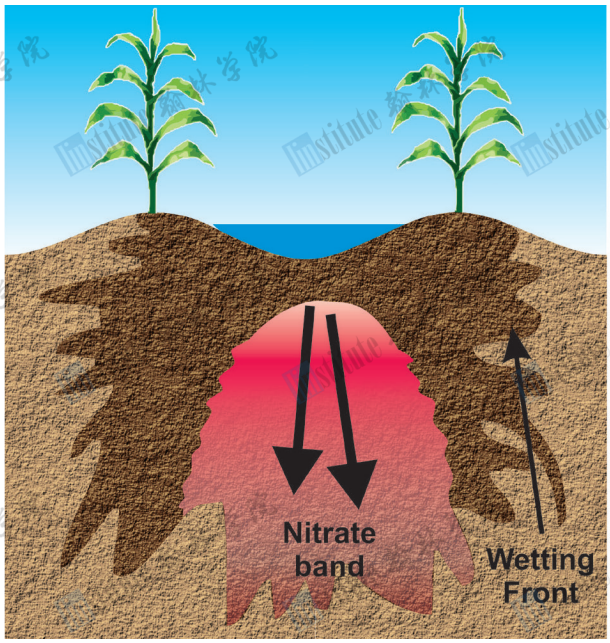


Figure D-12. Impact of furrow irrigation on a concentrated band of nitrogen applied below the soil surface.

Surface runoff

Whenever water runs off the land after rain or irrigation, the water carries sediment. Ammonium may be attached to the sediment and nitrate may be in solution in the runoff water. This physical process is another form of nitrogen loss from the field. Any practices that reduce runoff may reduce nitrogen losses. Incorporating any nitrogen resources that are applied to the field will reduce nitrogen losses by runoff, but may increase sediment losses because of reduced residue cover. Management practices that reduce sediment transfer or soil erosion such as no-till will also greatly decrease the potential for nitrogen movement through runoff.

More Extension Publications (available at ianrpubs.unl.edu)

EC91-735, The impact of nitrogen and irrigation management and vadose zone conditions on groundwater contamination by nitrate-nitrogen (archived publication)

G1338, Managing Furrow Irrigation Systems

G91-1043, Water runoff control practices for sprinkler irrigation systems (archived publication)

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NET News/Harvest Public Media

HEADLINE: Nitrates a costly, persistent problem for small towns.

Nitrogen fertilizer on farm fields helps crops grow. But if there's too much left over in the soil, it can pollute water supplies as nitrates. A big city lawsuit in Iowa over nitrates has grabbed headlines, but many small towns have the same problem.

Earlier this year, Des Moines, Iowa, made news when the city announced it would sue farmers in a legal battle over fertilizer. The city's water supply from the Des Moines and Raccoon Rivers often surpasses the legal limit for nitrates (10 mg/L), which commonly appear in water contaminated by runoff from farm fields.

Too many nitrates are a health hazard, particularly for infants whose blood can lose its ability to absorb oxygen. So nitrates must be reduced or removed, but cleaning nitrates from the city's water is a huge expense. When nitrate levels rise above the safe drinking water limit, Des Moines fires up a filtering system that costs thousands of dollars to operate each day.

Des Moines is unusual, though. In most cases, nitrate pollution is not a big city problem. It's most often a small town problem, says Bruce Dvorak, professor of environmental engineering at the University of Nebraska-Lincoln.

"Nitrates in drinking water is the most common source water problem in the region," Dvorak said. "And for many small towns this is a very major cost issue. It may mean water rates, if they're lucky, only double. And some cases it may go up by eight to ten times."
That's the case in Creighton, a small town in northeast Nebraska. Creighton installed a $1.3 million water filtering system in 1993 to reduce nitrate levels in town's drinking water. It has been running ever since, pulling nitrates out of about 300,000 gallons of water per day.

"Our nitrates coming in is 17 parts per million. Ten is the legal limit," said Kevin Sonnichsen, Creighton's water operator. "After treatment we're putting it out and distributing to the public at just about four or five parts per million."

Nitrate can come from your lawn or even the atmosphere. But Creighton is a rural town surrounded by farms. Farmers often put on more fertilizer than their crops can use. Then, rain or irrigation water can carry the nitrates down into the groundwater supply.

Creighton's problem is getting worse, not better. Sonnichsen says a plume of groundwater with even higher nitrate levels is moving toward the town's wells, and more filters may be needed. "Probably a new system now would cost $3 to $4 million, easy," Sonnichsen said.
For a town of just 1,200 people.

Hundreds of small towns in the Midwest have nitrate levels near or over federal limits for nitrate. From Burlington, Colorado; to Churdan, Iowa; to Pretty Prairie, Kansas; and Edgar, Nebraska, small towns often struggle with the bill for a clean water.

In Nebraska, 161 communities conducted additional tests on their water because nitrate levels are near the limit, according to state numbers collected by Bruce Dvorak at UNL. That's down from a peak of 343 towns required to do more frequent testing in 2010. But it doesn't mean the nitrates are gone. Dvorak says many towns have found ways to work around high nitrates by shutting down contaminated wells or drilling new ones. They found a safer water supply.

Workaround measures like that are expensive and are often not a permanent fix. Drilling a new well may cost $300,000. Shutting down a contaminated well can run $25,000-$30,000 according to Dvorak.

Funding for such projects often comes from a low-cost loan fund the state of Nebraska set aside for water systems. From 2002-2012, Dvorak said 75 percent of the money lent from that fund was spent on nitrate-related projects.

As expensive and difficult as nitrate issues can be for many communities, Dvorak says it would be hard to find one willing to take the issue to court as Des Moines has.

"Most small towns don't have the finances to run the legal challenges. As well as politically, I'm not sure it really would be sustainable in many small towns here in Nebraska," Dvorak said. "Clearly the farmers are the lifeblood of these communities."

Towns like Creighton need farmers to produce, and for that farmers will use fertilizers. But there are different ways to do it. Jim Fuchtman lives and farms just outside of town. On a clear fall day, he walked with me into a field scattered with slender, green blades of grass.

"This is a field where I had soybeans and then we planted a cover crop of rye," Fuchtman said.

The rye grass will hold nitrates near the surface, away from the groundwater. This is Fuchtman's first run with cover crops. He planted them as part of a voluntary project in the Bazile Creek watershed, which includes Creighton. The project encourages practices that reduce nitrate levels.

"Soil health is my main objective," Fuchtman said. "With soil health your nitrates don't leach as fast, you're getting better utilization of your chemicals."

Stephanie Butler of the Upper Elkhorn Natural Resources District oversees the Bazile Creek program. She says it's a step forward, but it could take years to pay off.

"We definitely have long term goals – 20, 30, 40 years down the road," Butler said. "I mean it took a long time to get to this level so it's going to take just as long to see some decline."

That means Creighton's water treatment plant will probably still be running for decades to come. Water operator Kevin Sonnichsen can't imagine the town suing local farmers like Des Moines. But, he says, many farmers will find their own motivation. He's tested water for rural residents, and some samples are four to five times the legal limit for nitrates.

"I mean it's not just for the good of our city but for them, too, and their kids," Sonnichsen said.

IANR NebGuide

University of Nebraska–Lincoln Extension, Institute of Agriculture and Natural Resources

Know how. Know now.

University of Nebraska Lincoln

G1784
(Revised December 2013)

Drinking Water: Nitrate-Nitrogen

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University of Nebraska–Lincoln Extension and the Nebraska Department of Health and Human Services place a high priority on water quality and jointly sponsor this series of educational publications.

DHHS NEBRASKA

Nitrate-nitrogen is sometimes present in drinking water. At certain levels it can present a health risk. Properly locating and constructing wells along with regularly testing water can help to manage the risk.

Many Nebraskans have questions about the impact of nitrate in their drinking water. Water quality monitoring shows that nitrate is present in groundwater throughout much of Nebraska and concentrations are increasing in some areas.

Nitrogen is essential for all living things, as it is an essential component of protein. Nitrogen exists in the environment in many forms and changes forms as it moves through the nitrogen cycle. However, excessive concentrations of nitrate-nitrogen in drinking water can be hazardous to health, especially for infants, nursing mothers, and pregnant women.

Sources of Nitrate in Drinking Water

Nitrogen is a nutrient applied for lawn and garden care and crop production to increase productivity. Feedlots, animal yards, septic systems, and other waste treatment systems are additional sources of nitrogen that is carried in waste. Nitrogen occurs naturally in the soil in organic forms from decaying plant and animal residues.

Bacteria in the soil convert various forms of nitrogen to nitrate, a form of nitrogen and oxygen. This is desirable since the majority of the nitrogen used by plants is absorbed in the nitrate form. However, nitrate is highly soluble and readily moves with water through the soil profile. If there is excessive rainfall or over-irrigation, nitrate will drain below the plant's root zone and may eventually reach groundwater.

Nitrate in groundwater may result from point sources such as sewage disposal systems and livestock facilities, from nonpoint sources such as fertilized cropland, parks, golf courses, lawns, and gardens, or from naturally occurring sources of nitrogen. Proper site selection for the location of domestic water wells can reduce potential nitrate contamination of drinking water. Important considerations include a sufficient well depth, an adequate distance from possible contamination sources, and a location upslope from possible contamination sources. Proper well construction and maintenance also reduce the risk of drinking water contamination. See NebGuide G2050 "Protecting Private Drinking Water Supplies: Water Well Location, Construction, Condition, and Management" for more information.

Indications of Nitrate

Nitrate in water is colorless, odorless, and tasteless, which makes it undetectable without laboratory testing.

Potential Health Effects

The U.S. Environmental Protection Agency (EPA) Maximum Contaminant Level (MCL) for nitrate-nitrogen in a public water supply is 10 milligrams per liter (mg/L), sometimes expressed as 10 parts per million (ppm) measured as nitrate-nitrogen (NO_3-N). It is based on acute health effects, specifically the risk of methemoglobinemia (explained below). Acute health effects result from ingesting a contaminant over a short time.

The acute health hazard associated with drinking water with elevated levels of nitrate occurs when bacteria in the digestive system transform nitrate to nitrite. The nitrite reacts with iron in the hemoglobin of red blood cells to

form methemoglobin, which lacks the oxygen-carrying ability of hemoglobin. This creates the condition known as methemoglobinemia (sometimes referred to as "blue baby syndrome"), in which blood lacks the ability to carry sufficient oxygen to the individual body cells.

Infants under one year of age have the highest risk of developing methemoglobinemia from consuming water with elevated levels of nitrate. Contributing risk factors include digestive and enzyme systems that are not fully developed. Older persons who have a gastrointestinal system disorder resulting in increased bacteria growth may be at greater risk than the general population. In addition, individuals who have a genetically impaired enzyme system for metabolizing methemoglobin may be at greater risk. The general population has a low risk of developing methemoglobinemia, even when ingesting relatively high levels of nitrate/nitrite.

Historical information on infants with methemoglobinemia suggests that a number of infants with the condition also showed signs of diarrhea, inflammation, and infection of the gastrointestinal track, or protein intolerance. The significance of these factors in regard to methemoglobinemia risk, if any, is not known.

Definitive guidelines for determining susceptibility to methemoglobinemia have not been developed. The EPA has established the regulatory threshold for acute health effects based on best available science. The intake from food, drugs, and other sources also is important and must be considered.

Although the EPA standard was set at 10 mg/L based on acute health effects, questions have been raised regarding possible chronic health effects from consuming water with nitrate at various concentrations. Chronic health effects are those that can occur when a contaminant has been ingested over a long time. Research is limited regarding the possibility of chronic health effects due to long-term ingestion of drinking water with nitrate at various concentrations. However, studies have shown a correlation between long-term ingestion of water with nitrate and increased incidence of certain diseases and cancers. Other studies have shown a correlation between increased birth defects and consumption of drinking water with elevated nitrate while pregnant. While correlations may not prove cause and effect, the possibility of chronic health risk resulting from ingestion of nitrate-nitrogen must be considered. The connections between the level of nitrate in drinking water, volume ingested, duration of exposure, and possible chronic risks are not fully understood.

Note: This publication is not a substitute for professional medical advice. If you have questions or concerns related to potential health effects from consuming water containing nitrate, consult your physician.

Testing

Testing Public Water Supplies

Public water supplies classified as either community or non-community are required to test for nitrate concentration. If water comes from a public water supply, users can contact the water utility to learn about the nitrate level in their water.

Testing Private Water Supplies

Water quality in private wells is not currently regulated by federal or state statutes; thus, the regular testing of a private water supply is not required under state or federal law. If users want to know the concentration of nitrate in a private water supply, they will need to have the water tested for a fee and on a confidential basis.

An initial test of a new water supply is recommended to determine the baseline nitrate concentration in the water source. Activities near a well potentially can contaminate the water supply, changing the nitrate concentration over time. Private drinking water wells should be tested annually to monitor changes in nitrate concentration. In addition, private drinking water wells should be tested any time an infant, pregnant woman, nursing mother, or elderly person begins to use the water supply. These groups are believed to be the most susceptible to nitrate health effects.

Tests to determine the presence of nitrate in drinking water should be done by a laboratory approved for nitrate testing. The Nebraska Department of Health and Human Services (DHHS) approves laboratories to conduct tests for drinking water supplies. This approval means that recognized, standard test and quality control procedures are used. See *Drinking Water: Approved Water Testing Laboratories in Nebraska* (G1614) for a list of approved laboratories and contact information for each.

Some Nebraska Natural Resources Districts (NRDs) may offer assistance or cost-sharing to help well owners with water testing. Individuals can contact their NRD to find out if testing assistance is provided.

Laboratories not specifically approved to test for nitrate may use the same equipment and procedures as approved laboratories. Such laboratories may provide accurate analysis, but there is no independent information about the laboratory's ability to obtain reliable nitrate concentration results.

In addition, a variety of test kits and dip strips are available for nitrate testing outside of a laboratory environment. These might be used for preliminary "screening" and to raise awareness of nitrate issues. When using these tests, users should understand the nature of the test and the accuracy of the test results. While an estimate of nitrate concentration level might be obtained, laboratory analysis is needed for an accurate and reliable nitrate measurement.

To have water tested, private water well owners or users must select a laboratory and obtain a drinking water nitrate test kit from the laboratory. The kit will usually include a pre-preserved sample bottle, an information form, and sampling instructions. The sample bottle for nitrate testing may contain a preservative to prevent any loss of nitrate in the sample. This sample bottle should not be rinsed before filling and should only be used for samples intended for nitrate analysis. It must be used within 90 days to ensure

validity of the analysis. The sampling instructions provide information on how to collect the sample. These instructions must be followed carefully to avoid contamination and to obtain a representative sample. The sample must be promptly mailed or delivered to the laboratory along with the completed information form.

Interpreting Test Results

Public Water Supply Test Results

The quality of water supplied by Public Water Systems is regulated by the EPA and the Nebraska DHHS. This includes any well with 15 or more service connections or that regularly serves 25 or more people.

Public drinking water standards established by EPA fall into two categories — Secondary Standards and Primary Standards. Secondary Standards are based on aesthetic factors such as taste, odor, color, corrosivity, foaming, and staining properties of water that may affect the suitability of a water supply for drinking and other domestic uses. Primary Standards are based on health considerations and are designed to protect human health. The EPA has established an enforceable Primary Standard for nitrate in public drinking water supplies.

The EPA Maximum Contaminant Level (MCL) is measured and reported as nitrate-nitrogen, (NO_3-N), which is the amount of nitrogen in the nitrate form. The MCL for nitrate-nitrogen in a public water supply is 10 milligrams per liter (mg/L) which can also be expressed as 10 parts per million (ppm). This drinking water standard was established to protect the health of infants and is based on risk assessment using the best knowledge available.

It is worth noting that the European standard is measured and reported as total nitrate (NO_3) with a maximum allowable level of 40 mg/L or 40 ppm. The two reporting systems can be compared as follows:

1 mg/L nitrate-nitrogen (NO_3-N) = 4.4 mg/L nitrate (NO_3)

Therefore, the U.S. standard of 10 mg/L nitrate-nitrogen would be reported as 44 mg/L nitrate if the European reporting method was used, or the European standard of 40 mg/L nitrate would be reported as 9 mg/L nitrate-nitrogen if the U.S. reporting method was used.

Although not common, a few U.S. laboratories report total nitrate (NO_3) rather than the more commonly used nitrate-nitrogen (NO_3-N) quantity. Because potential health risks are often unknown or hard to predict, many drinking water standards are set at some fraction of the level of "no observed adverse health effects." In general, the greater the uncertainty about potential health effects, the greater the margin of safety built into the standard. In the case of nitrate, there may not be a large safety factor. A 1977 report by the National Academy of Science concluded that "available evidence on the occurrence of methemoglobinemia in infants tends to confirm a value near 10 mg/L nitrate as nitrogen as a maximum no-observed adverse-health-effect level, but there is little margin of safety in this value."

Private Water Supply Test Results

While EPA and Nebraska regulations do not apply to private drinking water wells, users of private drinking water should consider the EPA guideline of 10 ppm nitrate-nitrogen when considering the risk associated with their water supply. If nitrate-nitrogen concentrations are found to be above 10 ppm, private drinking water users might voluntarily try to reduce the nitrate-nitrogen concentration in the water, taking into account health risks, cost, and benefits.

Options

Options for Public Water Supplies

If a test indicates that the nitrate-nitrogen concentration of public water exceeds the standard, the public must be notified and steps must be taken by the water supplier to bring the water into compliance. Often, the treatment may be as simple as blending the water that exceeds the standard with water that has a nitrate-nitrogen concentration less than 10 mg/L such that the average concentration of the delivered water is below the EPA standard. Another option for achieving compliance is water treatment, such as with ion exchange or reverse osmosis, to reduce the nitrate-nitrogen concentration. In some cases, compliance may be achieved by offering bottled water to vulnerable consumers in conjunction with developing a source water protection plan designed to eliminate or reduce the source of contamination. Over time, this should reduce the nitrate-nitrogen concentration in the water supply. Public water systems cannot achieve compliance by supplying bottled water as the only means of addressing high nitrate levels.

The Nebraska DHHS has the responsibility for implementing the federal requirements and can take action toward public water supplies that are not in compliance. This action includes Administrative Orders, a precursor to legal action. DHHS issues a Nitrate Administrative Order to public water systems exceeding 10 ppm twice in a three-quarter period. At any given time, a very small percentage of public water supplies in Nebraska may have a nitrate concentration above 10 ppm, and some systems may be under Administrative Order for noncompliance with the MCL. DHHS requires any public water system exceeding 20 ppm in any sample to discontinue the use of the well and provide alternate safe water to all consumers until the concentration of nitrate is less than 20 ppm for two consecutive quarters.

Options for Private Water Supplies

If nitrate-nitrogen exceeds 10 ppm, users should consider that their water exceeds the EPA MCL for nitrate-nitrogen in drinking water. If nitrate-nitrogen exceeds 20 ppm, users might consider that DHHS takes immediate action toward public water suppliers exceeding this concentration. In either case, users might voluntarily consider an alternative drinking water source or water treatment. Decisions should be based on a nitrate analysis by a reputable laboratory, and after consulting with a physician to help evaluate the level of risk.

It may be possible to obtain a satisfactory alternate water supply by drilling a new well in a different location or a deeper well in a different aquifer, especially if the nitrate contamination is from a point source such as livestock or human waste. If the water supply with high nitrate is coming from a shallow aquifer, there may be an uncontaminated, deeper aquifer protected by a clay layer that prevents the downward movement of the nitrate-contaminated water. A new well should be constructed so surface contamination cannot enter the well. It should be located away from any potential sources of contamination, such as septic systems or feedlots. Consult a Nebraska-licensed, water well professional regarding this option. Another alternate source of water is bottled water that can be purchased in stores or direct from bottling companies. This alternative especially might be considered if the primary concern is water for infant food and drinking.

Drinking water can be treated for nitrate-nitrogen by three treatment methods:

- distillation,
- reverse osmosis, and
- ion exchange.

Home treatment equipment using these processes is available from several manufacturers. **Carbon filters and standard water softeners do not remove nitrate-nitrogen. Merely boiling water does not remove nitrate-nitrogen. Boiling water for an extended time results in evaporation and a decrease in water volume. The nitrate does not evaporate with the water, resulting in an increased nitrate-nitrogen concentration in the remaining volume of water.**

The **distillation process** involves heating the water to boiling and collecting and condensing the steam by means of a coil. This process can remove nearly 100 percent of the nitrate-nitrogen since the nitrate-nitrogen does not volatilize with the steam. For information on this treatment method see NebGuide 1493, *Drinking Water Treatment: Distillation.*

In the **reverse osmosis process**, pressure is applied to water to force it through a semipermeable membrane. As the water passes through, the membrane filters out most of the impurities. This process can remove approximately 85 percent to 95 percent of the nitrate-nitrogen. Actual removal rates may vary, depending on the initial quality of the water, the system pressure, membrane technology, and water temperature. For information on this treatment method see NebGuide 1490, *Drinking Water Treatment: Reverse Osmosis.*

Ion exchange for nitrate-nitrogen removal operates on the same principle as a household water softener. However, for the nitrate-nitrogen removal process, special anion exchange resins are used that exchange chloride ions for nitrate and sulfate ions in the water as it passes through the resin. Since most anion exchange resins have a higher selectivity for sulfate than nitrate, the level of sulfate in the water is an important factor in the efficiency of an ion exchange system for removing nitrate-nitrogen.

Summary

Nitrate can be present in some water sources, most often as a result of point or nonpoint source pollution from fertilizer or human or animal waste. Proper well location and construction are key practices to avoiding nitrate contamination of drinking water. Management practices to reduce the risk of contamination from fertilizers and manure/sewage help keep the water supply safe. Ingesting drinking water containing nitrate-nitrogen can present an acute health risk, especially for infants. Public water supplies must comply with the EPA standard for nitrate-nitrogen of 10 ppm. Management of a private drinking water well for nitrate-nitrogen is determined by the well owner and/or water user. A water test is the only way to determine the nitrate-nitrogen concentration. If public drinking water exceeds the EPA nitrate-nitrogen standard, the utility must inform water users and must take steps to reduce the nitrate-nitrogen concentration. If private drinking water exceeds an acceptable nitrate-nitrogen concentration, choices are to use an alternate water supply or treat the water. An alternate supply may be bottled water or a new well in a different location or aquifer. Water treatment options include distillation, reverse osmosis, or ion exchange.

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FACT SHEET:

Precautions and Facts Regarding Harmful Algal Blooms (Toxic Algae) at Nebraska Lakes and Beaches

UpdatedMay 22, 2018

A Joint Publication from the
Department of Health and Human Services - Division of Public Health and the
Nebraska Department of Environmental Quality

What is a Harmful Algal Bloom Health Alert?

The Health Alert designation for Harmful Algal Blooms (also referred to as "toxic blue-green algae") means that the state has determined that the level of toxins in the water make it potentially unsafe for full-body recreational activities, such as swimming. The toxin being measured is microcystin, which is generated from certain strains of blue-green algae.

During a Health Alert at a public lake, signs will be posted advising the public to use caution. Affected swimming beaches will be closed. Boating and other recreational activities will be allowed, but the public will be advised to use caution and avoid prolonged exposure to the water, particularly avoiding any activity that could lead to swallowing the water.

The level to trigger a Health Alert declaration is 20 parts per billion of the toxin microcystin. Lakes under Health Alert will be sampled weekly, and the Health Alert will stay in effect until the level stays below 20 parts per billion for two consecutive weeks.



Harmful Algal Blooms usually have a heavy surface growth of pea-green colored clumps, scum or streaks

What is a Harmful Algal Bloom?

Harmful Algal Blooms (also known as toxic blue-green algae), refer to certain strains of cyanobacteria that produce toxins. Harmful Algal Blooms often are a distinct blue-green color but may also appear to be green, brown or red. The toxins associated with Harmful Algal Blooms have been found in a number of Nebraska lakes sampled.

Harmful Algal Blooms can dominate the algal populations of a lake under the right combinations of water temperature, low water depths, and nutrients (such as high nitrogen and phosphorus concentrations from wastewater discharges and runoff from agricultural land and communities).

What should I look for to avoid Harmful Algal Blooms?

Harmful Algal Blooms usually have heavy surface growths of pea-green colored clumps, scum or streaks, with a disagreeable odor. It can have a thickness similar to motor oil and often looks like thick paint in the water. Algae blooms usually accumulate near the shoreline where pets and toddlers have easy access and the water is shallow and more stagnant. It is important to keep a watchful eye on children and pets so that they do not enter the water. Aspects to watch out for include:

- Water that has a neon green, pea green, blue-green or reddish-brown color.
- Water that has a bad odor.
- Foam, scum or a thick paint-like appearance on the water surface.
- Green or blue-green streaks on the surface.
- Areas with algae that look like grass clippings floating in the water.
- When algal blooms are present at a lake, avoid protected bays and shorelines on the windward side of the lake. These are areas that generally have higher concentrations of algae, and potentially toxins.

What are the risks and symptoms?

Pets and farm animals have died from drinking water containing a Harmful Algal Bloom (or licking their wet hair/fur/paws after they have been in the water). Toxins produced by Harmful Algal Blooms have been known to persist in water for up to 14 days after the bloom has disappeared.

The risks to humans come from external exposure (prolonged contact with skin) and from swallowing the water. Symptoms from external exposure are skin rashes, lesions and blisters. More severe cases can include mouth ulcers, ulcers inside the nose, eye and/or ear irritation and blistering of the lips. Symptoms from ingestion can include headaches, nausea, muscular pains, central abdominal pain, diarrhea and vomiting. Severe cases could include seizures, liver failure, respiratory arrest - even death, although this is rare. The severity of the illness is related to the amount of water ingested, and the concentrations of the toxins.

Are some people more at risk?

Yes. Some people are at a greater risk from Harmful Algal Blooms than the general population. Those at greater risk include:

- Children enjoy playing along the shoreline of lakes, but may have less awareness about potentially hazardous conditions, causing for greater opportunity for exposure. Based on body weight, children tend to swallow a higher percentage of water than adults, and therefore could be at greater risk.
- Individuals with liver disease or kidney damage and those with weakened immune systems.

Here are some tips on what you can do, and things to avoid:

- Be aware of areas with thick clumps of algae and keep animals and children away from the water.
- Don't wade or swim in water containing visible algae. Avoid direct contact with algae.
- Make sure children are supervised at all times when they are near water. Drowning, not exposure to algae, remains the greatest hazard of water recreation.
- If you do come in contact with the algae, rinse off with fresh water as soon as possible.
- Don't boat or water ski through algal blooms.
- Don't drink the water, and avoid any situation that could lead to swallowing the water.

Is it safe to eat fish from lakes that are under a Health Alert?

Although research is limited, most information to date indicates that toxins do not accumulate significantly in fish tissue, which is the meat that most people eat. At this time, fishing is permitted at lakes that are under a Health Alert. This issue is continuing to be studied, and this fact sheet will be updated if more conclusive information becomes available.

Where can I find out more information about lake sampling for Harmful Algal Blooms?

The Nebraska Department of Environmental Quality (NDEQ) conducts weekly sampling at 51 public recreational lakes across the state from May 1 to September 30. Sampling information is updated weekly on the agency web site, http://deq.ne.gov

If I think a public lake has a Harmful Algal bloom, who do I contact?

Please contact NDEQ's Surface Water Unit at (402) 471-0096, or (402) 471-2186, or e-mail NDEQ.BeachWatch@Nebraska.gov

If I am experiencing health symptoms, who do I call?

If you experience health symptoms, notify your physician, and also report it to the Nebraska Department of Health and Human Services at (402) 471-8880. You can also contact the Nebraska Regional Poison Center at 800-222-1222 for more information.

Nebraska Department of Environment and Energy, P.O. Box 98922, Lincoln, Nebraska 68509, (402) 471-2186, 877-253-2603

Here's How Midwest Farmers Are Fighting Agricultural Water Pollution

By GRANT GERLOCK • SEP 20, 2016

Living in the Platte River Valley in central Nebraska means understanding that the water in your well may contain high levels of nitrates and may not be safe to drink.

“When our first son was born in 1980, we actually put a distiller in for our drinking water here in the house,” says Ken Seim, who lives in the Platte Valley near the town of Chapman, Nebraska. “And at that time our water level was a 12 parts per million.”

Nitrates are formed when nitrogen, from the air or fertilizer, is converted by bacteria in the soil to a form that is more plant-friendly. Nitrates help plants grow, but can be dangerous in large amounts. The legal limit in public water systems is 10ppm. Some nearby wells, Seim says, contain nitrates at dangerous levels, two or three times the legal threshold.

For Seim, nitrate pollution in groundwater is a problem that feels personal, because he’s a farmer. Seim and his sons grow about 1,000 acres of corn and soybeans, which means that some of nitrates in his water probably come from his farm.

“That really puts it in perspective of, we need to rein this in and get some management going,” Seim says, “because if we continue at this rate, what's our water going to be like in another 40 years?”

Corn fields can’t grow enough feed for livestock and ethanol for cars without big doses of nitrogen fertilizer. And excess fertilizer, which leaves behind nitrates, is damaging water quality across the Corn Belt.

In states like Nebraska and Colorado, where the climate is arid and soils are sandy and porous, nitrates can leach down into the groundwater. The High Plains Aquifer, which provides drinking water and water for irrigating farm crops, shows many hot spots with high nitrates at levels dangerous to human health.

In other states with rich soil and plentiful rainfall, like Iowa and Illinois, nitrates run off of fields into streams and rivers. The city of Des Moines, Iowa, is suing upstream water districts because its water supply is so contaminated. Nitrates carried by the Mississippi River contribute to the 'Dead Zone' in the Gulf of Mexico, an area the size of Connecticut that is inhospitable for fish and other marine life.

Nitrates can come from factories, power plants, city sewer systems, and even homeowners who put too much fertilizer on their lawns. But agriculture is a major contributor. Two-thirds of the nitrogen that lands in the Gulf is traced back to farms, corn and soybean farms in particular.

Some farmers are stepping up to address their part in nitrate pollution. Farmer Ken Seim is implementing two conservation methods he and other farmers hope will lessen their impact on downwater residents. Precision technology is allowing farmers to put less nitrogen on their fields, and conservation measures are helping to hold onto the nitrates that are already there.

Years ago, farmers would apply fertilizer evenly and generously across their fields. Some farmers figured that if some nitrogen fertilizer was good for their plants, more was better. That meant that some plants would get more than they could use, which left nitrates leeching into groundwater. Today, researchers at the University of Nebraska are studying how to "spoon-feed" corn with just the nutrients plants need. They call it Project Sense.

In July, a Project Sense sprayer made a test-run through one of Ken Seim's fields. As the sprayer rolled along, the sensors watched the rows of corn, measured how big and green they were, and calculated how much fertilizer was needed. The sprayer shot just enough fertilizer on the plants to push them through harvest.

Project Sense director Richard Ferguson says the objective is to be more efficient, to grow as much corn as possible with as little fertilizer as possible. When farmers are more efficient with fertilizer, he says, there are fewer nitrates left in the soil that can move into water.

"If we're applying less fertilizer and achieving basically the same yield, that's going to reduce the environmental impact significantly," Ferguson says.

Project Sense is still an experiment. But with the widespread availability of detailed soil and water testing, farmers already have ways to put on more precise amounts of fertilizer. Still, some nitrates are always left behind, threatening to trickle down into Nebraska groundwater or wash off into Iowa streams.

The second strategy farmers are putting into play can help with that. Cover cropping is a low-tech conservation method that can keep nitrates from getting away.

Cover crops like vetch, rye, kale, and winter peas grow after the corn is harvested, keeping live roots in the ground on farm fields. Noah Seim, Ken's son and farming partner, says his family plants cover crops because the roots control erosion and preserve moisture in the soil. But another effect of cover crops is that the roots hold nitrates on fields and keep them out of streams.

"If you're holding that moisture in place rather than just letting it go through, we know that we're doing a better job of holding everything in place," Noah Seim says.

Planting cover crops and spoon-feeding fertilizer are two examples of farm technology that could cut into agriculture's contribution to nitrates in water. At this point, though, not enough farmers are buying in. Nebraska conservationist John Heaston says, for some producers, investing in new equipment or learning a new practice is like going on a diet.

"If I would just walk more I'd weigh less. It sounds really easy when you say it, but it's doing it," says Heaston, who teaches farmers how to leverage ag technology for conservation benefits. "We have guys that lean into this stuff and they've got a 'techo-lust' and want to learn this. Then you have other guys that, you know, are pretty sure the Internet is on computers."

The U.S. Department of Agriculture occasionally surveys farmers on their practices. The most recent results, from 2010, showed farmers in the Corn Belt were the least likely to use cover crops, and had the most room for improvement on nitrogen management. Since then, these practices have become more popular, and studies suggest there is big potential for farm

conservation. But nitrate levels in Nebraska groundwater and Midwest rivers suggest there is still a long way to go.

Farmer Ken Seim says public pressure to address water quality is not going away. And he realizes that if farmers don't decide how to fix the problem, perhaps the government will.

"If we won't be stewards ourselves, someone will have to help us be a steward," Seim says.

Producers like the Seims are doing their share. But the effort across the landscape is inconsistent, and so far, so are the results.

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https://www.harvestpublicmedia.org/post/heres-how-midwest-farmers-are-fighting-agricultural-water-pollution

University of Nebraska-Lincoln Extension in Lancaster County

Headline: Urban Nonpoint Source Pollution

Background

What is nonpoint source pollution? Water washing over the land from rain, snowmelt and our everyday activities picks up an array of contaminants including oil and sand from roadways, agricultural chemicals from farmland and nutrients and toxic materials from urban and suburban areas. This runoff finds its way into our waterways, either directly or through storm drain collection systems.

The term nonpoint is used to distinguish this type of pollution from point source pollution, which comes from specific sources such as sewage treatment plants or industrial facilities. Although huge strides have been made in cleaning up major point sources, our water resources are still threatened by the effects of polluted runoff. The U.S. Environmental Protection Agency has estimated that this type of pollution is now the single largest cause of the deterioration of our nation's water quality.

With urbanization comes more intensive land use. People and the pollutants that result from their lifestyles are concentrated in areas largely covered by impervious surfaces (roads, parking lots, driveways, rooftops). This combination of people, pollutants and pavement produces runoff that can carry a greater pollutant load than municipal sewage. Sediment from construction sites, chemicals over-applied to lawns and golf courses, automobile wastes (petroleum products, heavy metals), road salt, pet wastes and industrial contaminants all end up in the nearest body of water.

Major Pollutants

Pathogens: Pathogens are disease-causing microorganisms, such as bacteria and viruses, that are carried in human and animal fecal waste. Pathogens wash off the land in wastes from wild animals, farm animals, pets and can also enter our waterways from improperly functioning septic tanks, leaky sewer lines and boat sanitary disposal systems.

Nutrients: Nutrients are compounds that stimulate plant growth, like nitrogen and phosphorous. Under normal conditions, nutrients are beneficial and necessary, but in high concentrations, they can become an environmental threat. Nitrogen contamination of drinking water can cause health problems, including "blue baby" syndrome. Nutrient loading of ponds, streams and lakes can lead to massive algal blooms, the decay of which can create odors and rob the waters of life-sustaining oxygen. Nutrients in polluted runoff can come from fertilizers, septic systems, home lawn care products, yard and pet wastes.

Sediment: Sand, dirt and gravel eroded by runoff usually ends up in stream beds, wetlands, or ponds and lakes, where they can alter stream flow and decrease the availability of healthy aquatic habitat. Poorly protected construction sites, roadways and suburban gardens can be major sources of sediment.

Toxins: Toxic contaminants are substances that can harm the health of aquatic life and/or human beings. Toxins are created by a wide variety of human practices and products and include heavy metals, pesticides and organic compounds like PCB's (poly-chlorinated biphenyls). Many toxins are very resistant to breakdown and tend to be passed through the food chain to be concentrated in top predators. Fish consumption health advisories are the result of concern over toxins. Oil, grease and gasoline from roadways, and chemicals used in homes, gardens and yards are major sources of toxic contaminants.

Debris: Trash is the simplest type of pollution to understand. It interferes with enjoyment of our water resources and, in the case of plastic and Styrofoam, it can be a health threat to aquatic organisms. Typically, this debris starts as street litter that is carried by runoff into our waterways.

Urban nonpoint source pollution and its management are likely to affect you and your town in the near future. Polluted runoff is largely the result of the way we develop, use and maintain our land. These policies are usually decided at the municipal level, through actions of town officials and local commissions. If you are on a local commission, learn a little about polluted runoff and how you can combat it in your everyday decisions. There are many techniques and regulations that can greatly reduce the effects of polluted runoff and there are more being developed every day. Also, there are many good publications and programs that can help each citizen do simple, but important things to help reduce runoff pollution like conserving water, properly disposing of hazardous wastes, gardening and maintaining lawns in an environmentally responsible manner.

