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RELATION OF STREAMS, LAKES, AND WETLANDS TO GROUNDWATER FLOW SYSTEMS

Thomas C. Winter

Abstract Surface-water bodies are integral parts of groundwater flow systems. Groundwater interacts with surface water in nearly all landscapes, ranging from small streams, lakes, and wetlands in headwater areas to major river valleys and seacoasts. Although it generally is assumed that topographically high areas are groundwater recharge areas and topographically low areas are groundwater discharge areas, this is true primarily for regional flow systems. The superposition of local flow systems associated with surface-water bodies on this regional framework results in complex interactions between groundwater and surface water in all landscapes, regardless of regional topographic position. Hydrologic processes associated with the surface water bodies themselves, such as seasonally high surface-water levels and evaporation and transpiration of groundwater from around the perimeter of surface water bodies, are a major cause of the complex and seasonally dynamic groundwater flow fields associated with surface water. These processes have been documented at research sites in glacial, dune, coastal, mantled karst, and riverine terrains.

Keywords: geologic fabric * groundwater * recharge/water budget * groundwater/surface-water relations * general hydrogeology * groundwater management

Introduction

Surface-water bodies are connected to groundwater in most types of landscapes. As a result, surface-water bodies are integral parts of groundwater flow systems. Even if a surface-water body is separated from the groundwater system by an unsaturated zone, seepage from the surface water may recharge groundwater. Because of the interchange of water between these two components of the hydrologic system, development or contamination of one commonly affects the other (Winter et al. 1998). Therefore, understanding the basic principles of the interaction of groundwater and surface water is needed for effective management of water resources.

The movement of surface water and groundwater is controlled to a large extent by topography and the geologic framework of an area, which is referred to herein as physiography. The sources of water to, and losses of water from, the earth's surface are controlled by climate. Therefore. it is necessary to understand the effects of physiography and climate on groundwater flow systems in order to understand the interaction of groundwater and surface water.

The purpose of this paper is to provide an overview of the effect of (1) regional physiographic framework: (2) local water-table configuration and geologic characteristics of surface-water beds, such as (a) the distribution of sediment types having different hydraulic conductivities. and (b) orientation of sediment particles; and (3) climate on seepage distribution in surface-water beds. This paper is not a literature review; studies cited were selected to provide specific examples of the effects of geology and (or) climate on the interaction of groundwater and surface water.

General Theoretical Considerations

Groundwater flow systems are defined by the boundary conditions imposed by their physiographic framework and by the distribution of recharge. In the simplest framework, a rectangular aquifer is bounded by no-flow boundaries at its base and on one side, surface water fully penetrates the aquifer on the other side, and internally it is isotropic and homogeneous. Flow from the aquifer to the stream in such a setting is largely one dimensional following a pulse of recharge uniformly distributed across the aquifer's upper boundary. However, natural groundwater systems generally do not have these simple boundary conditions and are not composed of isotropic and homogeneous porous media To address the need to understand more realistic hydrologic systems, several studies were conducted that evaluated the effects of geologic framework on regional groundwater flow systems. These studies led to increased understanding not only of regional groundwater flow systems, but also of how such flow systems interact with surface water.

Effect of Regional Physiographic Framework on the Interaction of Groundwater and Surface Water

Theoretical studies of two-dimensional groundwater flow in vertical sections by Tóth (1963) indicated that local, intermediate, and regional flow systems could be superimposed on one another within a groundwater basin. Because the groundwater flow equation was solved analytically, the following assumptions were made: (I) The porous medium is isotropic and homogeneous; (2) the flow fields are bounded by no-flow boundaries on the sides and base; and (3) the solutions are for steady-state conditions, where the upper boundary has a fixed prescribed-head distribution. Different sine functions were used to describe variations of the magnitude of local relief and overall regional slope of the water table.

Following the work of Tóth, Freeze and Witherspoon (1967) used numerical models of steady-state. two-dimensional vertical sections to further develop insight into regional groundwater flow systems. By using numerical methods, more complex configurations of the upper boundary. more complex internal geologic framework, and anisotopy of the porous media could be evaluated. Surface-water bodies w ere not specifically considered in the studies by Tóth and by Freeze and Witherspoon.

Winter (1976) used numerical models of steady-state, two-dimensional vertical sections to further build on the concepts developed in the above studies; however, the major difference from the previous studies was that surface-water bodies were incorporated into the sections, as illustrated in Figure 1. The study was designed to evaluate the interaction of groundwater and surface water that resulted from different (1) geometry of the groundwater svstem; (2) anisotropy; (3) hydraulic conductivity contrasts within the groundwater system; (4) water-table configuration; and (5) depth of the surface-water body. By analyzing two-dimensional vertical sections, the results have application only to long linear surface-water bodies (streams, lakes, or wetlands) aligned perpendicular to groundwater flow paths. Although the results of the study apply to all surface water in such settings, for convenience, the term lake is used to present the results.

Because of the presence of water-table mounds on both sides of the lake, flow in the upper part of the groundwater system is toward the lake for all conditions (*Figure 1A*). However, seepage is outward through deeper parts of the lake for some conditions (*Figure 1B*). The key to understanding these differences in seepage conditions is the continuity of the boundary of the local groundwater flow system that underlies the lake. lf the boundary is continuous, as shown in *Figure 1A,* all hydraulic heads within the local flow system are greater than the head represented by lake level, which prevents water from seeping from the lake. On the other hand, if the flow-system boundary is not continuous, lake water can seep into the ground water system. The presence of a stagnation point, which is the point of least head along the flow-system boundary, indicates that the flow-system boundary is continuous (Winter 1976).

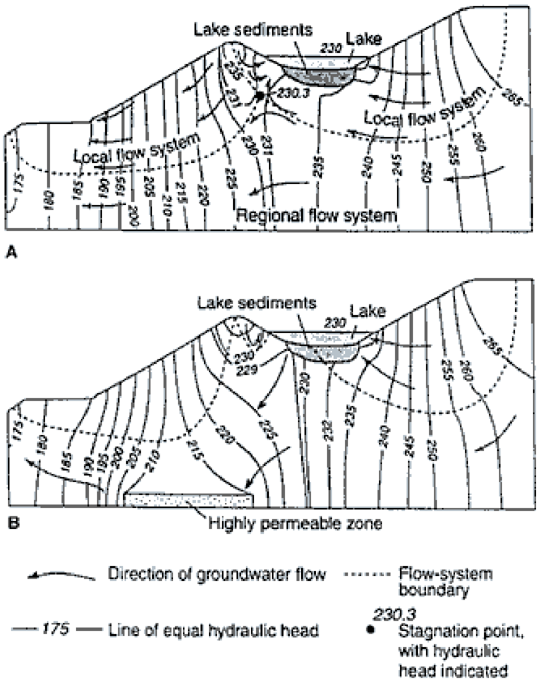

Figure 1A,B Numerical simulation of steady-state two-dimensional groundwater flow in a vertical section for two hypothetical settings. **A** A continuous local flow-system houndary. as indicated by the presence of a stagnation point, prevents seepage from the lake; **B** A discontinuous local flow-system houndary allows seepage from the lake. (Modified from Winter 1976)

The other general results of the study indicate that the following changes in hydrogeologic conditions tend to lessen the difference in head between the lake and the stagnation point, or cause seepage from the lake to occur or increase: (1) lowering the water table. especially on the downgradient side; (2) increasing the anisotropy; (3) increasing the hydraulic conductivity of highly permeable zones; (4) increasing the depth of the lake; and (5) moving highly permeable zones that are present beneath and downgradient of the lake from deep to shallower positions within the groundwater system.

The flow systems shown in *Figure 1* have important implications for understanding baseflow to streams. It commonly is assumed that baseflow to streams is an approximation of groundwater recharge over the entire basin. However, if a stream occupies the lowest topographic point on the left side of the diagram, the stream would receive discharge from two flow systems: (1) it would receive groundwater discharge from the contiguous local flow system in the nearshore part of its bed. and (2) farther offshore, it would receive groundwater discharge from the regional flow system that is recharged at the highest topographic point on the right side of the diagram and that passes at depth beneath the local flow system associated with the lake. In the case shown in *Figure 1A,* the stream would receive none of the recharge that takes place in the local flow system associated with the lake. In the case of *Figure IB,* the stream would receive groundwater discharge from the contiguous local flow system, the regional flow system. and the portion of the regional flow system that was contributed by seepage from the lake.

Although some streams, lakes, and wetlands are long, linear, and aligned perpendicular to groundwater flow paths, where two-dimensional analysis would be appropriate, most lakes and many wetlands are not. To evaluate a broader range of lake and wetland settings, Winter (1978) simulated lake and groundwater systems using a three-dimensional model. The study was designed and conducted much like that described above, including the dimensions of the lake and groundwater system and assuming steady-state conditions. As illustrated in *Figure 2,* the principal conclusions of the study are: (1) a single stagnation point is associated with a closed local groundwater flow system. This point lies along the line of section that transects the point of minimum head along the groundwater divide enclosing the lake (*Figure2A*); and (2) for lakes enclosed by a groundwater divide, a lake can have areas of seepage from it offshore that would not be detected using any number of water-table wells in the uplands contiguous to the lake, because the water table slopes toward the lake throughout its watershed (*Figure2B*). Seepage from the lake could be detected only by use of in-lake wells, piezometers. or seepage meters.

In the above studies. a water-table mound was assumed to be present on the downgradient side of lakes for all the settings that were simulated. Nield et al. (1994) use an analytical approach to simulate steady-state groundwater flow associated with hypothetical lakes in which a wide variety of boundary conditions was assumed. including most where a water-table mound was not present on the downgradient side. Although different overall geometric configurations of the lake/groundwater systems were evaluated, heterogeneous geologic configurations were not. Results of that study are similar to those of Winter's where similar boundary conditions were assumed. However, most of the lake/groundwater systems evaluated by Nield et al. (1994) were of flowthrough lakes with respect to groundwater; that is, they receive groundwater discharge on one side and seep to groundwater on the other.

