JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION
VOL. 37, NO. 2 AMERICAN WATER RESOURCES ASSOCIATION APRIL 2001

THE CONCEPT OF HYDROLOGIC LANDSCAPES[1]

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ABSTRACT: Hydrologic landscapes are multiples or variations of fundamental hydrologic landscape units. A fundamental hydrologic landscape unit is defined on the basis of land-surface form, geology, and climate. The basic land-surface form of a fundamental hydrologic landscape unit is an upland separated from a lowland by an intervening steeper slope. Fundamental hydrologic landscape units have a complete hydrologic system consisting of surface runoff, ground-water flow, and interaction with atmospheric water. By describing actual landscapes in terms of land-surface slope, hydraulic properties of soils and geologic framework, and the difference between precipitation and evapotranspiration, the hydrologic system of actual landscapes can be conceptualized in a uniform way. This conceptual framework can then be the foundation for design of studies and data networks, syntheses of information on local to national scales, and comparison of process research across small study units in a variety of settings. The Crow Wing River watershed in central Minnesota is used as an example of evaluating stream discharge in the context of hydrologic landscapes. Lake-research watersheds in Wisconsin, Minnesota, North Dakota, and Nebraska are used as an example of using the hydrologic-landscapes concept to evaluate the effect of ground water on the degree of mineralization and major-ion chemistry of lakes that lie within ground-water flow systems.
(KEY TERMS: water resources geography; ground water hydrology; surface water hydrology; watershed management; geographical analysis; watershed systems.)

INTRODUCTION

Government agencies, such as the U.S. Geological Survey, commonly are called on to provide perspectives on water-resource or environmental issues that affect large regions or the entire nation. Many national data programs and assessments of resources or environmental conditions are designed using a conceptual framework and spatial information that best fit the needs for the issue of concern. In some cases, a geologic or aquifer map may suffice; for others, maps of surface runoff, physiography, soils, climate, or ecoregions (Omernik, 1995) may provide the fundamental information needed. However, by using different concepts and mapped information as a foundation, it can be difficult to integrate the results of a number of studies into syntheses that might be of broader use. The location, movement, and chemical characteristics of water are fundamental to many water-resource and environmental issues; therefore, a conceptual framework for designing data networks, syntheses, and research is needed that is based on the hydrologic system.

Scientists interested in the development of landforms, the flow of rivers, and movement of sediment have long recognized that drainage basins are a fundamental hydrologic unit for understanding surface-water systems (Chorley *et al.*, 1964). They also recognized that the configuration of drainage basins was controlled to a large extent by their geologic framework and climatic setting (Chorley *et al.*, 1984; Leopold *et al.*, 1964). The movement of ground water also is affected by landform (Tóth, 1963), geologic framework (Freeze and Witherspoon, 1967), and climatic setting. However, for ground water development and resource assessment purposes, hydrogeologists have considered aquifer systems to be fundamental hydrologic units (Meinzer, 1923; Heath, 1984). To address the need for a framework that considers the complete hydrologic system, it is necessary to consider the movement of surface water and ground water, how they interact, and how they are affected by climate (Winter, 1999).

The purpose of this paper is to put forth the concept of hydrologic landscapes as a framework for

[1]Paper No. 00012 of the *Journal of the American Water Resources Association*. **Discussions are open until December 1, 2001.**
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objectively conceptualizing the movement of ground water, surface water, and atmospheric water in different types of terrain. This conceptual framework can then be used to develop hypotheses of how the hydrologic system might function in those terrains. The scope of the paper emphasizes physical hydrology because the location and movement of water is fundamental to most geochemical and biological processes. It is hoped that this framework based on physical hydrology can serve as a focal point for discussions of how geochemical and biological processes relate to the hydrologic system. Metric measures of landform, geology, and climate can be used to delineate hydrologic landscapes on maps. However, hydrologic-landscape maps are best constructed using multivariate statistics and GIS procedures. Description of methods for constructing such maps, presented in Wolock *et al.* (in review), is beyond the scope of this paper.