Ground Water and Surface Water
A Single Resource

U.S. Geological Survey Circular 1139

by Thomas C. Winter
Judson W. Harvey
O. Lehn Franke
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Denver, Colorado
1998

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FOREWORD

Traditionally, management of water resources has focused on surface water or ground water as if they were separate entities. As development of land and water resources increases, it is apparent that development of either of these resources affects the quantity and quality of the other. Nearly all surface-water features (streams, lakes, reservoirs, wetlands, and estuaries) interact with ground water. These interactions take many forms. In many situations, surface-water bodies gain water and solutes from ground-water systems and in others the surface-water body is a source of ground-water recharge and causes changes in ground-water quality. As a result, withdrawal of water from streams can deplete ground water or conversely, pumpage of ground water can deplete water in streams, lakes, or wetlands. Pollution of surface water can cause degradation of ground-water quality and conversely pollution of ground water can degrade surface water. Thus, effective land and water management requires a clear understanding of the linkages between ground water and surface water as it applies to any given hydrologic setting.

This Circular presents an overview of current understanding of the interaction of ground water and surface water, in terms of both quantity and quality, as applied to a variety of landscapes across the Nation. This Circular is a product of the Ground-Water Resources Program of the U.S. Geological Survey. It serves as a general educational document rather than a report of new scientific findings. Its intent is to help other Federal, State, and local agencies build a firm scientific foundation for policies governing the management and protection of aquifers and watersheds. Effective policies and management practices must be built on a foundation that recognizes that surface water and ground water are simply two manifestations of a single integrated resource. It is our hope that this Circular will contribute to the use of such effective policies and management practices.

(Signed)

Robert M. Hirsch
ChiefHydrologist

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PREFACE

- Understanding the interaction of ground water and surface water is essential to water managers and water scientists. Management of one component of the hydrologic system, such as a stream or an aquifer, commonly is only partly effective because each hydrologic component is in continuing interaction with other components. The following are a few examples of common water-resource issues where understanding the interconnections of ground water and surface water is fundamental to development of effective water-resource management and policy.

WATER SUPPLY

- It has become difficult in recent years to construct reservoirs for surface storage of water because of environmental concerns and because of the difficulty in locating suitable sites. An alternative, which can reduce or eliminate the necessity for surface storage, is to use an aquifer system for temporary storage of water. For example, water stored underground during times of high streamflow can be withdrawn during times of low streamflow. The characteristics and extent of the interactions of ground water and surface water affect the success of such conjunctive-use projects.

- Methods of accounting for water rights of streams invariably account for surface-water diversions and surface-water return flows. Increasingly, the diversions from a stream that result from ground-water withdrawals are considered in accounting for water rights as are ground-water return flows from irrigation and other applications of water to the land surface. Accounting for these ground-water components can be difficult and controversial. Another form of water-rights accounting involves the trading of ground-water rights and surface-water rights. This has been proposed as a water-management tool where the rights to the total water resource can be shared. It is an example of the growing realization that ground water and surface water are essentially one resource.

- In some regions, the water released from reservoirs decreases in volume, or is delayed significantly, as it moves downstream because some of the released water seeps into the streambanks. These losses of water and delays in traveltime can be significant, depending on antecedent ground-water and streamflow conditions as well as on other factors such as the condition of the channel and the presence of aquatic and riparian vegetation.

- Storage of water in streambanks, on flood plains, and in wetlands along streams reduces flooding downstream. Modifications of the natural interaction between ground water and surface water along streams, such as drainage of wetlands and construction of levees, can remove some of this natural attenuation of floods. Unfortunately, present knowledge is limited with respect to the effects of land-surface modifications in river valleys on floods and on the natural interaction of ground water and surface water in reducing potential flooding.

WATER QUALITY

- Much of the ground-water contamination in the United States is in shallow aquifers that are directly connected to surface water. In some settings where this is the case, ground water can be a major and potentially long-term contributor to contamination of surface water. Determining the contributions of ground water to contamination of streams and lakes is a critical step in developing effective water-management practices.

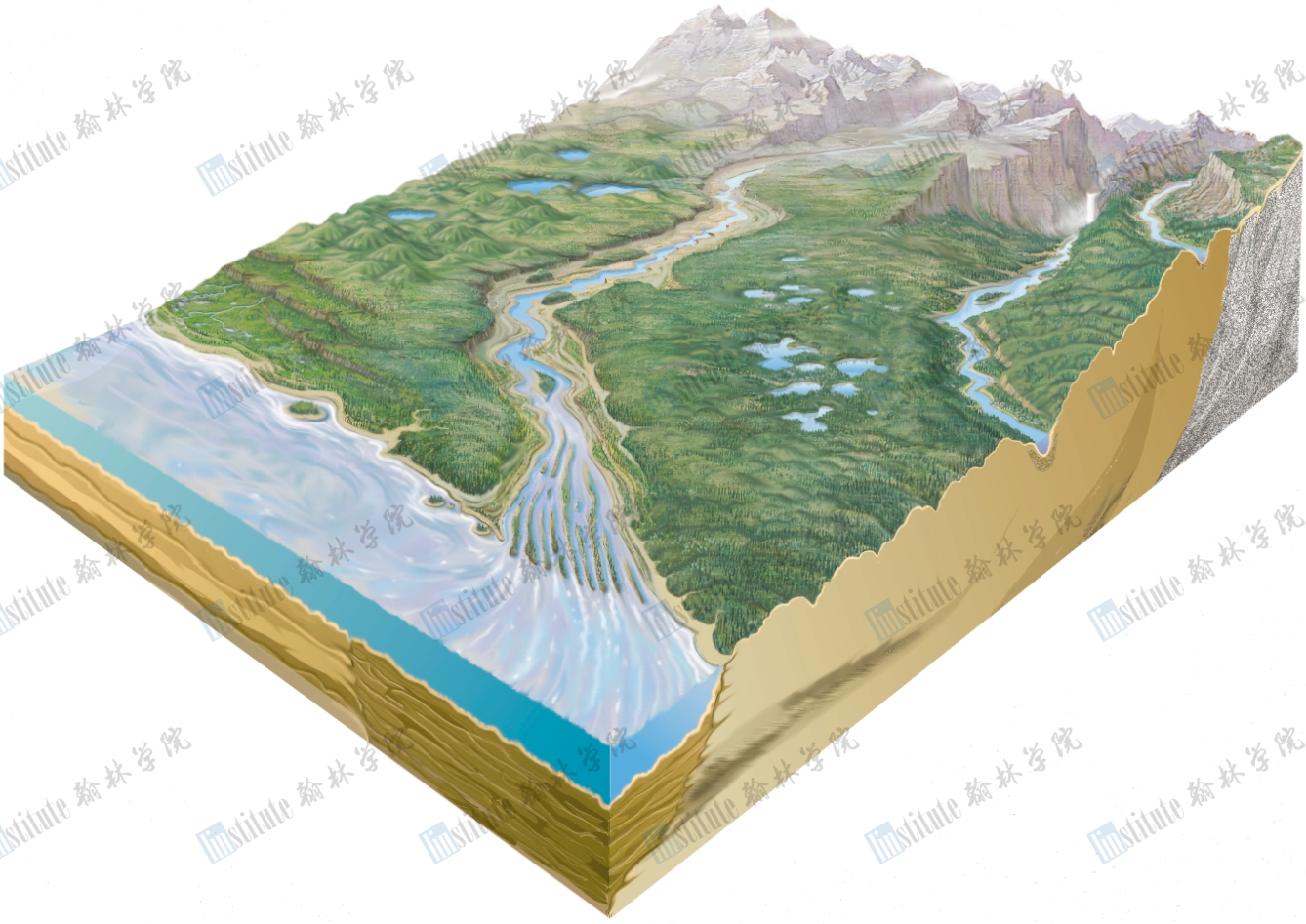
- A focus on watershed planning and management is increasing among government agencies responsible for managing water quality as well as broader aspects of the environment. The watershed approach recognizes that water, starting with precipitation, usually moves

through the subsurface before entering stream channels and flowing out of the watershed. Integrating ground water into this "systems" approach is essential, but challenging, because of limitations in knowledge of the interactions of ground water and surface water. These difficulties are further complicated by the fact that surface-water watersheds and ground-water watersheds may not coincide.

- To meet water-quality standards and criteria, States and local agencies need to determine the amount of contaminant movement (wasteload) to surface waters so they can issue permits and control discharges of waste. Typically, ground-water inputs are not included in estimates of wasteload; yet, in some cases, water-quality standards and criteria cannot be met without reducing contaminant loads from ground-water discharges to streams.
- It is generally assumed that ground water is safe for consumption without treatment. Concerns about the quality of ground water from wells near streams, where contaminated surface water might be part of the source of water to the well, have led to increasing interest in identifying when filtration or treatment of ground water is needed.
- Wetlands, marshes, and wooded areas along streams (riparian zones) are protected in some areas to help maintain wildlife habitat and the quality of nearby surface water. Greater knowledge of the water-quality functions of riparian zones and of the pathways of exchange between shallow ground water and surface-water bodies is necessary to properly evaluate the effects of riparian zones on water quality.

CHARACTERISTICS OF AQUATIC ENVIRONMENTS

- Mixing of ground water with surface water can have major effects on aquatic environments if factors such as acidity, temperature, and dissolved oxygen are altered. Thus, changes in the natural interaction of ground water and surface water caused by human activities can potentially have a significant effect on aquatic environments.
- The flow between surface water and ground water creates a dynamic habitat for aquatic fauna near the interface. These organisms are part of a food chain that sustains a diverse ecological community. Studies indicate that these organisms may provide important indications of water quality as well as of adverse changes in aquatic environments.
- Many wetlands are dependent on a relatively stable influx of ground water throughout changing seasonal and annual weather patterns. Wetlands can be highly sensitive to the effects of ground-water development and to land-use changes that modify the ground-water flow regime of a wetland area. Understanding wetlands in the context of their associated ground-water flow systems is essential to assessing the cumulative effects of wetlands on water quality, ground-water flow, and stream-flow in large areas.
- The success of efforts to construct new wetlands that replicate those that have been destroyed depends on the extent to which the replacement wetland is hydrologically similar to the destroyed wetland. For example, the replacement of a wetland that is dependent on ground water for its water and chemical input needs to be located in a similar ground-water discharge area if the new wetland is to replicate the original. Although a replacement wetland may have a water depth similar to the original, the communities that populate the replacement wetland may be completely different from communities that were present in the original wetland because of differences in hydrogeologic setting.



Ground Water and Surface Water
A Single Resource

by T.C. Winter
J.W. Harvey
O.L. Franke
W.M. Alley

INTRODUCTION

As the Nation's concerns over water resources and the environment increase, the importance of considering ground water and surface water as a single resource has become increasingly evident. Issues related to water supply, water quality, and degradation of aquatic environments are reported on frequently. The interaction of ground water and surface water has been shown to be a significant concern in many of these issues. For example, contaminated aquifers that discharge to streams can result in long-term contamination of surface water; conversely, streams can be a major source of contamination to aquifers. Surface water commonly is hydraulically connected to ground water, but the interactions are difficult to observe and measure and commonly have been ignored in water-management considerations and policies. Many natural processes and human activities affect the interactions of ground water and surface water. The purpose of this report is to present our current understanding of these processes and activities as well as limitations in our knowledge and ability to characterize them.

"Surface water commonly is hydraulically connected to ground water, but the interactions are difficult to observe and measure"

NATURAL PROCESSES OF GROUND-WATER AND SURFACE-WATER INTERACTION

The Hydrologic Cycle and Interactions of Ground Water and Surface Water

The hydrologic cycle describes the continuous movement of water above, on, and below the surface of the Earth. The water on the Earth's surface—surface water—occurs as streams, lakes, and wetlands, as well as bays and oceans. Surface water also includes the solid forms of water—snow and ice. The water below the surface of the Earth primarily is ground water, but it also includes soil water.

The hydrologic cycle commonly is portrayed by a very simplified diagram that shows only major transfers of water between continents and oceans, as in Figure 1. However, for understanding hydrologic processes and managing water resources, the hydrologic cycle needs to be viewed at a wide range of scales and as having a great deal of variability in time and space. Precipitation, which is the source of virtually all freshwater in the hydrologic cycle, falls nearly everywhere, but its distribution is highly variable. Similarly, evaporation and transpiration return water to the atmosphere nearly everywhere, but evaporation and transpiration rates vary considerably according to climatic conditions. As a result, much of the precipitation never reaches the oceans as surface and subsurface runoff before the water is returned to the atmosphere. The relative magnitudes of the individual components of the hydrologic cycle, such as evapotranspiration, may differ significantly even at small scales, as between an agricultural field and a nearby woodland.

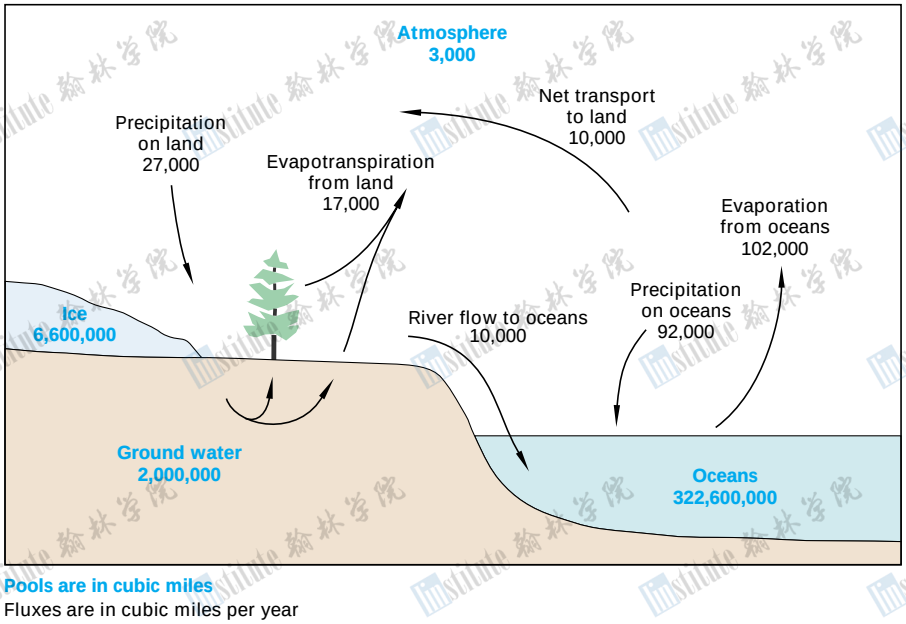


Figure 1. Ground water is the second smallest of the four main pools of water on Earth, and river flow to the oceans is one of the smallest fluxes, yet ground water and surface water are the components of the hydrologic system that humans use most. (Modified from Schelesinger, W.H., 1991, Biogeochemistry–An analysis of global change: Academic Press, San Diego, California.) (Used with permission.)

To present the concepts and many facets of the interaction of ground water and surface water in a unified way, a conceptual landscape is used (Figure 2). The conceptual landscape shows in a very general and simplified way the interaction of ground water with all types of surface water, such as streams, lakes, and wetlands, in many different terrains from the mountains to the oceans. The intent of Figure 2 is to emphasize that ground water and surface water interact at many places throughout the landscape.

Movement of water in the atmosphere and on the land surface is relatively easy to visualize, but the movement of ground water is not. Concepts related to ground water and the movement of ground water are introduced in Box A. As illustrated in Figure 3, ground water moves along flow paths of varying lengths from areas of recharge to areas of discharge. The generalized flow paths in Figure 3 start at the water table, continue through the ground-water system, and terminate at the stream or at the pumped well. The source of water to the water table (ground-water recharge) is infiltration of precipitation through the unsaturated zone. In the uppermost, unconfined aquifer, flow paths near the stream can be tens to hundreds of feet in length and have corresponding traveltimes of days to a few years. The longest and deepest flow paths in Figure 3 may be thousands of feet to tens of miles in length, and traveltimes may range from decades to millennia. In general, shallow ground water is more susceptible to contamination from human sources and activities because of its close proximity to the land surface. Therefore, shallow, local patterns of ground-water flow near surface water are emphasized in this Circular.

"Ground water moves along flow paths of varying lengths in transmitting water from areas of recharge to areas of discharge"

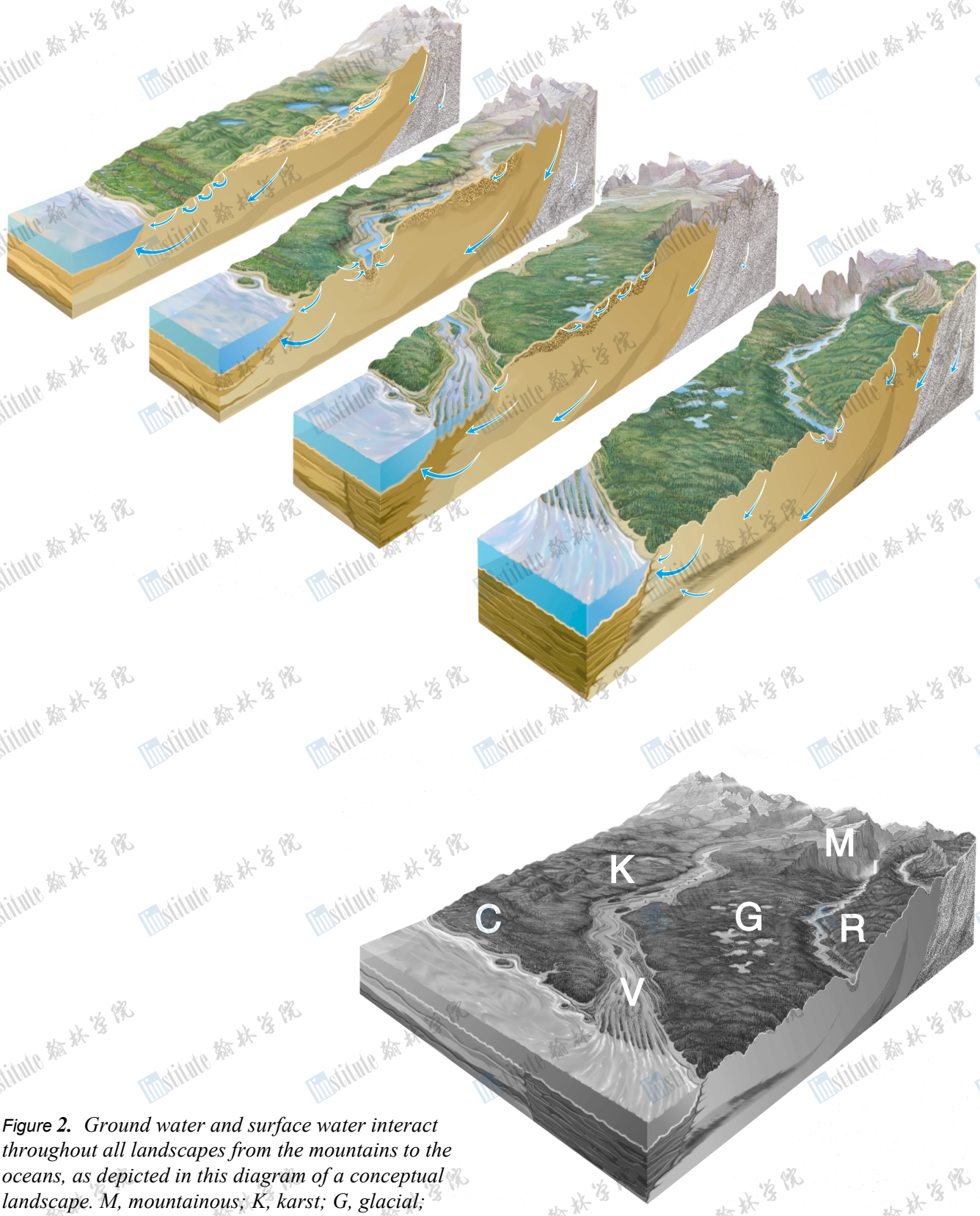


Figure 2. Ground water and surface water interact throughout all landscapes from the mountains to the oceans, as depicted in this diagram of a conceptual landscape. M, mountainous; K, karst; G, glacial; R, riverine (small); V, riverine (large); C, coastal.

Small-scale geologic features in beds of surface-water bodies affect seepage patterns at scales too small to be shown in Figure 3. For example, the size, shape, and orientation of the sediment grains in surface-water beds affect seepage patterns. If a surface-water bed consists of one sediment type, such as sand, inflow seepage is greatest at the shoreline, and it decreases in a nonlinear pattern away from the shoreline (Figure 4). Geologic units having different permeabilities also affect seepage distribution in surface-water beds. For example, a highly permeable sand layer within a surface-water bed consisting largely of silt will transmit water preferentially into the surface water as a spring (Figure 5).

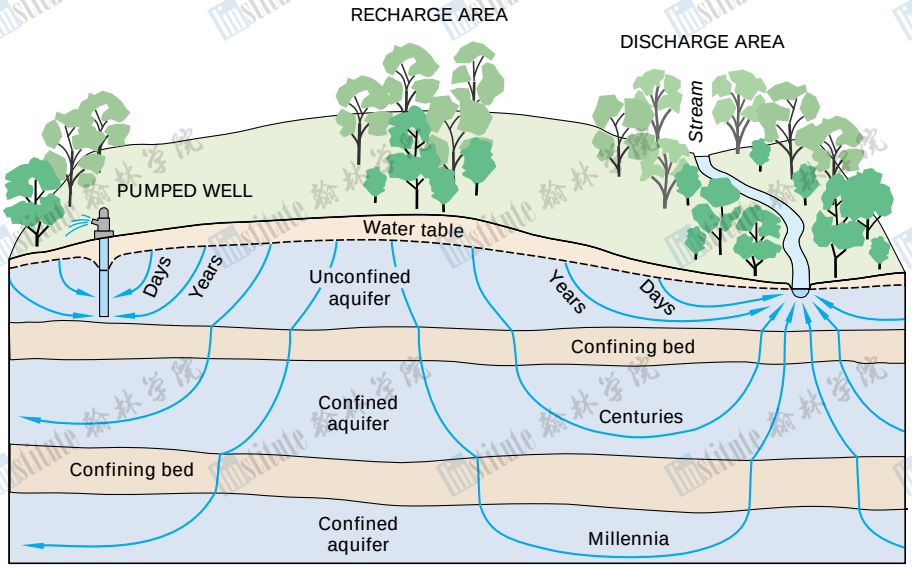


Figure 3. Ground-water flow paths vary greatly in length, depth, and traveltime from points of recharge to points of discharge in the ground-water system.

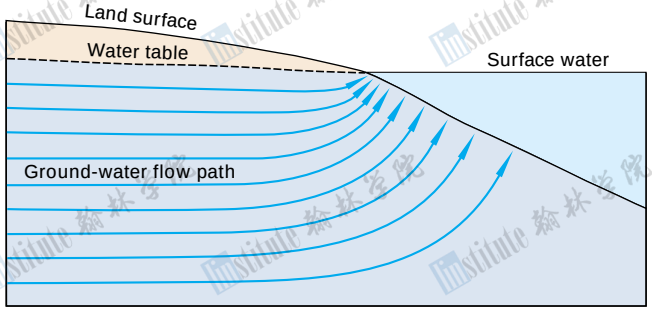


Figure 4. Ground-water seepage into surface water usually is greatest near shore. In flow diagrams such as that shown here, the quantity of discharge is equal between any two flow lines; therefore, the closer flow lines indicate greater discharge per unit of bottom area.

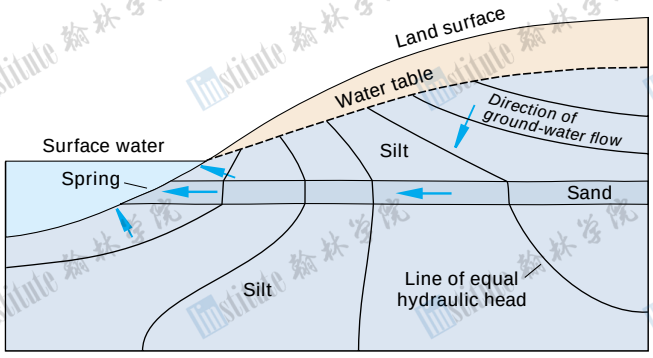


Figure 5. Subaqueous springs can result from preferred paths of ground-water flow through highly permeable sediments.

A

Concepts of Ground Water, Water Table, and Flow Systems

SUBSURFACE WATER

Water beneath the land surface occurs in two principal zones, the unsaturated zone and the saturated zone (Figure A–1). In the unsaturated zone, the voids—that is, the spaces between grains of gravel, sand, silt, clay, and cracks within rocks—contain both air and water. Although a considerable amount of water can be present in the unsaturated zone, this water cannot be pumped by wells because it is held too tightly by capillary forces. The upper part of the unsaturated zone is the soil-water zone. The soil zone is crisscrossed by roots, voids left by decayed roots, and animal and worm burrows, which enhance the infiltration of precipitation into the soil zone. Soil water is used by plants in life functions and transpiration, but it also can evaporate directly to the atmosphere.

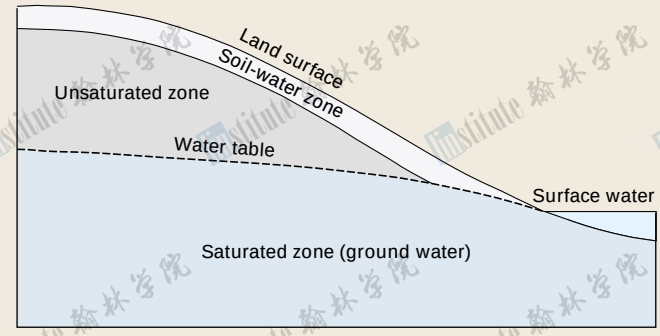


Figure A–1. The water table is the upper surface of the saturated zone. The water table meets surface-water bodies at or near the shoreline of surface water if the surface-water body is connected to the ground-water system.

In contrast to the unsaturated zone, the voids in the saturated zone are completely filled with water. Water in the saturated zone is referred to as ground water. The upper surface of the saturated zone is referred to as the water table. Below the water table, the water pressure is great enough to allow water to enter wells, thus permitting ground water to be withdrawn for use. A well is constructed by inserting a pipe into a drilled hole; a screen is attached, generally at its base, to prevent earth materials from entering the pipe along with the water pumped through the screen.

The depth to the water table is highly variable and can range from zero, when it is at land surface, to hundreds or even thousands of feet in some types of landscapes. Usually, the depth to the water table is small near permanent bodies of surface water such as streams, lakes, and wetlands. An important characteristic of the water table is that its configuration varies seasonally and from year to year because ground-water recharge, which is the accretion of water to the upper surface of the saturated zone, is related to the wide variation in the quantity, distribution, and timing of precipitation.

THE WATER TABLE

The depth to the water table can be determined by installing wells that penetrate the top of the saturated zone just far enough to hold standing water. Preparation of a water-table map requires that only wells that have their well screens placed near the water table be used. If the depth to water is measured at a number of such wells throughout an area of study, and if those water levels are referenced to a common datum such as sea level, the data can be contoured to indicate the configuration of the water table (Figure A–2).

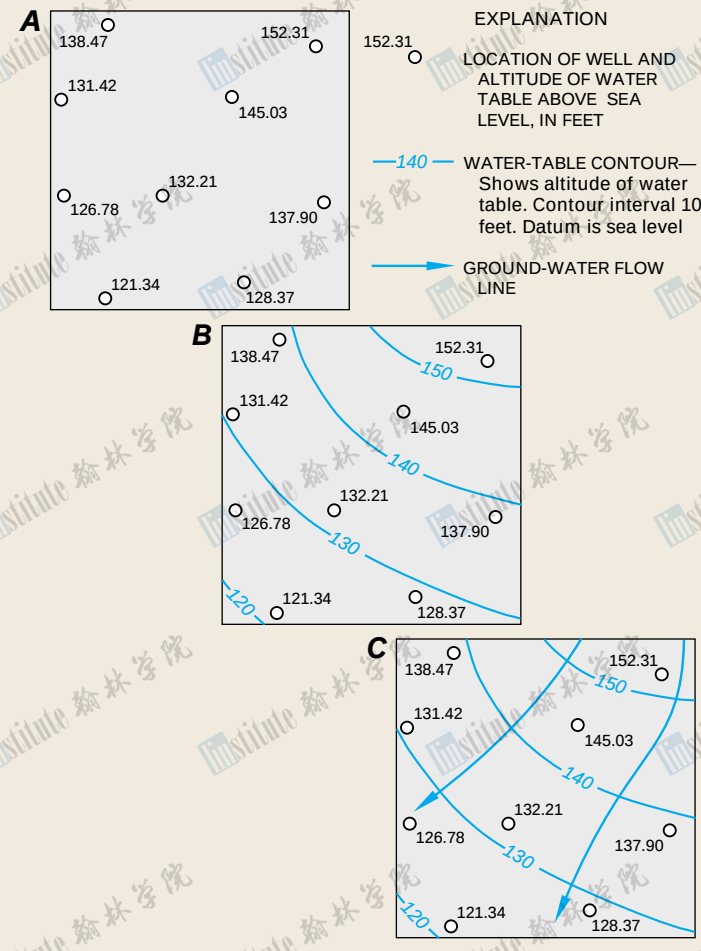


Figure A–2. Using known altitudes of the water table at individual wells (A), contour maps of the water-table surface can be drawn (B), and directions of ground-water flow along the water table can be determined (C) because flow usually is approximately perpendicular to the contours.

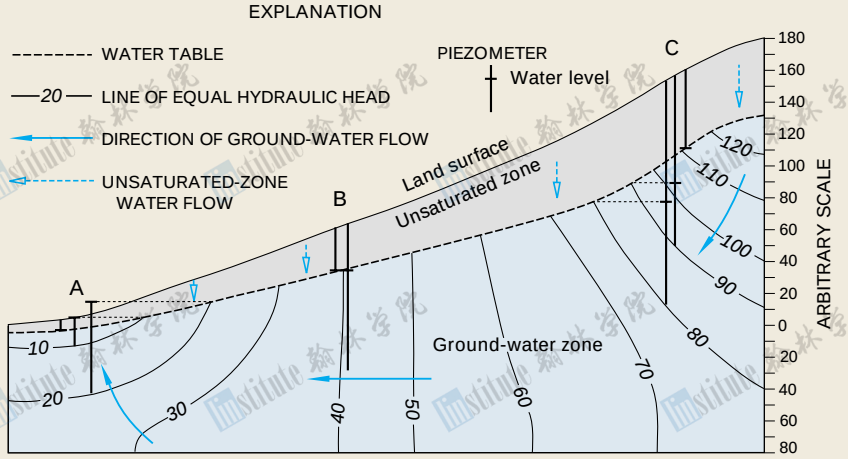
In addition to various practical uses of a water-table map, such as estimating an approximate depth for a proposed well, the configuration of the water table provides an indication of the approximate direction of ground-water flow at any location

on the water table. Lines drawn perpendicular to water-table contours usually indicate the direction of ground-water flow along the upper surface of the ground-water system. The water table is continually adjusting to changing recharge and discharge patterns. Therefore, to construct a water-table map, water-level measurements must be made at approximately the same time, and the resulting map is representative only of that specific time.

GROUND-WATER MOVEMENT

The ground-water system as a whole is actually a three-dimensional flow field; therefore, it is important to understand how the vertical components of ground-water movement affect the interaction of ground water and surface water. A vertical section of a flow field indicates how potential energy is distributed beneath the water table in the ground-water system and how the energy distribution can be used to determine vertical components of flow near a surface-water body. The term hydraulic head, which is the sum of elevation and water pressure divided by the weight density of water, is used to describe potential energy in ground-water flow systems. For example, Figure A–3 shows a generalized vertical section of subsurface water flow. Water that infiltrates at land surface moves vertically downward to the water table to become ground water. The ground water then moves both vertically and laterally within the ground-water system. Movement is downward and lateral on the right side of the diagram, mostly lateral in the center, and lateral and upward on the left side of the diagram.

Flow fields such as these can be mapped in a process similar to preparing water-table maps, except that vertically distributed piezometers need to be used instead of water-table wells. A piezometer is a well that has a very short screen so the water level represents hydraulic head in only a very small part of the ground-water system. A group of piezometers completed at different depths at the same location is referred to as a piezometer nest. Three such piezometer nests are shown in Figure A–3 (locations A, B, and C). By starting at a water-table contour, and using the water-level data from the piezometer nests, lines of equal hydraulic head can be drawn. Similar to drawing flow direction on water-table maps, flow lines can be drawn approximately perpendicular to these lines of equal hydraulic head, as shown in Figure A–3.



Actual flow fields generally are much more complex than that shown in Figure A–3. For example, flow systems of different sizes and depths can be present, and they can overlie one another, as indicated in Figure A–4. In a local flow system, water that recharges at a water-table high discharges to an adjacent lowland. Local flow systems are the most dynamic and the shallowest flow systems; therefore, they have the greatest interchange with surface water. Local flow systems can be underlain by intermediate and regional flow systems. Water in deeper flow systems have longer flow paths and longer contact time with subsurface materials; therefore, the water generally contains more dissolved chemicals. Nevertheless, these deeper flow systems also eventually discharge to surface water, and they can have a great effect on the chemical characteristics of the receiving surface water.

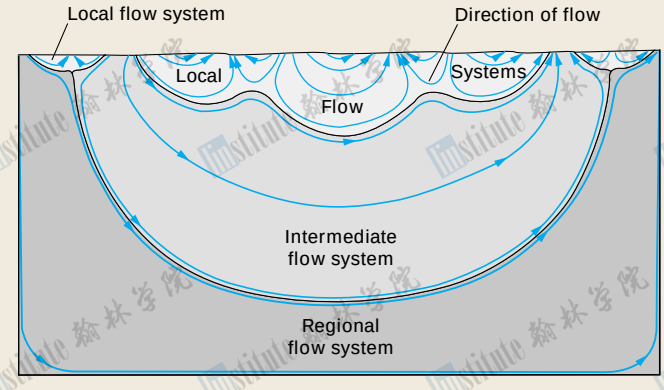


Figure A–4. Ground-water flow systems can be local, intermediate, and regional in scale. Much ground-water discharge into surface-water bodies is from local flow systems. (Figure modified from Toth, J., 1963, A theoretical analysis of groundwater flow in small drainage basins: p. 75–96 in Proceedings of Hydrology Symposium No. 3, Groundwater, Queen's Printer, Ottawa, Canada.)

GROUND-WATER DISCHARGE

The quantity of ground-water discharge (flux) to and from surface-water bodies can be determined for a known cross section of aquifer by multiplying the hydraulic gradient, which is determined from the hydraulic-head measurements in wells and piezometers, by the permeability of the aquifer materials. Permeability is a quantitative measure of the ease of water movement through aquifer materials. For example, sand is more permeable than clay because the pore spaces between sand grains are larger than pore spaces between clay particles.

Figure A–3. If the distribution of hydraulic head in vertical section is known from nested piezometer data, zones of downward, lateral, and upward components of ground-water flow can be determined.

Changing meteorological conditions also strongly affect seepage patterns in surface-water beds, especially near the shoreline. The water table commonly intersects land surface at the shoreline, resulting in no unsaturated zone at this point. Infiltrating precipitation passes rapidly through a thin unsaturated zone adjacent to the shoreline, which causes water-table mounds to form quickly adjacent to the surface water (Figure 6). This process, termed focused recharge, can result in increased ground-water inflow to surface-water bodies, or it can cause inflow to surface-water bodies that normally have seepage to ground water. Each precipitation event has the potential to cause this highly transient flow condition near shorelines as well as at depressions in uplands (Figure 6).

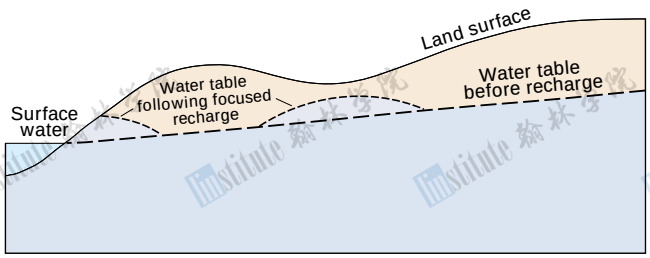


Figure 6. Ground-water recharge commonly is focused initially where the unsaturated zone is relatively thin at the edges of surface-water bodies and beneath depressions in the land surface.

Transpiration by nearshore plants has the opposite effect of focused recharge. Again, because the water table is near land surface at edges of surface-water bodies, plant roots can penetrate into the saturated zone, allowing the plants to transpire water directly from the ground-water system (Figure 7). Transpiration of ground water commonly results in a drawdown of the water table much like the effect of a pumped well. This highly variable daily and seasonal transpiration of ground water may significantly reduce ground-water discharge to a surface-water body or even cause movement of surface water into the subsurface. In many places it is possible to measure diurnal changes in the direction of flow during seasons of active plant growth; that is, ground water moves into the surface water during the night, and surface water moves into shallow ground water during the day.