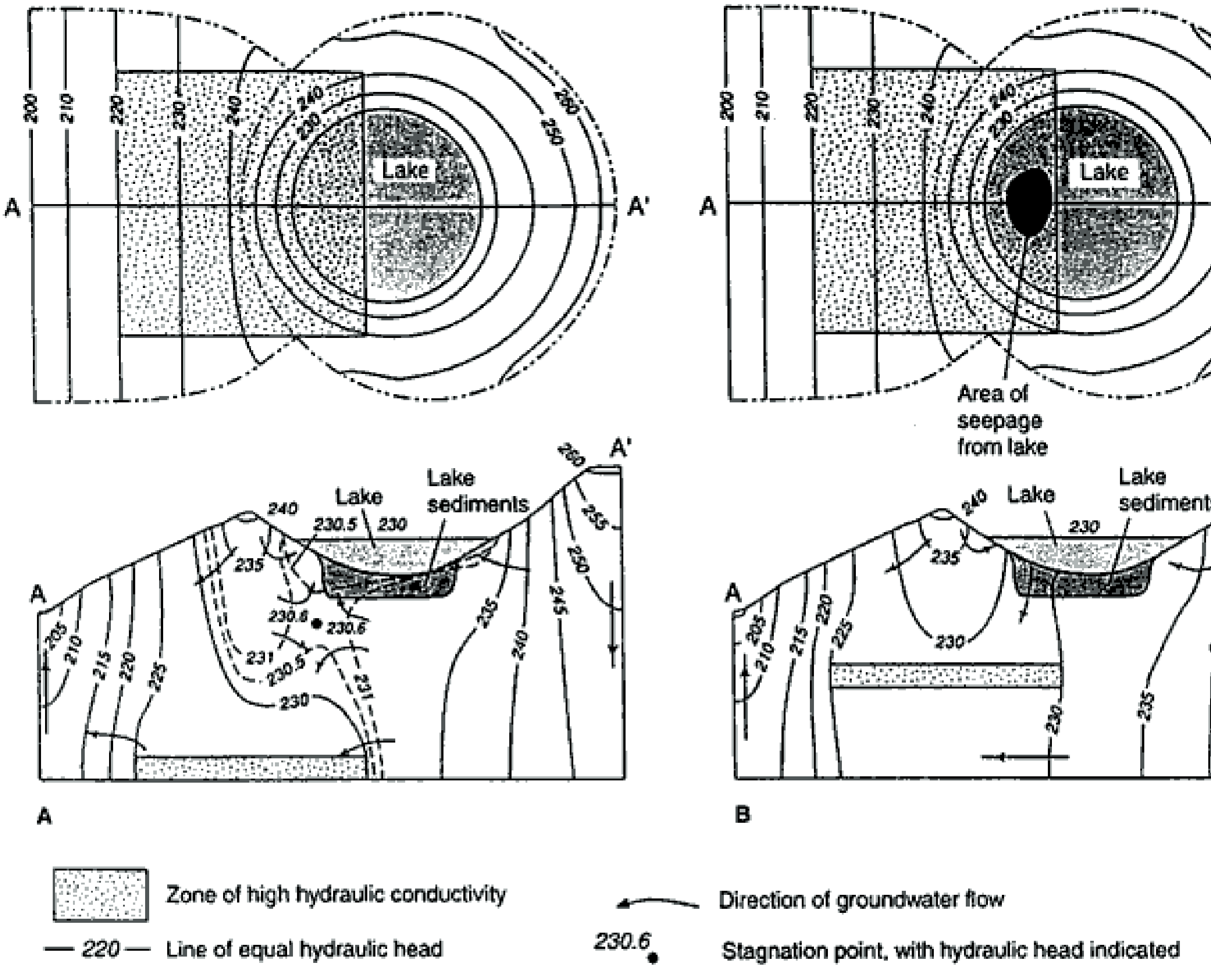

Figure 2A,B Numerical simulation of steady-state three-dimensionai groundwater flow for two hypothetical settings. **A** A continuous local flow system boundary prevents seepage from the lake; **B** A discontinuous locai flow-system boundary allows seepage from the lake throuch an area offshore. (Modified from Winter 1978)

Effect of Local Water-Table Configuration and Geologic Conditions on Seepage Distribution in Surface-Water Beds

Theoretical modeling studies have also resulted in increased understanding of smaller scale groundwater flow processes associated with surface water. For example, upward breaks-in-slope of the water table result in upward components of groundwater flow beneath the area of lower slope, and downward breaks-in-slope of the water table result in downward components of groundwater flow, as shown in Figure 3. These flow patterns apply to parts of many landscapes. For example, the upward moving groundwater near upward breaks-in-slope of the water table commonly results in: (1) groundwater discharge to surface water because water tables generally have a steeper slope relative to the flat surface of surface-water bodies; (2) the presence of wetlands at the edges of river valleys and other flat landscapes adjacent to uplands; and (3) the formation of saline soils, especially in semiarid and arid landscapes. The groundwater flux through a surface-water bed or to land surface associated with these breaks-in-slope is not uniformly distributed areally. Where groundwater moves to or from a surface-water body underlain by isotropic and homogeneous porous media, the flux is greatest near the shoreline and it decreases approximately exponentially away from the shoreline (McBride and Pfannkuch 1975; Pfannkuch and Winter 1984). Anisotropy of the porous media affects this pattern of seepage by causing the width of areas of equal flux to increase with increasing anisotropy; yet, the decreasing seepage away from the shoreline remains nonlinear (Barwell and Lee 1981).

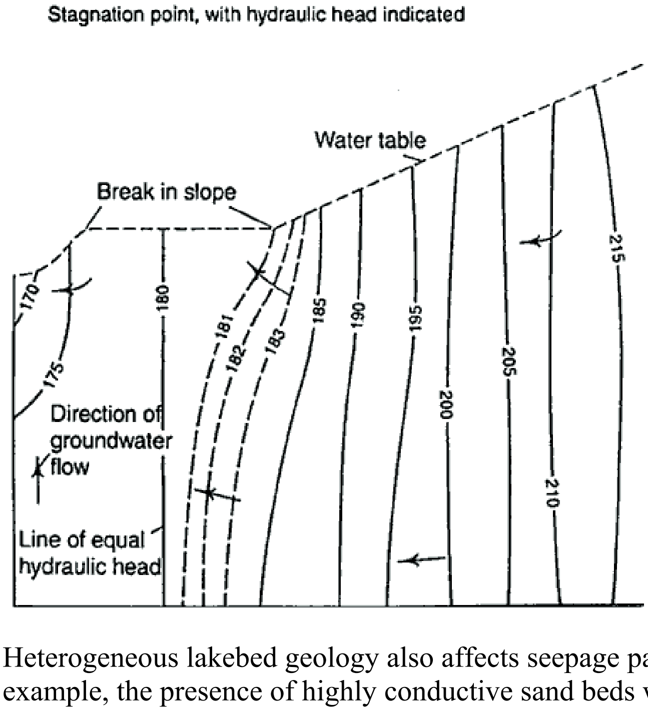

Figure 3 Numerical simulation of groundwater flow in a vertical section near breaks-in-slope of the water table

Heterogeneous lakebed geology also affects seepage patterns in beds of surface water. For example, the presence of highly conductive sand beds within finer grained porous media that intersect a surface-water bed results in subaqeous springs. In a generalized, numerical modeling study of the effect of small-scale variations in sediment type on seepage patterns, Guyonnet (1991) indicates that relatively thin, either high or low hydraulic conductivity layers, can have a substantial effect on the distribution of seepage to surface water.

Effect of Climate on Seepage Distribution in Surface Water Beds

The most dynamic boundary of most groundwater flow systems is the water table. The configuration of the water table changes continually in response to recharge to and discharge from the groundwater system. To evaluate the effect of the distribution of recharge on the interaction of surface water and groundwater, Winter (1983) used a model developed by Cooley (1983) that simulates variably-saturated subsurface conditions. Using this modeling approach, water is infiltrated at the land surface and the process of redistribution through the unsaturated zone and the distribution of recharge can be determined for given time steps. The principal results of that study indicate that recharge is focused initially where the unsaturated zone is thin relative to adjacent areas. Recharge then progresses laterally over time to areas that have thicker unsaturated zones. This process has significant implications for the interaction of groundwater and surface water because the unsaturated zone in most landscapes is thin in the vicinity of surface water, and in fact has zero thickness at the shoreline. The changing volumes and distribution of recharge results in dynamic growth and dissipation of transient local groundwater flow systems directly adjacent to surface water, which causes highly variable seepage conditions in the near-shore beds of surface water. These changes are illustrated in *Figure 4.*