It needs to be emphasized that the concept of hydrologic landscapes is not intended to replace other hydrologic or land classification systems. The concept presents a structured thought process that can be used to dissect landscapes into their fundamental hydrologic characteristics in order to better understand the movement of surface water, ground water, and atmospheric water through drainage basins, aquifers, ecoregions, etc. Such thought processes are not new, as hydrologists routinely do this. However, concepts of water movement over and through the earth commonly reflect the specific training and experience of individuals. The hydrologic-landscape concept is intended to provide a conceptualization tool that could be used uniformly regardless of the training and experience of individuals. In a sense, the hydrologic-landscape concept is intended to put all hydrologists "on the same page" by starting with a relatively simple concept. In doing so, it might be easier to develop conceptual frameworks for: (1) design or evaluation of hydrologic monitoring networks; (2) evaluation or synthesis of the hydrologic and environmental condition of localities, regions, or the Nation; and (3) comparisons of hydrologic and ecological processes on local to national scales.

THE CONCEPT OF HYDROLOGIC LANDSCAPES

The characteristics of the earth and its climate that affect the location, movement, and chemistry of water are complex. The many different types of landforms, geologic settings, and climatic conditions that make up many regions of the earth may make it seem that a unifying conceptual hydrologic framework is impossible to achieve. Indeed, it is not unusual for scientists and water and land managers to emphasize the uniqueness and complexity of a given locality rather than the similarities that it might have with other localities. However, with respect to the movement of water, many seemingly diverse landscapes have some features in common, and it is these commonalities that need to be identified in developing a conceptual hydrologic framework. By evaluating landscapes from a common conceptual framework, hydrologic processes common to some or all landscapes can be distinguished from hydrologic processes unique to specific landscapes.

The Fundamental Hydrologic Landscape Unit and Its Primary Hydrologic Properties

The concept of hydrologic landscapes is based on the idea that the complete hydrologic system interacts with a single, simple physiographic feature, and that this feature becomes the basic building block of all hydrologic landscapes. This physiographic feature is termed a fundamental hydrologic landscape unit (FHLU) (Figure 1), and it is defined by: (1) its land-surface form of an upland adjacent to a lowland separated by an intervening steeper slope, (2) its geologic framework, and (3) its climatic setting. The hydrologic system of a FHLU consists of the movement of: (1) surface water, which is controlled by the slopes and permeability of the unit's surfaces; (2) ground water, which is controlled by the hydraulic characteristics of the unit's geologic framework; and (3) atmospheric water, which exchanges water with the unit and is controlled by climate.

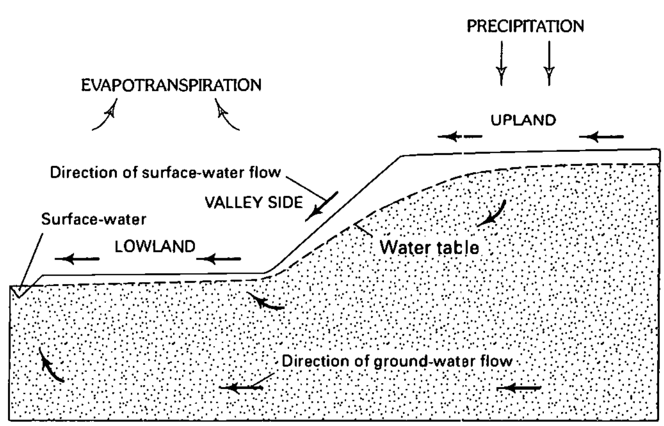


Figure 1. Fundamental Hydrologic Landscape Unit (FHLU) Showing General Movement of Surface Water, Ground Water, and Atmospheric Water.

Surface runoff will flow over landscape surfaces that have steeper slopes faster than it will flow over those that have flatter slopes. In addition, the quantity and rate of runoff versus infiltration is dependent on the permeability of the surficial geologic materials. These features have implications for streamflow characteristics as well as ground water recharge. For example, the flatter the land slope, the longer it will take water to run off the surface, resulting in a greater opportunity for ground water recharge if the surficial materials are permeable, or the formation of wetlands if they are not.

Assuming that the water table reflects the configuration of the land surface, the water table will be at a higher altitude in the upland than in the lowland (Figure 1), which will create a ground water flow field from the upland to the lowland. One feature of this flow field is that downward components of flow are generated at downward breaks-in-slope of the water table and upward components of flow are generated at upward breaks-in-slope of the water table. In some settings, this feature of flow fields may result in the presence of wetlands in the area of lower slope. In settings where the water table may intersect the lower part of the steeper land-surface slope, seepage faces may be present, which also may result in the presence of wetlands.