These periodic changes in the direction of flow also take place on longer time scales: focused recharge from precipitation predominates during wet periods and drawdown by transpiration predominates during dry periods. As a result, the two processes, together with the geologic controls on seepage distribution, can cause flow conditions at the edges of surface-water bodies to be extremely variable. These "edge effects" probably affect small surface-water bodies more than large surface-water bodies because the ratio of edge length to total volume is greater for small water bodies than it is for large ones.

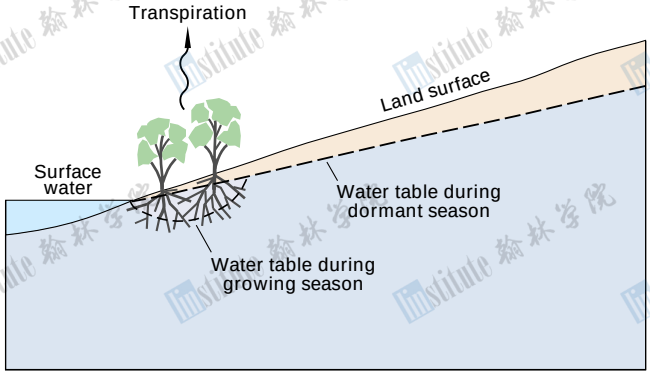


Figure 7. Where the depth to the water table is small adjacent to surface-water bodies, transpiration directly from ground water can cause cones of depression similar to those caused by pumping wells. This sometimes draws water directly from the surface water into the subsurface.

INTERACTION OF GROUND WATER AND STREAMS

Streams interact with ground water in all types of landscapes (see Box B). The interaction takes place in three basic ways: streams gain water from inflow of ground water through the streambed (gaining stream, Figure 8*A*), they lose water to ground water by outflow through the streambed (losing stream, Figure 9*A*), or they do both, gaining in some reaches and losing in other reaches. For ground water to discharge into 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-water surface. Contours of water-table elevation indicate gaining streams by pointing in an upstream direction (Figure 8*B*), and they indicate losing streams by pointing in a downstream direction (Figure 9*B*) in the immediate vicinity of the stream.

Losing streams can be connected to the ground-water system by a continuous saturated zone (Figure 9*A*) or can be disconnected from

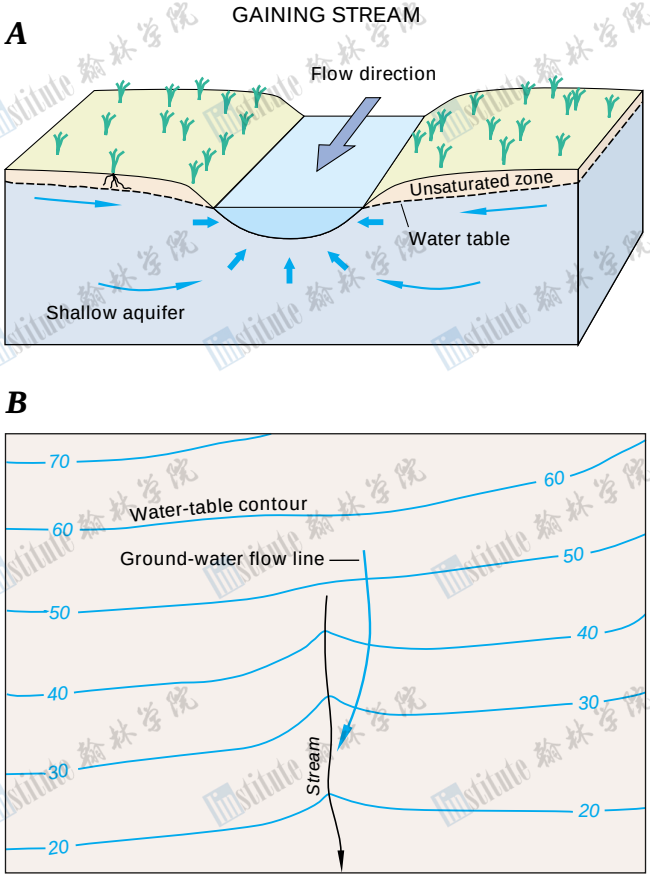


Figure 8. Gaining streams receive water from the ground-water system (A). This can be determined from water-table contour maps because the contour lines point in the upstream direction where they cross the stream (B).

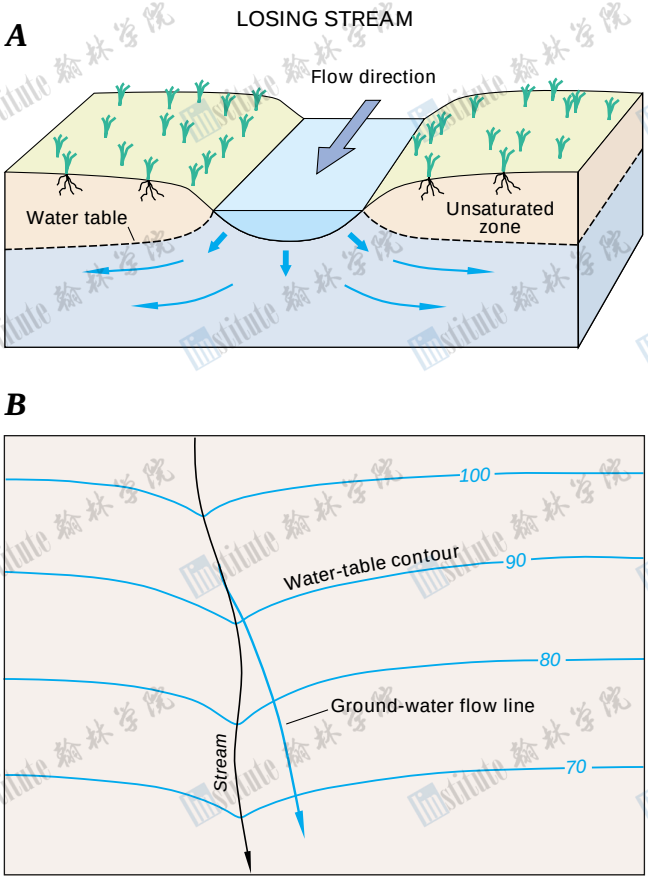


Figure 9. Losing streams lose water to the ground-water system (A). This can be determined from water-table contour maps because the contour lines point in the downstream direction where they cross the stream (B).

the ground-water system by an unsaturated zone. Where the stream is disconnected from the ground-water system by an unsaturated zone, the water table may have a discernible mound below the stream (Figure 10) if the rate of recharge through the streambed and unsaturated zone is greater than the rate of lateral ground-water flow away from the water-table mound. An important feature of streams that are disconnected from ground water is that pumping of shallow ground water near the stream does not affect the flow of the stream near the pumped wells.

In some environments, streamflow gain or loss can persist; that is, a stream might always gain water from ground water, or it might always lose water to ground water. However, in other environments, flow direction can vary a great deal along a stream; some reaches receive ground water, and other reaches lose water to ground water. Furthermore, flow direction can change in very short timeframes as a result of individual storms causing focused recharge near the streambank, temporary flood peaks moving down the channel, or transpiration of ground water by streamside vegetation.

A type of interaction between ground water and streams that takes place in nearly all streams at one time or another is a rapid rise in stream stage that causes water to move from the stream into the streambanks. This process, termed bank storage (Figures 11 and 12*B*), usually is caused by storm precipitation, rapid snowmelt, or release of water

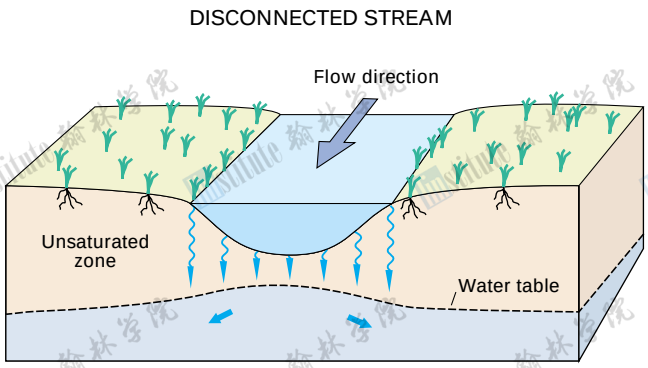


*Figure **10.** Disconnected streams are separated from the ground-water system by an unsaturated zone.*

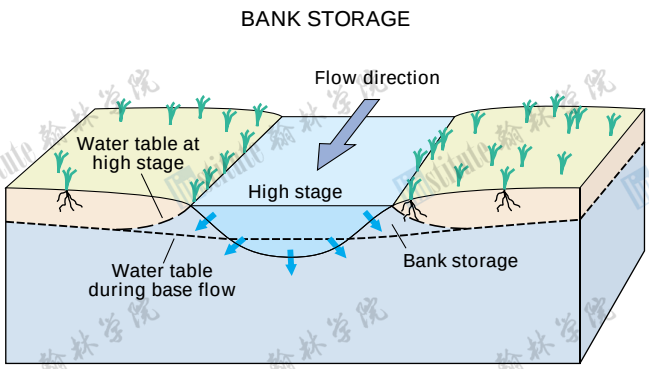


*Figure **11**. If stream levels rise higher than adjacent ground-water levels, stream water moves into the streambanks as bank storage.*

"Streams interact with ground water in three basic ways: streams gain water from inflow of ground water through the streambed (gaining stream), they lose water to ground water by outflow through the streambed (losing stream), or they do both, gaining in some reaches and losing in other reaches"

from a reservoir upstream. As long as the rise in stage does not overtop the streambanks, most of the volume of stream water that enters the streambanks returns to the stream within a few days or weeks. The loss of stream water to bank storage and return of this water to the stream in a period of days or weeks tends to reduce flood peaks and later supplement stream flows. If the rise in stream stage is sufficient to overtop the banks and flood large areas of the land surface, widespread recharge to the water table can take place throughout the flooded area (Figure 12*C*). In this case, the time it takes for the recharged floodwater to return to the stream by ground-water flow may be weeks, months, or years because the lengths of the ground-water flow paths are much longer than those resulting from local bank storage. Depending on the frequency, magnitude, and intensity of storms and on the related magnitude of increases in stream stage, some streams and adjacent shallow aquifers may be in a continuous readjustment from interactions related to bank storage and overbank flooding.

In addition to bank storage, other processes may affect the local exchange of water between streams and adjacent shallow aquifers. Changes in streamflow between gaining and losing conditions can also be caused by pumping ground water near streams (see Box C). Pumping can intercept ground water that would otherwise have discharged to a gaining stream, or at higher pumping rates it can induce flow from the stream to the aquifer.

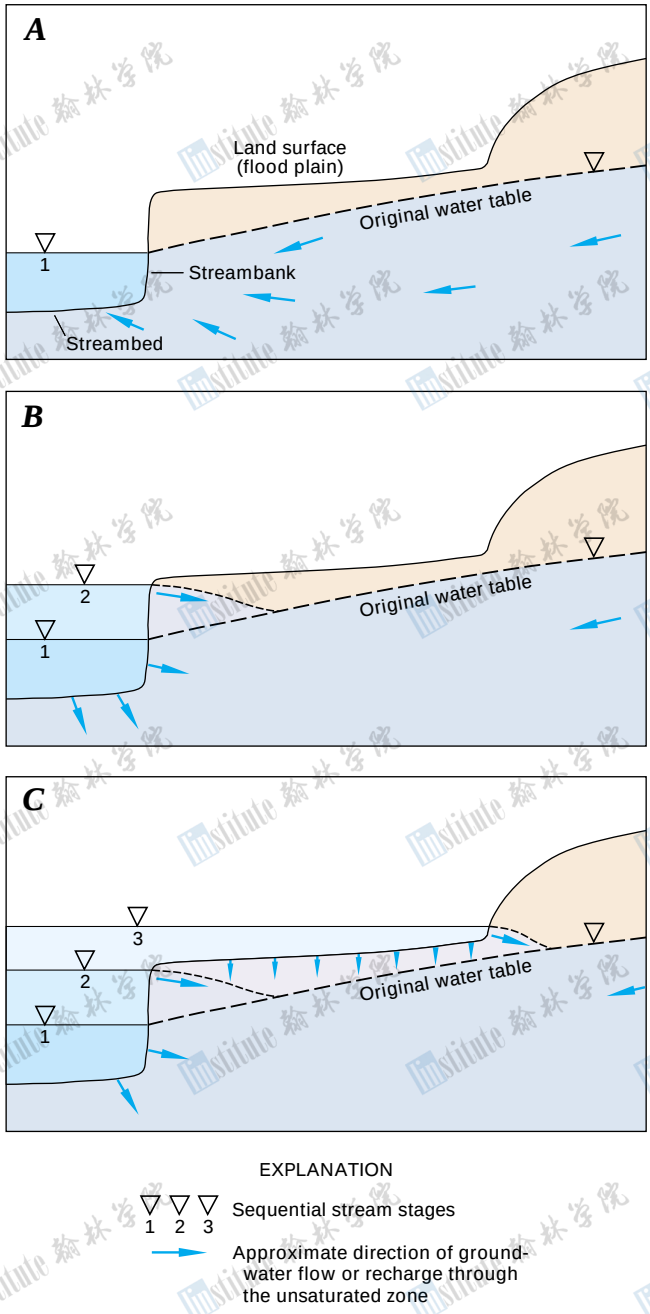


*Figure **12.** If stream levels rise higher than their streambanks (C), the floodwaters recharge ground water throughout the flooded areas.*

B

The Ground-Water Component of Streamflow

Ground water contributes to streams in most physiographic and climatic settings. Even in settings where streams are primarily losing water to ground water, certain reaches may receive ground-water inflow during some seasons. The proportion of stream water that is derived from ground-water inflow varies across physiographic and climatic settings. The amount of water that ground water contributes to streams can be estimated by analyzing streamflow hydrographs to determine the ground-water component, which is termed base flow (Figure B–1). Several different methods of analyzing hydrographs have been used by hydrologists to determine the base-flow component of streamflow.

One of the methods, which provides a conservative estimate of base flow, was used to determine the ground-water contribution to streamflow in 24 regions in the conterminous United States. The regions, delineated on the basis of physiography and climate, are believed to have common characteristics with respect to the interactions of ground water and surface water (Figure B–2). Fifty-four streams were selected for the analysis, at least two in each of the 24 regions. Streams were selected that had drainage basins less than 250 square miles and that had less than 3 percent of the drainage area covered by lakes and wetlands. Daily streamflow values for the 30-year period, 1961–1990, were used for the analysis of each stream. The analysis indicated that, for the 54 streams over the 30-year period, an average of 52 percent of the streamflow was contributed by ground water. Ground-water contributions ranged from 14 percent to 90 percent, and the median was 55 percent. The ground-water contribution to streamflow for selected streams can be compared in Figure B–2. As an example of the effect that geologic setting has on the contribution of ground water to streamflow, the Forest River in North Dakota can be compared to the Sturgeon River in Michigan. The Forest River Basin is underlain by poorly permeable silt and clay deposits, and only about 14 percent of its average annual flow is contributed by ground water; in contrast, the Sturgeon River Basin is underlain by highly permeable sand and gravel, and about 90 percent of its average annual flow is contributed by ground water.

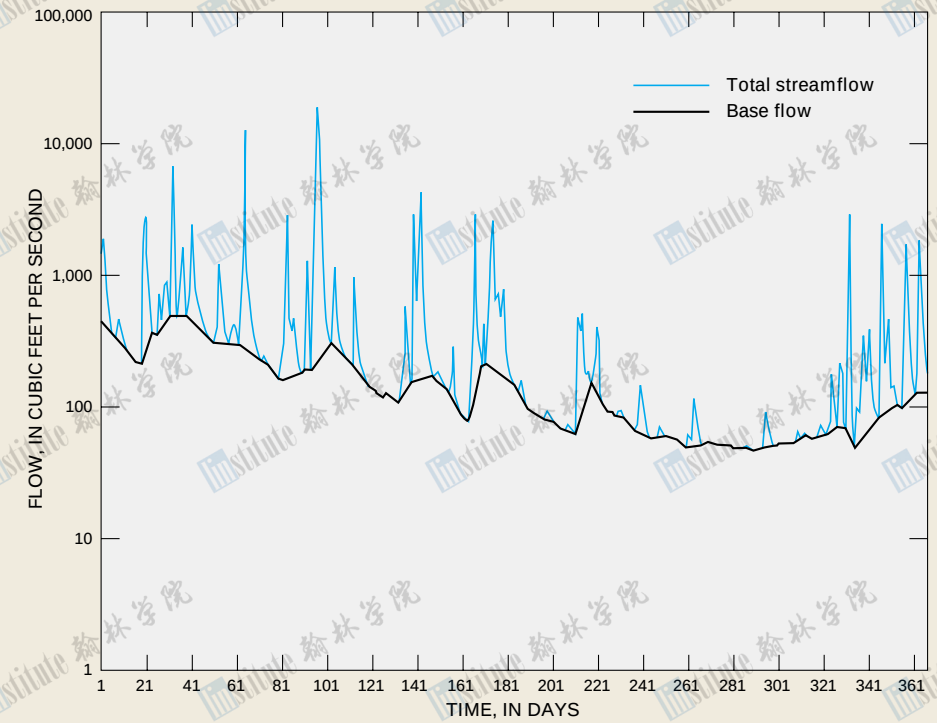


Figure B–1. The ground-water component of streamflow was estimated from a streamflow hydrograph for the Homochitto River in Mississippi, using a method developed by the institute of Hydrology, United Kingdom. (Institute of Hydrology, 1980, Low flow studies: Wallingford, Oxon, United Kingdom, Research Report No. 1.)

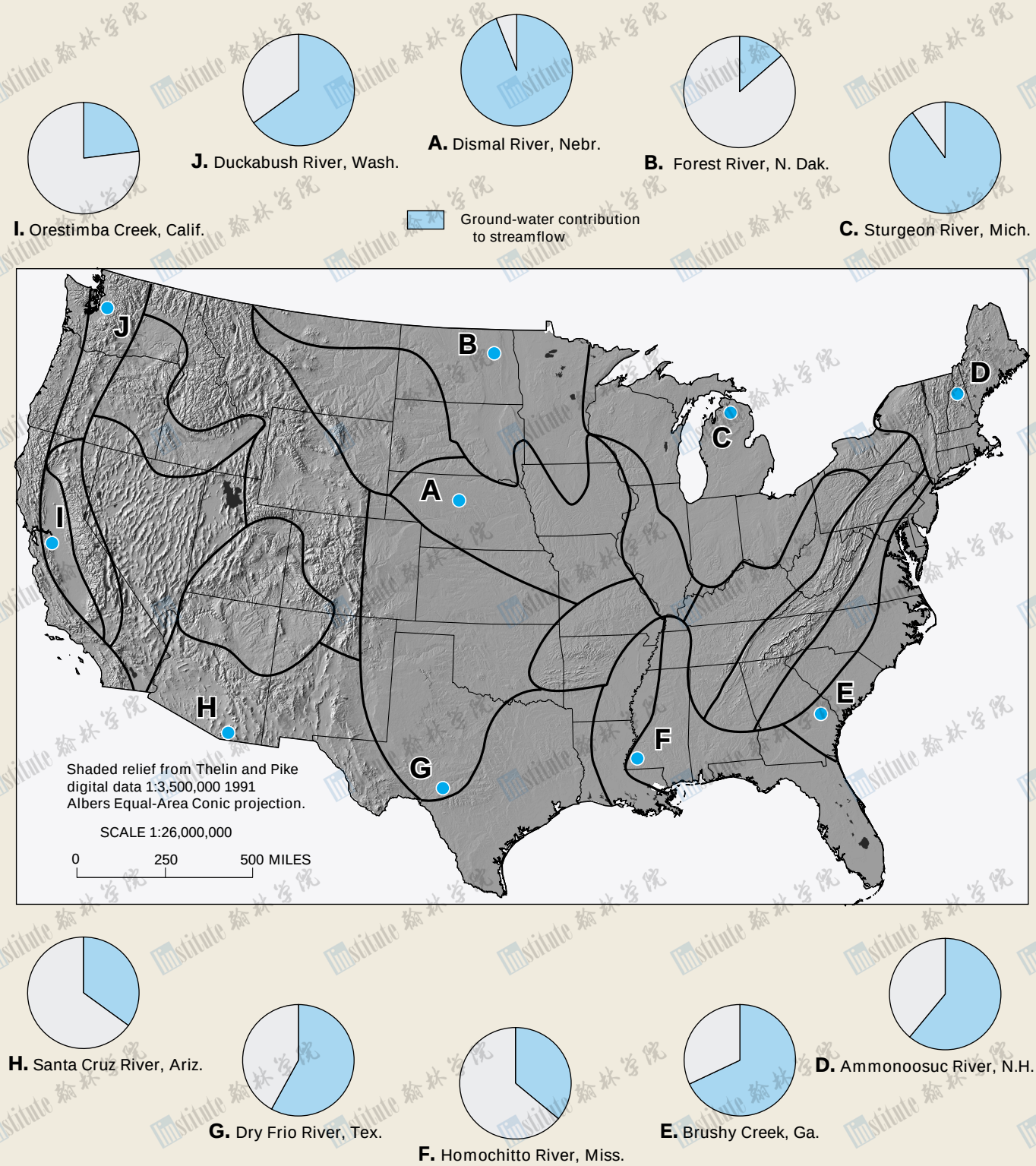


Figure B–2. In the conterminous United States, 24 regions were delineated where the interactions of ground water and surface water are considered to have similar characteristics. The estimated ground-water contribution to streamflow is shown for specific streams in 10 of the regions.

C

The Effect of Ground-Water Withdrawals on Surface Water

Withdrawing water from shallow aquifers that are directly connected to surface-water bodies can have a significant effect on the movement of water between these two water bodies. The effects of pumping a single well or a small group of wells on the hydrologic regime are local in scale. However, the effects of many wells withdrawing water from an aquifer over large areas may be regional in scale.

Withdrawing water from shallow aquifers for public and domestic water supply, irrigation, and industrial uses is widespread. Withdrawing water from shallow aquifers near surface-water bodies can diminish the available surface-water supply by capturing some of the ground-water flow that otherwise would have discharged to surface water or by inducing flow from surface water into the surrounding aquifer system. An analysis of the sources of water to a pumping well in a shallow aquifer that discharges to a stream is provided here to gain insight into how a pumping well can change the quantity and direction of flow between the shallow aquifer and the stream. Furthermore, changes in the direction of flow between the two water bodies can affect transport of contaminants associated with the moving water. Although a stream is used in the example, the results apply to all surface-water bodies, including lakes and wetlands.

A ground-water system under predevelopment conditions is in a state of dynamic equilibrium—for example, recharge at the water table is equal to ground-water discharge to a stream (Figure C–1*A*). Assume a well is installed and is pumped continually at a rate, Q_1. 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 (Figure C–1*B*). If the well is pumped at a higher rate, Q_2, at a later time a new equilibrium is reached. 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 (Figure C–1*C*). Thus, pumpage reverses the hydrologic condition of the stream in this reach from a ground-water discharge feature to a ground-water recharge feature.

In the hydrologic system depicted in Figures C–1*A* and C–1*B*, the quality of the stream water generally will have little effect on the quality of the shallow ground water. However, in the case of the well pumping at the higher rate, Q_2 (Figure C–1*C*), the quality of the stream water, which locally recharges the shallow aquifer, can affect the quality of ground water between the well and the stream as well as the quality of the ground water withdrawn from the well.

This hypothetical withdrawal of water from a shallow aquifer that discharges to a nearby surface-water body is a simplified but compelling illustration of the concept that ground water and surface water are one resource. In the long term, the quantity of ground water withdrawn is approximately equal to the reduction in streamflow that is potentially available to downstream users.

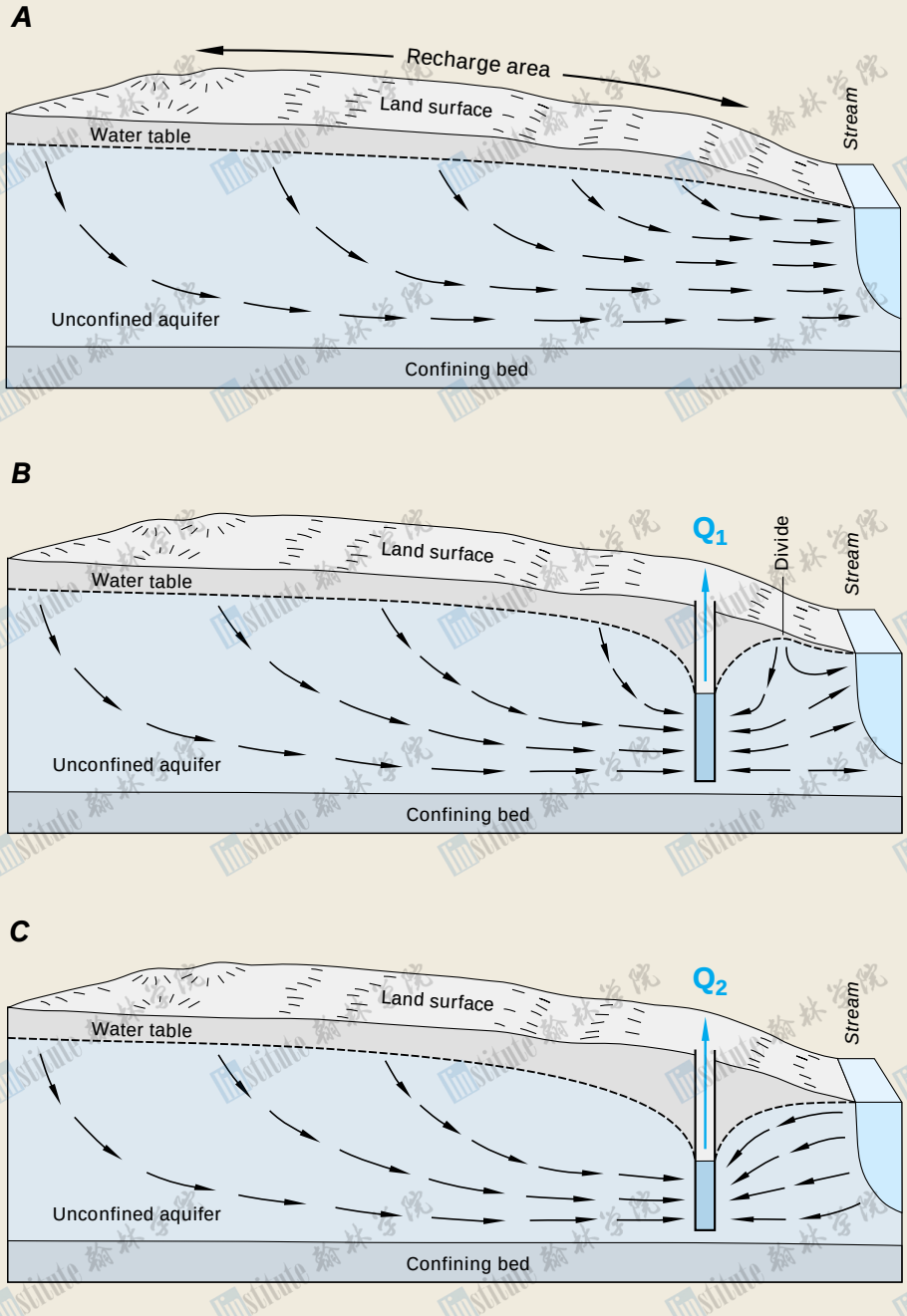


Figure C–1. In a schematic hydrologic setting where ground water discharges to a stream under natural conditions (A), placement of a well pumping at a rate (Q_1) near the stream will intercept part of the ground water that would have discharged to the stream (B). If the well is pumped at an even greater rate (Q_2), it can intercept additional water that would have discharged to the stream in the vicinity of the well and can draw water from the stream to the well (C).

Where streamflow is generated in headwaters areas, the changes in streamflow between gaining and losing conditions may be particularly variable (Figure 13). The headwaters segment of streams can be completely dry except during storm events or during certain seasons of the year when snowmelt or precipitation is sufficient to maintain continuous flow for days or weeks. During these times, the stream will lose water to the unsaturated zone beneath its bed. However, as the water table rises through recharge in the headwaters area, the losing reach may become a gaining reach as the water table rises above the level of the stream. Under these conditions, the point where ground water first contributes to the stream gradually moves upstream.

Some gaining streams have reaches that lose water to the aquifer under normal conditions of streamflow. The direction of seepage through the bed of these streams commonly is related to abrupt changes in the slope of the streambed (Figure 14*A*) or to meanders in the stream channel (Figure 14*B*). For example, a losing stream reach usually is located at the downstream end of pools in pool and riffle streams (Figure 14*A*), or upstream from channel bends in meandering streams (Figure 14*B*). The subsurface zone where stream water flows through short segments of its adjacent bed and banks is referred to as the hyporheic zone. The size and geometry of hyporheic zones surrounding streams vary greatly in time and space. Because of mixing between ground water and surface water in the hyporheic zone, the chemical and biological character of the hyporheic zone may differ markedly from adjacent surface water and ground water.

Ground-water systems that discharge to streams can underlie extensive areas of the land surface (Figure 15). As a result, environmental conditions at the interface between ground water and surface water reflect changes in the broader landscape. For example, the types and numbers of organisms in a given reach of streambed result, in part, from interactions between water in the hyporheic zone and ground water from distant sources.

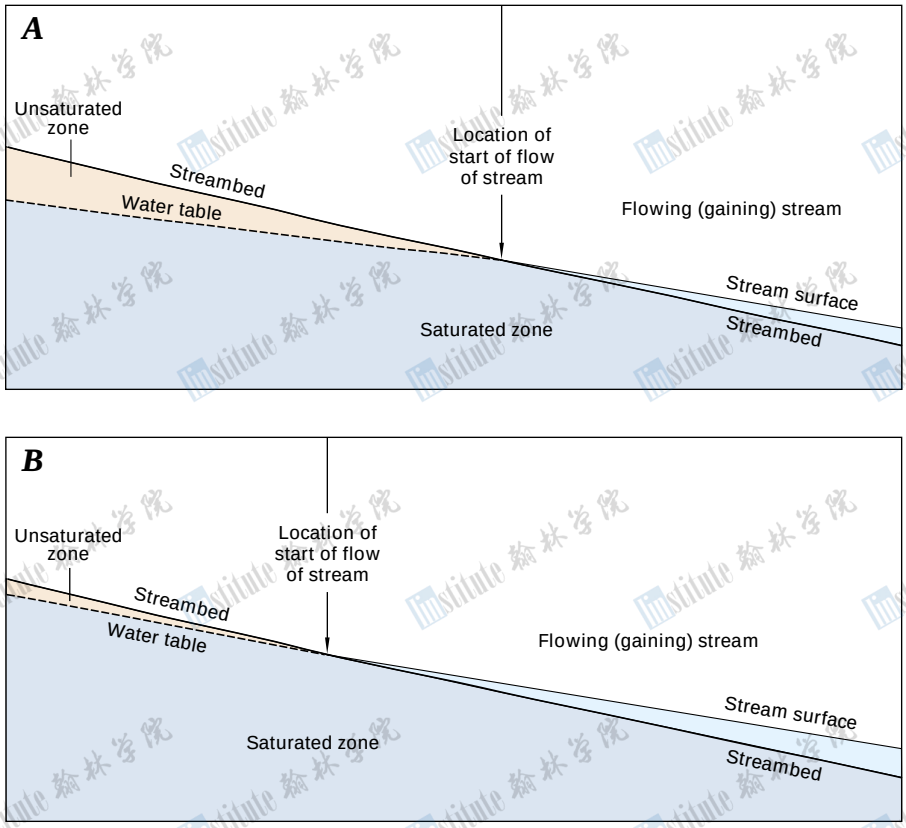


*Figure **13.** The location where perennial streamflow begins in a channel can vary depending on the distribution of recharge in headwaters areas. Following dry periods (A), the start of streamflow will move upchannel during wet periods as the ground-water system becomes more saturated (B).*

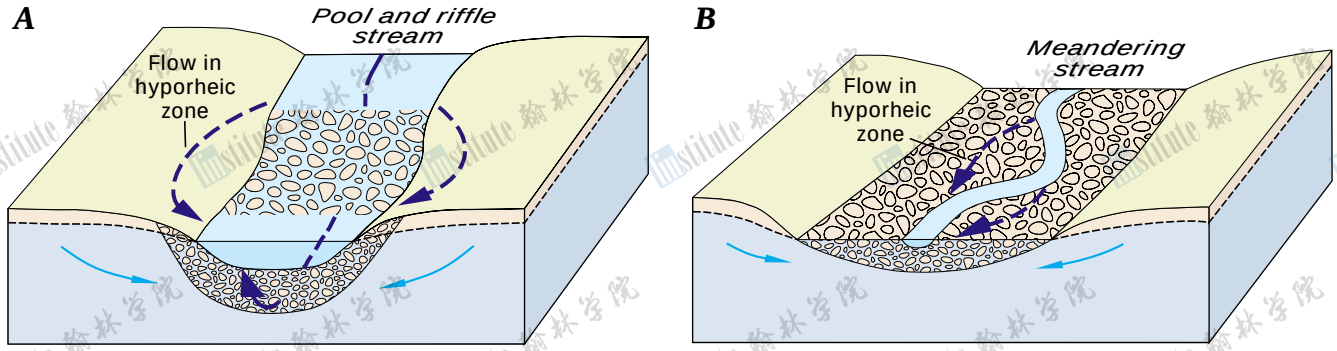


Figure 14. Surface-water exchange with ground water in the hyporheic zone is associated with abrupt changes in streambed slope (A) and with stream meanders (B).

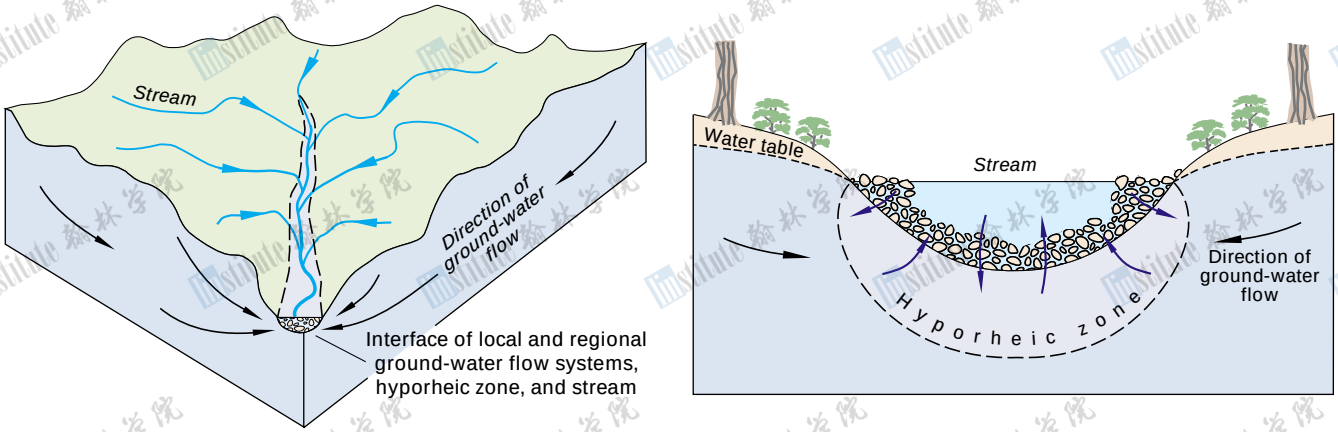


Figure 15. Streambeds and banks are unique environments because they are where ground water that drains much of the subsurface of landscapes interacts with surface water that drains much of the surface of landscapes.

INTERACTION OF GROUND WATER AND LAKES

Lakes interact with ground water in three basic ways: some receive ground-water inflow throughout their entire bed; some have seepage loss to ground water throughout their entire bed; but perhaps most lakes receive ground-water inflow through part of their bed and have seepage loss to ground water through other parts (Figure 16). Although these basic interactions are the same for lakes as they are for streams, the interactions differ in several ways.

The water level of natural lakes, that is, those not controlled by dams, generally does not change as rapidly as the water level of streams; therefore, bank storage is of lesser importance in lakes than it is in streams. Evaporation generally has a greater effect on lake levels than on stream levels because the surface area of lakes is generally larger and less shaded than many reaches of streams, and because lake water is not replenished as readily as a reach of a stream. Lakes can be present in many different parts of the landscape and can have complex ground-water flow systems associated with them. This is especially true for lakes in glacial and dune terrain, as is discussed in a later section of this Circular. Furthermore, lake sediments commonly have greater volumes of organic deposits than streams. These poorly permeable organic deposits can affect the distribution of seepage and biogeochemical exchanges of water and solutes more in lakes than in streams.