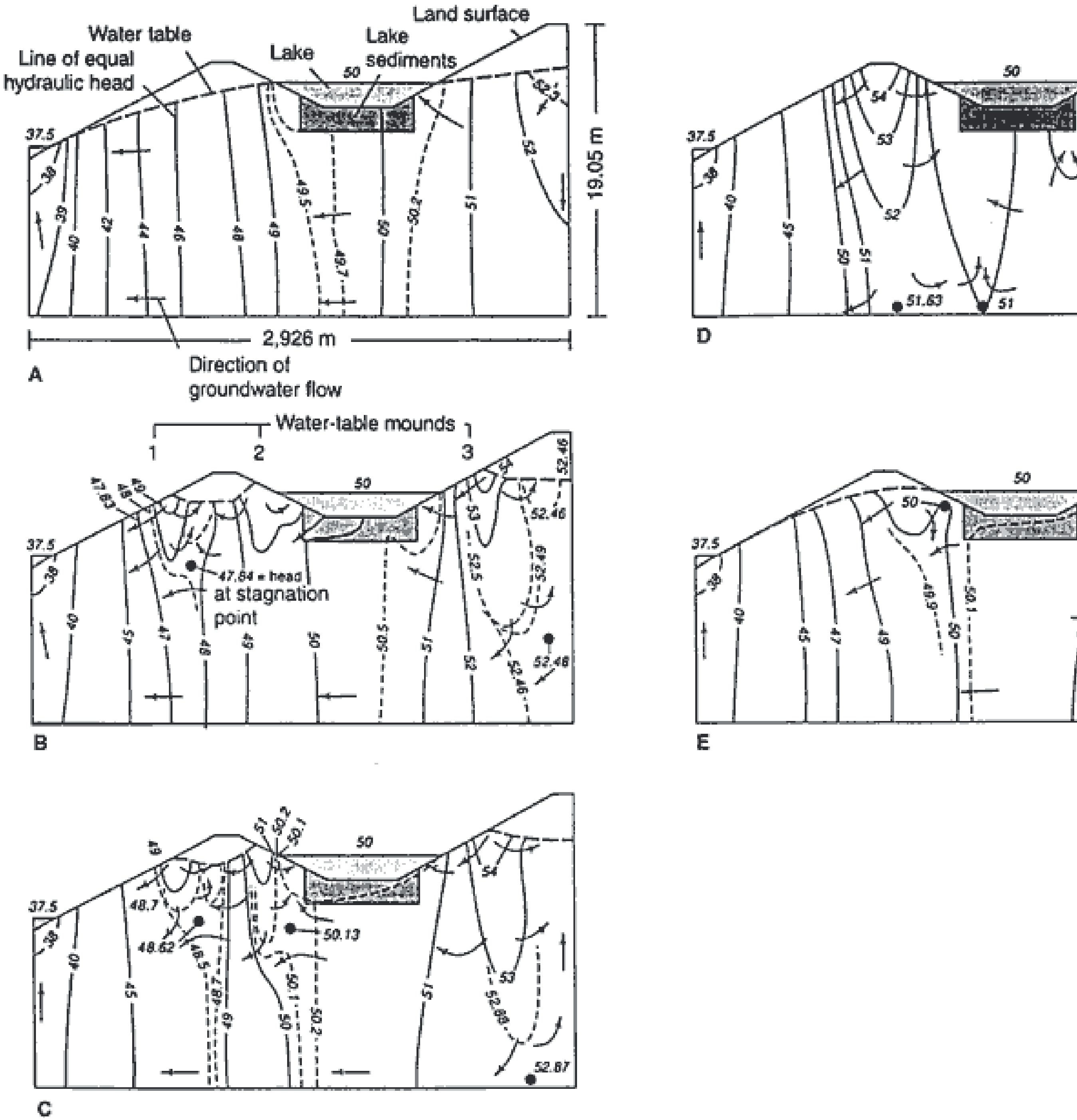

Figure 4 A-E Distribution of hydraulic head and direction of groundwater flow for variably saturated porous media near surface water. Beginning with a steady-state water table **A**, results are of conditions following 5 days **B**, 10 days **C**, and 15 days **D** of infiltration. **E** Conditions after 7 months of redistribution. (Modified from Winter 1983)

The shallow depth to groundwater near surface water results in another very dynamic climate-driven hydrologic process that affects the interaction of groundwater and surface water. Because of the shallow depth of groundwater near surface water, transpiration directly from groundwater by nearshore vegetation can intercept groundwater that would otherwise discharge to surface water. Furthermore, it is not uncommon for transpiration from groundwater to create cones of depression that cause surface water to seep out through the near-shore parts of its bed (Meyboom 1966; Winter and Rosenberry 1995).

Studies of the Effect of Geology on the Interaction of Groundwater and Surface Water

Various field studies or modeling studies of actual fied areas document the concepts and processes discussed above. The following examples indicate the effects of regional geologic framework and local geologic conditions on the interaction of groundwater and surface water.

Regional Geologic Framework

Several studies of regional groundwater flow in the northern prairie of North America indicate the relationship of surface water to regional groundwater flow systems. The first two examples present results of modeling studies, and the third example is of an extensively instrumented field site.

Tóth (1970) used electric analog models to simulate two-dimensional, steady-state, vertical sections to evaluate the relationship of groundwater hydrodynamics to the accumulation of hydrocarbons in a thick sequence of sedimentary rocks overlain by a relatively thin mantle of glacial deposits in Alberta. The sections were considered to be "experimental" and did not include much of the detailed structure and stratigraphy of the region. Although the purpose of Tóth's study was not related to evaluating the interaction of oroundwater and surface water, one of the sections, which is about 170 km long, intersects several lakes. as shown in *Figure 5*. The section shows numerous stagnation points related to regional. intermediate. and local flow systems. Furthermore, a stagnation point is presen downgradient of each of the lakes along the line of section, much like those indicated by numerical models of hypothetical settings described above. The results indicate that Buck Lake receives discharge from a relatively large, probably intermediate, groundwater flow system. In contrast, Wizard and Ministic Lakes receive discharge from much smaller local groundwater flow systems.

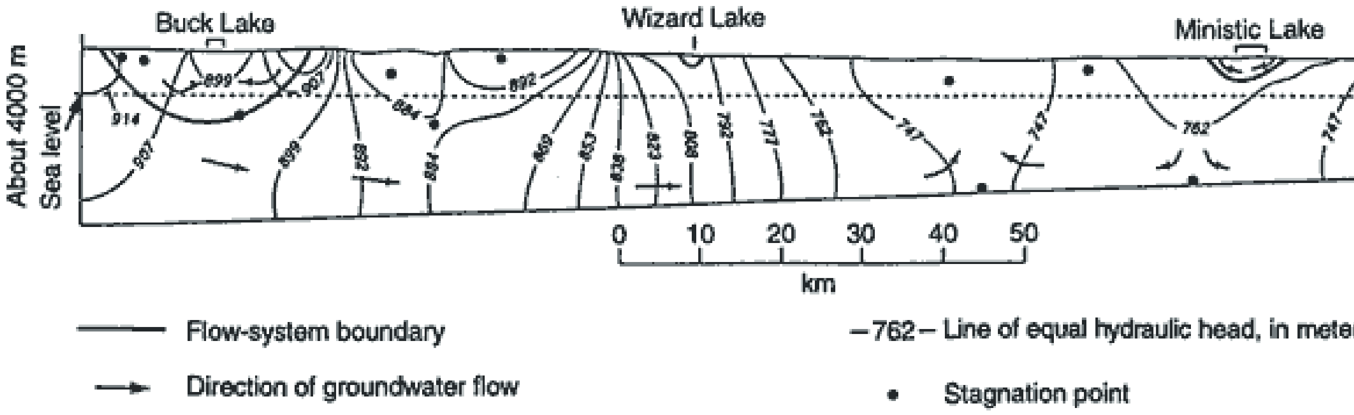

Figure 5 Electric analog model of groundwater flow of the Beaverhill Lake section in Alberta, Canada. (Modified from Tóth 1970)

Winter and Carr (1980) used a numerical model to simulate two-dimensional, steady-state, vertical sections to evaluate the relationship of intermediate and regional groundwater flow systems to lakes and wetlands along an 80-km section through the Missouri Coteau, which is a large moraine that transects North Dakota. The section is shown in *Figure 6*. The model considered groundwater flow systems only in glacial deposits because they are thick and are underlain by poorly permeable shale. Furthermore. because of the availability of geologic data from numerous drill logs the distributions of various types of glacial deposit were considered in the models. The main goal of the modeling was to relate discharge from groundwater flow systems of different magnitudes to the wide variation in water chemistry of lakes in the prairies. Result indicate that lakes having highly mineralized water receive discharge from regional or deep intermediate flow systems that are recharged at the major topographic highs. Nearby lakes having less mineralized water receive discharge from small intermediate flow systems (*Figure 6)*. Because of the scale of the model, local groundwater flow systems are not shown.

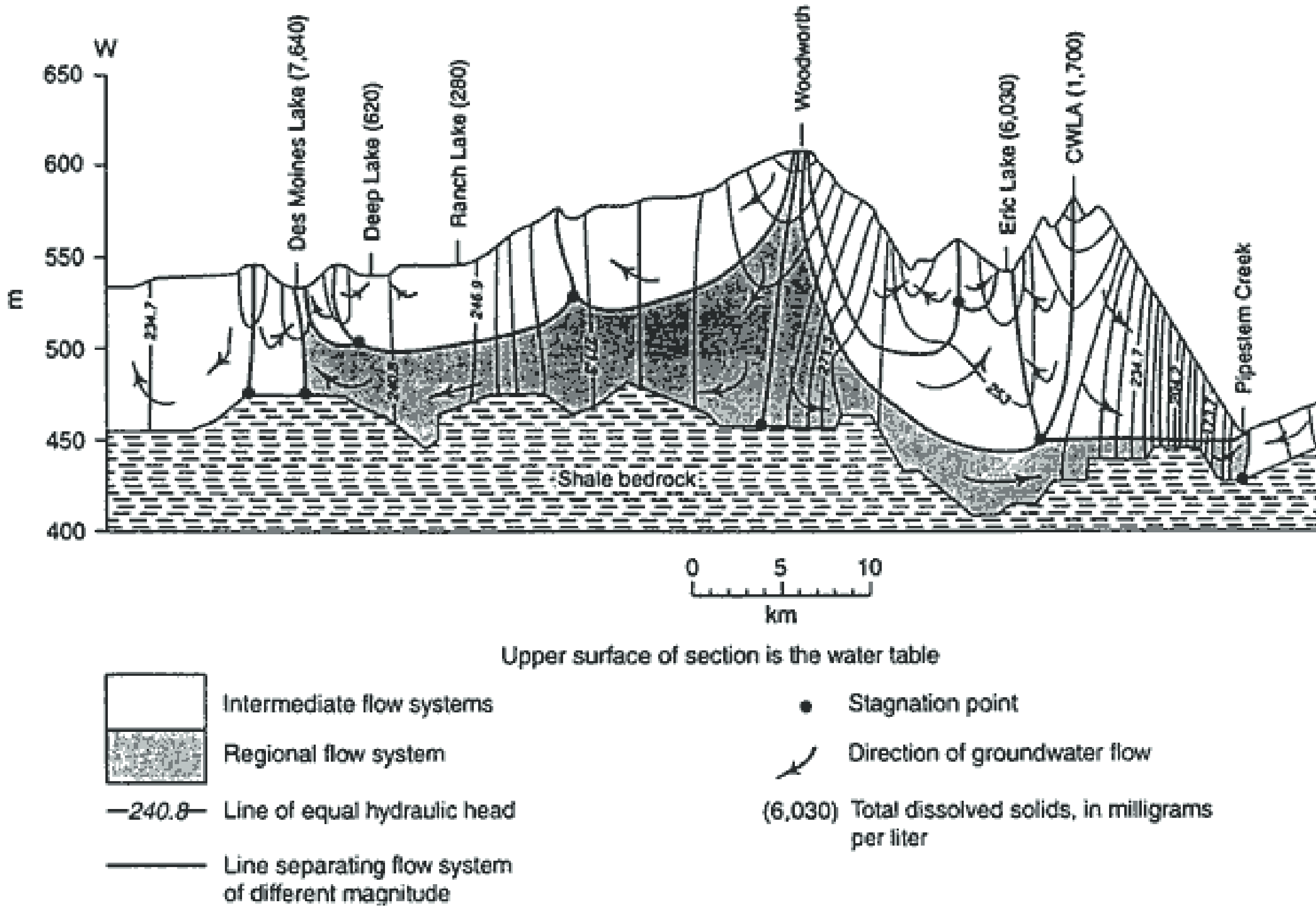

Figure 6 Numerical model of groundwater flow through part of the Missouri Coteau in Kidder and Stutsman Counties, North Dakota, showing high values of total dissolved solids in lakes receiving groundwater discharge from regional (Des Moines Lake) and deep intermediate (Eric Lake) flow systems (Modified from Winter and Carr (1980)

Groundwater from local flow systems discharges into nearly all the lakes and wetlands, whether topographically high or low. These local flow systems are recharged in the uplands near the lakes and wetlands. commonly at small depressions in those uplands (Lissey 1971; Winter and Rosenberry 1995).