The geologic characteristics of FHLUs is one factor that affects ground water flow fields. On a large scale, different rock types result in different configurations and lengths of ground water flow paths (Figure 2). Rates of water movement and geochemical interactions between rocks and water also differ substantially between the different types of geologic units. On a small scale, if a FHLU has a surface-water body at its lowest boundary, geologic features in beds of surface-water bodies affect seepage patterns. For example, the size, shape, and orientation of the sediment grains in surface-water beds affect seepage patterns. Even 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. 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. In addition to the effects of land-surface form and geology on ground water flow fields and surface runoff, the exchange of

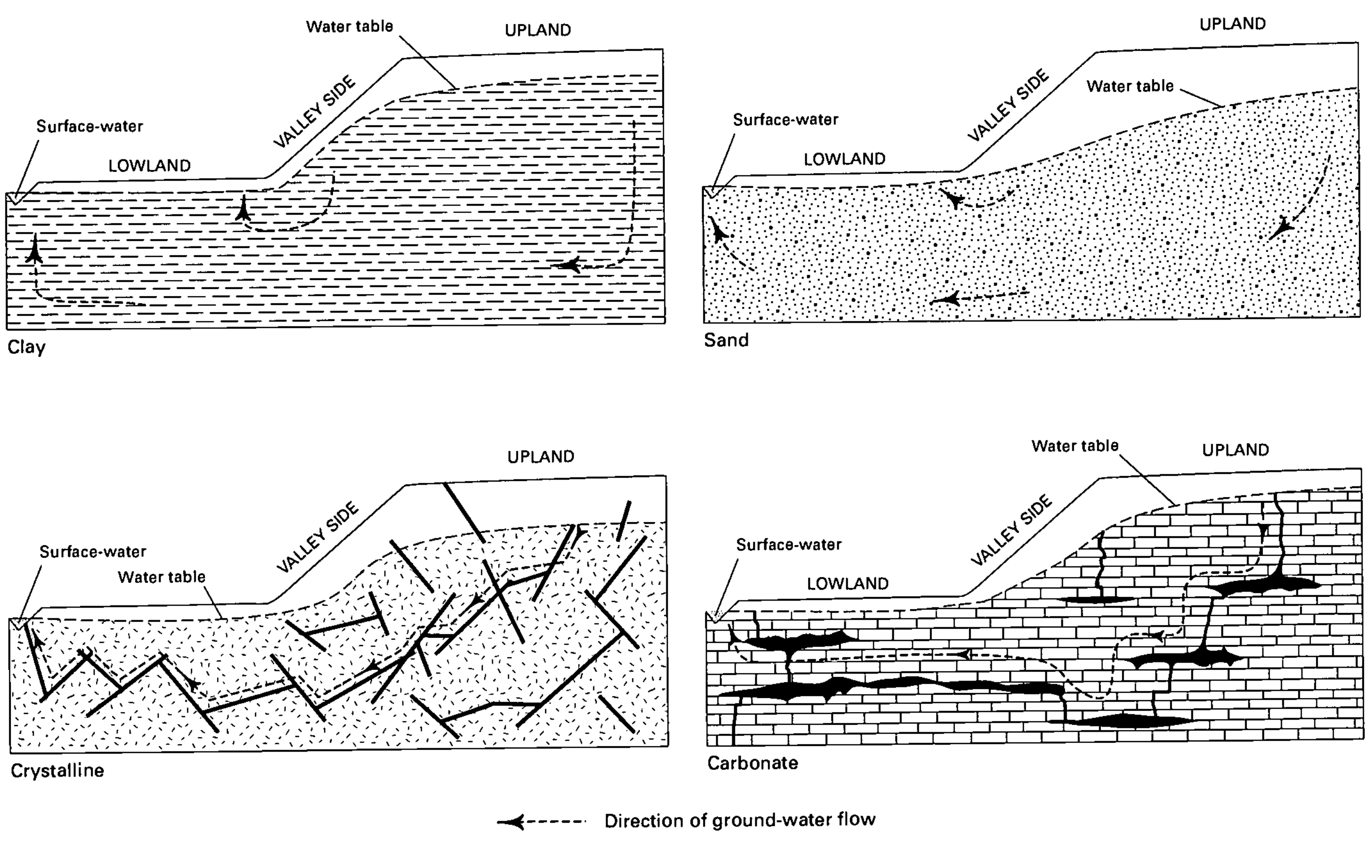


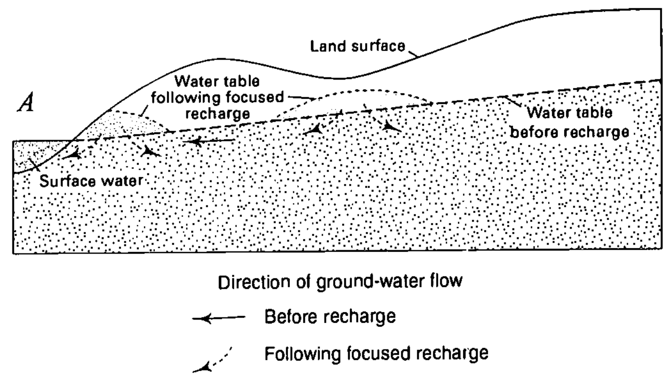
Figure 2. Examples of the Movement of Ground Water Through Several Types of Geologic Frameworks.

water with the atmosphere further affects the movement of water.

Precipitation and evapotranspiration affect the distribution, timing, and magnitude of surface runoff and ground water recharge throughout a FHLU. However, infiltration of precipitation to and transpiration directly from ground water can have pronounced temporal effects on ground water recharge and discharge in the parts of landscapes that are close to surface water. Here, the water table commonly intersects the land surface at the shoreline, resulting in no unsaturated zone at this point. Infiltrating precipitation passes rapidly through the thin unsaturated zone adjacent to the shoreline, which causes water-table mounds to form quickly adjacent to the surface water (Figure 3A). 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 3A).