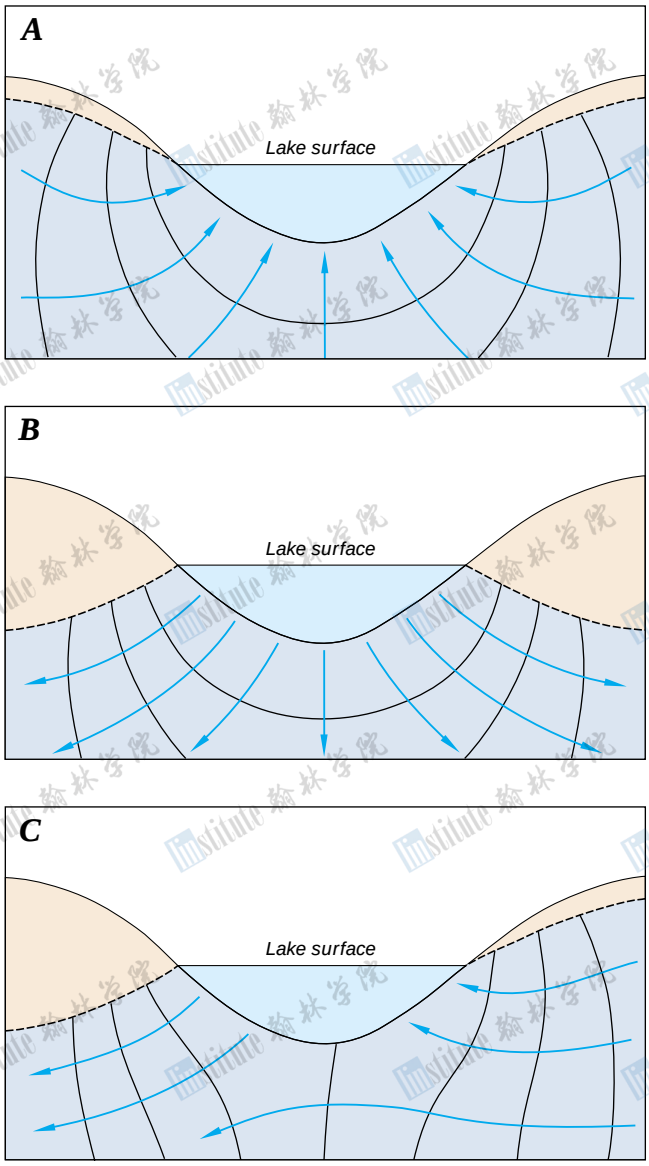


Figure 16. Lakes can receive ground-water inflow (A), lose water as seepage to ground water (B), or both

Reservoirs are human-made lakes that are designed primarily to control the flow and distribution of surface water. Most reservoirs are constructed in stream valleys; therefore, they have some characteristics both of streams and lakes. Like streams, reservoirs can have widely fluctuating levels, bank storage can be significant, and they commonly have a continuous flushing of water through them. Like lakes, reservoirs can have significant loss of water by evaporation, significant cycling of chemical and biological materials within their waters, and extensive biogeochemical exchanges of solutes with organic sediments.

"Lakes and wetlands can receive ground-water inflow throughout their entire bed, have outflow throughout their entire bed, or have both inflow and outflow at different localities"

INTERACTION OF GROUND WATER AND WETLANDS

Wetlands are present in climates and landscapes that cause ground water to discharge to land surface or that prevent rapid drainage of water from the land surface. Similar to streams and lakes, wetlands can receive ground-water inflow, recharge ground water, or do both. Those wetlands that occupy depressions in the land surface have interactions with ground water similar to lakes and streams. Unlike streams and lakes, however, wetlands do not always occupy low points and depressions in the landscape (Figure 17*A*); they also can be present on slopes (such as fens) or even on drainage divides (such as some types of bogs). Fens are wetlands that commonly receive ground-water discharge (Figure 17*B*); therefore, they receive a continuous supply of chemical constituents dissolved in the ground water. Bogs are wetlands that occupy uplands (Figure 17*D*) or extensive flat areas, and they receive much of their water and chemical constituents from precipitation. The distribution of major wetland areas in the United States is shown in Figure 18.

In areas of steep land slopes, the water table sometimes intersects the land surface, resulting in ground-water discharge directly to the land surface. The constant source of water at these seepage faces (Figure 17*B*) permits the growth of wetland plants. A constant source of ground water to wetland plants is also provided to parts of the landscape that are downgradient from breaks in slope of the water table (Figure 17*B*), and where subsurface discontinuities in geologic units cause upward movement of ground water (Figure 17*A*). Many wetlands are present along streams, especially slow-moving streams. Although these riverine wetlands (Figure 17*C*) commonly receive ground-water discharge, they are dependent primarily on the stream for their water supply.

Wetlands in riverine and coastal areas have especially complex hydrological interactions because they are subject to periodic water-level changes. Some wetlands in coastal areas are affected by very predictable tidal cycles. Other coastal wetlands and riverine wetlands are more affected by seasonal water-level changes and by flooding. The combined effects of precipitation, evapotranspiration, and interaction with surface water and ground water result in a pattern of water depths in wetlands that is distinctive.

Hydroperiod is a term commonly used in wetland science that refers to the amplitude and frequency of water-level fluctuations. Hydroperiod affects all wetland characteristics, including the type of vegetation, nutrient cycling, and the types of invertebrates, fish, and bird species present.

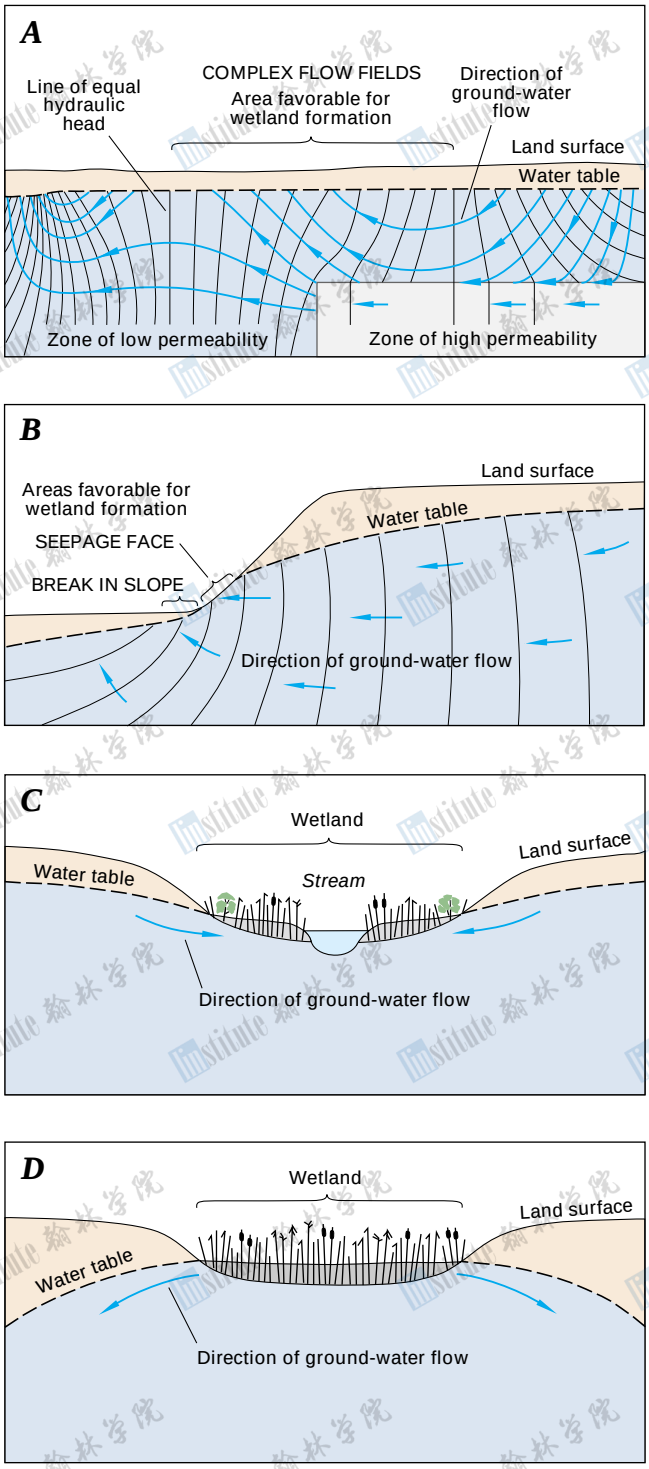


Figure 17. The source of water to wetlands can be from ground-water discharge where the land surface is underlain by complex ground-water flow fields (A), from ground-water discharge at seepage faces and at breaks in slope of the water table (B), from streams (C), and from precipitation in cases where wetlands have no stream inflow and ground-water gradients slope away from the wetland (D).

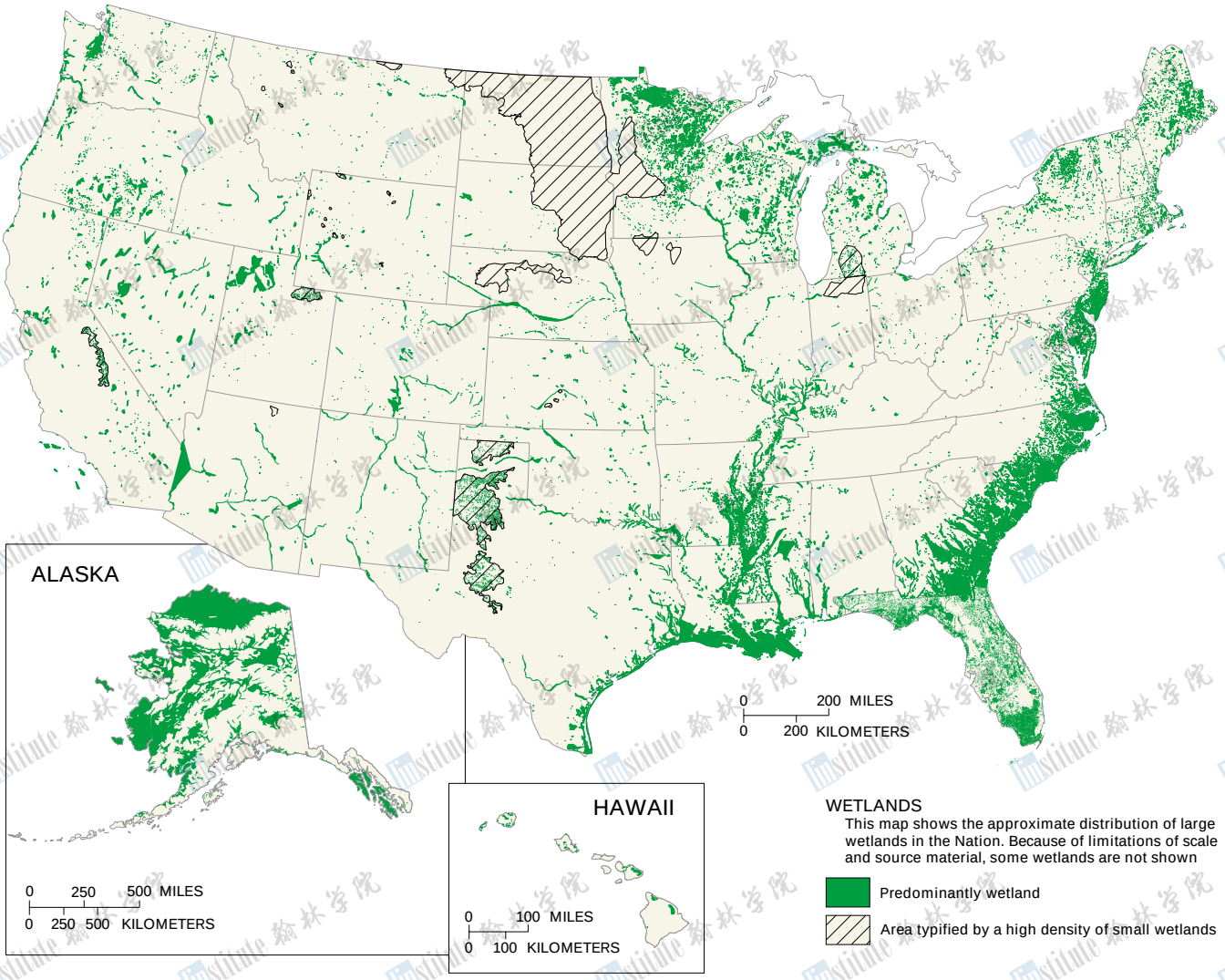


*Figure **18**. Wetlands are present throughout the Nation, but they cover the largest areas in the glacial terrain of the north-central United States, coastal terrain along the Atlantic and gulf coasts, and riverine terrain in the lower Mississippi River Valley.*

A major difference between lakes and wetlands, with respect to their interaction with ground water, is the ease with which water moves through their beds. Lakes commonly are shallow around their perimeter where waves can remove fine-grained sediments, permitting the surface water and ground water to interact freely. In wetlands, on the other hand, if fine-grained and highly decomposed organic sediments are present near the wetland edge, the transfer of water and solutes between ground water and surface water is likely to be much slower.

Another difference in the interaction between ground water and surface water in wetlands compared to lakes is determined by rooted vegetation in wetlands. The fibrous root mat in wetland soils is highly conductive to water flow; therefore, water uptake by roots of emergent plants results in significant interchange between surface water and pore water of wetland sediments. The water exchanges in this upper soil zone even if exchange between surface water and ground water is restricted at the base of the wetland sediments.

Chemical Interactions of Ground Water and Surface Water

EVOLUTION OF WATER CHEMISTRY IN DRAINAGE BASINS

Two of the fundamental controls on water chemistry in drainage basins are the type of geologic materials that are present and the length of time that water is in contact with those materials. Chemical reactions that affect the biological and geochemical characteristics of a basin include (1) acid-base reactions, (2) precipitation and dissolution of minerals, (3) sorption and ion exchange, (4) oxidation-reduction reactions, (5) biodegradation, and (6) dissolution and exsolution of gases (see Box D). When water first infiltrates the land surface, microorganisms in the soil have a significant effect on the evolution of water chemistry. Organic matter in soils is degraded by microbes, producing high concentrations of dissolved carbon dioxide (CO_2). This process lowers the pH by increasing the carbonic acid (H_2CO_3) concentration in the soil water. The production of carbonic acid starts a number of mineral-weathering reactions, which result in bicarbonate (HCO_3^-) commonly being the most abundant anion in the water. Where contact times between water and minerals in shallow ground-water flow paths are short, the dissolved-solids concentration in the water generally is low. In such settings, limited chemical changes take place before ground water is discharged to surface water.

"Two of the fundamental controls on water chemistry in drainage basins are the type of geologic materials that are present and the length of time that water is in contact with those materials"

In deeper ground-water flow systems, the contact time between water and minerals is much longer than it is in shallow flow systems. As a result, the initial importance of reactions relating to microbes in the soil zone may be superseded over time by chemical reactions between minerals and water (geochemical weathering). As weathering progresses, the concentration of dissolved solids increases. Depending on the chemical composition of the minerals that are weathered, the relative abundance of the major inorganic chemicals dissolved in the water changes (see Box E).

Surface water in streams, lakes, and wetlands can repeatedly interchange with nearby ground water. Thus, the length of time water is in contact with mineral surfaces in its drainage basin can continue after the water first enters a stream, lake, or wetland. An important consequence of these continued interchanges between surface water and ground water is their potential to further increase the contact time between water and chemically reactive geologic materials.

CHEMICAL INTERACTIONS OF GROUND WATER AND SURFACE WATER IN STREAMS, LAKES, AND WETLANDS

Ground-water chemistry and surface-water chemistry cannot be dealt with separately where surface and subsurface flow systems interact. The movement of water between ground water and surface water provides a major pathway for chemical transfer between terrestrial and aquatic systems (see Box F). This transfer of chemicals affects the supply of carbon, oxygen, nutrients such as nitrogen and phosphorus, and other chemical constituents that enhance biogeo-chemical processes on both sides of the interface. This transfer can ultimately affect the biological and chemical characteristics of aquatic systems downstream.

"The movement of water between ground water and surface water provides a major pathway for chemical transfer between terrestrial and aquatic systems"

D

Some Common Types of Biogeochemical Reactions Affecting Transport of Chemicals in Ground Water and Surface Water

ACID-BASE REACTIONS

Acid-base reactions involve the transfer of hydrogen ions (H^+) among solutes dissolved in water, and they affect the effective concentrations of dissolved chemicals through changes in the H^+ concentration in water. A brief notation for H^+ concentration (activity) is pH, which represents a negative logarithmic scale of the H^+ concentration. Smaller values of pH represent larger concentrations of H^+, and larger values of pH represent smaller concentrations of H^+. Many metals stay dissolved when pH values are small; increased pH causes these metals to precipitate from solution.

PRECIPITATION AND DISSOLUTION OF MINERALS

Precipitation reactions result in minerals being formed (precipitated) from ions that are dissolved in water. An example of this type of reaction is the precipitation of iron, which is common in areas of ground-water seeps and springs. At these locations, the solid material iron hydroxide is formed when iron dissolved in ground water comes in contact with oxygen dissolved in surface water. The reverse, or dissolution reactions, result in ions being released into water by dissolving minerals. An example is the release of calcium ions (Ca^{++}) and bicarbonate ions (HCO_3^-) when calcite ($CaCO_3$) in limestone is dissolved.

SORPTION AND ION EXCHANGE

Sorption is a process in which ions or molecules dissolved in water (solutes) become attached to the surfaces (or near-surface parts) of solid materials, either temporarily or permanently. Thus, solutes in ground water and surface water can be sorbed either to the solid materials that comprise an aquifer or streambed or to particles suspended in ground water or surface water. The attachments of positively charged ions to clays and of pesticides to solid surfaces are examples of sorption. Release of sorbed chemicals to water is termed desorption.

When ions attached to the surface of a solid are replaced by ions that were in water, the process is known as ion exchange. Ion exchange is the process that takes place in water softeners; ions that contribute to water hardness—calcium and magnesium—are exchanged for sodium on the surface of the solid. The result of this process is that the amount of calcium and magnesium in the water declines and the amount of sodium increases. The opposite takes place when saltwater enters an aquifer; some of the sodium in the saltwater is exchanged for calcium sorbed to the solid material of the aquifer.

OXIDATION-REDUCTION REACTIONS

Oxidation-reduction (redox) reactions take place when electrons are exchanged among solutes. In these reactions, oxidation (loss of electrons) of certain elements is accompanied by the reduction (gain of electrons) of other elements.

For example, when iron dissolved in water that does not contain dissolved oxygen mixes with water that does contain dissolved oxygen, the iron and oxygen interact by oxidation and reduction reactions. The result of the reactions is that the dissolved iron loses electrons (the iron is oxidized) and oxygen gains electrons (the oxygen is reduced). In this case, the iron is an electron donor and the oxygen is an electron acceptor. Bacteria can use energy gained from oxidation-reduction reactions as they decompose organic material. To accomplish this, bacterially mediated oxidation-reduction reactions use a sequence of electron acceptors, including oxygen, nitrate, iron, sulfate, and carbon dioxide. The presence of the products of these reactions in ground water and surface water can be used to identify the dominant oxidation-reduction reactions that have taken place in those waters. For example, the bacterial reduction of sulfate (SO_4^{2-}) to sulfide (HS^-) can result when organic matter is oxidized to CO_2.

BIODEGRADATION

Biodegradation is the decomposition of organic chemicals by living organisms using enzymes. Enzymes are specialized organic compounds made by living organisms that speed up reactions with other organic compounds. Microorganisms degrade (transform) organic chemicals as a source of energy and carbon for growth. Microbial processes are important in the fate and transport of many organic compounds. Some compounds, such as petroleum hydrocarbons, can be used directly by microorganisms as food sources and are rapidly degraded in many situations. Other compounds, such as chlorinated solvents, are not as easily assimilated. The rate of biodegradation of an organic chemical is dependent on its chemical structure, the environmental conditions, and the types of microorganisms that are present. Although biodegradation commonly can result in complete degradation of organic chemicals to carbon dioxide, water, and other simple products, it also can lead to intermediate products that are of environmental concern. For example, deethylatrazine, an intermediate degradation product of the pesticide atrazine (see Box P), commonly is detected in water throughout the corn-growing areas of the United States.

DISSOLUTION AND EXSOLUTION OF GASES

Gases are directly involved in many geochemical reactions. One of the more common gases is carbon dioxide (CO_2). For example, stalactites can form in caves when dissolved CO_2 exsolves (degasses) from dripping ground water, causing pH to rise and calcium carbonate to precipitate. In soils, the microbial production of CO_2 increases the concentration of carbonic acid (H_2CO_3), which has a major control on the solubility of aquifer materials. Other gases commonly involved in chemical reactions are oxygen, nitrogen, hydrogen sulfide (H_2S), and methane (CH_4). Gases such as chlorofluorocarbons (CFCs) and radon are useful as tracers to determine the sources and rates of ground-water movement (see Box G).

E

Evolution of Ground-Water Chemistry from Recharge to Discharge Areas in the Atlantic Coastal Plain

Changes in the chemical composition of ground water in sediments of the Atlantic Coastal Plain (Figure E–1) provide an example of the chemical evolution of ground water in a regional flow system. In the shallow regime, infiltrating water comes in contact with gases in the unsaturated zone and shallow ground water. As a result of this contact, localized, short-term, fast reactions take place that dissolve minerals and degrade organic material. In the deep regime, long-term, slower chemical reactions, such as precipitation and dissolution of minerals and ion-exchange, add or remove solutes. These natural processes and reactions commonly produce a predictable sequence of hydrochemical facies. In the Atlantic Coastal Plain, ground water evolves from water containing abundant bicarbonate ions and small concentrations of dissolved solids near the point of recharge to water containing abundant chloride ions and large concentrations of dissolved solids where it discharges into streams, estuaries, and the Atlantic Ocean.

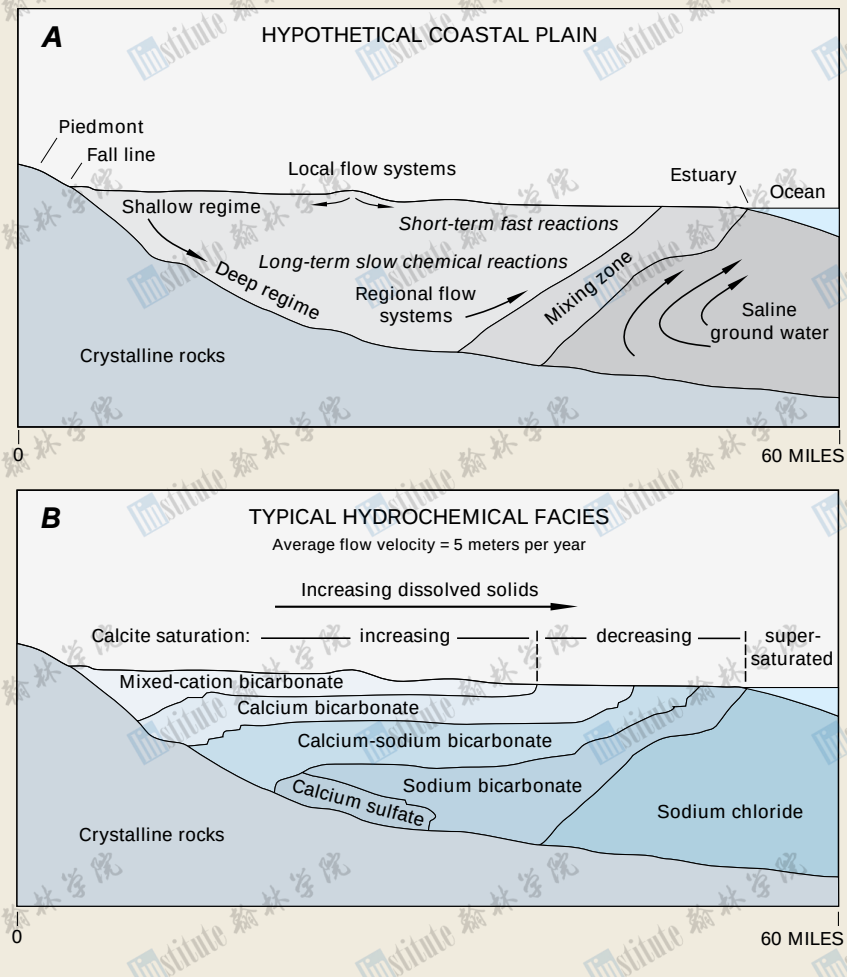


Figure E–1. In a coastal plain, such as along the Atlantic Coast of the United States, the interrelations of different rock types, shallow and deep ground-water flow systems (regimes), and mixing with saline water (A) results in the evolution of a number of different ground-water chemical types (B). (Modified from Back, William, Baedecker, M.J., and Wood, W.W., 1993, Scales in chemical hydrogeology—A historical perspective, in Alley, W.M., ed., Regional Ground-Water Quality: New York, van Nostrand Reinhold, p. 111–129.) (Reprinted by permission of John Wiley & Sons, Inc.)

Many streams are contaminated. Therefore, the need to determine the extent of the chemical reactions that take place in the hyporheic zone is widespread because of the concern that the contaminated stream water will contaminate shallow ground water (see Box G). Streams offer good examples of how interconnections between ground water and surface water affect chemical processes. Rough channel bottoms cause stream water to enter the streambed and to mix with ground water in the hyporheic zone. This mixing establishes sharp changes in chemical concentrations in the hyporheic zone.

A zone of enhanced biogeochemical activity usually develops in shallow ground water as a result of the flow of oxygen-rich surface water into the subsurface environment, where bacteria and geochemically active sediment coatings are abundant (Figure 19). This input of oxygen to the streambed stimulates a high level of activity by aerobic (oxygen-using) microorganisms if dissolved oxygen is readily available. It is not uncommon for dissolved oxygen to be completely used up in hyporheic flow paths at some distance into the streambed, where anaerobic microorganisms dominate microbial activity. Anaerobic bacteria can use nitrate, sulfate, or other solutes in place of oxygen for metabolism. The result of these processes is that many solutes are highly reactive in shallow ground water in the vicinity of streambeds.

The movement of nutrients and other chemical constituents, including contaminants, between ground water and surface water is affected by biogeochemical processes in the hyporheic zone. For example, the rate at which organic contaminants biodegrade in the hyporheic zone can exceed rates in stream water or in ground water away from the stream. Another example is the removal of dissolved metals in the hyporheic zone. As water passes through the hyporheic zone, dissolved metals are removed by precipitation of metal oxide coatings on the sediments.

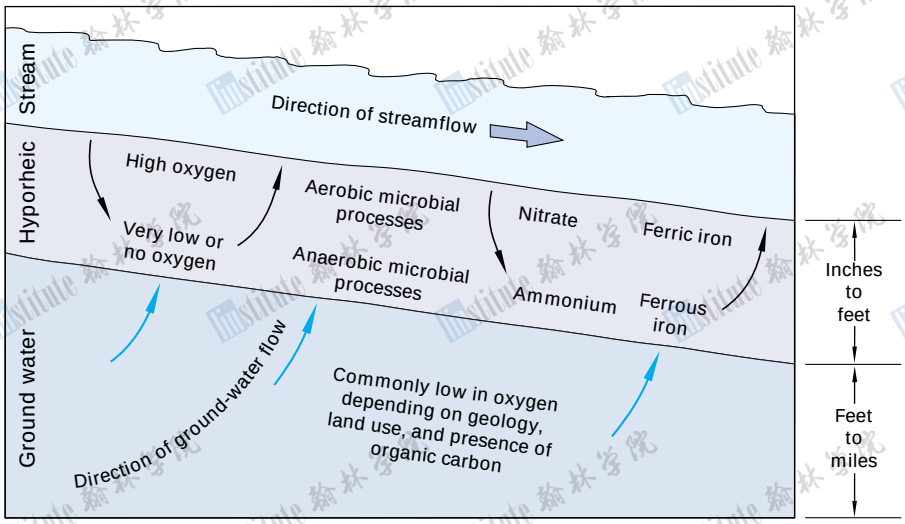


Figure 19. Microbial activity and chemical transformations commonly are enhanced in the hyporheic zone compared to those that take place in ground water and surface water. This diagram illustrates some of the processes and chemical transformations that may take place in the hyporheic zone. Actual chemical interactions depend on numerous factors including aquifer mineralogy, shape of the aquifer, types of organic matter in surface water and ground water, and nearby land use.

F

The Interface Between Ground Water and Surface Water as an Environmental Entity

In the bed and banks of streams, water and solutes can exchange in both directions across the streambed. This process, termed hyporheic exchange, creates subsurface environments that have variable proportions of water from ground water and surface water. Depending on the type of sediment in the streambed and banks, the variability in slope of the streambed, and the hydraulic gradients in the adjacent ground-water system, the hyporheic zone can be as much as several feet in depth and hundreds of feet in width. The dimensions of the hyporheic zone generally increase with increasing width of the stream and permeability of streambed sediments.

The importance of the hyporheic zone was first recognized when higher than expected abundances of aquatic insects were found in sediments where concentrations of oxygen were high. Caused by stream-water input, the high oxygen concentrations in the hyporheic zone make it possible for organisms to live in the pore spaces in the sediments, thereby providing a refuge for those organisms. Also, spawning success of salmon is greater where flow from the stream brings oxygen into contact with eggs that were deposited within the coarse sediment.



The hyporheic zone also can be a source of nutrients and algal cells to streams that foster the recovery of streams following catastrophic storms. For example, in a study of the ecology of Sycamore Creek in Arizona, it was found that the algae that grew in the top few inches of streambed sediment were quickest to recover following storms in areas where water in the sediments moved upward (Figure F–1).

These algae recovered rapidly following storms because concentrations of dissolved nitrogen were higher in areas of the streambed where water moved upward than in areas where water moved downward. Areas of streambed where water moved upward are, therefore, likely to be the first areas to return to more normal ecological conditions following flash floods in desert streams.

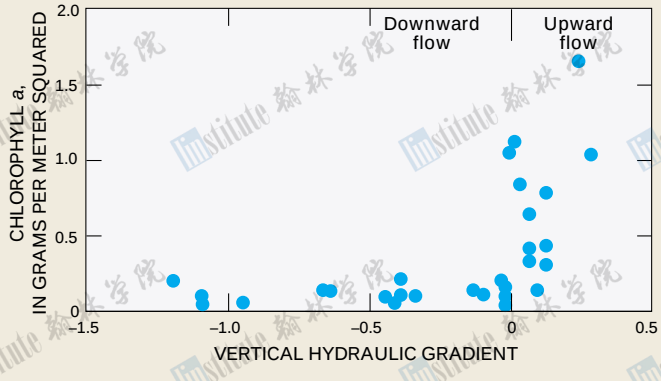


Figure F–1. Abundance of algae in streambed sediments, as indicated by concentration of chlorophyll a, was markedly greater in areas where water moved upward through the sediments than in areas where water moved downward through the sediments in Sycamore Creek in Arizona. (Modified from Valett, H.M., Fisher, S.G., Grimm, N.B., and Camill, P., 1994, Vertical hydrologic exchange and ecologic stability of a desert stream ecosystem: Ecology, v. 75, p. 548–560.) (Reprinted with permission.)

Hyporheic zones also serve as sites for nutrient uptake. A study of a coastal mountain stream in northern California indicated that transport of dissolved oxygen, dissolved carbon, and dissolved nitrogen in stream water into the hyporheic zone stimulated uptake of nitrogen by microbes and algae attached to sediment. A model simulation of nitrogen uptake (Figure F–2) indicated that both the physical process of water exchange between the stream and the hyporheic zone and the biological uptake of nitrate in the hyporheic zone affected the concentration of dissolved nitrogen in the stream.

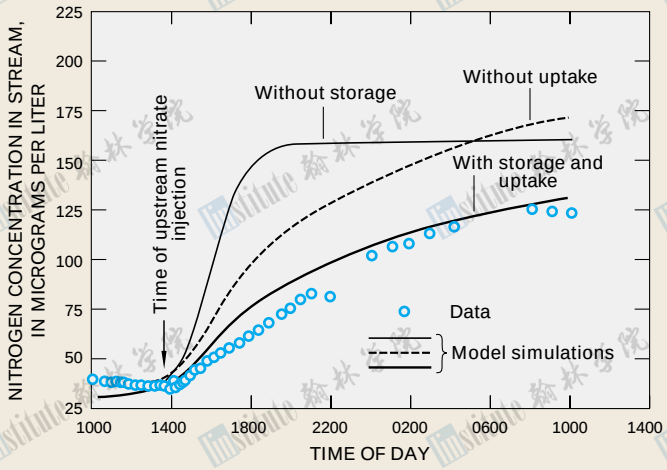


Figure F–2. Nitrate injected into Little Lost Man Creek in northern California was stored and taken up by algae and microbes in the hyporheic zone. (Modified from Kim, B.K.A., Jackman, A.P., and Triska, F.J., 1992, Modeling biotic uptake by periphyton and transient hyporheic storage of nitrate in a natural stream: Water Resources Research, v. 28, no.10, p. 2743–2752.)

The importance of biogeochemical processes that take place at the interface of ground water and surface water in improving water quality for human consumption is shown by the following example. Decreasing metal concentrations (Figure F–3) in drinking-water wells adjacent to the River Glatt in Switzerland was attributed to the interaction of the river with subsurface water. The improvement in ground-water quality started with improved sewage-treatment plants, which lowered phosphate in the river. Lower phosphate concentrations lowered the amount of algal production in the river, which decreased the amount of dissolved organic carbon flowing into the riverbanks. These factors led to a decrease in the bacteria-caused dissolution of manganese and cadmium that were present as coatings on sediment in the aquifer. The result was substantially lower dissolved metal concentrations in ground water adjacent to the river, which resulted in an unexpected improvement in the quality of drinking water.

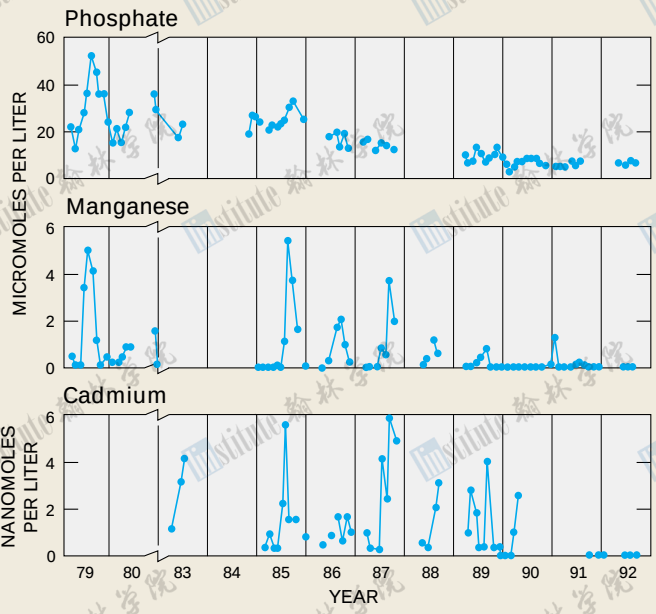
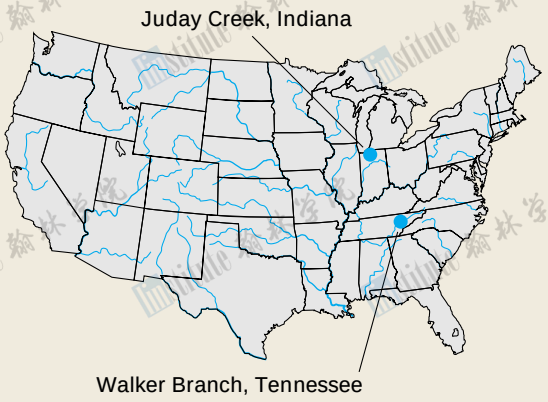


Figure F–3. A decline in manganese and cadmium concentrations after 1990 in drinking-water wells near the River Glatt in Switzerland was attributed to decreased phosphate in the river and hydrologic and biogeochemical interactions between river water and ground water. (Modified from von Gunten, H.R., and Lienert, Ch., 1993, Decreased metal concentrations in ground water caused by controls on phosphate emissions: Nature, v. 364, p. 220–222.) (Reprinted with permission from Nature, Macmillan Magazines Limited.)