In an extensive field study. van Everdingen (1967) used nested piezometers to evaluate the effect of the formation of a large reservoir on groundwater flow in bedrock aquifers in Saskatchewan. As shown in *Figure 7,* most piezometer nests were near the South Saskatchewan River valley, but others were several km from the valley. Prior to construction of the dam, all groundwater in the bedrock aquifers flowed toward the South Saskatchewan River (Figure 7A). As the reservoir filled, the increased heads caused groundwater to reverse direction and flow away from the valley in part of the bedrock aquifers (*Figure 7B*). The reversed gradients reached as deep as 100 m below the reservoir level. This example indicates the close interaction of a major river with regional groundwater flow systems, and how changes in surface-water levels can affect relatively deep groundwater movement.

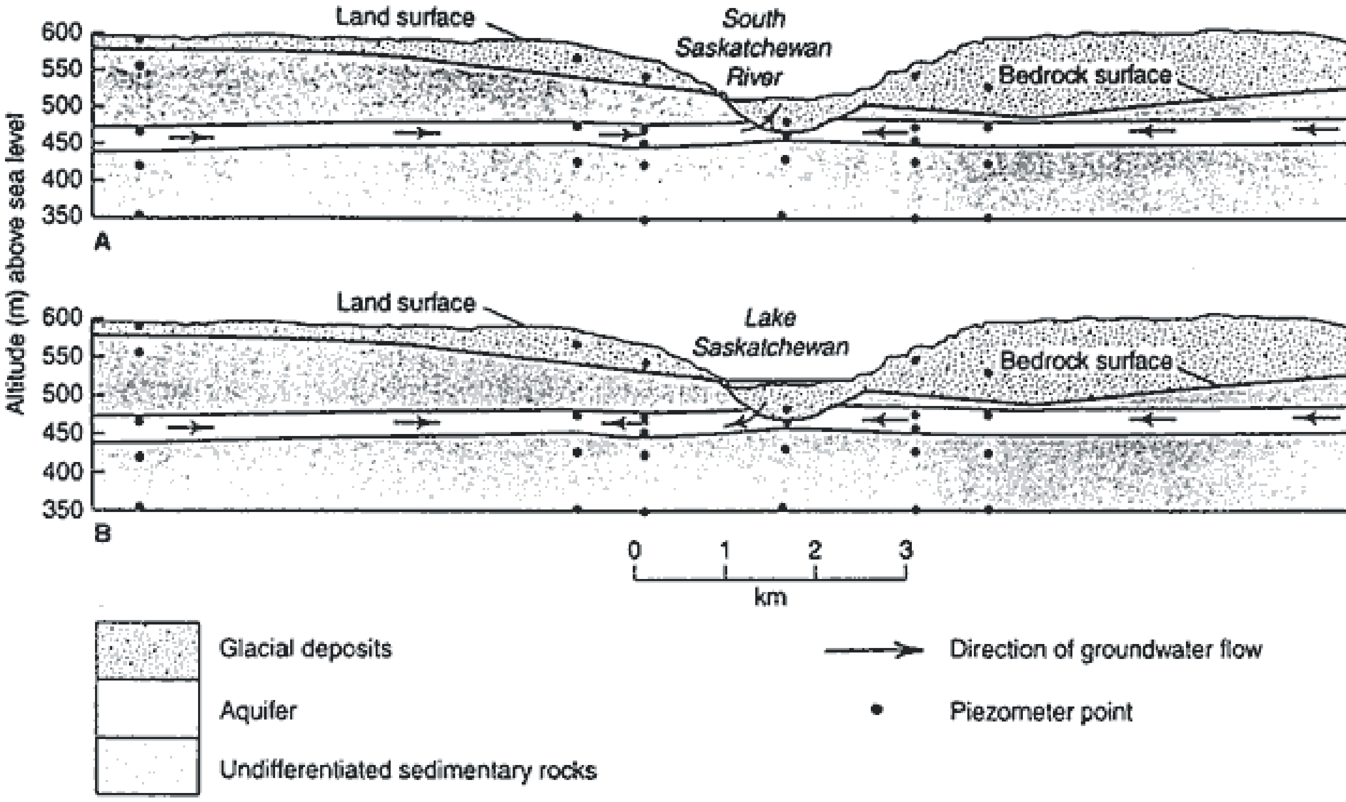

Figure 7A,B Hydrologic section across the Saskatchewan River, Canada. **A** Groundwater flow in a bedrock aquifer before construction of a reservoir on thc South Saskatchewan River. **B**, Reversal of flow in part of the aquifer following filling of the reservoir. Only the principal aquifer is shown. (Modified from van Everdingen 1967)

Local Geologic Conditions

In the regional studies presented above, in which the goal was to understand general, large-scale processes, many local geologic details were not considered. However. Iocal geologic conditions can have a substantial effect on the interaction of a surface-water body with groundwater. as indicated bv the field studie presented below. In the following five examples, three are of locally complex geologic frameworks and two are of the effect of lakebed geology on seepage distribution in lakes: all examples are from the USA (4) or Canada (1).

Local geologic setting

In glacial terrain, glacial deposits commonly fill buried bedrock valleys. In a study designed to determine recharge to bedrock via the valley-fill deposits north of Minneapolis, Minnesota, a piezometer nest was constructed in the bedrock aquifers adjacent to the valley, and a second piezometer nest was constructed in the valley-fill deposits. The setting is shown in *Figure 8*. Although the site was considered to be within the bedrock recharge area near the north edge of the Twin Cities artesian basin, the data indicate that groundwater from the bedrock was moving into the valley-fill deposits (Winter and Pfannkuch 1976). Furthermore, the results indicate some unexpected implications for the hydrology of the lakes overlying the buried valley. For example, George Watch Lake, which is underlain entirely by surficial sand. receives most of its groundwater inflow from local and intermediate flow systems within the surficial sand. Although water from the bedrock moves toward the lake. that water is impeded by till and clay layers in the valley fill (*Figure 8*). Centerville Lake receives much less water from the surficial sand aquifer, because it receives groundwater only from a local flow system. Furthermore it is partly underlain by low-permeability till, which limits groundwater inflow from both the till and the underlying bedrock.

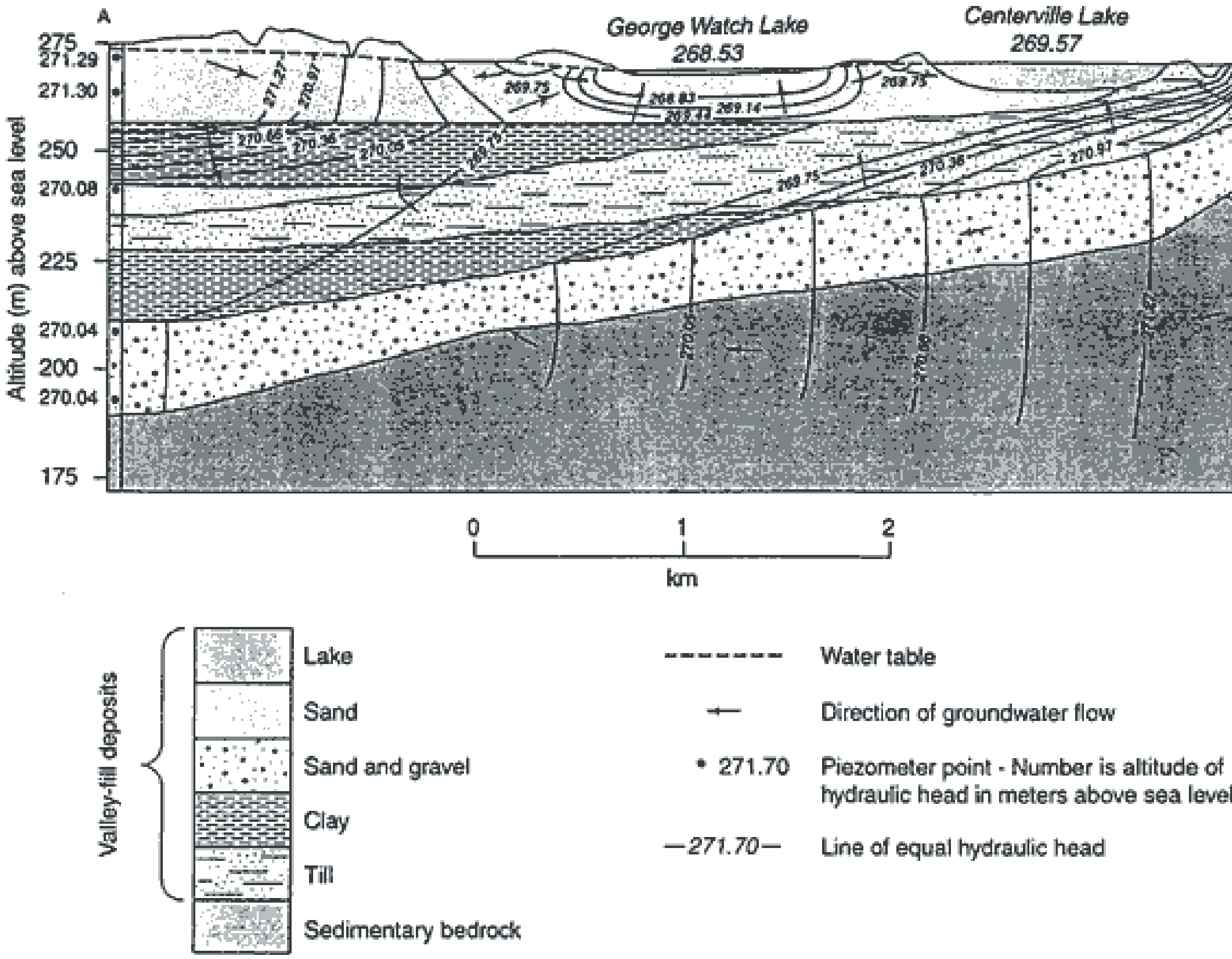

Figure 8 Hydrologic section showing groundwater movement associated with lakes overying a buried bedrock valey near Lino Lakes, Minnesota (Modified from Winter and Pfannkuch 1976)

Mirror Lake lies in the lower end of the Hubbard Brook valley in the White Mountains of New Hampshire; a section is shown in *Figure 9*. Glacial deposits underlie most of the lake, but crystalline bedrock is in direct contact with the lake in a few small areas. A saddle on the bedrock surface lies directly beneath Mirror Lake, and the bedrock valleys that extend to the north and south from the saddle are filled with glacial deposits. Numerous piezometer nests and water-table wells have been drilled in the Mirror Lake area for the purpose of conducting long-term research on the hydrology of lakes in mountainous terrain (Winter 1984). The hydrologic section through Mirror Lake, using data from four piezometer nests and some of the water-table wells, reveal a very complex groundwater flow field in the vicinity of the lake (*Figure 9)*. Most of the groundwater that is recharged on the north side of the lake moves through the till and discharges to the lake. However, some of the groundwater moves into bedrock, passes beneath the lake, and discharges to the lake offshore in the littoral zone on the downgradient side. Although Mirror Lake receives groundwater that has moved through the bedrock, the quantity of this water is small and it is a minor part of the water budget of the lake (Rosenberry and Winter 1993). Lake water seeps to groundwater in the nearshore part of the littoral zone on the downgradient side. Some of this water discharges to Hubbard Brook, but much of it discharges to a fen wetland, because of a break-in-slope of the water table, as explained in the discussion of *Figure 3*.