Transpiration by nearshore plants has the opposite effect of focused recharge. Again, because the water table is near land surface near the edges of surface-water bodies, plant roots can penetrate into the capillary fringe of the saturated zone, allowing the plants to transpire water directly from the ground water system (Figure 3B). 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 shallow ground water system. In many places, it is possible to measure diurnal changes in the direction of ground water flow during seasons of active plant growth. These periodic changes in the direction of flow also take place on longer time scales of days to weeks. 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.

Surface water and ground water can move back and forth across the beds and banks of surface-water bodies in many landscapes. It has been shown for both high gradient streams (Triska *et al.*, 1993) and low-gradient streams (Duff *et al.*, 1997) that complex biogeochemical processes are present where this exchange of flow takes place. The part of the bed and banks of streams where this exchange of flow takes place is termed the hyporheic zone. The exchange of water between ground water and surface water caused by focused recharge, wave action, and transpiration from ground water also has been shown to result in complex biogeochemical processes in lake and wetland sediments. The part of the bed of lakes and wetlands where this exchange of flow takes place is termed the hypolentic zone.



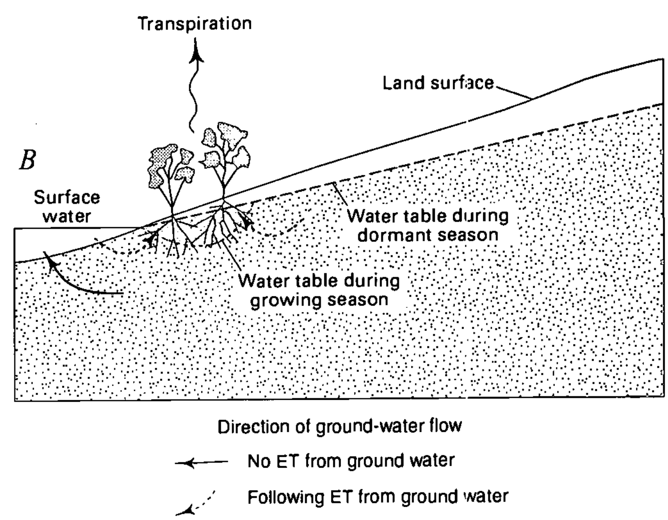


Figure 3. Distribution of Ground-Water Discharge to Surface Water Related to Meteorological Factors. (A) Recharge Focused at the Edge of Surface Water and at a Depression in the Land Surface Caused by Infiltration of Precipitation Through Relatively Thin Unsaturated Zones. (B) Drawdown of Water Table Caused by Transpiration Directly From Ground Water.