G

Use of Environmental Tracers to Determine the Interaction of Ground Water and Surface Water

Environmental tracers are naturally occurring dissolved constituents, isotopes, or physical properties of water that are used to track the movement of water through watersheds. Useful environmental tracers include (1) common dissolved constituents, such as major cations and anions; (2) stable isotopes of oxygen (^{18}O) and hydrogen (^{2}H) in water molecules; (3) radioactive isotopes such as tritium (^{3}H) and radon (^{222}Rn); and (4) water temperature. When used in simple hydrologic transport calculations, environmental tracers can be used to (1) determine source areas of water and dissolved chemicals in drainage basins, (2) calculate hydrologic and chemical fluxes between ground water and surface water, (3) calculate water ages that indicate the length of time water and dissolved chemicals have been present in the drainage basin (residence times), and (4) determine average rates of chemical reactions that take place during transport. Some examples are described below.



Major cations and anions have been used as tracers in studies of the hydrology of small watersheds to determine the sources of water to streamflow during storms (see Figure G–1). In addition, stable isotopes of oxygen and hydrogen, which are part of water molecules, are useful for determining the mixing of waters from different source areas because of such factors as (1) differences in the isotopic composition of precipitation among recharge areas, (2) changes in the isotopic composition of shallow subsurface water caused by evaporation, and (3) temporal variability in the isotopic composition of precipitation relative to ground water.

Radioactive isotopes are useful indicators of the time that water has spent in the ground-water system. For example, tritium (^{3}H) is a well-known radioactive isotope of hydrogen that had peak concentrations in precipitation in the mid-1960s as a result of above-ground nuclear-bomb testing conducted at that time. Chlorofluorocarbons (CFCs), which are industrial chemicals that are present in ground water less than 50 years old, also can be used to calculate ground-water age in different parts of a drainage basin.

$^{222}Radon$ is a chemically inert, radioactive gas that has a half-life of only 3.83 days. It is produced naturally in ground water as a product of the radioactive decay of $^{226}radium$ in uranium-bearing rocks and sediment. Several studies have documented that radon can be used to identify locations of

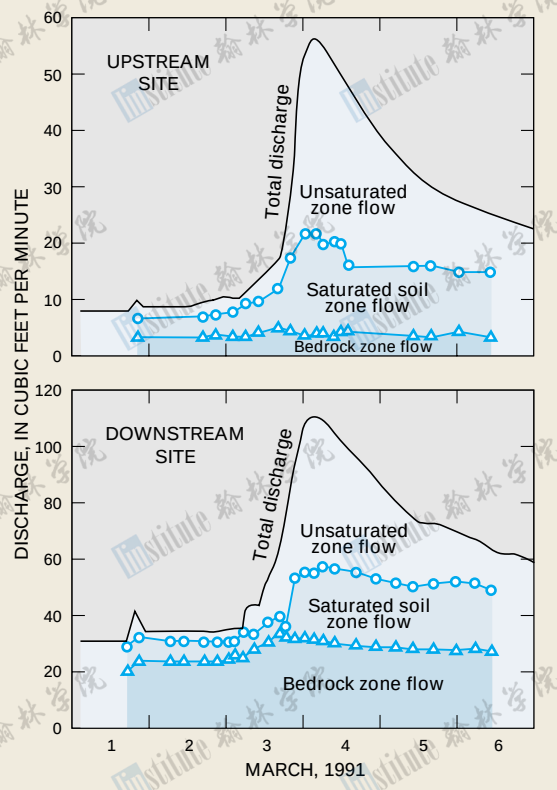


Figure G–1. The relative contributions of different subsurface water sources to streamflow in a stream in Tennessee were determined by analyzing the relative concentrations of calcium and sulfate. Note that increases in bedrock zone (ground water) flow appear to contribute more to the stormflow response at the downstream site than to the stormflow response at the upstream site in this small watershed. (Modified from Mulholland, P.J., 1993, Hydrometric and stream chemistry evidence of three storm flowpaths in Walker Branch Watershed: Journal of Hydrology, v. 151, p. 291–316.) (Reprinted with permission from Elsevier Science-NL, Amsterdam, The Netherlands.)

significant ground-water input to a stream, such as from springs. Radon also has been used to determine stream-water movement to ground water. For example, radon was used in a study in France to determine stream-water loss to ground water as a result of ground-water withdrawals. (See Figure G–2.)

An example of using stream-water temperature and sediment temperature for mapping gaining and losing reaches of a stream is shown in Figure G–3. In gaining reaches of the stream, sediment temperature and stream-water temperature are markedly different. In losing reaches of the stream, the diurnal fluctuations of temperature in the stream are reflected more strongly in the sediment temperature.

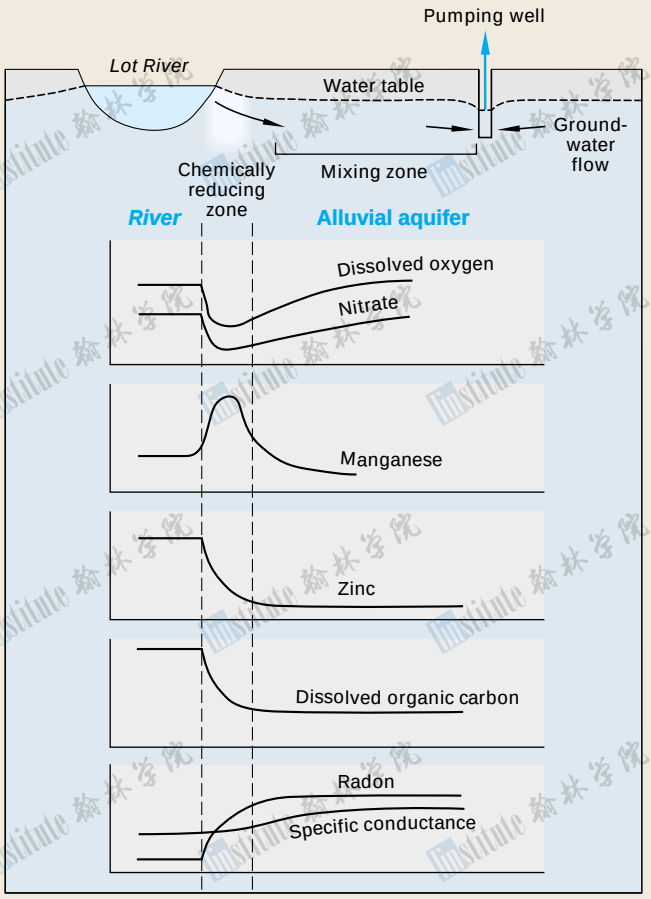


Figure G–2. Sharp changes in chemical concentrations were detected over short distances as water from the Lot River in France moved into its contiguous alluvial aquifer in response to pumping from a well. Specific conductance of water was used as an environmental tracer to determine the extent of mixing of surface water with ground water, and radon was used to determine the inflow rate of stream water. Both pieces of information were then used to calculate the rate at which dissolved metals reacted to form solid phases during movement of stream water toward the pumping well. (Modified from Bourg, A.C.M., and Bertin, C., 1993, Biogeochemical processes during the infiltration of river water into an alluvial aquifer: Environmental Science and Technology, v. 27, p. 661–666.) (Reprinted with permission from the American Chemical Society.)

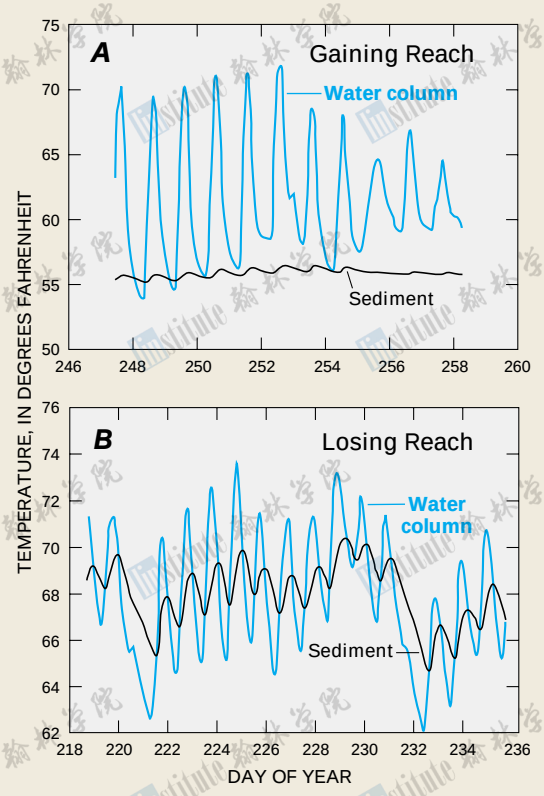


Figure G–3. Ground-water temperatures generally are more stable than surface-water temperatures. Therefore, gaining reaches of Juday Creek in Indiana are characterized by relatively stable sediment temperatures compared to stream-water temperatures (A). Conversely, losing reaches are characterized by more variable sediment temperatures caused by the temperature of the inflowing surface water (B). (Modified from Silliman, S.E., and Booth, D.F., 1993, Analysis of time series measurements of sediment temperature for identification of gaining versus losing portions of Juday Creek, Indiana: Journal of Hydrology, v. 146, p. 131–148.) (Reprinted with permission from Elsevier Science-NL, Amsterdam, The Netherlands.)

Lakes and wetlands also have distinctive biogeochemical characteristics with respect to their interaction with ground water. The chemistry of ground water and the direction and magnitude of exchange with surface water significantly affect the input of dissolved chemicals to lakes and wetlands. In general, if lakes and wetlands have little interaction with streams or with ground water, input of dissolved chemicals is mostly from precipitation; therefore, the input of chemicals is minimal. Lakes and wetlands that have a considerable amount of ground-water inflow generally have large inputs of dissolved chemicals. In cases where the input of dissolved nutrients such as phosphorus and nitrogen exceeds the output, primary production by algae and wetland plants is large. When this large amount of plant material dies, oxygen is used in the process of decomposition. In some cases the loss of oxygen from lake water can be large enough to kill fish and other aquatic organisms.

The magnitude of surface-water inflow and outflow also affects the retention of nutrients in wetlands. If lakes or wetlands have no stream outflow, retention of chemicals is high. The tendency to retain nutrients usually is less in wetlands that are flushed substantially by throughflow of surface water. In general, as surface-water inputs increase, wetlands vary from those that strongly retain nutrients to those that both import and export large amounts of nutrients. Furthermore, wetlands commonly have a significant role in altering the chemical form of dissolved constituents. For example, wetlands that have throughflow of surface water tend to retain the chemically oxidized forms and release the chemically reduced forms of metals and nutrients.

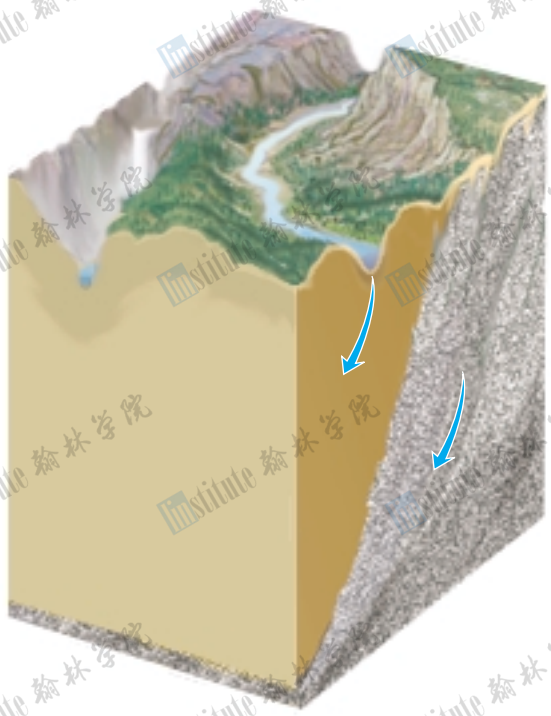
"The chemistry of ground water and the direction and magnitude of exchange with surface water significantly affect the input of dissolved chemicals to lakes and wetlands"

Interaction of Ground Water and Surface Water in Different Landscapes

Ground water is present in virtually all landscapes. The interaction of ground water with surface water depends on the physiographic and climatic setting of the landscape. For example, a stream in a wet climate might receive ground-water inflow, but a stream in an identical physiographic setting in an arid climate might lose water to ground water. To provide a broad and unified perspective of the interaction of ground water and surface water in different landscapes, a conceptual landscape (Figure 2) is used as a reference. Some common features of the interaction for various parts of the conceptual landscape are described below. The five general types of terrain discussed are mountainous, riverine, coastal, glacial and dune, and karst.

MOUNTAINOUS TERRAIN

The hydrology of mountainous terrain (area M of the conceptual landscape, Figure 2) is characterized by highly variable precipitation and water movement over and through steep land slopes. On mountain slopes, macropores created by burrowing organisms and by decay of plant roots have the capacity to transmit subsurface flow downslope quickly. In addition, some rock types underlying soils may be highly weathered or fractured and may transmit significant additional amounts of flow through the subsurface. In some settings this rapid flow of water results in hillside springs.



A general concept of water flow in mountainous terrain includes several pathways by which precipitation moves through the hillside to a stream (Figure 20). Between storm and snowmelt periods, streamflow is sustained by discharge from the ground-water system (Figure 20*A*). During intense storms, most water reaches streams very rapidly by partially saturating and flowing through the highly conductive soils. On the lower parts of hillslopes, the water table sometimes rises to the land surface during storms, resulting in overland flow (Figure 20*B*). When this occurs, precipitation on the saturated area adds to the quantity of overland flow. When storms or snowmelt persist in mountainous areas, near-stream saturated areas can expand outward from streams to include areas higher on the hillslope. In some settings, especially in arid regions, overland flow can be generated when the rate of rainfall exceeds the infiltration capacity of the soil (Figure 20*C*).

Near the base of some mountainsides, the water table intersects the steep valley wall some distance up from the base of the slope (Figure 21, left side of valley). This results in perennial

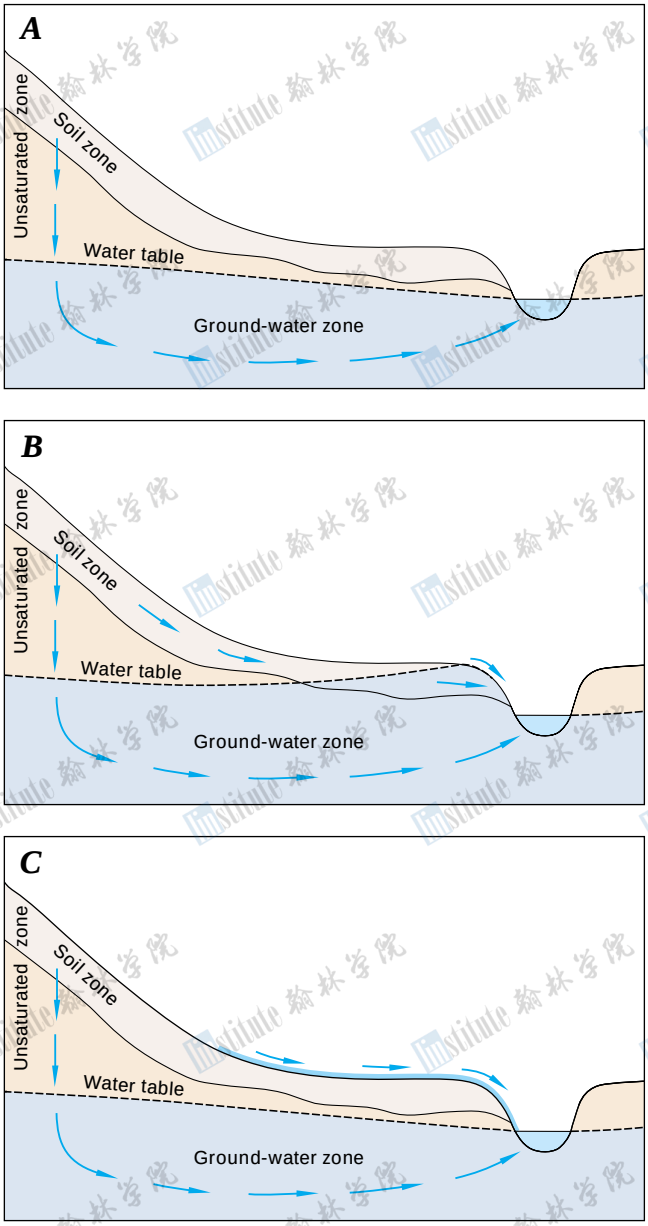


Figure 20. Water from precipitation moves to mountain streams along several pathways. Between storms and snowmelt periods, most inflow to streams commonly is from ground water (A). During storms and snowmelt periods, much of the water inflow to streams is from shallow flow in saturated macropores in the soil zone. If infiltration to the water table is large enough, the water table will rise to the land surface and flow to the stream is from ground water, soil water, and overland runoff (B). In arid areas where soils are very dry and plants are sparse, infiltration is impeded and runoff from precipitation can occur as overland flow (C). (Modified from Dunne, T., and Leopold, L.B., 1978, Water in environmental planning: San Francisco, W.H. Freeman.) (Used with permission.)

discharge of ground water and, in many cases, the presence of wetlands. A more common hydrologic process that results in the presence of wetlands in some mountain valleys is the upward discharge of ground water caused by the change in slope of the water table from being steep on the valley side to being relatively flat in the alluvial valley (Figure 21, right side of valley). Where both of these water-table conditions exist, wetlands fed by ground water, which commonly are referred to as fens, can be present.

Another dynamic aspect of the interaction of ground water and surface water in mountain settings is caused by the marked longitudinal component of flow in mountain valleys. The high gradient of mountain streams, coupled with the coarse texture of streambed sediments, results in a strong down-valley component of flow accompanied by frequent exchange of stream water with water in the hyporheic zone (Figure 14) (see Box H). The driving force for water exchange between a stream and its hyporheic zone is created by the surface water flowing over rough streambeds, through pools and riffles, over cascades, and around boulders and logs. Typically, the stream enters the hyporheic zone at the downstream end of pools and then flows beneath steep sections of the stream (called riffles), returning to the stream at the upstream end of the next pool (Figure 14*A*). Stream water also may enter the hyporheic zone upstream from channel meanders, causing stream water to flow through a gravel bar before reentering the channel downstream (Figure 14*B*).

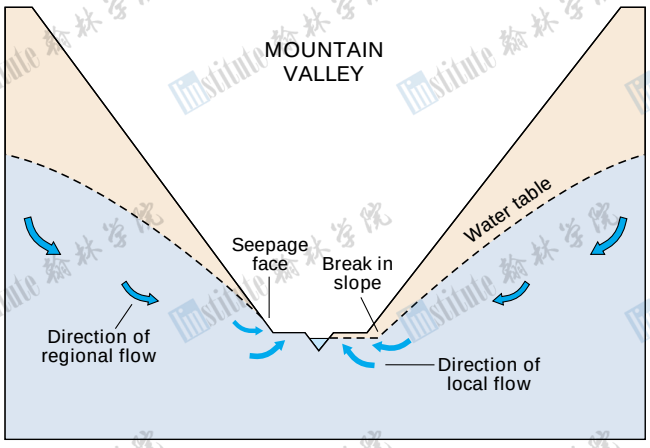


Figure 21. In mountainous terrain, ground water can discharge at the base of steep slopes (left side of valley), at the edges of flood plains (right side of valley), and to the stream.

Streams flowing from mountainous terrain commonly flow across alluvial fans at the edges of the valleys. Most streams in this type of setting lose water to ground water as they traverse the highly permeable alluvial fans. This process has long been recognized in arid western regions, but it also has been documented in humid regions, such as the Appalachian Mountains. In arid and semiarid regions, seepage of water from the stream can be the principal source of aquifer recharge. Despite its importance, ground-water recharge from losing streams remains a highly uncertain part of the water balance of aquifers in these regions. Promising new methods of estimating ground-water recharge, at least locally, along mountain fronts are being developed—these methods include use of environmental tracers, measuring vertical temperature profiles in streambeds, measuring hydraulic characteristics of streambeds, and measuring the difference in hydraulic head between the stream and the underlying aquifer.

The most common natural lakes in mountainous terrain are those that are dammed by rock sills or glacial deposits high in the mountains. Termed cirque lakes, they receive much of their water from snowmelt. However, they interact with ground water much like the processes shown in Figure 21, and they can be maintained by ground water throughout the snow-free season.

The geochemical environment of mountains is quite diverse because of the effects of highly variable climate and many different rock and soil types on the evolution of water chemistry. Geologic materials can include crystalline, volcanic, and sedimentary rocks and glacial deposits. Sediments can vary from those having well-developed soil horizons to stream alluvium that has no soil development. During heavy precipitation, much water flows through shallow flow paths, where it interacts with microbes and soil gases. In the deeper flow through fractured bedrock, longer term geochemical interactions of ground water with minerals determine the chemistry of water that eventually discharges to streams. Base flow of streams in mountainous terrain is derived by drainage from saturated alluvium in valley bottoms and from drainage of bedrock fractures. Mixing of these chemically different water types results in geochemical reactions that affect the chemistry of water in streams. During downstream transport in the channel, stream water mixes with ground water in the hyporheic zone. In some mountain streams, the volume of water in the hyporheic zone is considerably larger than that in the stream channel. Chemical reactions in hyporheic zones can, in some cases, substantially alter the water chemistry of streams (Figure 19).

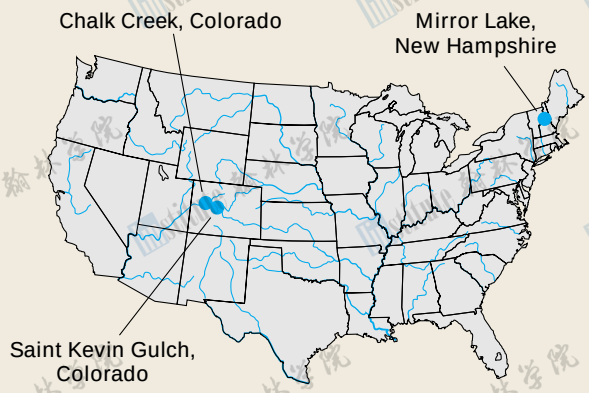
H

Field Studies of Mountainous Terrain

The steep slopes and rocky characteristics of mountainous terrain make it difficult to determine interactions of ground water and surface water. Consequently, few detailed hydrogeologic investigations of these interactions have been conducted in mountainous areas. Two examples are given below.

A field and modeling study of the Mirror Lake area in the White Mountains of New Hampshire indicated that the sizes of ground-water flow systems contributing to surface-water bodies were considerably larger than their topographically defined watersheds. For example, much of the ground water in the fractured bedrock that discharges to Mirror Lake passes beneath the local flow system associated with Norris Brook (Figure H–1). Furthermore, a more extensive deep ground-water flow system that discharges to the Pemigewasset River passes beneath flow systems associated with both Norris Brook and Mirror Lake.

Studies in mountainous terrain have used tracers to determine sources of ground water to streams (see Box G). In addition to revealing processes of water exchange between ground water and stream water, solute tracers have proven useful for defining the limits of the hyporheic zone surrounding mountain streams. For example, solute tracers such as chloride or bromide ions are injected into the stream to artificially raise concentrations above natural background concentrations. The locations and amounts of ground-water inflow are determined from a simple dilution model. The extent that tracers move into the hyporheic zone can be estimated by the models and commonly is verified by sampling wells placed in the study area.



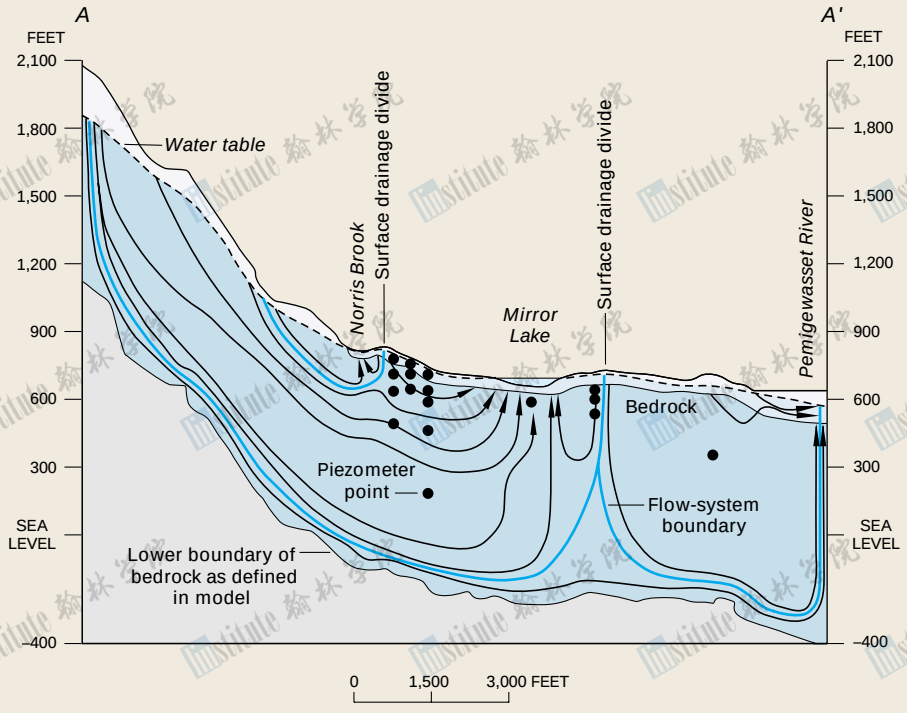


Figure H–1. Ground-water flow systems in the Mirror Lake area extend beyond the topographically defined surface-water watersheds. (Modified from Harte, P.T., and Winter, T.C., 1996, Factors affecting recharge to crystalline rock in the Mirror Lake area, Grafton County, New Hampshire: in Morganwalp, D.W., and Aronson, D.A., eds., U.S. Geological Survey Toxic Substances Hydrology Program—Proceedings of Technical Meeting, Colorado Springs, Colorado, September 20–24, 1993: U.S. Geological Survey Water-Resources Investigations Report 94–4014, p. 141–150.)

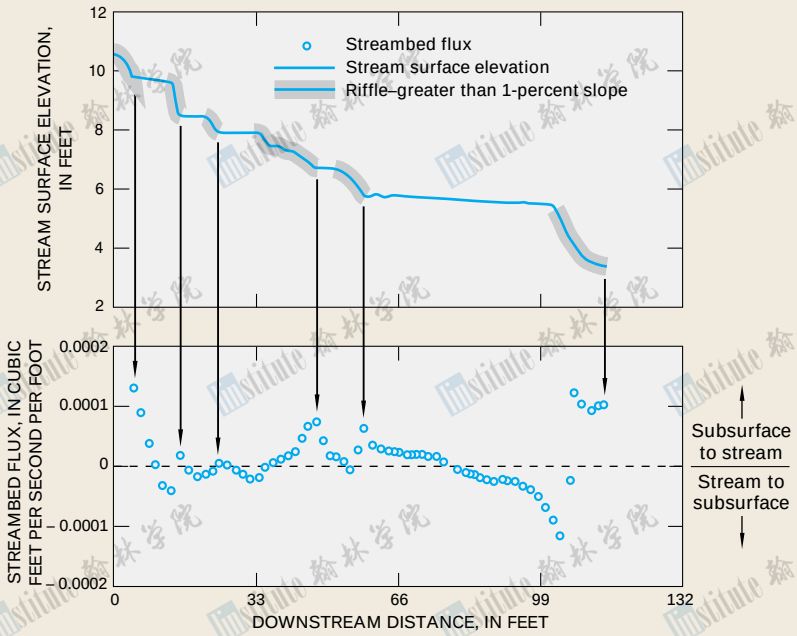


Figure H–2. In mountain streams characterized by pools and riffles, such as at Saint Kevin Gulch in Colorado, inflow of water from the hyporheic zone to the stream was greatest at the downstream end of riffles. (Modified from Harvey, J.W., and Bencala, K.E., 1993, The effect of streambed topography on surface-subsurface water exchange in mountain catchments: Water Resources Research, v. 29, p. 89–98.)

A study in Colorado indicated that hyporheic exchange in mountain streams is caused to a large extent by the irregular topography of the streambed, which creates pools and riffles characteristic of mountain streams. Ground water enters streams most readily at the upstream end of deep pools, and stream water flows into the subsurface beneath and to the side of steep sections of streams (riffles) (Figure H–2). Channel irregularity, therefore, is an important control on the location of ground-water inflow to streams and on the size of the hyporheic zone in mountain streams because changes in slope determine the length and depth of hyporheic flow paths.

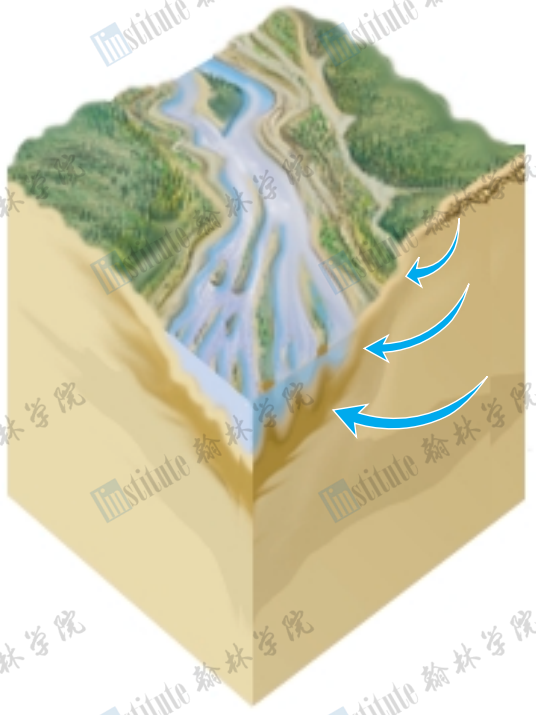
The source and fate of metal contaminants in streams receiving drainage from abandoned mines can be determined by using solute tracers. In addition to surface drainage from mines, a recent study of Chalk Creek in Colorado indicated that contaminants were being brought to the stream by ground-water inflow. The ground water had been contaminated from mining activities in the past and is now a new source of contamination to the stream. This nonpoint ground-water source of contamination will very likely be much more difficult to clean up than the point source of contamination from the mine tunnel.

RIVERINE TERRAIN

In some landscapes, stream valleys are small and they commonly do not have well-developed flood plains (area R of the conceptual landscape, Figure 2) (see Box I). However, major rivers (area V of the reference landscape, Figure 2) have valleys that usually become increasingly wider downstream. Terraces, natural levees, and abandoned river meanders are common landscape features in major river valleys, and wetlands and lakes commonly are associated with these features.

The interaction of ground water and surface water in river valleys is affected by the interchange of local and regional ground-water flow systems with the rivers and by flooding and evapotranspiration. Small streams receive ground-water inflow primarily from local flow systems, which usually have limited extent and are highly variable seasonally. Therefore, it is not unusual for small streams to have gaining or losing reaches that change seasonally.

For larger rivers that flow in alluvial valleys, the interaction of ground water and surface water usually is more spatially diverse than it is for smaller streams. Ground water from regional flow systems discharges to the river as well as at various places across the flood plain (Figure 22).
If terraces are present in the alluvial valley, local ground-water flow systems may be associated with each terrace, and lakes and wetlands may be formed because of this source of ground water. At some locations, such as at the valley wall and at the river, local and regional ground-water flow systems may discharge in close proximity. Furthermore, in large alluvial valleys, significant down-valley components of flow in the streambed and in the shallow alluvium also may be present (see Box I).



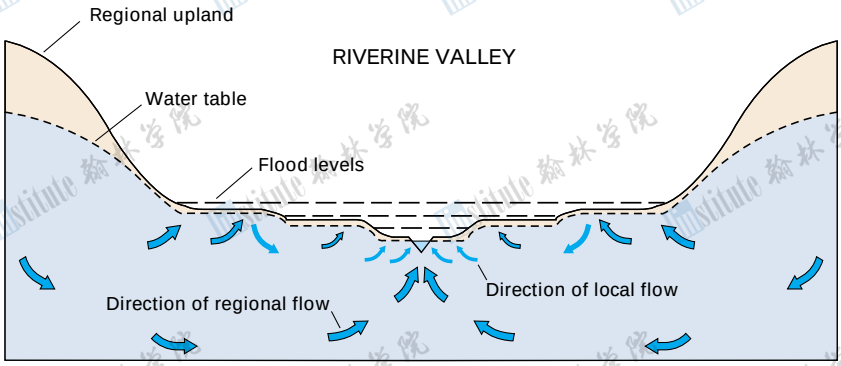


Figure 22. In broad river valleys, small local ground-water flow systems associated with terraces overlie more regional ground-water flow systems. Recharge from flood waters superimposed on these ground-water flow systems further complicates the hydrology of river

Added to this distribution of ground-water discharge from different flow systems to different parts of the valley is the effect of flooding. At times of high river flows, water moves into the ground-water system as bank storage (Figure 11). The flow paths can be as lateral flow through the river-bank (Figure 12*B*) or, during flooding, as vertical seepage over the flood plain (Figure 12*C*). As flood waters rise, they cause bank storage to move into higher and higher terraces.

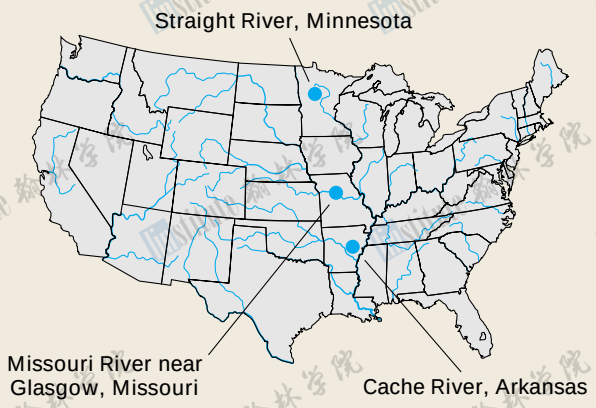
The water table generally is not far below the land surface in alluvial valleys. Therefore, vegetation on flood plains, as well as at the base of some terraces, commonly has root systems deep enough so that the plants can transpire water directly from ground water. Because of the relatively stable source of ground water, particularly in areas of ground-water discharge, the vegetation can transpire water near the maximum potential transpiration rate, resulting in the same effect as if the water were being pumped by a well (see Figure 7). This large loss of water can result in drawdown of the water table such that the plants intercept some of the water that would otherwise flow to the river, wetland, or lake. Furthermore, in some settings it is not uncommon during the growing season for the pumping effect of transpiration to be significant enough that surface water moves into the subsurface to replenish the transpired ground water.

Riverine alluvial deposits range in size from clay to boulders, but in many alluvial valleys, sand and gravel are the predominant deposits. Chemical reactions involving dissolution or precipitation of minerals (see Box D) commonly do not have a significant effect on water chemistry in sand and gravel alluvial aquifers because the rate of water movement is relatively fast compared to weathering rates. Instead, sorption and desorption reactions and oxidation/reduction reactions related to the activity of microorganisms probably have a greater effect on water chemistry in these systems. As in small streams, biogeochemical processes in the hyporheic zone may have a significant effect on the chemistry of ground water and surface water in larger riverine systems. Movement of oxygen-rich surface water into the subsurface, where chemically reactive sediment coatings are abundant, causes increased chemical reactions related to activity of microorganisms. Sharp gradients in concentration of some chemical constituents in water, which delimit this zone of increased biogeochemical activity, are common near the boundary between ground water and surface water. In addition, chemical reactions in the hyporheic zone can cause precipitation of some reactive solutes and contaminants, thereby affecting water quality.

Field Studies of Riverine Terrain

Streams are present in virtually all landscapes, and in some landscapes, they are the principal surface-water features. The interaction of ground water with streams varies in complexity because they vary in size from small streams near headwaters areas to large rivers flowing in large alluvial valleys, and also because streams intersect ground-water flow systems of greatly different scales. Examples of the interaction of ground water and surface water for small and large riverine systems are presented below.

The Straight River, which runs through a sand plain in central Minnesota, is typical of a small stream that does not have a flood plain and that derives most of its water from ground-water inflow. The water-table contours near the river bend sharply upstream (Figure I–1), indicating that ground water moves directly into the river. It is estimated from base-flow studies (see Box B) that, on an annual basis, ground water accounts for more than 90 percent of the water in the river.