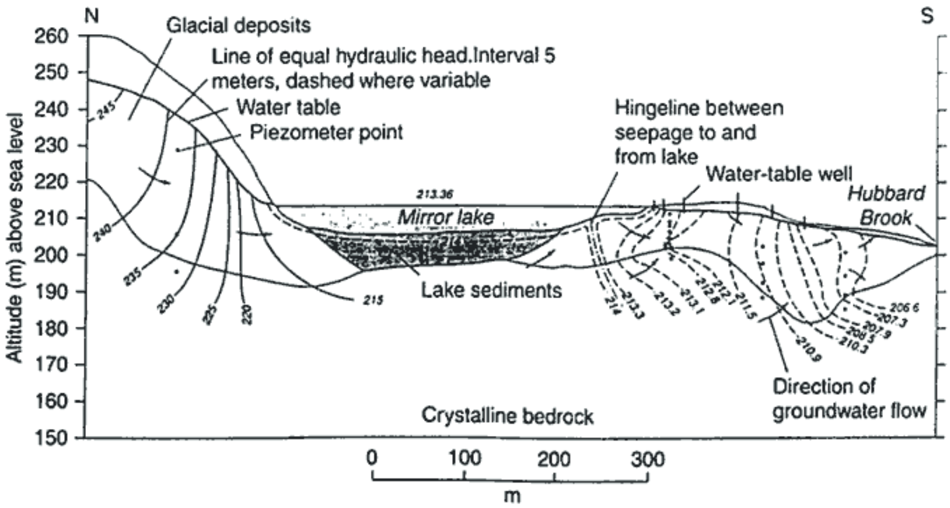

Figure 9 Hydrologic section showing groundwater flow in the Mirror Lake area, New Hampshire

The Cache River flows through the Black Swamp wetland in the Mississippi Delta floodplain in eastern Arkansas; a section is shown in *Figure 10*. Results of a three-year study of the interaction of the river with groundwater (Gonthier 1996) indicate that the river valley has a relatively complex pattern of groundwater movement. The Cache River is the focus of groundwater discharge from local and regional flow systems. However, groundwater also discharges at the edge of the valley because of a break-in-slope of the water table (*Figure 3*) associated with a terrace. Local geologic conditions have an additional effect in this setting because of the presence of the confining bed. Groundwater flow directions within the confining unit are particularly complex during flooding, because floodwaters move downward into this unit while deeper groundwater moves upward into the unit.

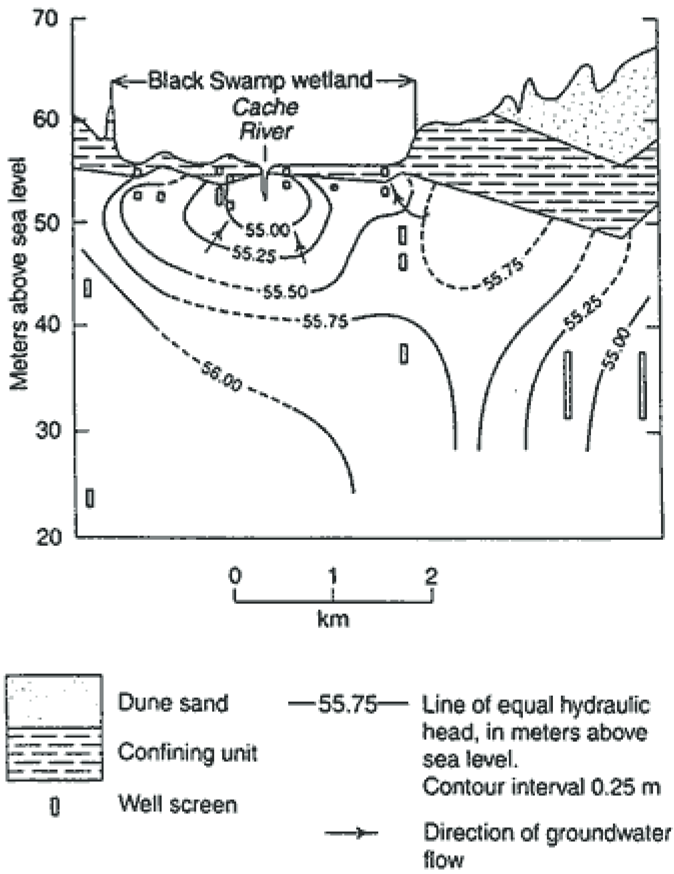

Figure 10 Hydrogeologic section showing groundwater flow during June 18-22, 1990, in part of the Cache River valley in Arkansas. (Modified from Gonthier 1996)

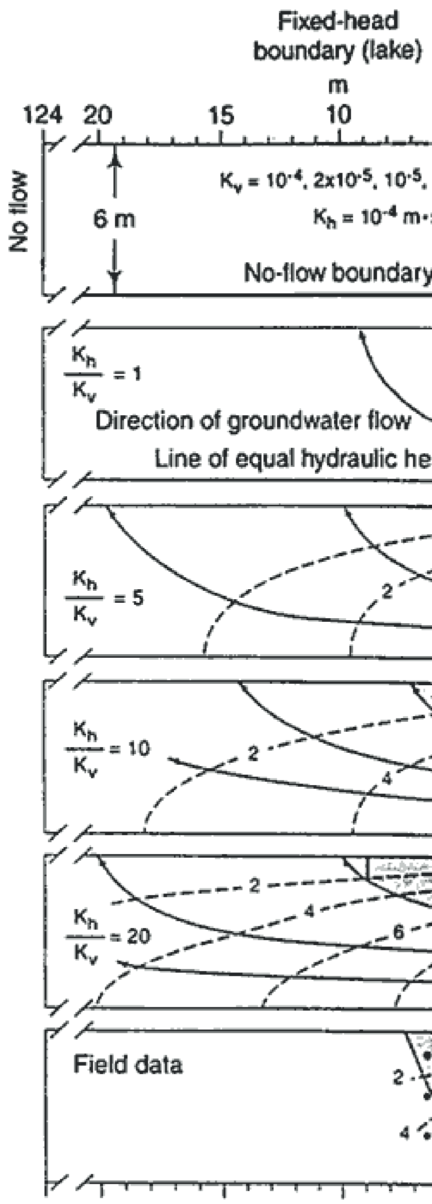

Figure 11 Numerical simulations of groundwater flow into Perch Lake in Ontario for various values of anisotropy. *Bottom panel* shows field results at same scale as flow nets. *Shading* indicates total zone of tracer migration. Vertical bars indicate successive positions of center of mass of tracer pulse beginning on day 0 beneath shoreline and then on days 10, 20. 40, and 80. (Modified from Lee et al. 1980)

Geology of surface-water beds

The effects of heterogeneous geology of surface-water beds on groundwater discharge to surface water are shown by comparing two lakes and a stream that lie within the same headwaters area in north-central Minnesota. The Shingobee River headwaters area, which incudes numerous kettle lakes, was covered by a proglacial lake between about 9000 and 12,000 years ago (Schwalb et al. 1995). Present-day lakes that occupy what were the shallow parts of the proglacial lake, such as Williams Lake, are underlain by sand and gravel. Present -day lakes that occupy what were the deeper parts of the proglacial lake, such as Shingobee Lake, are underlain by silt and very fine sand. The Shingobee River also has incised a steep-walled valley into the finer grained deposits near Shingobee Lake. Groundwater flow into the sandy bed of Williams Lake is diffuse, and in places the seepage rate decreases nearly exponentially away from the shoreline (Erickson 1981; Rosenberry 1985). In contrast, most groundwater flow into Shingobee Lake and the Shingobee River is focused at springs in the nearshore zones and along the perimeter of the water bodies, where slightly more permeable fine sand layers within the silt intersect the lakebed and streambed.

To investigate the effect of anisotropy on groundwater inflow through a lakebed, Lee et al. (1980) placed a network of piezometers and seepage meters in the bed of Perch Lake, Ontario. A salt tracer was injected into the groundwater system upgradient of the lake, and the piezometers and seepage meters were used to map the salt plume as it moved toward and passed through the lakebed. Results of the study indicate that by matching simulations of different anisotropy to the field data, the actual anisotropy of the porous media underlying the lake could be estimated. In this case, the field data best matched the anisotropy of 10, as shown in *Figure 11*. The study also documents that plumes of a contaminant, such as the salt in this case, that are present below the water table discharge into surface water offshore.

Integrated Effects of Geology and Climate on the Interaction of Groundwater and Surface Water

Various studies have integrated detailed information about geology, groundwater movement, and climate to evaluate transient characteristics of the interaction of groundwater and surface water. The sites of these it studies are in landscapes that have greatly different hydrogeologic and (or) climatic settings. The following examples, all from the USA, are of field studies in glacial, dune, coastal, mantled-karst, and riverine terrains.