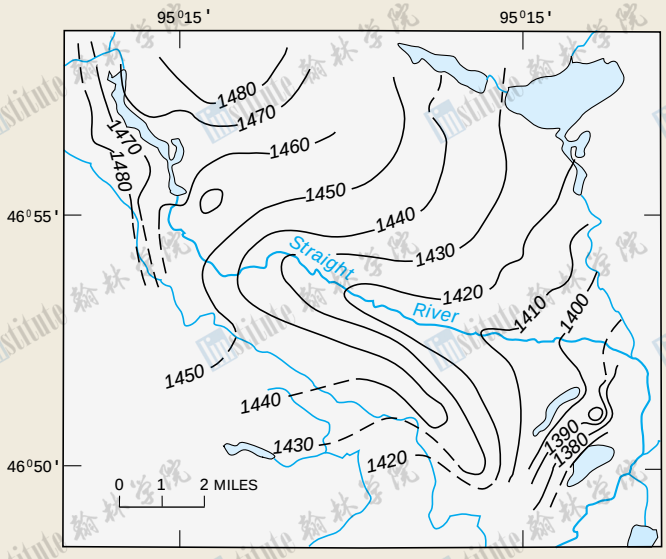


Figure I–1. Small streams, such as the Straight River in Minnesota, commonly do not have flood plains. The flow of ground water directly into the river is indicated by the water-table contours that bend sharply upstream. (Modified from Stark, J.R., Armstrong, D.S., and Zwilling, D.R., 1994, Stream-aquifer interactions in the Straight River area, Becker and Hubbard Counties, Minnesota: U.S. Geological Survey Water-Resources Investigations Report 94–4009, 83 p.)

In contrast, the results of a study of the lower Missouri River Valley indicate the complexity of ground-water flow and its interaction with streams in large alluvial valleys. Configuration of the water table in this area indicates that ground water flows into the river at right angles in some reaches, and it flows parallel to the river in others (Figure I–2*A*). This study also resulted in a map that showed patterns of water-table fluctuations with respect to proximity to the river (Figure I–2*B*). This example shows the wide variety of ground-water flow conditions that can be present in large alluvial valleys.

Another study of part of a large alluvial valley provides an example of the presence of smaller scale flow conditions. The Cache River is a stream within the alluvial valley of the Mississippi River Delta system in eastern Arkansas. In a study of the Black Swamp, which lies along a reach of the river, a number of wells and piezometers were installed to determine the interaction of ground water with the swamp and the river. By measuring hydraulic head at different depths in the

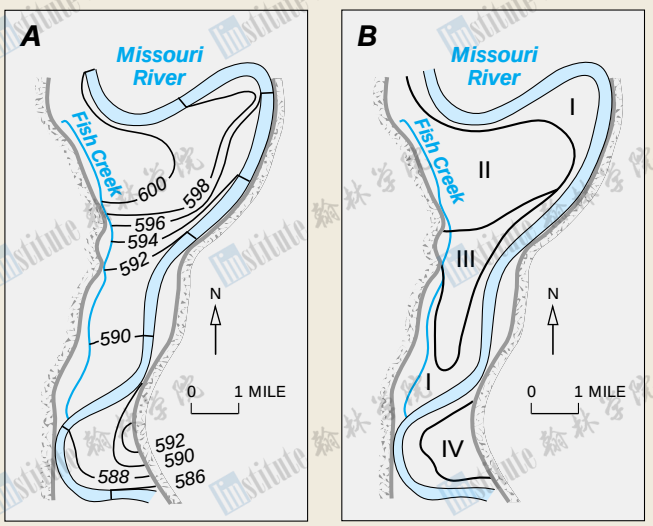


Figure I–2. In flood plains of large rivers, such as the Missouri River near Glasgow, Missouri, patterns of ground-water movement (A) and water-table fluctuations (B) can be complex. Zone I is an area of rapidly fluctuating water levels, zone II is an area of long-term stability, zone III is an area of down-valley flow, and zone IV is a persistent ground-water high. (Modified from Grannemann, N.G., and Sharp, J.M., Jr., 1979, Alluvial hydrogeology of the lower Missouri River: Journal of Hydrology, v. 40, p. 85–99.) (Reprinted with permission from Elsevier Science-NL, Amsterdam, The Netherlands.)

alluvium, it was possible to construct a hydrologic section through the alluvium (Figure I–3), showing that the river receives ground-water discharge from both local and regional ground-water flow systems. In addition, the section also shows the effect of the break in slope associated with the terrace at the edge of the swamp, which causes ground water from a local flow system to discharge into the edge of the swamp rather than to the river.

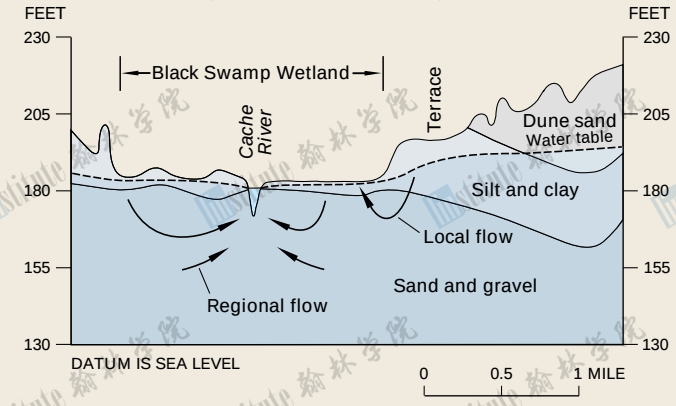


Figure I–3. The Cache River in Arkansas provides an example of contributions to a river from regional and local ground-water flow systems. In addition, a small local ground-water flow system associated with a terrace discharges to the wetland at the edge of the flood plain. (Modified from Gonthier, G.J., 1996, Ground-water flow conditions within a bottomland hardwood wetland, eastern Arkansas: Wetlands, v. 16, no. 3, p. 334–346.) (Used with permission.)

COASTAL TERRAIN

Coastal terrain, such as that along the east-central and southern coasts of the United States, extends from inland scarps and terraces to the ocean (area C of the conceptual landscape, Figure 2). This terrain is characterized by (1) low scarps and terraces that were formed when the ocean was higher than at present; (2) streams, estuaries, and lagoons that are affected by tides; (3) ponds that are commonly associated with coastal sand dunes; and (4) barrier islands. Wetlands cover extensive areas in some coastal terrains (see Figure 18).

The interaction of ground water and surface water in coastal terrain is affected by discharge of ground water from regional flow systems and from local flow systems associated with scarps and terraces (Figure 23), evapotranspiration, and tidal flooding. The local flow systems associated with scarps and terraces are caused by the configuration of the water table near these features (see Box J). Where the water table has a downward break in slope near the top of scarps and terraces, downward components of ground-water flow are present; where the water table has an upward break in slope near the base of these features, upward components of ground-water flow are present.

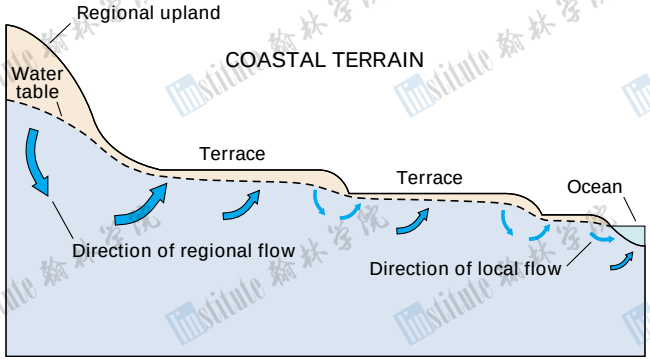
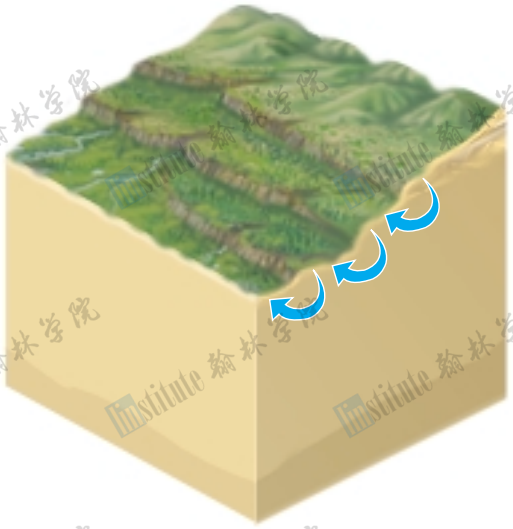


Figure 23. In coastal terrain, small local ground-water flow cells associated with terraces overlie more regional ground-water flow systems. In the tidal zone, saline and brackish surface water mixes with fresh ground water from local and regional flow systems.



Evapotranspiration directly from ground water is widespread in coastal terrain. The land surface is flat and the water table generally is close to land surface; therefore, many plants have root systems deep enough to transpire ground water at nearly the maximum potential rate. The result is that evapotranspiration causes a significant water

loss, which affects the configuration of ground-water flow systems as well as how ground water interacts with surface water.

In the parts of coastal landscapes that are affected by tidal flooding, the interaction of ground water and surface water is similar to that in alluvial valleys affected by flooding. The principal difference between the two is that tidal flooding is more predictable in both timing and magnitude than river flooding. The other significant difference is in water chemistry. The water that moves into bank storage from rivers is generally fresh, but the water that moves into bank storage from tides generally is brackish or saline.

Estuaries are a highly dynamic interface between the continents and the ocean, where discharge of freshwater from large rivers mixes with saline water from the ocean. In addition, ground water discharges to estuaries and the ocean, delivering nutrients and contaminants directly to coastal waters. However, few estimates of the location and magnitude of ground-water discharge to coasts have been made.

In some estuaries, sulfate-rich regional ground water mixes with carbonate-rich local ground water and with chloride-rich seawater, creating sharp boundaries that separate plant and wildlife communities. Biological communities associated with these sharp boundaries are adapted to different hydrochemical conditions, and they undergo periodic stresses that result from inputs of water having different chemistry. The balance between river inflow and tides causes estuaries to retain much of the particulate and dissolved matter that is transported in surface and subsurface flows, including contaminants.

"Ground water discharges to estuaries and the ocean, delivering nutrients and contaminants directly to coastal waters"

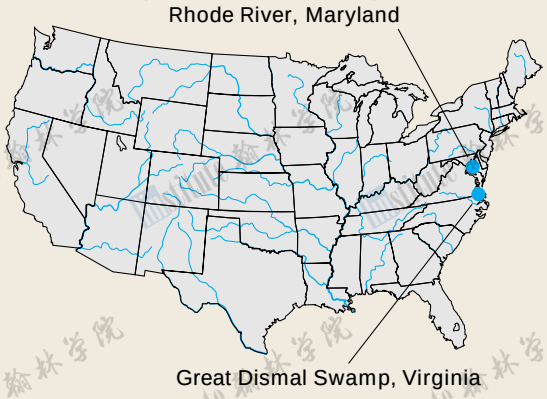
J

Field Studies of Coastal Terrain

Along the Atlantic, Gulf of Mexico, and Arctic Coasts of the United States, broad coastal plains are transected by streams, scarps, and terraces. In some parts of these regions, local ground-water flow systems are associated with scarps and terraces, and freshwater wetlands commonly are present. Other parts of coastal regions are affected by tides, resulting in very complex flow and biogeochemical processes.

Underlying the broad coastal plain of the mid-Atlantic United States are sediments 600 or more feet thick. The sands and clays were deposited in stratigraphic layers that slope gently from west to east. Ground water moves regionally toward the east in the more permeable sand layers. These aquifers are separated by discontinuous layers of clay that restrict vertical ground-water movement. Near land surface, local ground-water flow systems are associated with changes in land slope, such as at major scarps and at streams.

Studies of the Dismal Swamp in Virginia and North Carolina provide examples of the interaction of ground water and wetlands near a coastal scarp. The Suffolk Scarp borders the west side of Great Dismal Swamp. Water-table wells and deeper piezometers placed across the scarp indicated a downward component of ground-water flow in the upland and an upward component of ground-water flow in the lowland at the edge of the swamp (Figure J–1*A*). However, at the edge of the swamp the direction of flow changed several times between May and October in 1982 because transpiration of ground water lowered the water table below the water level of the deep piezometer (Figure J–1*B*).



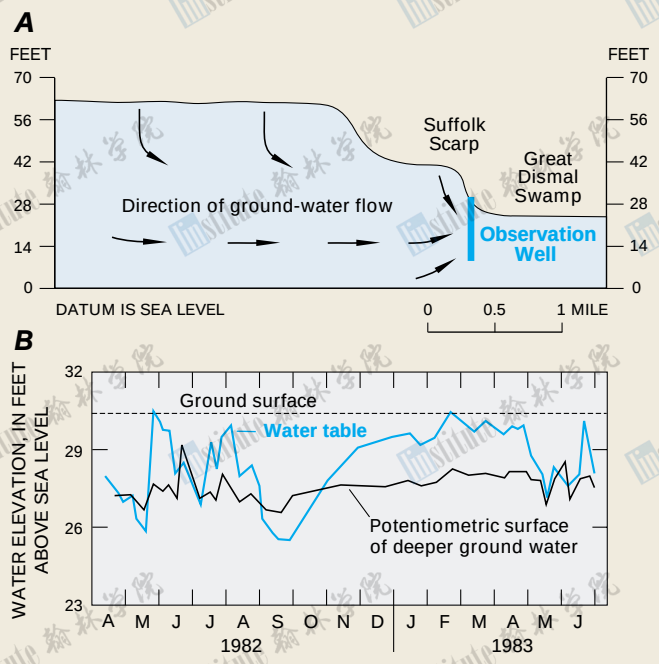


Figure J–1. Ground-water discharge at the edge of the Great Dismal Swamp in Virginia provides an example of local ground-water flow systems associated with coastal scarps (A). The vertical components of flow can change direction seasonally, partly because evapotranspiration discharges shallower ground water during part of the year (B). (Modified from Carter, Virginia, 1990, The Great Dismal Swamp—An illustrated case study, chapter 8, in Lugo, A.E., Brinson, Mark, and Brown, Sandra, eds., Ecosystems of the world, 15: Forested wetlands, Elsevier, Amsterdam, p. 201–211.) (Reprinted with permission from Elsevier Science-NL, Amsterdam, The Netherlands.)

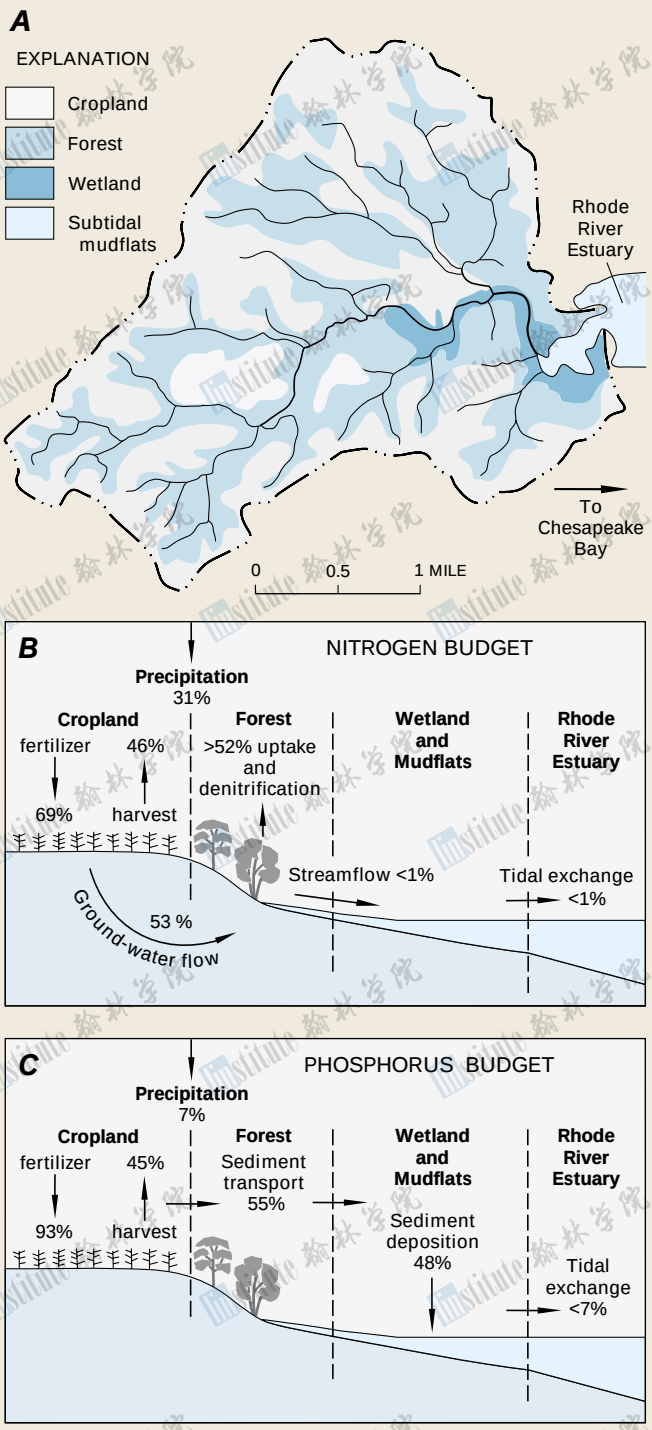


Figure J–2. Forests and wetlands separate cropland from streams in the Rhode River watershed in Maryland (A). More than half of the nitrogen applied to cropland is transported by ground water toward riparian forests and wetlands (B). More than half of the total phosphorus applied to cropland is transported by streams to wetlands and mudflats, where most is deposited in sediments (C). (Modified from Correll, D.L., Jordan, T.E., and Weller, D.E., 1992, Nutrient flux in a landscape—Effects of coastal land use and terrestrial community mosaic on nutrient transport to coastal waters: Estuaries, v. 15, no. 4, p. 431–442.) (Reprinted by permission of the Estuarine Research Federation.)

The gentle relief and sandy, well-drained soils of coastal terrain are ideal for agriculture. Movement of excess nutrients to estuaries are a particular problem in coastal areas because the slow rate of flushing of coastal bays and estuaries can cause them to retain nutrients. At high concentrations, nutrients can cause increased algal production, which results in overabundance of organic matter. This, in turn, can lead to reduction of dissolved oxygen in surface water to the extent that organisms are killed throughout large areas of estuaries and coastal bays.

Movement of nutrients from agricultural fields has been documented for the Rhode River watershed in Maryland (Figure J–2). Application of fertilizer accounts for 69 percent of nitrogen and 93 percent of phosphorus input to this watershed (Figure J–2*B* and J–2*C*). Almost all of the nitrogen that is not removed by harvested crops is transported in ground water and is taken up by trees in riparian forests and wetlands or is denitrified to nitrogen gas in ground water before it reaches streams. On the other hand, most of the phosphorus not removed by harvested crops is attached to soil particles and is transported only during heavy precipitation when sediment from fields is transported into streams and deposited in wetlands and subtidal mudflats at the head of the Rhode River estuary. Whether phosphorus is retained in sediments or is released to the water column depends in part on whether sediments are exposed to oxygen. Thus, the uptake of nutrients and their storage in riparian forests, wetlands, and subtidal mudflats in the Rhode River watershed has helped maintain relatively good water quality in the Rhode River estuary.

In other areas, however, agricultural runoff and input of nutrients have overwhelmed coastal systems, such as in the northern Gulf of Mexico near the mouth of the Mississippi River. The 1993 flood in the Mississippi River system delivered an enormous amount of nutrients to the Gulf of Mexico. Following the flood, oxygen-deficient sediments created areas of black sediment devoid of animal life in parts of the northern Gulf of Mexico.

GLACIAL AND DUNE TERRAIN

Glacial and dune terrain (area G of the conceptual landscape, Figure 2) is characterized by a landscape of hills and depressions. Although stream networks drain parts of these landscapes, many areas of glacial and dune terrain do not contribute runoff to an integrated surface drainage network. Instead, surface runoff from precipitation falling on the landscape accumulates in the depressions, commonly resulting in the presence of lakes and wetlands. Because of the lack of stream outlets, the water balance of these "closed" types of lakes and wetlands is controlled largely by exchange of water with the atmosphere (precipitation and evapotranspiration) and with ground water (see Box K).

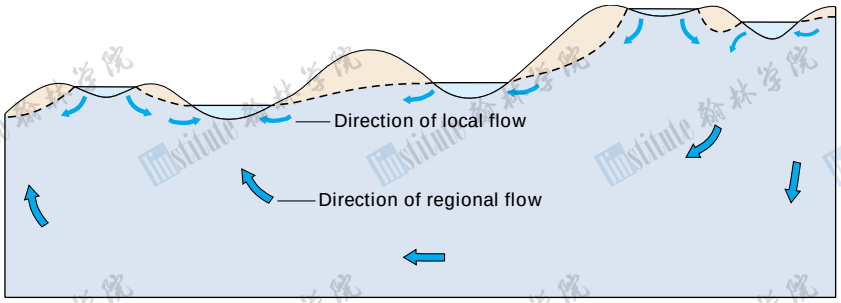
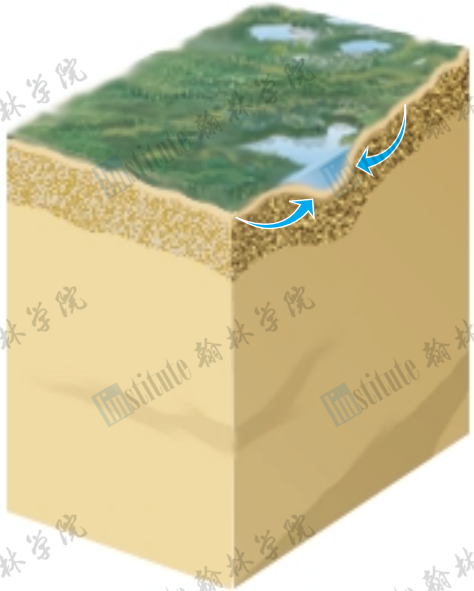


Figure 24. In glacial and dune terrain, local, intermediate, and regional ground-water flow systems interact with lakes and wetlands. It is not uncommon for wetlands that recharge local ground-water flow systems to be present in lowlands and for wetlands that receive discharge from local ground water to be present in uplands.



Lakes and wetlands in glacial and dune terrain can have inflow from ground water, outflow to ground water, or both (Figure 16).
The interaction between lakes and wetlands and ground water is determined to a large extent by their position with respect to local and regional ground-water flow systems. A common conception is that lakes and wetlands that are present in topographically high areas recharge ground water, and that lakes and wetlands that are present in low areas receive discharge from ground water. However, lakes and wetlands underlain by deposits having low permeability can receive discharge from local ground-water flow systems even if they are located in a regional ground-water recharge area. Conversely, they can lose water to local ground-water flow systems even if they are located in a regional ground-water discharge area (Figure 24).

Lakes and wetlands in glacial and dune terrain underlain by highly permeable deposits commonly have ground-water seepage into one side and seepage to ground water on the other side. This relation is relatively stable because the water-table gradient between surface-water bodies in this type of setting is relatively constant. However, the boundary between inflow to the lake or wetland and outflow from it, termed the hinge line, can move up and down along the shoreline. Movement of the hinge line between inflow and outflow is a result of the changing slope of the water table in response to changes in ground-water recharge in the adjacent uplands.

Transpiration directly from ground water has a significant effect on the interaction of lakes and wetlands with ground water in glacial and dune terrain. Transpiration from ground water (Figure 7) has perhaps a greater effect on lakes and wetlands underlain by low-permeability deposits than in any other landscape. The lateral movement of ground water in low-permeability deposits may not be fast enough to supply the quantity of water at the rate it is removed by transpiration, resulting in deep and steep-sided cones of depression. These cones of depression commonly are present around the perimeter of the lakes and wetlands (Figure 7 and Box K).

In the north-central United States, cycles in the balance between precipitation and evapotranspiration that range from 5 to 30 years can result in large changes in water levels, chemical concentrations, and major-ion water type of individual wetlands. In some settings, repeated cycling of water between the surface and subsurface in the same locale results in evaporative concentration of solutes and eventually in mineral precipitation in the subsurface. In addition, these dynamic hydrological and chemical conditions can cause significant changes in the types, number, and distribution of wetland plants and invertebrate animals within wetlands. These changing hydrological conditions that range from seasons to decades are an essential process for rejuvenating wetlands that provide ideal habitat and feeding conditions for migratory waterfowl.

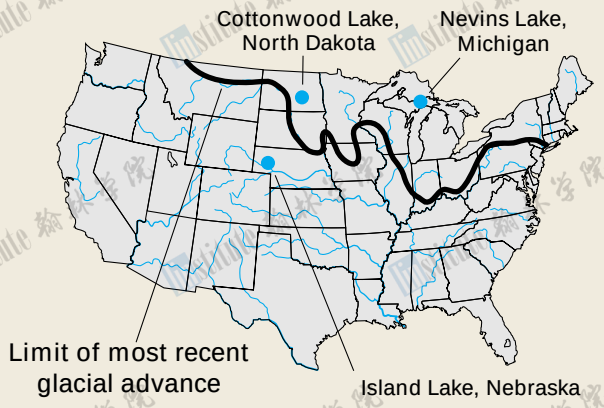
"The hydrological and chemical characteristics of lakes and wetlands in glacial and dune terrain are determined to a large extent by their position with respect to local and regional ground-water flow systems"

K

Field Studies of Glacial and Dune Terrain

Glacial terrain and dune terrain are characterized by land-surface depressions, many of which contain lakes and wetlands. Although much of the glacial terrain covering the north-central United States (see index map) has low topographic relief, neighboring lakes and wetlands are present at a sufficiently wide range of altitudes to result in many variations in how they interact with ground water, as evidenced by the following examples.

The Cottonwood Lake area, near Jamestown, North Dakota, is within the prairie-pothole region of North America. The hydrologic functions of these small depressional wetlands are highly variable in space and time. With respect to spatial variation, some wetlands recharge ground water, some receive ground-water inflow and have outflow to ground water, and some receive ground-water discharge. Wetland P1 provides an example of how their functions can vary in time. The wetland receives ground-water discharge most of the time; however, transpiration of ground water by plants around the perimeter of the wetland can cause water to seep from the wetland. Seepage from wetlands commonly is assumed to be ground-water recharge, but in cases like Wetland P1, the water is actually lost to transpiration. This process results in depressions in the water table around the perimeter of the wetland at certain times, as shown in



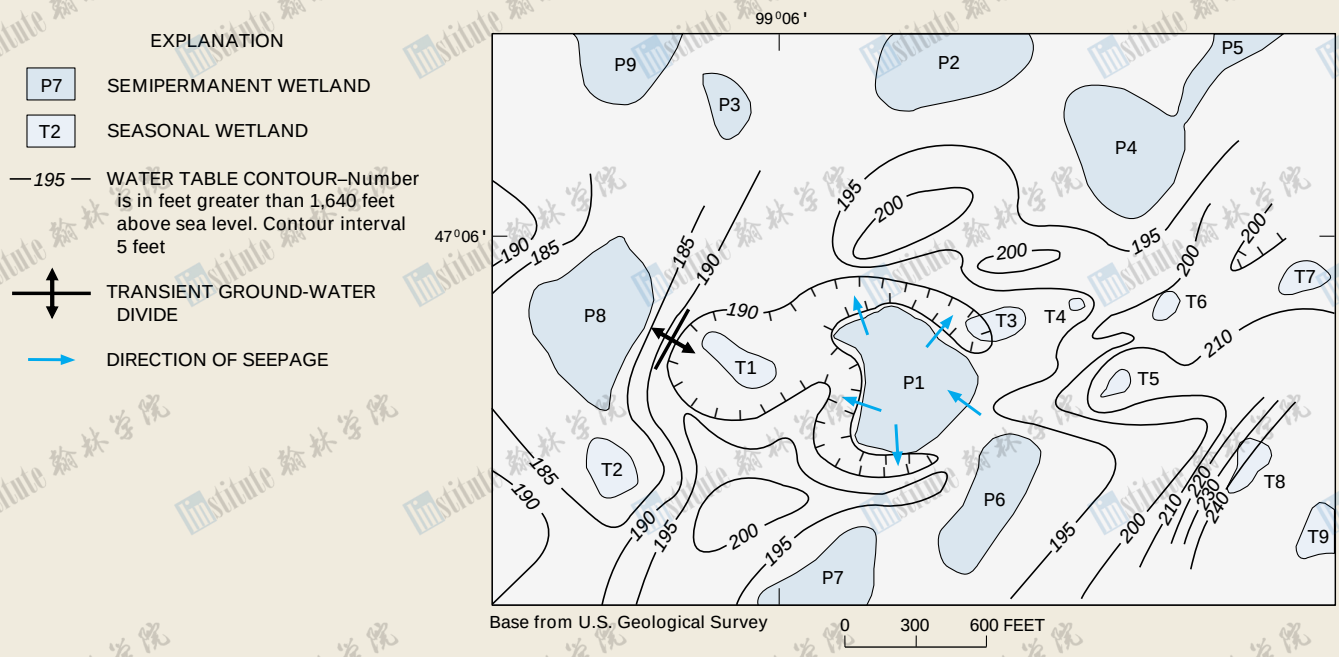


Figure K–1. Transpiration directly from ground water causes cones of depression to form by late summer around the perimeter of prairie pothole Wetland P1 in the Cottonwood Lake area in North Dakota. (Modified from Winter, T.C., and Rosenberry, D.O., 1995, The interaction of ground water with prairie pothole wetlands in the Cottonwood Lake area, east-central North Dakota, 1979–1990: Wetlands, v. 15, no. 3, p. 193–211.) (Used with permission.)

Figure K–1. Transpiration-induced depressions in the water table commonly are filled in by recharge during the following spring, but then form again to some extent by late summer nearly every year.

Nevins Lake, a closed lake in the Upper Peninsula of Michigan, illustrates yet another type of interaction of lakes with ground water in glacial terrain. Water-chemistry studies of Nevins Lake indicated that solutes such as calcium provide an indicator of ground-water inflow to the lake. Immediately following spring snowmelt, the mass of dissolved calcium in the lake increased rapidly because of increased ground-water inflow. Calcium then decreased steadily throughout the summer and early fall as the lake received less ground-water inflow (Figure K–2). This pattern varied annually depending on the amount of ground-water recharge from snowmelt and spring rains. The chemistry of water in the pores of the lake sediments was used to determine the spatial variability in the direction of seepage on the side of the lake that had the most ground-water inflow. Seepage was always out of the lake at the sampling site farthest from shore and was always upward into the lake at the site nearest to shore. Flow reversals were documented at sites located at intermediate distances from shore.

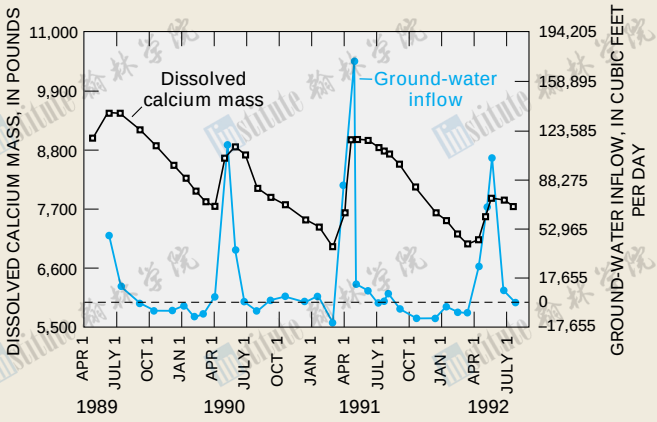


Figure K–2. A large input of ground water during spring supplies the annual input of calcium to Nevins Lake in the Upper Peninsula of Michigan. (Modified from Krabbenhoft, D.P., and Webster, K.E., 1995, Transient hydrogeological controls on the chemistry of a seepage lake: Water Resources Research, v. 31, no. 9, p. 2295–2305.)

Dune terrain also commonly contains lakes and wetlands. Much of the central part of western Nebraska, for example, is covered by sand dunes that have lakes and wetlands in most of the lowlands between the dunes. Studies of the interaction of lakes and wetlands with ground water at the Crescent Lake National Wildlife Refuge indicate that most of these lakes have seepage inflow from ground water and seepage outflow to ground water. The chemistry of inflowing ground water commonly has an effect on lake water chemistry. However, the chemistry of lake water can also affect ground water in areas of seepage from lakes. In the Crescent Lake area, for example, plumes of lake water were detected in ground water downgradient from the lakes, as indicated by the plume of dissolved organic carbon downgradient from Roundup Lake and Island Lake (Figure K–3).

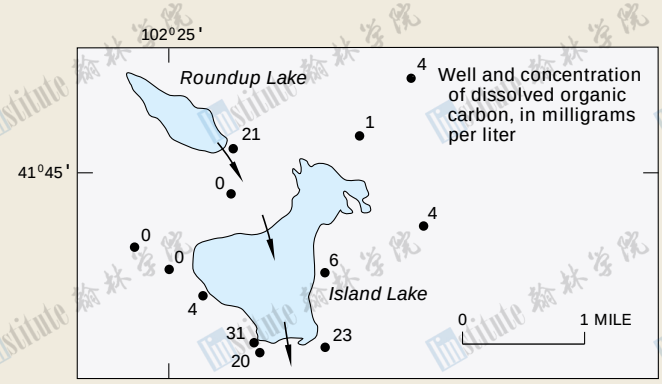
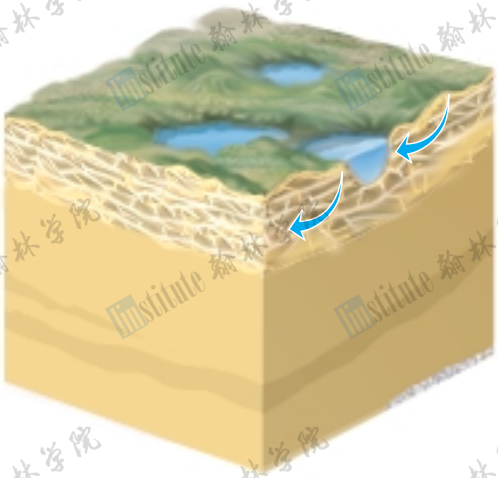


Figure K–3. Seepage from lakes in the sandhills of Nebraska causes plumes of dissolved organic carbon to be present in ground water on the downgradient sides of the lakes. (Modified from LaBaugh, J.W., 1986, Limnological characteristics of selected lakes in the Nebraska sandhills, U.S.A., and their relation to chemical characteristics of adjacent ground water: Journal of Hydrology, v. 86, p. 279–298.) (Reprinted with permission of Elsevier Science-NL, Amsterdam, The Netherlands.)

KARST TERRAIN

Karst may be broadly defined as all landforms that are produced primarily by the dissolution of rocks, mainly limestone and dolomite. Karst terrains (area K of the conceptual landscape, Figure 2) are characterized by (1) closed surface depressions of various sizes and shapes known as sinkholes, (2) an underground drainage network that consists of solution openings that range in size from enlarged cracks in the rock to large caves, and (3) highly disrupted surface drainage systems, which relate directly to the unique character of the underground drainage system.

Dissolution of limestone and dolomite guides the initial development of fractures into solution holes that are diagnostic of karst terrain. Perhaps nowhere else is the complex interplay between hydrology and chemistry so important to changes in landform. Limestone and dolomite weather quickly, producing calcium and magnesium carbonate waters that are relatively high in ionic strength. The increasing size of solution holes allows higher ground-water flow rates across a greater surface area of exposed minerals, which stimulates the dissolution process further, eventually leading to development of caves. Development of karst terrain also involves biological processes. Microbial production of carbon dioxide in the soil affects the carbonate equilibrium of water as it recharges ground water, which then affects how much mineral dissolution will take place before solute equilibrium is reached.



Ground-water recharge is very efficient in karst terrain because precipitation readily infiltrates through the rock openings that intersect the land surface. Water moves at greatly different rates through karst aquifers; it moves slowly through fine fractures and pores and rapidly through solution-enlarged fractures and conduits. As a result, the water discharging from many springs in karst terrain may be a combination of relatively slow-moving water draining from pores and rapidly moving storm-derived water. The slow-moving component tends to reflect the chemistry of the aquifer materials, and the more rapidly moving water associated with recent rainfall tends to reflect the chemical characteristics of precipitation and surface runoff.

Water movement in karst terrain is especially unpredictable because of the many paths ground water takes through the maze of fractures and solution openings in the rock (see Box L). Because of the large size of interconnected openings in well-developed karst systems, karst terrain can have true underground streams. These underground streams can have high rates of flow, in some places as great as rates of flow in surface streams. Furthermore, it is not unusual for medium-sized streams to disappear into the rock openings, thereby completely

disrupting the surface drainage system, and to reappear at the surface at another place. Seeps and springs of all sizes are characteristic features of karst terrains. Springs having sufficiently large ground-water recharge areas commonly are the source of small- to medium-sized streams and constitute a large part of tributary flow to larger streams. In addition, the location where the streams emerge can change, depending on the spatial distribution of ground-water recharge in relation to individual precipitation events. Large spring inflows to streams in karst terrain contrast sharply with the generally more diffuse ground-water inflow characteristic of streams flowing across sand and gravel aquifers.

Because of the complex patterns of surface-water and ground-water flow in karst terrain, many studies have shown that surface-water drainage divides and ground-water drainage divides do not coincide. An extreme example is a stream that disappears in one surface-water basin and reappears in another basin. This situation complicates the identification of source areas for water and associated dissolved constituents, including contaminants, in karst terrain.

Water chemistry is widely used for studying the hydrology of karst aquifers. Extensive tracer studies (see Box G) and field mapping to locate points of recharge and discharge have been used to estimate the recharge areas of springs, rates of ground-water movement, and the water balance of aquifers. Variations in parameters such as temperature, hardness, calcium/magnesium ratios, and other chemical characteristics have been used to identify areas of ground-water recharge, differentiate rapid- and slow-moving ground-water flow paths, and compare springflow characteristics in different regions. Rapid transport of contaminants within karst aquifers and to springs has been documented in many locations. Because of the rapid movement of water in karst aquifers, water-quality problems that might be localized in other aquifer systems can become regional problems in karst systems.

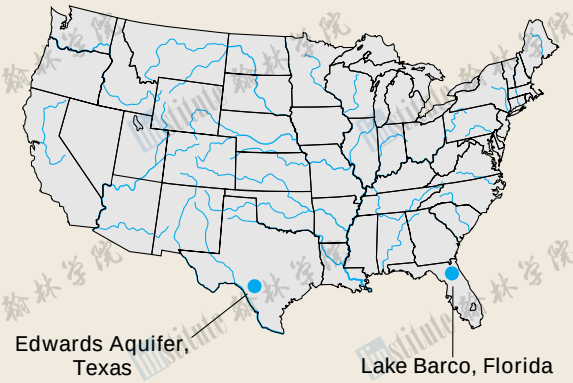
Some landscapes considered to be karst terrain do not have carbonate rocks at the land surface. For example, in some areas of the southeastern United States, surficial deposits overlie carbonate rocks, resulting in a “mantled” karst terrain. Lakes and wetlands in mantled karst terrain interact with shallow ground water in a manner similar to that in sandy glacial and dune terrains. The difference between how lakes and wetlands interact with ground water in sandy glacial and dune terrain and how they interact in the mantled karst is related to the buried carbonate rocks. If dissolution of the buried carbonate rocks causes slumpage of an overlying confining bed, such that water can move freely through the confining bed, the lakes and wetlands also can be affected by changing hydraulic heads in the aquifers underlying the confining bed (see Box L).

Field Studies of Karst Terrain

Karst terrain is characteristic of regions that are underlain by limestone and dolomite bedrock. In many karst areas, the carbonate bedrock is present at land surface, but in other areas it may be covered by other deposits and is referred to as "mantled" karst. The Edwards Aquifer in south-central Texas is an example of karst terrain where the limestones and dolomites are exposed at land surface (Figure L–1). In this outcrop area, numerous solution cavities along vertical joints and sinkholes provide an efficient link between the land surface and the water table. Precipitation on the outcrop area tends to infiltrate rapidly into the ground, recharging ground water. In addition, a considerable amount of recharge to the aquifer is provided by losing streams that cross the outcrop area. Even the largest streams that originate to the north are dry in the outcrop area for most of the year. The unusual highway signs in this area go beyond local pride in a prolific water supply—they reflect a clear understanding of how vulnerable this water supply is to contamination by human activities at the land surface.

Just as solution cavities are major avenues for ground-water recharge, they also are focal points for ground-water discharge from karst aquifers. For example, springs near the margin of the Edwards Aquifer provide a continuous source of water for streams to the south.

An example of mantled karst can be found in north-central Florida, a region that has many sinkhole lakes. In this region, unconsolidated deposits overlie the highly soluble limestone of the Upper Floridan aquifer. Most land-surface depressions containing lakes in Florida are formed when unconsolidated surficial deposits slump into sinkholes that form in the underlying limestone. Thus, although the lakes are not situated directly in limestone, the sinkholes in the bedrock underlying lakes commonly have a significant effect on the hydrology of the lakes.



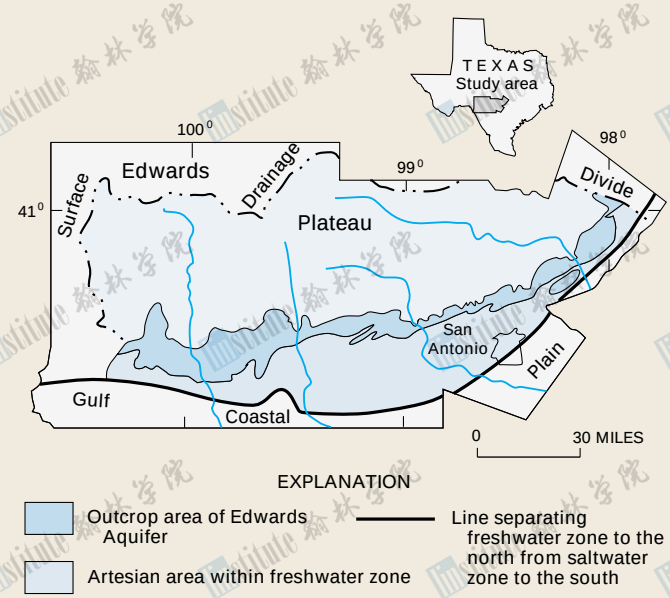


Figure L–1. A large area of karst terrain is associated with the Edwards Aquifer in south-central Texas. Large streams lose a considerable amount of water to ground water as they traverse the outcrop area of the Edwards Aquifer. (Modified from Brown, D.S., and Patton, J.T., 1995, Recharge to and discharge from the Edwards Aquifer in the San Antonio area, Texas, 1995: U.S. Geological Survey Open-File Report 96–181, 2 p.)

Lake Barco is one of numerous lakes occupying depressions in northern Florida. Results of a study of the interaction of Lake Barco with ground water indicated that shallow ground water flows into the northern and northeastern parts of the lake, and lake water seeps out to shallow ground water in the western and southern parts (Figure L–2*A*). In addition, ground-water flow is downward beneath most of Lake Barco (Figure L–2*B*).

The studies of lake and ground-water chemistry included the use of tritium, chlorofluorocarbons (CFCs), and isotopes of oxygen (see Box G). The results indicated significant differences in the chemistry of (1) shallow ground water flowing into Lake Barco, (2) Lake Barco water, (3) shallow

ground water downgradient from Lake Barco, and (4) deeper ground water beneath Lake Barco. Oxygen-rich lake water moving through the organic-rich lake sediments is reduced, resulting in discharge of oxygen-depleted water into the ground water beneath Lake Barco. This downward-moving ground water may have an undesired effect on the chemical quality of ground water in the underlying Upper Floridan aquifer, which is the principal source of water supply for the region. The patterns of ground-water movement determined from hydraulic-head data were corroborated by chemical tracers. For example, the dates that ground water in different parts of the flow system was recharged, as determined from CFC dating, show a fairly consistent increase in the length of time since recharge with depth (Figure L–2*C*).

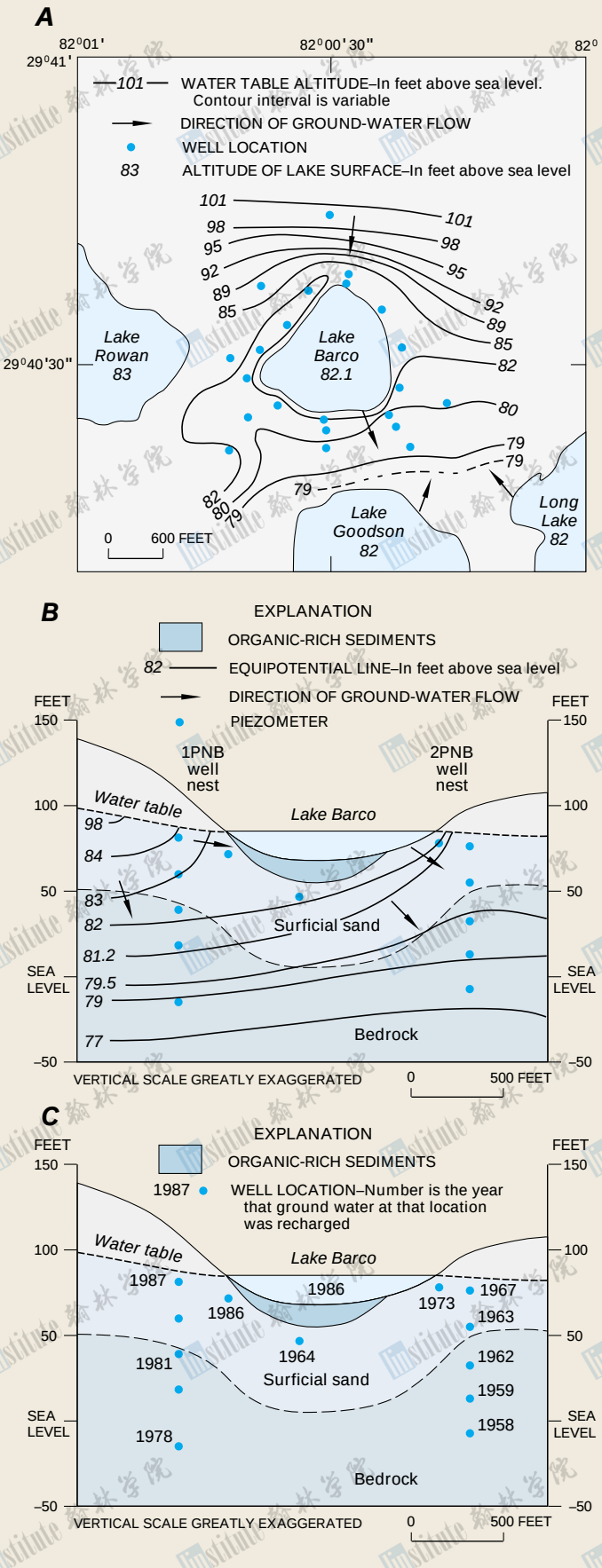


Figure L–2. Lake Barco, in northern Florida, is a flow-through lake with respect to ground water (A and B). The dates that ground water in different parts of the ground-water system was recharged indicate how long it takes water to move from the lake or water table to a given depth (C). (Modified from Katz, B.G., Lee, T.M., Plummer, L.N., and Busenberg, E., 1995, Chemical evolution of groundwater near a sinkhole lake, northern Florida, 1. Flow patterns, age of groundwater, and influence of lake water leakage: Water Resources Research, v. 31, no. 6, p. 1549–1564.)

EFFECTS OF HUMAN ACTIVITIES ON THE INTERACTION OF GROUND WATER AND SURFACE WATER

Human activities commonly affect the distribution, quantity, and chemical quality of water resources. The range in human activities that affect the interaction of ground water and surface water is broad. The following discussion does not provide an exhaustive survey of all human effects but emphasizes those that are relatively widespread. To provide an indication of the extent to which humans affect the water resources of virtually all landscapes, some of the most relevant structures and features related to human activities are superimposed on various parts of the conceptual landscape (Figure 25).

The effects of human activities on the quantity and quality of water resources are felt over a wide range of space and time scales. In the following discussion, "short term" implies time scales from hours to a few weeks or months, and "long term" may range from years to decades. "Local scale" implies distances from a few feet to a few thousand feet and areas as large as a few square miles, and "subregional and regional scales" range from tens to thousands of square miles. The terms point source and nonpoint source with respect to discussions of contamination are used often; therefore, a brief discussion of the meaning of these terms is presented in Box M.

Agricultural Development

Agriculture has been the cause of significant modification of landscapes throughout the world. Tillage of land changes the infiltration and runoff characteristics of the land surface, which affects recharge to ground water, delivery of water and sediment to surface-water bodies, and evapotranspiration. All of these processes either directly or indirectly affect the interaction of ground water and surface water. Agriculturalists are aware of the substantial negative effects of agriculture on water resources and have developed methods to alleviate some of these effects. For example, tillage practices have been modified to maximize retention of water in soils and to minimize erosion of soil from the land into surface-water bodies. Two activities related to agriculture that are particularly relevant to the interaction of ground water and surface water are irrigation and application of chemicals to cropland.

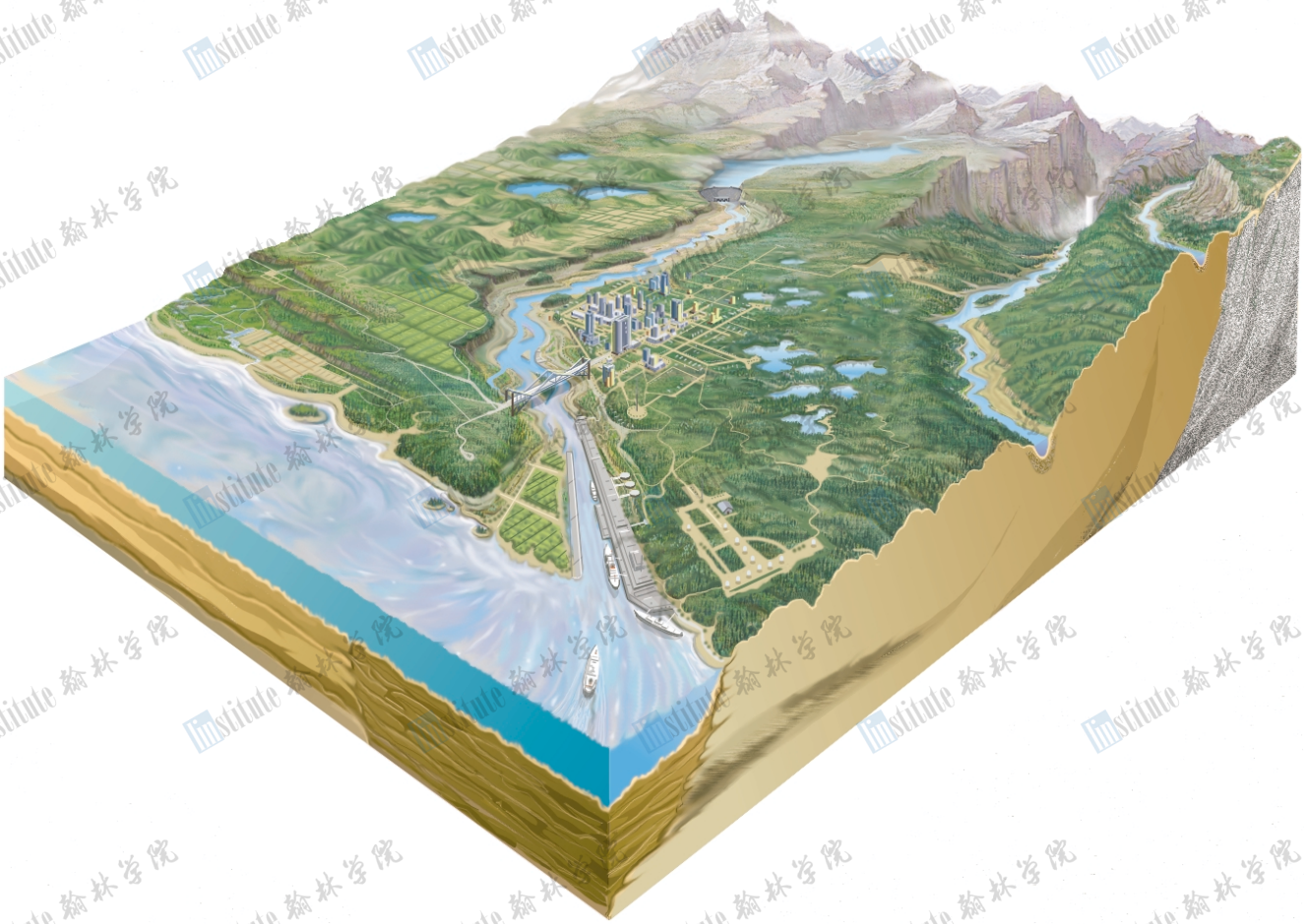


Figure 25. Human activities and structures, as depicted by the distribution of various examples in the conceptual landscape, affect the interaction of ground water and surface water in all types of landscapes.

M

Point and Nonpoint Sources of Contaminants

Contaminants may be present in water or in air as a result of natural processes or through mechanisms of displacement and dispersal related to human activities. Contaminants from point sources discharge either into ground water or surface water through an area that is small relative to the area or volume of the receiving water body. Examples of point sources include discharge from sewage-treatment plants, leakage from gasoline storage tanks, and seepage from landfills (Figure M–1).

Nonpoint sources of contaminants introduce contaminants to the environment across areas that are large compared to point sources, or nonpoint sources may consist of multiple, closely spaced point sources. A nonpoint source of contamination that can be present anywhere, and affect large areas, is deposition from the atmosphere, both by precipitation (wet deposition) or by dry fallout (dry deposition). Agricultural fields, in aggregate, represent large areas through which fertilizers and pesticides can be released to the environment.

The differentiation between point and nonpoint sources of contamination is arbitrary to some extent and may depend in part on the scale at which a problem is considered. For example, emissions from a single smokestack is a point source, but these emissions may be meaningless in a regional analysis of air pollution. However, a fairly even distribution of tens or hundreds of smokestacks might be considered as a nonpoint source. As another example, houses in suburban areas that do not have a combined sewer system have individual septic tanks. At the local scale, each septic tank may be considered as point source of contamination to shallow ground water. At the regional scale, however, the combined contamination of ground water from all the septic tanks in a suburban area may be considered a nonpoint source of contamination to a surface-water body.

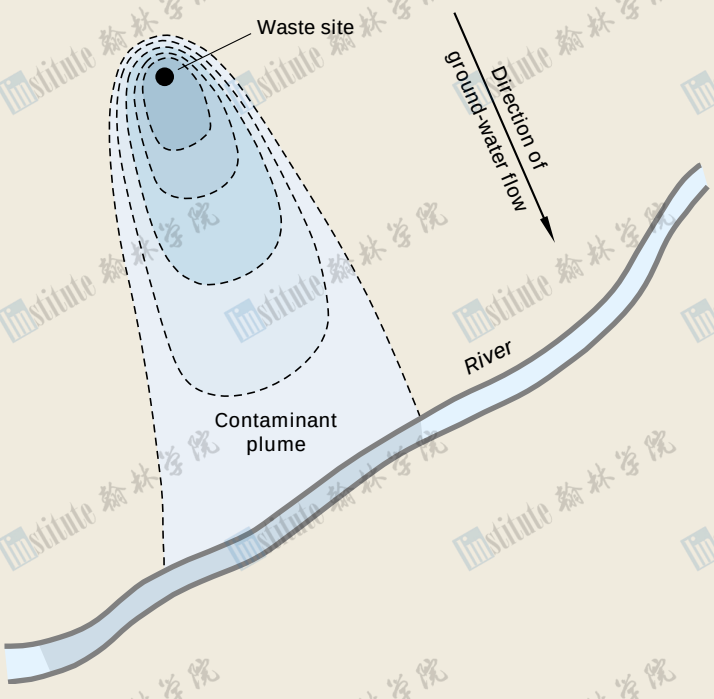


Figure M–1. The transport of contamination from a point source by ground water can cause contamination of surface water, as well as extensive contamination of ground water.

IRRIGATION SYSTEMS

Surface-water irrigation systems represent some of the largest integrated engineering works undertaken by humans. The number of these systems greatly increased in the western United States in the late 1840s. In addition to dams on streams, surface-water irrigation systems include (1) a complex network of canals of varying size and carrying capacity that transport water, in many cases for a considerable distance, from a surface-water source to individual fields, and (2) a drainage system to carry away water not used by plants that may be as extensive and complex as the supply system. The drainage system may include underground tile drains. Many irrigation systems that initially used only surface water now also use ground water. The pumped ground water commonly is used directly as irrigation water, but in some cases the water is distributed through the system of canals.

Average quantities of applied water range from several inches to 20 or more inches of water per year, depending on local conditions, over the entire area of crops. In many irrigated areas, about 75 to 85 percent of the applied water is lost to evapotranspiration and retained in the crops (referred to as consumptive use). The remainder of the water either infiltrates through the soil zone to recharge ground water or it returns to a local surface-water body through the drainage system (referred to as irrigation return flow). The quantity of irrigation water that recharges ground water usually is large relative to recharge from precipitation because large irrigation systems commonly are in regions of low precipitation and low natural recharge. As a result, this large volume of artificial recharge can cause the water table to rise (see Box N), possibly reaching the land surface in some areas and waterlogging the fields. For this reason, drainage systems that maintain the level of the water table below the root zone of the crops, generally 4 to 5 feet below the land surface, are an essential component of some irrigation systems. The permanent rise in the water table that is maintained by continued recharge from irrigation return flow commonly results in an increased outflow of shallow ground water to surface-water bodies downgradient from the irrigated area.

N

Effects of Irrigation Development on the Interaction of Ground Water and Surface Water

Nebraska ranks second among the States with respect to the area of irrigated acreage and the quantity of water used for irrigation. The irrigation water is derived from extensive supply systems that use both surface water and ground water (Figure N–1). Hydrologic conditions in different parts of Nebraska provide a number of examples of the broad-scale effects of irrigation development on the interactions of ground water and surface water. As would be expected, irrigation systems based on surface water are always located near streams. In general, these streams are perennial and (or) have significant flow for at least part of the year. In contrast, irrigation systems based on ground water can be located nearly anywhere that has an adequate ground-water resource. Areas of significant rise and decline in ground-water levels due to irrigation systems are shown in Figure N–2. Ground-water levels rise in some areas irrigated with surface water and decline in some areas irrigated with ground water. Rises in ground-water levels near streams result in increased ground-water inflow to gaining streams or decreased flow from the stream to ground water for losing streams. In some areas, it is possible that a stream that was losing water before development of irrigation could become a gaining stream following irrigation. This effect of surface-water irrigation probably caused the rises in ground-water levels in areas F and G in south-central Nebraska (Figure N–2).

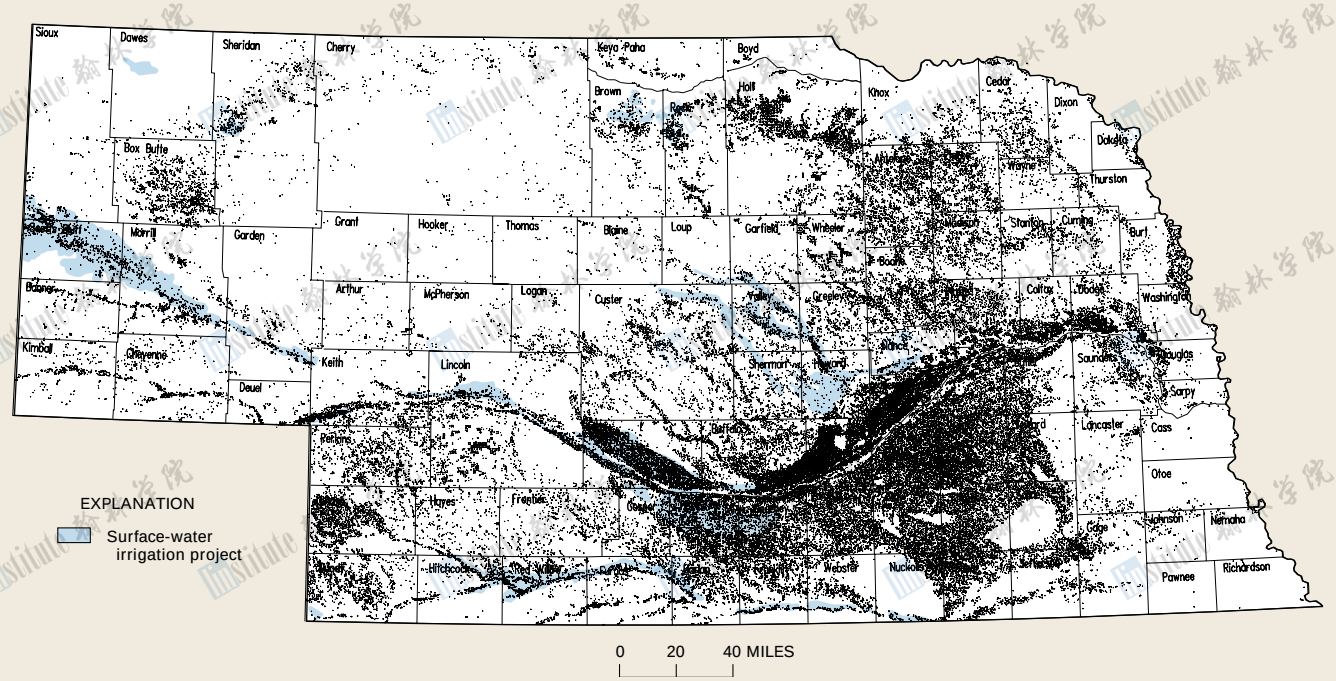


Figure N–1. Nebraska is one of the most extensively irrigated States in the Nation. The irrigation water comes from both ground-water and surface-water sources. Dots are irrigation wells. (Map provided by the University of Nebraska, Conservation and Survey Division.)

Average annual precipitation ranges from less than 15 inches in western Nebraska to more than 30 inches in eastern Nebraska. A large concentration of irrigation wells is present in area E (Figure N–2). The ground-water withdrawals by these wells caused declines in ground-water levels that could not be offset by recharge from precipitation and the presence of nearby flowing streams. In this area, the withdrawals cause decreases in ground-water discharge to the streams and (or) induce flow from the streams to shallow ground water. In contrast, the density of irrigation wells in areas A, B, and C is less than in area E, but water-level declines in these three western areas are similar to area E. The similar decline caused by fewer wells in the west compared to the east is related to less precipitation, less ground-water recharge, and less streamflow available for seepage to ground water.

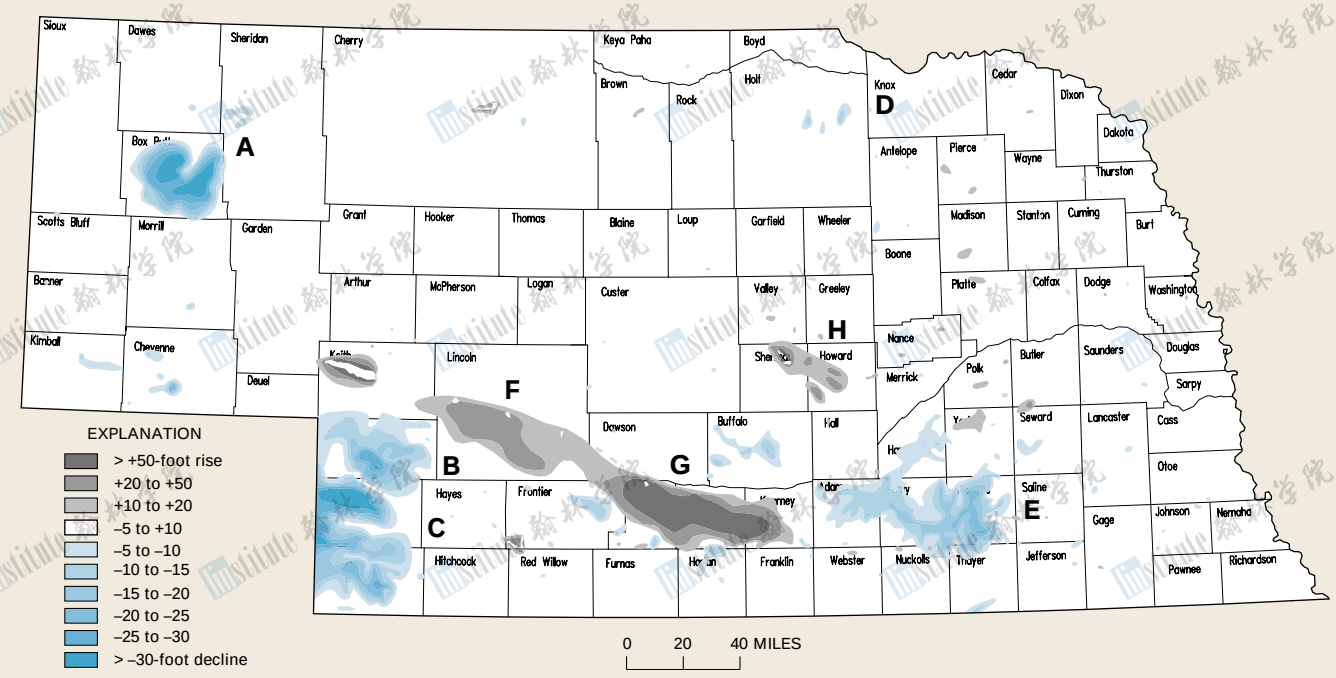


Figure N–2. The use of both ground water and surface water for irrigation in Nebraska has resulted in significant rises and declines of ground-water levels in different parts of the State. (Map provided by the University of Nebraska, Conservation and Survey Division.)

Although early irrigation systems made use of surface water, the development of large-scale sprinkler systems in recent decades has greatly increased the use of ground water for irrigation for several reasons: (1) A system of supply canals is not needed, (2) ground water may be more readily available than surface water, and (3) many types of sprinkler systems can be used on irregular land surfaces; the fields do not have to be as flat as they do for gravity-flow, surface-water irrigation.

Whether ground water or surface water was used first to irrigate land, it was not long before water managers recognized that development of either water resource could affect the other. This is particularly true in many alluvial aquifers in arid regions where much of the irrigated land is in valleys.

Significant changes in water quality accompany the movement of water through agricultural fields. The water lost to evapotranspiration is relatively pure; therefore, the chemicals that are left behind precipitate as salts and accumulate in the soil zone. These continue to increase as irrigation continues, resulting in the dissolved-solids concentration in the irrigation return flows being significantly higher in some areas than that in the original irrigation water. To prevent excessive buildup of salts in the soil, irrigation water in excess of the needs of the crops is required to dissolve and flush out the salts and transport them to the ground-water system. Where these dissolved solids reach high concentrations, the artificial recharge from irrigation return flow can result in degradation of the quality of ground water and, ultimately, the surface water into which the ground water discharges.

"Whether ground water or surface water was used first to irrigate land, it was not long before water managers recognized that development of either water resource could affect the other"

USE OF AGRICULTURAL CHEMICALS

Applications of pesticides and fertilizers to cropland can result in significant additions of contaminants to water resources. Some pesticides are only slightly soluble in water and may attach (sorb) to soil particles instead of remaining in solution; these compounds are less likely to cause contamination of ground water. Other pesticides, however, are detected in low, but significant, concentrations in both ground water and surface water. Ammonium, a major component of fertilizer and manure, is very soluble in water, and increased concentrations of nitrate that result from nitrification of ammonium commonly are present in both ground water and surface water associated with agricultural lands (see Box O). In addition to these nonpoint sources of water contamination, point sources of contamination are common in agricultural areas where livestock are concentrated in small areas, such as feedlots. Whether the initial contamination is present in ground water or surface water is somewhat immaterial because the close interaction of the two sometimes results in both being contaminated (see Box P).

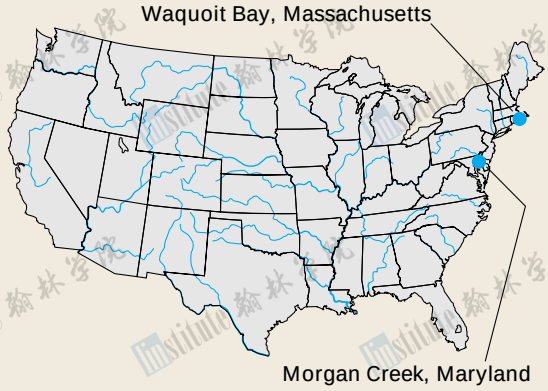
"Whether the initial contamination is present in ground water or surface water is somewhat immaterial because the close interaction of the two sometimes results in both being contaminated"

O

Effects of Nitrogen Use on the Quality of Ground Water and Surface Water

Nitrate contamination of ground water and surface water in the United States is widespread because nitrate is very mobile in the environment. Nitrate concentrations are increasing in much of the Nation's water, but they are particularly high in ground water in the midcontinent region of the United States. Two principal chemical reactions are important to the fate of nitrogen in water: (1) fertilizer ammonium can be nitrified to form nitrate, which is very mobile as a dissolved constituent in shallow ground water, and (2) nitrate can be denitrified to produce nitrogen gas in the presence of chemically reducing conditions if a source of dissolved organic carbon is available.

High concentrations of nitrate can contribute to excessive growth of aquatic plants, depletion of oxygen, fishkills, and general degradation of aquatic habitats. For example, a study of Waquoit Bay in Massachusetts linked the decline in eelgrass beds since 1950 to a progressive increase in nitrate input due to expansion of domestic septic-field developments in the drainage basin (Figure O–1). Loss of eelgrass is a concern because this aquatic plant stabilizes sediment and provides ideal habitat for juvenile fish and other fauna in coastal bays and estuaries. Larger nitrate concentrations supported algal growth that caused turbidity and shading, which contributed to the decline of eelgrass.



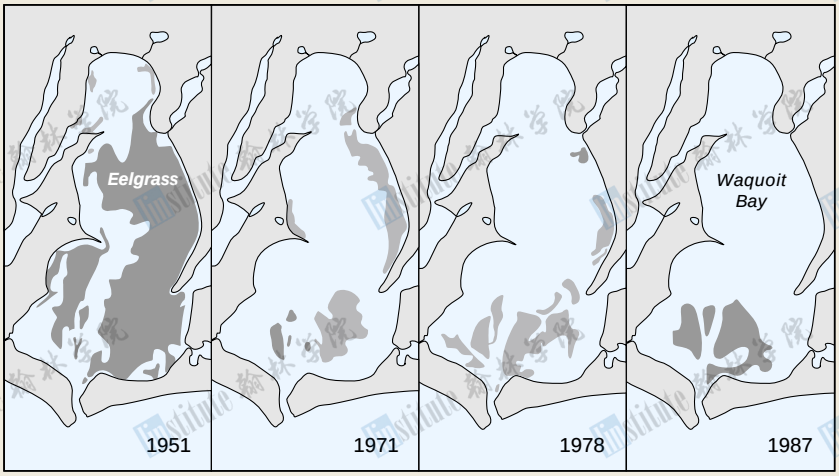


Figure O–1. The areal extent of eelgrass in Waquoit Bay, Massachusetts, decreased markedly between 1951 and 1987 because of increased inputs of nitrogen related to domestic septic-field developments. (Modified from Valiela, I., Foreman, K., LaMontagne, M., Hersh, D., Costa, J., Peckol, P., DeMeo-Andeson, B., D'Avanzo, C., Babione, M., Sham, C.H., Brawley, J., and Lajtha, K., 1992, Couplings of watersheds and coastal waters—Sources and consequences of nutrient enrichment in Waquoit Bay, Massachusetts: Estuaries, v. 15, no. 4, p. 433–457.) (Reprinted by permission of the Estuarine Research Federation.)

Significant denitrification has been found to take place at locations where oxygen is absent or present at very low concentrations and where suitable electron-donor compounds, such as organic carbon, are available. Such locations include the interface of aquifers with silt and clay confining beds and along riparian zones adjacent to streams. For example, in a study on the eastern shore of Maryland, nitrogen isotopes and other environmental tracers were used to show that the degree of denitrification that took place depended on the extent of interaction between ground-water and the chemically reducing sediments near or below the bottom of the Aquia Formation. Two drainage basins were studied: Morgan Creek and Chesterville Branch (Figure O–2). Ground-water discharging beneath both streams had similar nitrate concentration when recharged. Significant denitrification took place in the Morgan Creek basin where a large fraction of local ground-water flow passed through the reducing sediments, which are present at shallow depths (3 to 10 feet) in this area. Evidence for the denitrification included decreases in nitrate concentrations along the flow path to Morgan Creek and enrichment of the ^{15}N isotope. Much less denitrification took place in the Chesterville Branch basin because the top of the reducing sediments are deeper (10 to 20 feet) in this area and a smaller fraction of ground-water flow passed through those sediments.