Glacial Terrain

The Cottonwood Lake area, designated as CWLA in *Figure 6,* is on one of the topographic highs on the east side of the Missouri Coteau in North Dakota. The area is underlain primarily by low-permeability till, and much subsurface water flow is through fractures in the till. Evaporation exceeds precipitation by about 300mm in this area. Studies of the interaction of groundwater with prairie pothole wetlands positioned along a topographic slope in the Cottonwood Lake area, conducted over a 20-year period, indicate that most wetlands that hold water only seasonally recharge groundwater through part or all of their lakebeds. Even though the area is on a major topographic high, only a small percentage of the recharge is to regional groundwater flow systems; most recharge moves to nearby more permanent wetlands (Winter and Rosenberry 1995), where it is discharged primarily by evaporation.

The small-scale hydrologic processes related to climate are particularly relevant to these small prairie wetlands. Focused recharge directly adjacent to these wetlands is well documented for the Cottonwood Lake area (Rosenberry and Winter 1997), as well as for other sites in the northern prairies (Mills and Zwarich 1986; Zebarth et al. 1989; Gerla 1992). Transpiration directly from groundwater also has a substantial effect on the movement of water between the wetlands and groundwater. Transpiration from groundwater by upland plants around the perimeter of the wetlands causes surface water to seep to groundwater, then to be transpired. Thus, by mid- to late-summer nearly every year, the wetlands lose water to the atmosphere by evaporation and by transpiration via groundwater. During periods of drought, this process can result in troughs of depression that extend around much of the wetlands, as shown for wetland P 1 in *Figure 12.* Arndt and Richardson (1993) indicate that these transient flow processes around the perimeter of prairie wetlands, result in unique soil development that is particularly useful for wetland delineation. Furthermore. even though the water balance of these prairie wetlands is dominated by interchange with the atmosphere because of the relatively low permeability of the fractured till, their water chemistry is determined by their interaction with groundwater (LaBaugh et al. 1987).

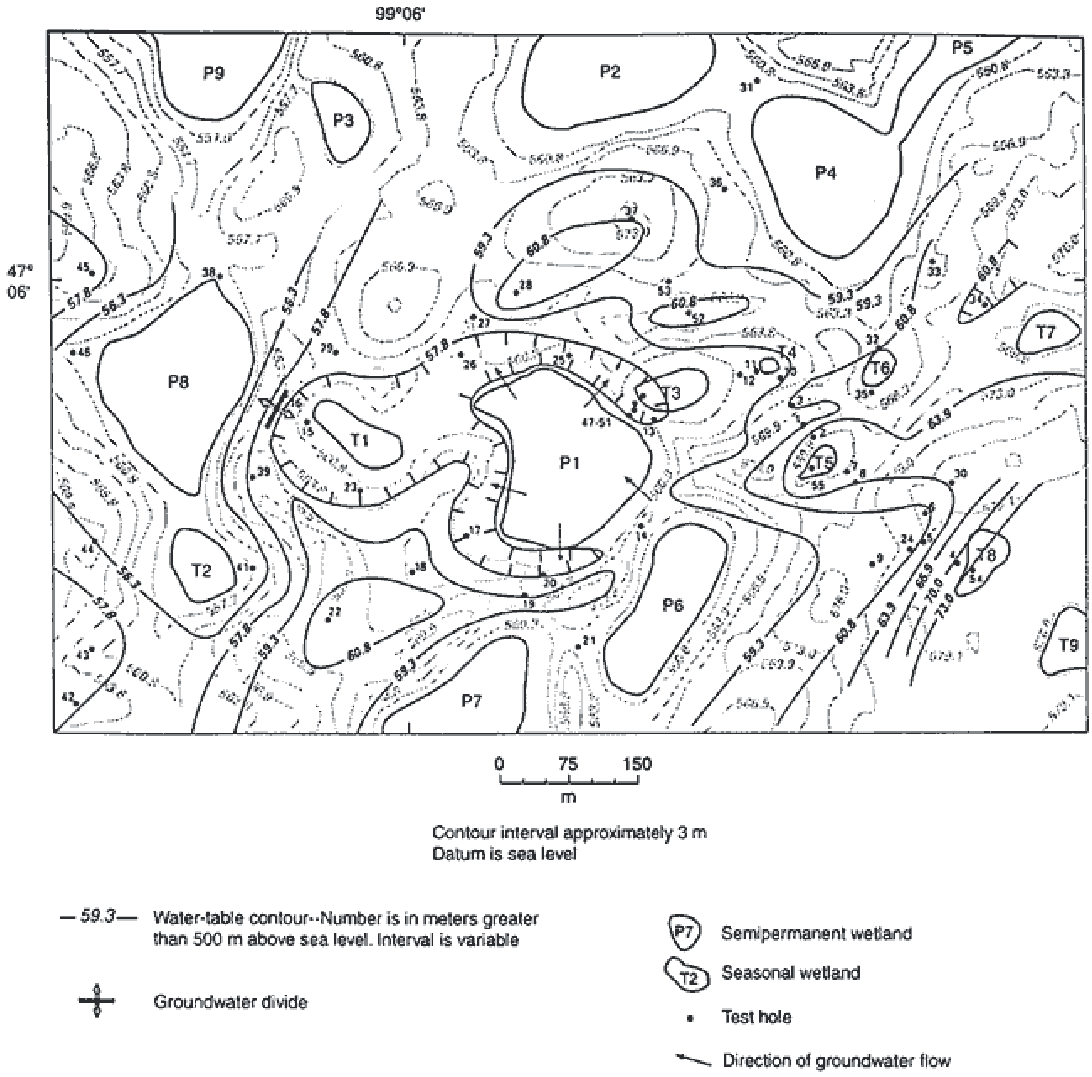

Figure 12 Configuration of the water table in the Cottonwood Lake area, North Dakota, for August 31, 1989, showing the water-table depression around much of the perimeter of wetland P1 caused by transpiration directly from groundwater. (After Winter and Rosenberry 1995)

Crystal Lake is located in the headwaters of the Trout River in northern Wisconsin. The area is under lain primarily by sandy glacial deposits that overlie crystalline bedrock. Precipitation exceeds evaporation by about 180 mm in this area. Much of the time, Crystal Lake has seepage outflow to groundwater through most of its bed. However, flow reversals caused by transient focused recharge in the nearby uplands are common, as illustrated in *Figure 13.* During a lO-year period of data collection, five years of relatively wet conditions were followed by several years of dry conditions. Using data from nested piezometers on four sides of the lake, Anderson and Cheng (1993) indicate that flow reversals from groundwater to the lake, on sides that normally have seepage outflow, were common during the wet periods. The flow reversals extended as deep as 10m into the groundwater system. Flow did not reverse from groundwater to the lake at these localities during the dry years.

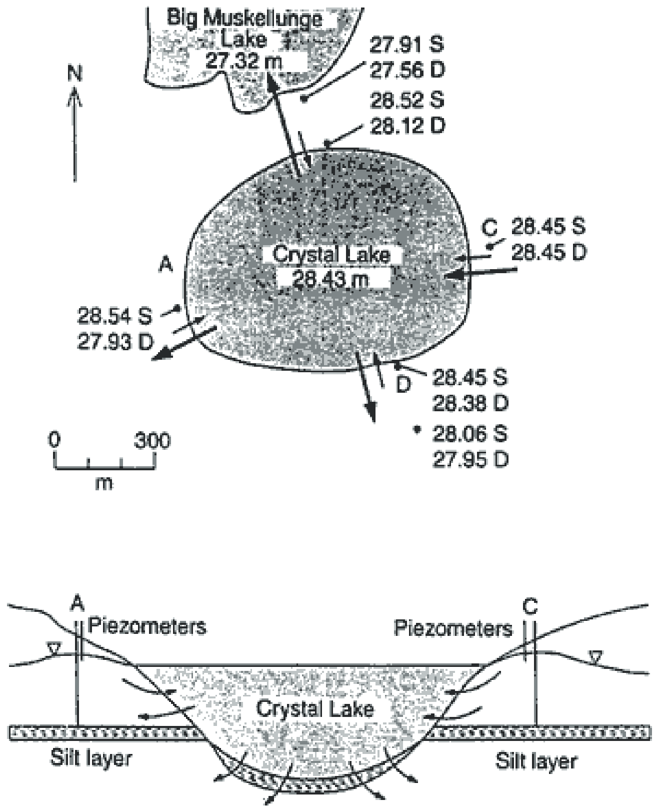

Figure 13 A Water levels in shallow (S) and deep (D) piezometers near Crystal Lake, Wisconsin for July 13 1987. Long arrows indicate the direction of flow in the deep flow system and short arrows indicate the direction of flow in the shallow flow system. The shallow piezometers were completed near the water table and the deep piezometers were completed at a depth of about 10 m. **B** Schematic section showing seepage directions at Crystal Lake. The saturated thickness of the aquifer above the silt layer is ahout 19 m. (Modified from Anderson and Cheng 1993)

Dune Terrain

Dunes are present along some reaches of the shorelines of the North American Great Lakes, and wetlands are common in the interdunal lowlands. Studies of groundwater interaction with wetlands in the Indiana Dunes National Lakeshore along the south shore of Lake Michigan, where precipitation exceeds evaporation by about 150 mm, indicate that groundwater flow fields of several magnitudes affect the interdunal wetlands (Shedlock et al. 1993). Of particular note is the determination that discharge from an intermediate flow system is the source of water to an isolated peat mound, Cowles Bog, in the Great Marsh. Locations and hydrology are shown in *Figure 14.* The peat mound is located over a breach in a till confining bed underlying the marsh, where the head in the aquifer underlying the till is greater than the head in the marsh. The studies were conducted for more than five years.