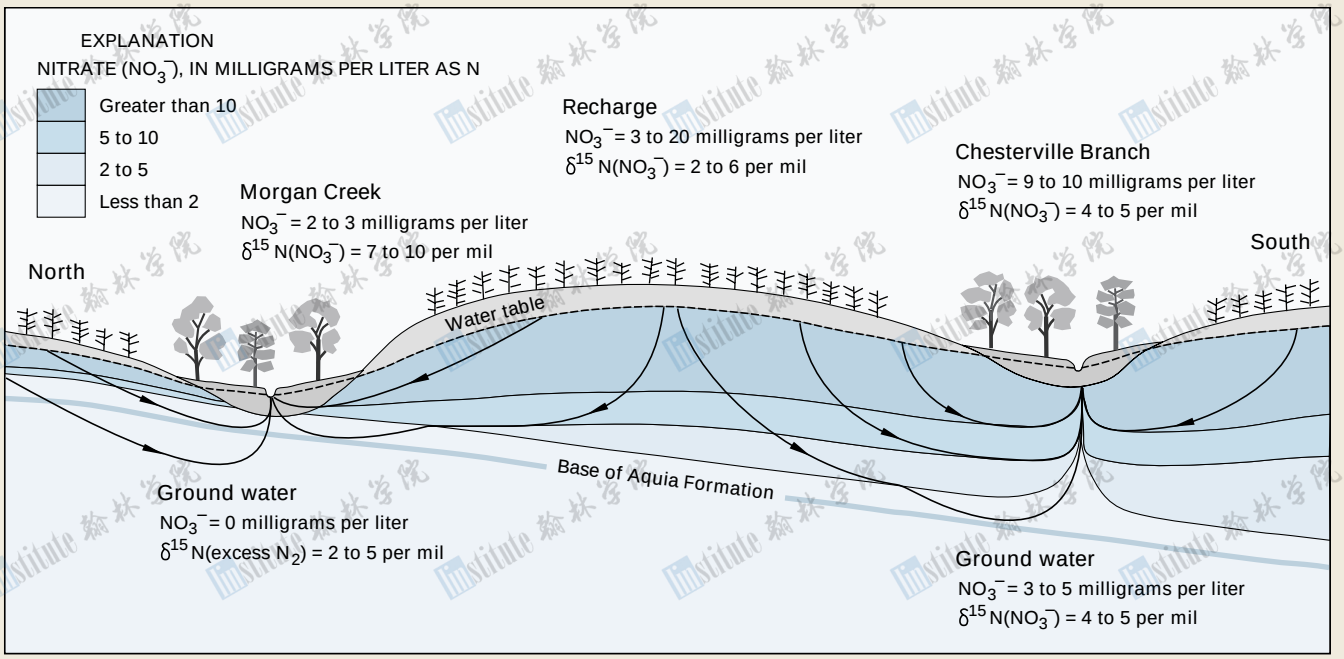


Figure O–2. Denitrification had a greater effect on ground water discharging to Morgan Creek than to Chesterville Branch in Maryland because a larger fraction of the local flow system discharging to Morgan Creek penetrated the reduced calcareous sediments near or below the bottom of the Aquia Formation than the flow system associated with the Chesterville Branch. (Modified from Bolke, J.K., and Denver, J.M., 1995, Combined use of ground-water dating, chemical, and isotopic analyses to resolve the history and fate of nitrate contamination in two agricultural watersheds, Atlantic coastal plain, Maryland: Water Resources Research, v. 31, no. 9, p. 2319–2337.)

P

Effects of Pesticide Application to Agricultural Lands on the Quality of Ground Water and Surface Water

Pesticide contamination of ground water and surface water has become a major environmental issue. Recent studies indicate that pesticides applied to cropland can contaminate the underlying ground water and then move along ground-water flow paths to surface water. In addition, as indicated by the following examples, movement of these pesticides between surface water and ground water can be dynamic in response to factors such as bank storage during periods of high runoff and ground-water withdrawals.

A study of the sources of atrazine, a widely used herbicide detected in the Cedar River and its associated alluvial aquifer in Iowa, indicated that ground water was the major source of atrazine in the river during base-flow conditions. In addition, during periods of high streamflow, surface water containing high concentrations of atrazine moved into the bank sediments and alluvial aquifer, then slowly discharged back to the river as the river level declined. Reversals of flow related to bank storage were documented using data for three sampling periods (Figure P–1). The first sampling (Figure P–1*A*) was before atrazine was applied to cropland, when concentrations in the river and aquifer were relatively low. The second sampling (Figure P–1*B*) was after atrazine was applied to cropland upstream. High streamflow at this time caused the river stage to peak almost 6 feet above its base-flow level, which caused the herbicide to move with the river water into the aquifer. By the third sampling date (Figure P–1*C*), the hydraulic gradient between the river and the alluvial aquifer had reversed again, and atrazine-contaminated water discharged back into the river.

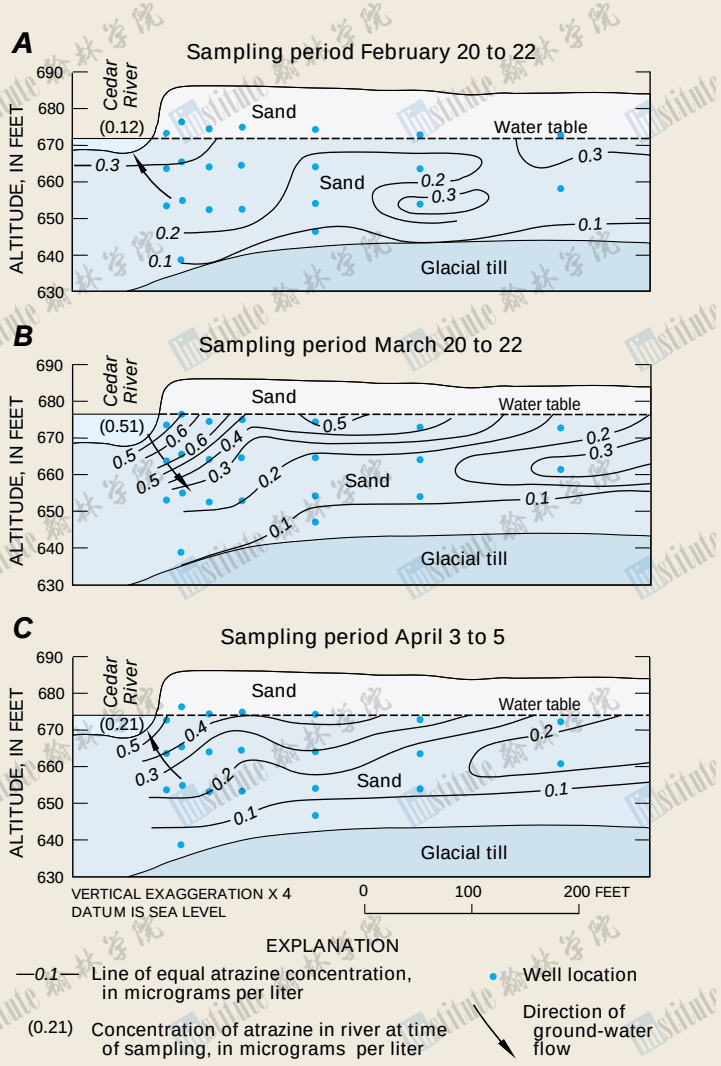
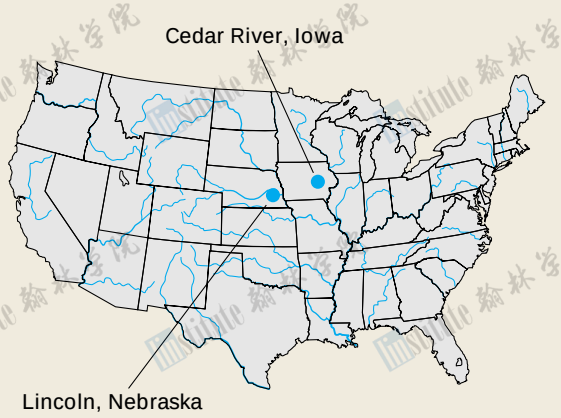


Figure P–1. Concentrations of atrazine increased in the Cedar River in Iowa following applications of the chemical on agricultural areas upstream from a study site. During high streamflow (B), the contaminated river water moved into the alluvial aquifer as bank storage, contaminating ground water. After the river level declined (C), part of the contaminated ground water returned to the river. (Modified from Squillace, P.J., Thurman, E.M., and Furlong, E.T., 1993, Groundwater as a nonpoint source of atrazine and deethylatrazine in a river during base flow conditions: Water Resources Research, v. 29, no. 6, p. 1719–1729.)

In a second study, atrazine was detected in ground water in the alluvial aquifer along the Platte River near Lincoln, Nebraska. Atrazine is not applied in the vicinity of the well field, so it was suspected that ground-water withdrawals at the well field caused contaminated river water to move into the aquifer. To define the source of the atrazine, water samples were collected from monitoring wells located at different distances from the river near the well field. The pattern of concentrations of atrazine in the ground water indicated that peak concentrations of the herbicide showed up sooner in wells close to the river compared to wells farther away (Figure P–2). Peak concentrations of atrazine in ground water were much higher and more distinct during periods of large ground-water withdrawals (July and August) than during periods of much smaller withdrawals (May to early June).



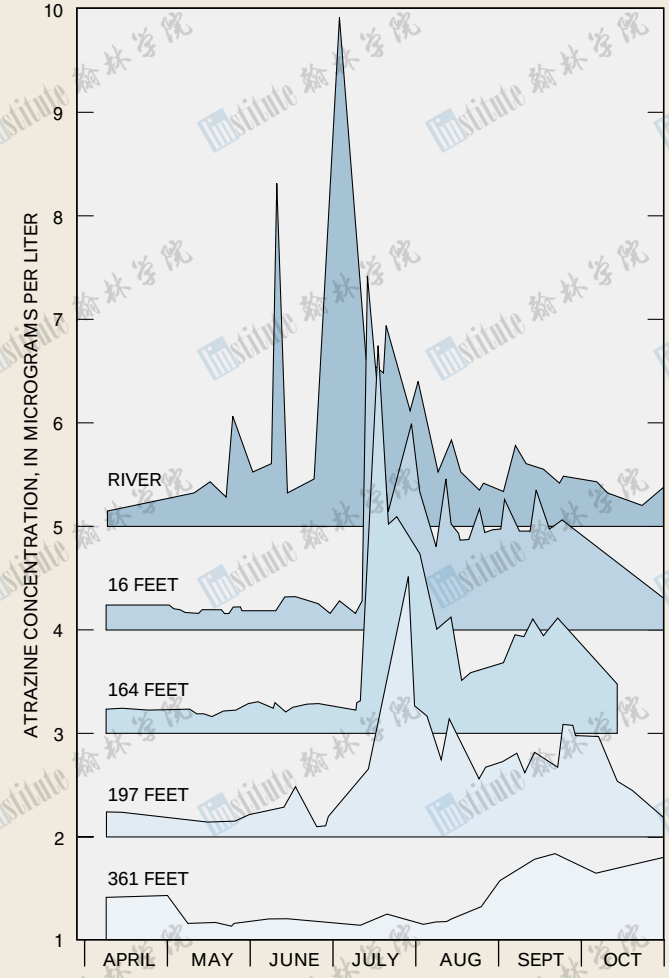


Figure P–2. Pumping of municipal water-supply wells near Lincoln, Nebraska, has induced Platte River water contaminated with atrazine to flow into the aquifer. Distances shown are from river to monitoring well. (Modified from Duncan, D., Pederson, D.T., Shepherd, T.R., and Carr, J.D., 1991, Atrazine used as a tracer of induced recharge: Ground Water Monitoring Review, v. 11, no. 4, p. 144–150.) (Used with permission.)

Urban and Industrial Development

Point sources of contamination to surface-water bodies are an expected side effect of urban development. Examples of point sources include direct discharges from sewage-treatment plants, industrial facilities, and stormwater drains. These facilities and structures commonly add sufficient loads of a variety of contaminants to streams to strongly affect the quality of the stream for long distances downstream. Depending on relative flow magnitudes of the point source and of the stream, discharge from a point source such as a sewage-treatment plant may represent a large percentage of the water in the stream directly downstream from the source. Contaminants in streams can easily affect ground-water quality, especially where streams normally seep to ground water, where ground-water withdrawals induce seepage from the stream, and where floods cause stream water to become bank storage.

Point sources of contamination to ground water can include septic tanks, fluid storage tanks, landfills, and industrial lagoons. If a contaminant is soluble in water and reaches the water table, the contaminant will be transported by the slowly moving ground water. If the source continues to supply the contaminant over a period of time, the distribution of the dissolved contaminant will take a characteristic "plumelike" shape (see Box M). These contaminant plumes commonly discharge into a nearby surface-water body. If the concentration of contaminant is low and the rate of discharge of plume water also is small relative to the volume of the receiving surface-water body, the discharging contaminant plume will have only a small, or perhaps unmeasurable, effect on the quality of the receiving surface-water body. Furthermore, biogeochemical processes may decrease the concentration of the contaminant as it is transported through the shallow ground-water system and the hyporheic zone. On the other hand, if the discharge of the contaminant plume is large or has high concentrations of contaminant, it could significantly affect the quality of the receiving surface-water body.

"Contaminants in streams can easily affect ground-water quality, especially where streams normally seep to ground water, where ground-water withdrawals induce seepage from the stream, and where floods cause stream water to become bank storage"

Drainage of the Land Surface

In landscapes that are relatively flat, have water ponded on the land surface, or have a shallow water table, drainage of land is a common practice preceding agricultural and urban development. Drainage can be accomplished by constructing open ditches or by burying tile drains beneath the land surface. In some glacial terrain underlain by deposits having low permeability, drainage of lakes and wetlands can change the areal distribution of ground-water recharge and discharge, which in turn can result in significant changes in the biota that are present and in the chemical and biological processes that take place in wetlands. Furthermore, these changes can ultimately affect the baseflow to streams, which in turn affects riverine ecosystems. Drainage also alters the water-holding capacity of topographic depressions as well as the surface runoff rates from land having very low slopes. More efficient runoff caused by drainage systems results in decreased recharge to ground water and greater contribution to flooding.

Drainage of the land surface is common in regions having extensive wetlands, such as coastal, riverine, and some glacial-lake landscapes. Construction of artificial drainage systems is extensive in these regions because wetland conditions generally result in deep, rich, organic soils that are much prized for agriculture. In the most extensive artificially drained part of the Nation, the glacial terrain of the upper Midwest, it is estimated that more than 50 percent of the original wetland areas have been destroyed. In Iowa alone, the destruction exceeds 90 percent. Although some wetlands were destroyed by filling, most were destroyed by drainage.

Modifications to River Valleys

CONSTRUCTION OF LEVEES

Levees are built along riverbanks to protect adjacent lands from flooding. These structures commonly are very effective in containing smaller magnitude floods that are likely to occur regularly from year to year. Large floods that occur much less frequently, however, sometimes overtop or breach the levees, resulting in widespread flooding. Flooding of low-lying land is, in a sense, the most visible and extreme example of the interaction of ground water and surface water. During flooding, recharge to ground water is continuous; given sufficient time, the water table may rise to the land surface and completely saturate the shallow aquifer (see Figure 12). Under these conditions, an extended period of drainage from the shallow aquifer takes place after the floodwaters recede. The irony of levees as a flood protection mechanism is that if levees fail during a major flood, the area, depth, and duration of flooding in some areas may be greater than if levees were not present.

CONSTRUCTION OF RESERVOIRS

The primary purpose of reservoirs is to store water for uses such as public water supply, irrigation, flood attentuation, and generation of electric power. Reservoirs also can provide opportunities for recreation and wildlife habitat. Water needs to be stored in reservoirs because streamflow is highly variable, and the times when streamflow is abundant do not necessarily coincide with the times when the water is needed. Streamflow can vary daily in response to individual storms and seasonally in response to variation in weather patterns.

The effects of reservoirs on the interaction of ground water and surface water are greatest near the reservoir and directly downstream from it. Reservoirs can cause a permanent rise in the water table that may extend a considerable distance from the reservoir, because the base level of the stream, to which the ground-water gradients had adjusted, is raised to the higher reservoir levels. Near the

dam, reservoirs commonly lose water to shallow ground water, but this water commonly returns to the river as base flow directly downstream from the dam. In addition, reservoirs can cause temporary bank storage at times when reservoir levels are high. In some cases, this temporary storage of surface water in the ground-water system has been found to be a significant factor in reservoir management (see Box Q).

Human-controlled reservoir releases and accumulation of water in storage may cause high flows and low flows to differ considerably in magnitude and timing compared to natural flows. As a result, the environmental conditions in river valleys downstream from a dam may be altered as organisms try to adjust to the modified flow conditions. For example, the movement of water to and from bank storage under controlled conditions would probably be much more regular in timing and magnitude compared to the highly variable natural flow conditions, which probably would lead to less biodiversity in river systems downstream from reservoirs. The few studies that have been made of riverine ecosystems downstream from a reservoir indicate that they are different from the pre-reservoir conditions, but much more needs to be understood about the effects of reservoirs on stream channels and riverine ecosystems downstream from dams.

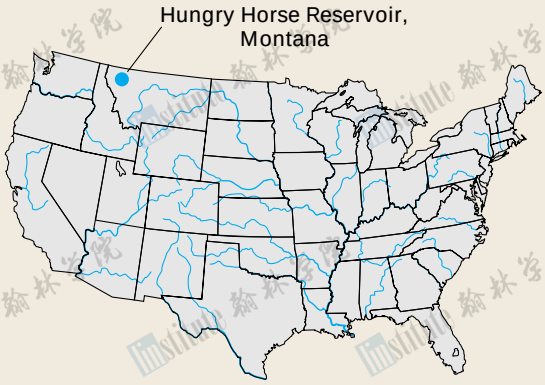
REMOVAL OF NATURAL VEGETATION

To make land available for agriculture and urban growth, development sometimes involves cutting of forests and removal of riparian vegetation and wetlands. Forests have a significant role in the hydrologic regime of watersheds. Deforestation tends to decrease evapotranspiration, increase storm runoff and soil erosion, and decrease infiltration to ground water and base flow of streams. From the viewpoint of water-resource quality and management, the increase in storm runoff and soil erosion and the decrease in base flow of streams are generally viewed as undesirable.

In the western United States, removal of riparian vegetation has long been thought to result in an increase in streamflow. It commonly is believed that the phreatophytes in alluvial valleys transpire ground water that otherwise would flow to the river and be available for use (see Box R). Some of the important functions of riparian vegetation and riparian wetlands include preservation of aquatic habitat, protection of the land from erosion, flood mitigation, and maintenance of water quality. Destruction of riparian vegetation and wetlands removes the benefits of erosion control and flood mitigation, while altering aquatic habitat and chemical processes that maintain water quality.

Effects of Surface-Water Reservoirs on the Interaction of Ground Water and Surface Water

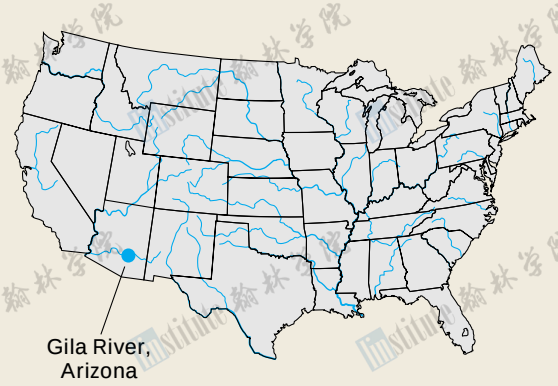
The increase of water levels in reservoirs causes the surface water to move into bank storage. When water levels in reservoirs are decreased, this bank storage will return to the reservoir. Depending on the size of the reservoir and the magnitude of fluctuation of the water level of the reservoir, the amount of water involved in bank storage can be large. A study of bank storage associated with Hungry Horse Reservoir in Montana, which is part of the Columbia River system, indicated that the amount of water that would return to the reservoir from bank storage after water levels are lowered is large enough that it needs to be considered in the reservoir management plan for the Columbia River system. As a specific example, if the water level of the reservoir is raised 100 feet, held at that level for a year, then lowered 100 feet, the water that would drain back to the reservoir during a year would be equivalent to an additional 3 feet over the reservoir surface. (Information from Simons, W.D., and Rorabaugh, M.I., 1971, Hydrology of Hungry Horse Reservoir, northwestern Montana: U.S. Geological Survey Professional Paper 682.)



R

Effects of the Removal of Flood-Plain Vegetation on the Interaction of Ground Water and Surface Water

In low-lying areas where the water table is close to land surface, such as in flood plains, transpiration directly from ground water can reduce ground-water discharge to surface water and can even cause surface water to recharge ground water (see Figure 7). This process has attracted particular attention in arid areas, where transpiration by phreatophytes on flood plains of western rivers can have a significant effect on streamflows. To assess this effect, a study was done on transpiration by phreatophytes along a reach of the Gila River upstream from San Carlos Reservoir in Arizona. During the first few years of the 10-year study, the natural hydrologic system was monitored using observation wells, streamflow gages, and meteorological instruments. Following this initial monitoring period, the phreatophytes were removed from the flood plain and the effects on streamflow were evaluated. The average effect of vegetation removal over the entire study reach was that the Gila River changed from a continually losing river for most years before clearing to a gaining stream during some months for most years following clearing. Specifically, average monthly values of gain or loss from the stream indicated that before clearing, the river lost water to ground water during all months for most years. After clearing, the river gained ground-water inflow during March through June and during September for most years (Figure R–1).



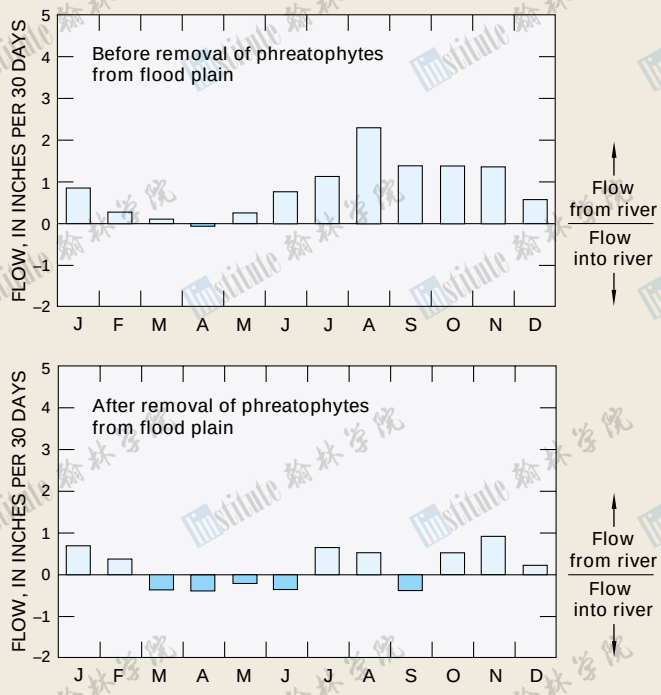


Figure R–1. Removal of phreatophytes from the flood plain along a losing reach of the Gila River in Arizona resulted in the river receiving ground-water inflow during some months of the year. (Modified from Culler, R.C., Hanson, R.L., Myrick, R.M., Turner, R.M., and Kipple, F.P., 1982, Evapotranspiration before and after clearing phreatophytes, Gila River flood plain, Graham County, Arizona: U.S. Geological Professional Paper 655–P.)

Modifications to the Atmosphere

ATMOSPHERIC DEPOSITION

Atmospheric deposition of chemicals, such as sulfate and nitrate, can cause some surface-water bodies to become acidic. Concern about the effects of acidic precipitation on aquatic ecosystems has led to research on the interaction of ground water and surface water, especially in small headwaters catchments. It was clear when the problem was first recognized that surface-water bodies in some environments were highly susceptible to acidic precipitation, whereas in other environments they were not. Research revealed that the interaction of ground water and surface water is important to determining the susceptibility of a surface-water body to acidic precipitation (see Box S). For example, if a surface-water body received a significant inflow of ground water, chemical exchange while the water passed through the subsurface commonly neutralized the acidic water, which can reduce the acidity of the surface water to tolerable levels for aquatic organisms. Conversely, if runoff of acidic precipitation was rapid and involved very little flow through the ground-water system, the surface-water body was highly vulnerable and could become devoid of most aquatic life.

"The interaction of ground water and surface water is important to determining the susceptibility of a surface-water body to acidic precipitation"

*G*LOBAL WARMING

The concentration of gases, such as carbon dioxide (CO_2) and methane, in the atmosphere has a significant effect on the heat budget of the Earth's surface and the lower atmosphere. The increase in concentration of CO_2 in the atmosphere of about 25 percent since the late 1700s generally is thought to be caused by the increase in burning of fossil fuels. At present, the analysis and prediction of "global warming" and its possible effects on the hydrologic cycle can be described only with great uncertainty. Although the physical behavior of CO_2 and other greenhouse gases is well understood, climate systems are exceedingly complex, and long-term changes in climate are embedded in the natural variability of the present global climate regime.

Surficial aquifers, which supply much of the streamflow nationwide and which contribute flow to lakes, wetlands, and estuaries, are the aquifers most sensitive to seasonal and longer term climatic variation. As a result, the interaction of ground water and surface water also will be sensitive to variability of climate or to changes in climate. However, little attention has been directed at determining the effects of climate change on shallow aquifers and their interaction with surface water, or on planning how this combined resource will be managed if climate changes significantly.



S

Effects of Atmospheric Deposition on the Quality of Ground Water and Surface Water

In areas where soils have little capacity to buffer acids in water, acidic precipitation can be a problem because the infiltrating acidic water can increase the solubility of metals, which results in the flushing of high concentrations of dissolved metals into surface water. Increased concentrations of naturally occurring metals such as aluminum may be toxic to aquatic organisms. Studies of watersheds have indicated that the length of subsurface flow paths has an effect on the degree to which acidic water is buffered by flow through the subsurface. For example, studies of watersheds in England have indicated that acidity was higher in streams during storms when more of the subsurface flow moved through the soil rather than through the deeper flow paths (Figure S–1). Moreover, in a study of the effects of acid precipitation on lakes in the Adirondack Mountains of New York, the length of time that water was in contact with deep subsurface materials was the most important factor affecting acidity because contact time determined the amount of buffering that could take place (Figure S–2).

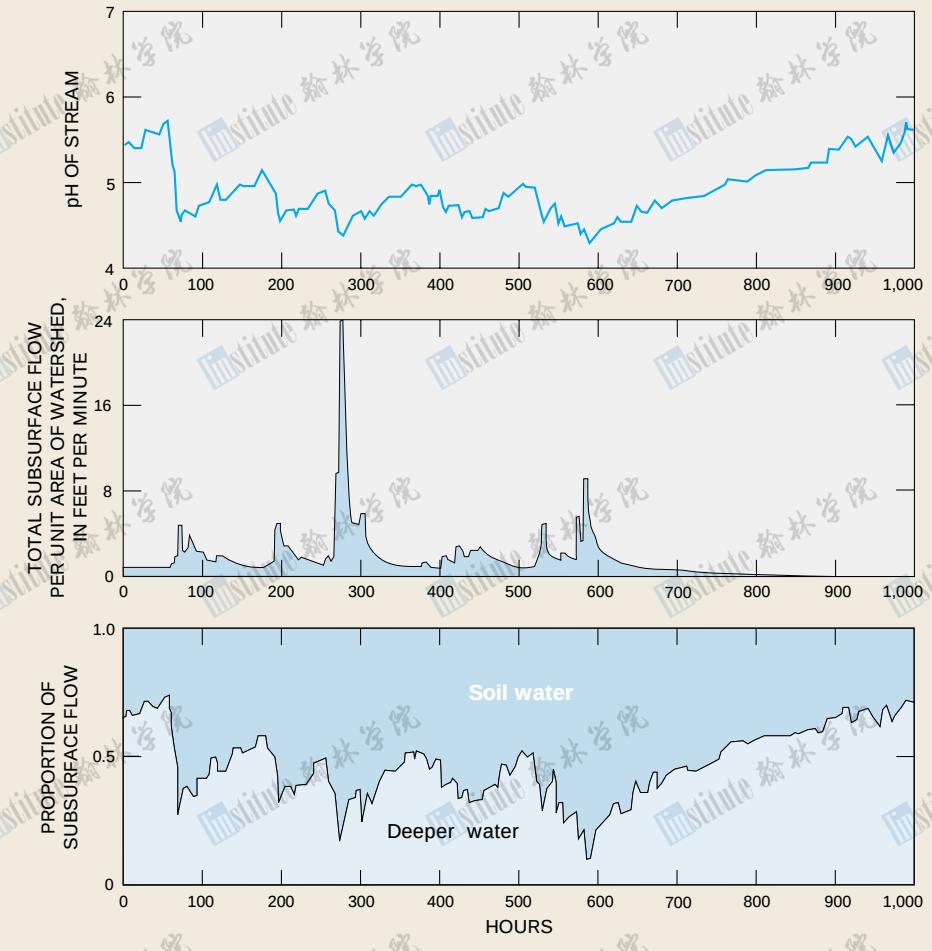
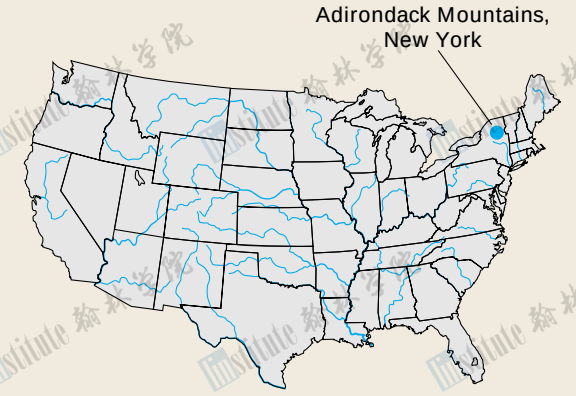


Figure S–1. Acidity is higher (pH is lower) in streams when most of the flow is contributed by shallow soil water because the water has had less time to be neutralized by contact with minerals compared to water that has traversed deeper flow paths. (Modified from Robson, A., Beven, K.J., and Neal, C., 1992, Towards identifying sources of subsurface flow—A comparison of components identified by a physically based runoff model and those determined by chemical mixing techniques: Hydrological Processes, v. 6, p. 199–214.) (Reprinted with permission from John Wiley & Sons Limited.)



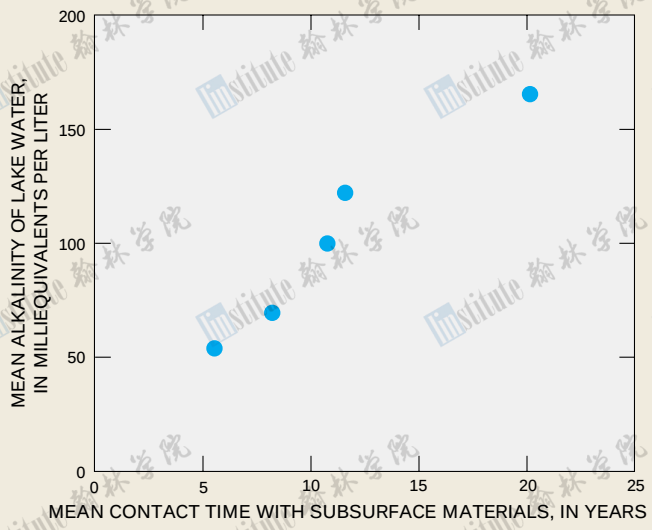


Figure S–2. The longer water is in contact with deep subsurface materials in a watershed, the higher the alkalinity in lakes receiving that water. (Modified from Wolock, D.M., Hornberger, G.M., Beven, K.J., and Campbell, W.G., 1989, The relationship of catchment topography and soil hydraulic characteristics to lake alkalinity in the northeastern United States: Water Resources Research, v. 25, p. 829–837.)

CHALLENGES AND OPPORTUNITIES

The interaction of ground water and surface water involves many physical, chemical, and biological processes that take place in a variety of physiographic and climatic settings. For many decades, studies of the interaction of ground water and surface water were directed primarily at large alluvial stream and aquifer systems. Interest in the relation of ground water to surface water has increased in recent years as a result of widespread concerns related to water supply; contamination of ground water, lakes, and streams by toxic substances (commonly where not expected); acidification of surface waters caused by atmospheric deposition of sulfate and nitrate; eutrophication of lakes; loss of wetlands due to development; and other changes in aquatic environments. As a result, studies of the interaction of ground water and surface water have expanded to include many other settings, including headwater streams, lakes, wetlands, and coastal areas.

Issues related to water management and water policy were presented at the beginning of this report. The following sections address the need for greater understanding of the interaction of ground water and surface water with respect to the three issues of water supply, water quality, and characteristics of aquatic environments.

Water Supply

Water commonly is not present at the locations and times where and when it is most needed. As a result, engineering works of all sizes have been constructed to distribute water from places of abundance to places of need. Regardless of the scale of the water-supply system, development of either ground water or surface water can eventually affect the other. For example, whether the source of irrigation water is ground water or surface water, return flows from irrigated fields will eventually reach surface water either through ditches or through ground-water discharge. Building dams to store surface water or diverting water from a stream changes the hydraulic connection and the hydraulic gradient between that body of surface water and the adjacent ground water, which in turn results in gains or losses of ground water. In some landscapes, development of ground water at even a great distance from surface water can reduce the amount of ground-water inflow to surface water or cause surface water to recharge ground water.

The hydrologic system is complex, from the climate system that drives it, to the earth materials that the water flows across and through, to the modifications of the system by human activities. Much research and engineering has been devoted to the development of water resources for water supply. However, most past work has concentrated on either surface water or ground water without much concern about their interrelations. The need to understand better how development of one water resource affects the other is universal and will surely increase as development intensifies.

Water Quality

For nearly every type of water use, whether municipal, industrial, or agricultural, water has increased concentrations of dissolved constituents or increased temperature following its use. Therefore, the water quality of the water bodies that receive the discharge or return flow are affected by that use. In addition, as the water moves downstream, additional water use can further degrade the water quality. If irrigation return flow, or discharge from a municipal or industrial plant, moves downstream and is drawn back into an aquifer because of ground-water withdrawals, the ground-water system also will be affected by the quality of that surface water.

Application of irrigation water to cropland can result in the return flow having poorer quality because evapotranspiration by plants removes some water but not the dissolved salts. As a result, the dissolved salts can precipitate as solids, increasing the salinity of the soils. Additional application of water dissolves these salts and moves them farther downgradient in the hydrologic system. In addition, application of fertilizers and pesticides to cropland can result in poor-quality return flows to both ground water and surface water. The transport and fate of contaminants caused by agricultural practices and municipal and industrial discharges are a widespread concern that can be addressed most effectively if ground water and surface water are managed as a single resource.

Water scientists and water managers need to design data-collection programs that examine the effects of biogeochemical processes on water quality at the interface between surface water and near-surface sediments. These processes can have a profound effect on the chemistry of ground water recharging surface water and on the chemistry of surface water recharging ground water. Repeated exchange of water between surface water and near-surface sediments can further enhance the importance of these processes. Research on the interface between ground water and surface water has increased in recent years, but only a few stream environments have been studied, and the transfer value of the research results is limited and uncertain.

The tendency for chemical contaminants to move between ground water and surface water is a key consideration in managing water resources. With an increasing emphasis on watersheds as a focus for managing water quality, coordination between watershed-management and ground-water-protection programs will be essential to protect the quality of drinking water. Furthermore, ground-water and surface-water interactions have a major role in affecting chemical and biological processes in lakes, wetlands, and streams, which in turn affect water quality throughout the hydrologic system. Improved scientific understanding of the interconnections between hydrological and biogeochemical processes will be needed to remediate contaminated sites, to evaluate applications for waste-discharge permits, and to protect or restore biological resources.

Characteristics of Aquatic Environments

The interface between ground water and surface water is an areally restricted, but particularly sensitive and critical niche in the total environment. At this interface, ground water that has been affected by environmental conditions on the terrestrial landscape interacts with surface water that has been affected by environmental conditions upstream. Furthermore, the chemical reactions that take place where chemically distinct surface water meets chemically distinct ground water in the hyporheic zone may result in a biogeochemical environment that in some cases could be used as an indicator of changes in either terrestrial or aquatic ecosystems. The ability to understand this interface is challenging because it requires the focusing of many different scientific and technical disciplines at the same, areally restricted locality. The benefit of this approach to studying the interface of ground water and surface water could be the identification of useful biological or chemical indicators of adverse or positive changes in larger terrestrial and aquatic ecosystems.

Wetlands are a type of aquatic environment present in most landscapes; yet, in many areas, their perceived value is controversial. The principal characteristics and functions of wetlands are determined by the water and chemical balances that maintain them. These factors in large part determine the value of a wetland for flood control, nutrient retention, and wildlife habitat. As a result, they are especially sensitive to changing hydrological conditions. When the hydrological and chemical balances of a wetland change, the wetland can take on a completely different function, or it may be destroyed. Generally, the most devastating impacts on wetlands result from changes in land use. Wetlands commonly are drained to make land available for agricultural use or filled to make land available for urban and industrial development. Without understanding how wetlands interact with ground water, many plans to use land formerly occupied by wetlands fail. For example, it is operationally straightforward to fill in or drain a wetland, but the groundwater flow system that maintains many wetlands may continue to discharge at that location. Many structures and roads built on former wetlands and many wetland restoration or construction programs fail for this reason. Saline soils in many parts of the central prairies also result from evaporation of ground water that continues to discharge to the land surface after the wetlands were drained.

Riparian zones also are particularly sensitive to changes in the availability and quality of ground water and surface water because these ecosystems commonly are dependent on both sources of water. If either water source changes, riparian zones may be altered, changing their ability to provide aquatic habitat, mitigate floods and erosion, stabilize shorelines, and process chemicals, including contaminants. Effective management of water resources requires an understanding of the role of riparian zones and their dependence on the interaction of ground water and surface water.

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