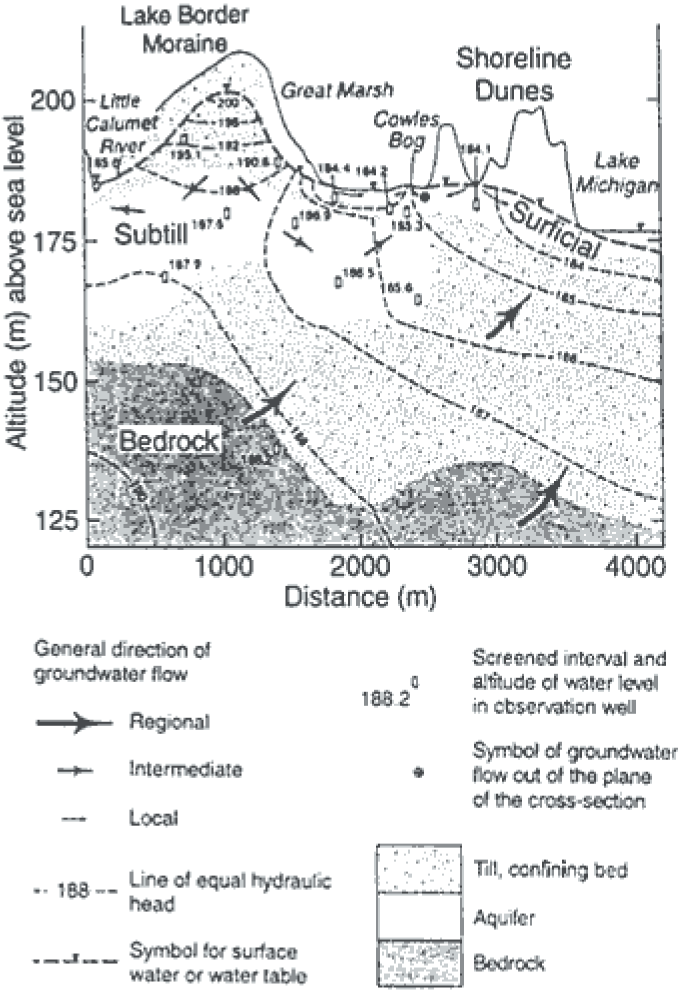

Figure 14 Hydrologic section showing groundwater flow in the Great Marsh area of the Indiana Dunes along the southern shore of Lake Michigan, Indiana. (Modified from Shedlock et al. 1993)

The superposition of the effects of climate on the interaction of groundwater with these wetlands is provided by a study of another part of the Indiana Dune complex. Doss (1993) observed that the interaction of groundwater with interdunal wetlands was highly transient. During the one-year study, some of the wetlands changed from flow-through, to groundwater recharge, to groundwater discharge. The transient conditions were caused by the interchange of recharge focused near the perimeter of the wetlands and evapotranspiration from them in the same perimeter areas. Similar dynamic interactions between groundwater and wetlands occurred during a one-year study of dune terrain in Spain (Sacks et al. 1992).

Lakes and wetlands also are common in the semiarid dune terrain in Nebraska. Evaporation exceeds precipitation by about 750 mm in the vicinity of the Crescent Lake National Wildlife Refuge, where a 20-year study of the interaction of groundwater with lakes and wetlands has been conducted. Regionally. the lakes and wetlands in this area are flow-through with respect to groundwater. However, water-level data from wells near the lakeshores indicate that transient water-table mounds can be present following precipitation. Far more commonly, transpiration from nearshore upland vegetation lowers the water table below the lake level, inducing seepage from the lakes during parts of some summers.

The Nebraska site also was used for a detailed study of focused recharge associated with land-surface depressions. Data from that study indicate that recharge occurs sooner and involves greater quantities of water where the interlake dune terrain contains small depressions compared to where a single sharpcrested dune occupies the interlake area (Winter 1986). During the study, water-table mounds persisted beneath the hummocky dune terrain during extended wet and dry periods.

Coastal Terrain

Small seasonal ponds are present in the forested coastal plain of the Delmarva Peninsula, which includes parts of Delaware, Maryland, and Virginia, between Chesapeake Bay and the Atlantic Ocean. Precipitation exceeds evaporation by about 200 mm in this area. Results of a five-year study of the interaction of groundwater with several ponds indicate that focused recharge around the perimeter of the ponds causes a substantial part of their water inflow during spring (Phillips and Shedlock 1993). Hydrologic conditions are shown in *Figure 15.* The transient water-table mounds caused by focused recharge are indicated by the rise of the water table at some wells above the pond level associated with some precipitation events (*Figure 15A*). During summer and fall, maximum water-table altitude commonly is beneath the ponds (*Figure 15B*). The chemistry of groundwater in the transient mounds beneath the upland and the chemistry of the pond water are similar during the times of pond filling. Chemistry of groundwater in those parts of the aquifer that do not have transient mounding of the water table due to focused recharge is considerably different from the groundwater chemistry in those parts of the aquifer that do have the transient mounding.

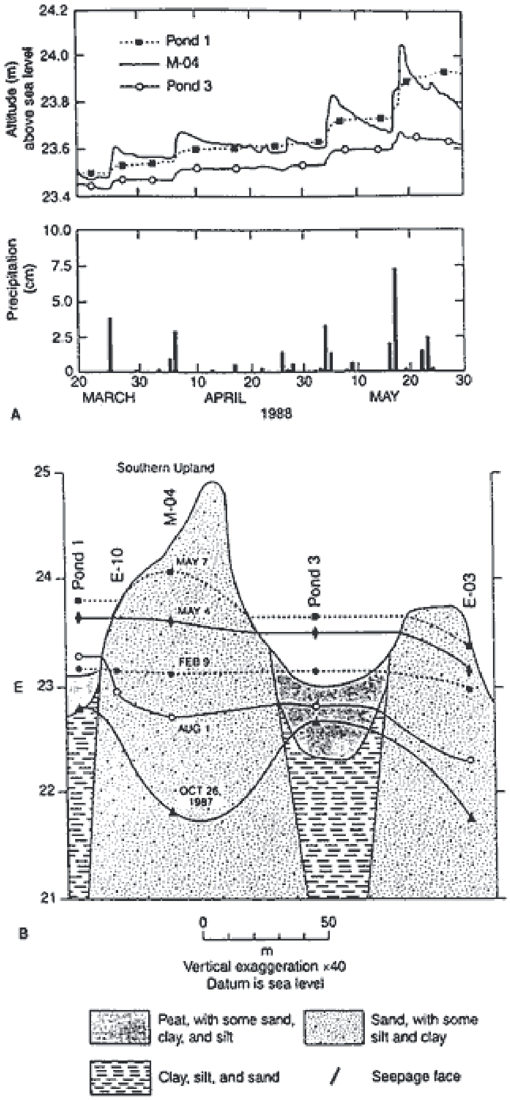

Figure 15 A,B Hydrologic conditions near seasonal ponds on the Atlantic Coastal Plain, Delaware. **A** Hydrographs showing responses of two ponds and one well to precipitation during spring of 1988. **B** Profiles of the water table for October 216, 1987, and for several dates in 1988. (Modified from Phillips and Shedlock 1993)

Mantled Karst Terrain

Florida contains many lakes that were formed when unconsolidated surficial deposits slumped into sinkholes that resulted from dissolution of the underlying Floridan aquifer, a thick sequence of carbonate rocks. Lake Lucerne, which lies along the central topographic ridge of Florida, was formed in this manner. Precipitation exceeds evaporation by about 100 mm in this area. Local hydrology is shown in *Figure 16.* Lake Lucerne is underlain by a sequence of surficial deposits, a thin confining bed, and carbonate rocks of the Floridan aquifer. Slumpage into the sinkhole in the carbonates caused the confining bed beneath the lake to be partially breached and filled with surficial deposits.

A detailed study of the lake involved construction of three piezometer nests around the perimeter of the lake, as well as lines of water-table wells radiating away from the shoreline. Results of the three-year study indicate that local flow systems are recharged in the uplands near the lake, and that they discharge in the littoral zone of the lake (Lee and Swancar 1997). Groundwater that is recharged farther from the lake in the higher parts of the upland moves toward the lake, but then is diverted downward to recharge the Floridan aquifer by way of the breaches in the confining bed (*Figure 16*). Seepage from the lake offshore of the band of inflow also moves downward through the breaches in the confining bed to recharge the Floridan aquifer. Thus, a band of recharge beneath the nearshore upland and a band of discharge to the lake in the nearshore littoral zone is present around the entire perimeter of the lake. In addition, automated water-level recorders on water-table wells near the lake have documented the common occurrence of focused recharge and transpiration directly from groundwater in the nearshore vicinity of the lake.

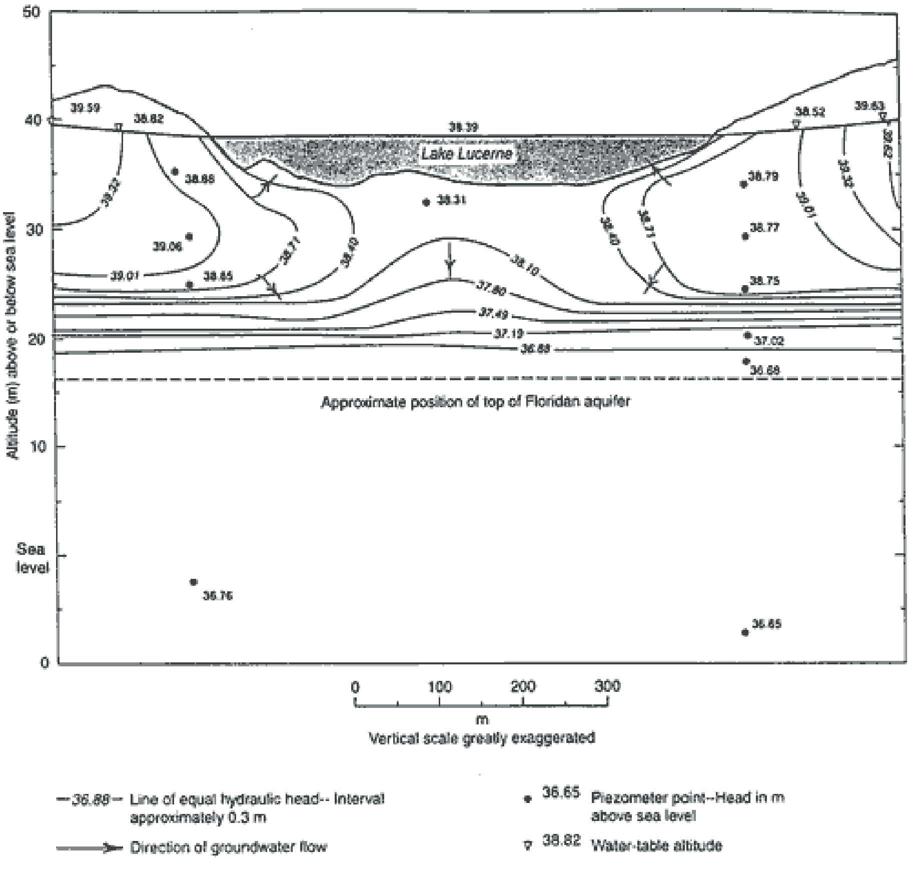

Figure 16 Hydrologic sectiion showing groundwater flow near Lake Lucerne, Florida. (Modified from Lee and Swancar 1997)

Riverine Terrain

An example of the effects of seasonal variability of surface-water levels on groundwater flow systems is provided by a study of the Cedar River in Iowa (Squillace et al. 1993). Because the groundwater in the alluvial valley contained atrazine, an agricultural chemical not used locally, the interaction of groundwater with the stream was of particular interest. Numerous nested piezometers were constructed across the flood plain to measure hydraulic heads as well as to determine the distribution of chemical constituents. Results of the study, shown in *Figure 17,* indicate that during high river stages atrazine was transported into the groundwater system (*Figure 17B*), and that some of it was slowly released back to the river as stages fell (*Figure 17C*).

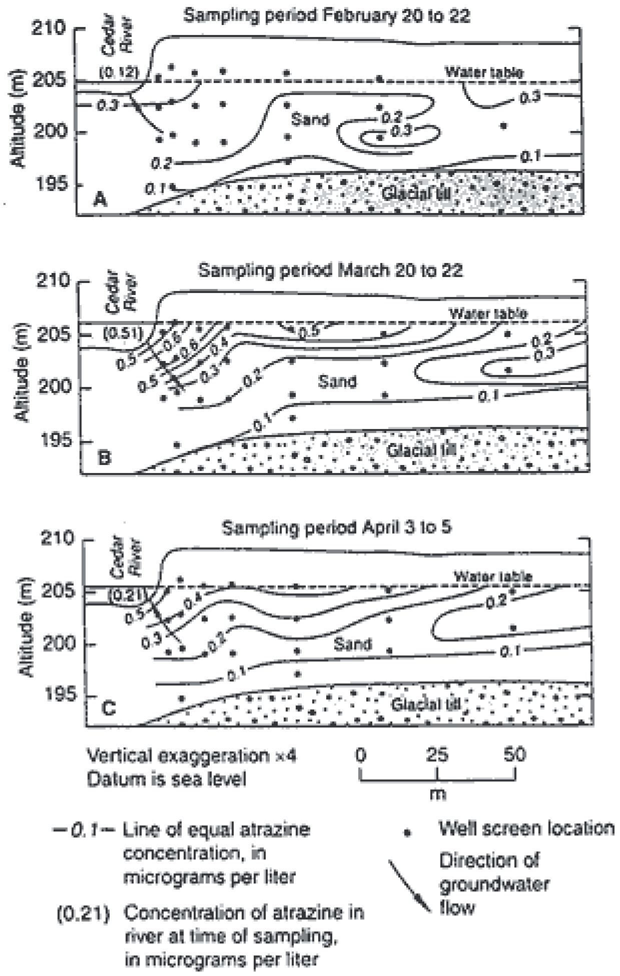

Figure 17 A-C Hydrogeologic sections for part of the Cedar River, lowa, for three time periods in 1990. **A** Movement of groundwater into the river prior to a period of high river stage. **B** Movement of river water into the contiguous aquifer during high river stage. **C** Return of some of the water from the aquifer during declining river stage. (Modified from Squillace et al. 1993)

The substantial effect of transpiration on groundwater flow systems near streams is indicated by a study of the Pawcatuck River in Rhode Island (Ryan and Kipp 1997). The study, which was designed to evaluate flow paths and travel times of a contaminant that had seeped from a containment lagoon, involved construction of numerous piezometer nests between the lagoon and the river. A section is shown in *Figure 18*. Although the river was expected to be the primary drain of the groundwater flow system. Ryan and Kipp (1997) observed that the large riverine wetland contiguous to the river was receiving groundwater discharge as well. In places. the seasonal transpiration directly from groundwater in the wetland caused the contaminant plume to pass beneath the river to the wetland.

Discussion

The interactions of streams, lakes, and wetlands with groundwater are affected by the positions of the water bodies with respect to groundwater flow systems, geologic characteristics of their beds. and their climatic settings. Therefore, for thorough understanding of the hydrology of these surface-water bodies, all three factors need to be taken into account. Results portrayed in the hydrologic section of part of North Dakota (*Figure 6*) indicate that the chemistry of lake waters reflects the magnitude of the groundwater flow systems that discharge to them. For many purposes of watershed and ecosystem management, this general knowledge may be sufficient. However, knowledge of local geology and the effects of climate on these prairie systems, as indicated by studies of the Cottonwood Lake area (*Figure 12*, which lies along this hydrologic section, provides a more thorough understanding of the hydrologic processes that define these surface-water bodies. For example, although the area is situated on one of the topographically highest parts of a morainal complex, which is considered to be a regional recharge area, local geologic and topographic features within the area cause most of the groundwater to discharge locally to the wetlands. Furthermore, Winter and Rosenberry (1998) document substantial changes in the relation of these wetlands to groundwater that resulted from century-scale periods of drought and precipitation. Additionally, long-term studies of wetlands in the Cottonwood Lake area indicate that the major-ion water type can change with major variations in climate. For example, wetlands that normally contain bicarbonate water can become dominated by sulfate water during major droughts, and wetlands having sulfate water can become dominated by bicarbonate water during major wet periods (LaBaugh et al. 1996).

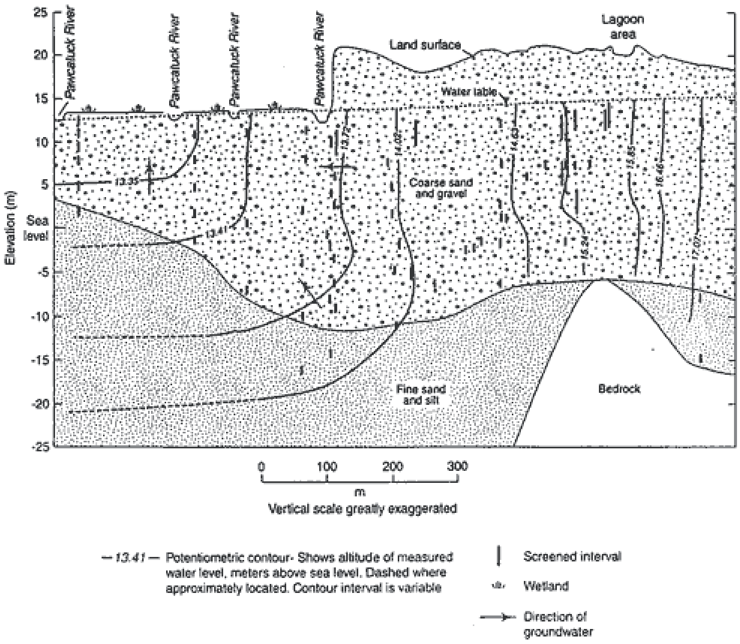

Figure 18 Hydrogeologic section along part of the Pawcatuck River, Rhode Island, showing groundwater movement to the river as well as to an extensive riparian wetland. (Modified from Ryan and Kipp 1997)

Studies of wetlands in the Indiana Dunes along the south shore of Lake Michigan also provide evidence that the integrated knowledge of regional position within groundwater flow systems, local geology, and climate is needed to understand and effectively manage these ecosystems. For example, although the wetlands lie along a regional flow system from a moraine to Lake Michigan, a local geologic feature, such as a discontinuity in a confining bed, results in a unique wetland ecosystem, Cowles Bog, within the more extensive Great Marsh (Shedlock et al. 1993). Furthermore, studies of transient reversals in flow direction between wetlands and groundwater in the Indiana Dunes wetland complex indicate the significant effect that climate-driven processes of focused recharge and transpiration directly from groundwater have on these ecosystems (Doss 1993).

The lakes and wetlands in the Nebraska Sand Hills lie along a regional groundwater flow system that is tens of kilometers in length. From a regional perspective, these lakes are largely flow-through with respect to groundwater. However, the segments of lakebed that have seepage in and seepage out change continually, depending on the distribution of depression-focused recharge in the uplands (Winter 1986) and transpiration from groundwater around their perimeter.

Focused recharge occurs directly adjacent to surface water, thereby causing transient water-table mounds and enhanced seepage rates or reversals of seepage direction. These conditions are documented in field studies of glacial, dune, coastal, mantled karst, and riverine terrain, as well as from from semiarid to humid climates. Similarly, transpiration directly from groundwater that affects seepage rates and direction also has been documented in these terrains.

Changes in direction of groundwater flow also can be caused by seepage of surface water into the groundwater system at times of high surface-water stages, which in most cases is driven by variations in climate. The three examples of riverine systems presented herein provide a perspective of these changes at greatly different scales. Raising the river stage by impounding a major river, the South Saskatchewan River, which receives discharge from a regional groundwater system, resulted in reversal of groundwater flow in bedrock aquifers as much as 100 m below the river. Although this study was done while the reservoir was filling, substantial variations in reservoir level related to climate variability and water needs probably will also result in changes in groundwater gradients and flow directions at other times. On a smaller scale, changes in seepage direction between the Cedar River and its contiguous aquifer in Iowa, which is caused by seasonally high river stages, have resulted in contamination of the aquifer, even without overbank flooding. On an even smaller scale. flooding in the Black Swamp area along the Cache River in Arkansas has resulted in very complex flow fields in the confining bed. Groundwater in the aquifer underlying the confining bed moves upward into the lower part of the confining bcd at all times; seasonal flood uaters move downward into the upper part of the confining bed.

The field studies discussed herein reveal unexpected similarities in the hydrology of some of the surfacewater bodies. For example. prairie pothole wetlands in North Dakota and lakes along the central ridge of Florida have much in common in that many do not have streamflow in or out. and their major gain and loss of water is from and to the atmosphere. Thus, lakes and wetlands in both regions are especially vulnerable to drought. The interchange between surface water and groundwater in both regions is limited, but for very different reasons. Groundwater input to and seepage from most prairie pothole wetlands is limited because of the low permeability of the till underlying the wetlands and their watersheds. Groundwater input to and seepage from many Florida lakes is limited because recharge is divided between local flow and regional flow. Recharge that takes place in the narrow band of upland around the lakes discharges to the lakes, but the remainder of recharge in the uplands moves dounward through breaches in the confining bed to recharge the Floridan aquifer.

Conclusions

Streams, lakes, and wetlands are integral parts of groundwater flow systems. Fluxes of water and chemicals from and to groundwater reflect the positions of the surface-water bodies with respect to different-scale groundwater flow systems; local geologic controls on seepage distribution through their beds; and the magnitude of transpiration directly from groundwater around their perimeters, which intercepts potential groundwater inflow or draws water from the surface-water body. Understanding the relative importance of all these factors for a given water body is needed for effective management of the integrated water resource.

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