General Hydrologic Landscapes as Variations and Multiples of Fundamental Hydrologic Landscape Units

General hydrologic landscapes can be conceived of as variations and multiples of FHLUs. For example: (1) the width of the lowland, valley side and (or) upland can range from narrow to wide; (2) the slopes of the three surfaces can vary; (3) the topographic relief between lowland and upland can range from small to large; and (4) smaller FHLUs can be superimposed on any or all of the surfaces of larger-scale FHLUs.

Hydrologic landscape configurations such as these can be used to define general landscape types that describe major physiographic features of the earth. A hydrologic landscape consisting of narrow lowlands and uplands separated by high and steep valley sides is characteristic of mountainous terrain (Figure 4A). This general configuration can be nested into multiples at different scales within mountainous terrain; from high mountain basins to larger and larger valleys within a mountain range complex. A hydrologic landscape consisting of very wide lowlands separated from much narrower uplands by steep valley sides is characteristic of basin and range physiography and basins of interior drainage that commonly contain playas (Figure 4B). In this type of terrain, the uplands may range from being slightly higher to much higher than the lowlands. A hydrologic landscape consisting of narrow lowlands separated from very broad uplands by valley sides of various slopes and heights is characteristic of plateaus and high plains (Figure 4C). A hydrologic landscape consisting of one or more small FHLUs (terraces) nested within a larger lowland is characteristic of riverine valleys (Figure 4D) and coastal terrain (Figure 4E). A hydrologic landscape consisting of numerous small FHLUs superimposed on both the uplands and lowlands of larger FHLUs is characteristic of hummocky glacial and dune terrain (Figure 4F).

Some Common Hydrologic Characteristics of Generalized Hydrologic Landscapes

The movement of water over the surface and through the subsurface of generalized hydrologic landscapes is controlled by common physical principles regardless of the geographic location of the landscapes. For example, if a hydrologic landscape has low land slope and low-permeability soils, surface runoff will be slow and recharge to ground water will be limited. In contrast, if the soils are permeable in a region of low land slope, surface runoff may be slow but ground water recharge will be high. In hydrologic landscapes that have a shallow water table, transpiration directly from ground water may have a substantial effect on ground water flow systems, and on the movement of ground water to and from surface water.

Hydrologic landscapes characterized by multiples of FHLUs can have complex ground water flow systems because small-scale local flow systems associated with each small-scale FHLU are superimposed on larger, more regional flow systems associated with larger FHLUs. The commonality is shown by sketches of ground water flow conditions in riverine (Figure 4D) and coastal (Figure 4E) terrain. Ground water flow conditions in hummocky terrain are even more complex because of the numerous small FHLUs superimposed on larger and larger FHLUs. Indeed, in glacial and dune terrain, many multiples of scale can be present. Furthermore, generally shallow water tables (characteristic of coastal, riverine, and hummocky terrain) result in the opportunity for highly transient local ground water flow systems caused by focused recharge and transpiration directly from ground water.

Describing Hydrologic Landscapes

The description of hydrologic landscapes needs to include for each FHLU: (1) land-surface form, which involves determination of the surface slopes and areas of the upland, lowland, and intervening steeper slopes; (2) geologic framework, which involves description of the hydraulic properties of the geologic units; and (3) climatic setting, which involves determination of the precipitation minus evapotranspiration balance.

Much of the basis for hydrologic landscapes is related to characteristics of surface runoff and ground water flow systems. The definition of a FHLU includes the presence of a simple ground water flow cell from the upland to the lowland (Figure 1); therefore, the minimum size would need to have this characteristic. Considering these requirements, an area, region, or drainage basin could be subdivided into areas likely to have different surface-runoff characteristics and/or different ground water flow fields. Areas having relatively uniform land-surface form and uniform geology could be conceived of as a single hydrologic landscape. This hydrologic-landscape type might transect a number of drainage basins. Similarly, drainage basins might transect a number of hydrologic landscapes. For example, in the eastern United States, a number of streams that flow from the Appalachian Mountains to the Atlantic Ocean cross what could be considered three general hydrologic landscapes; mountain, plateau, and plain. Each of these hydrologic landscapes have different characteristics of surface runoff, ground water flow, interaction of ground water and surface water, and climate. Therefore, where these drainage basins cross a common hydrologic landscape, they have many hydrologic commonalities.

The hydrologic-landscape concept is intended to be flexible. It can be used in a quantitative manner by statistically synthesizing metric measures of land

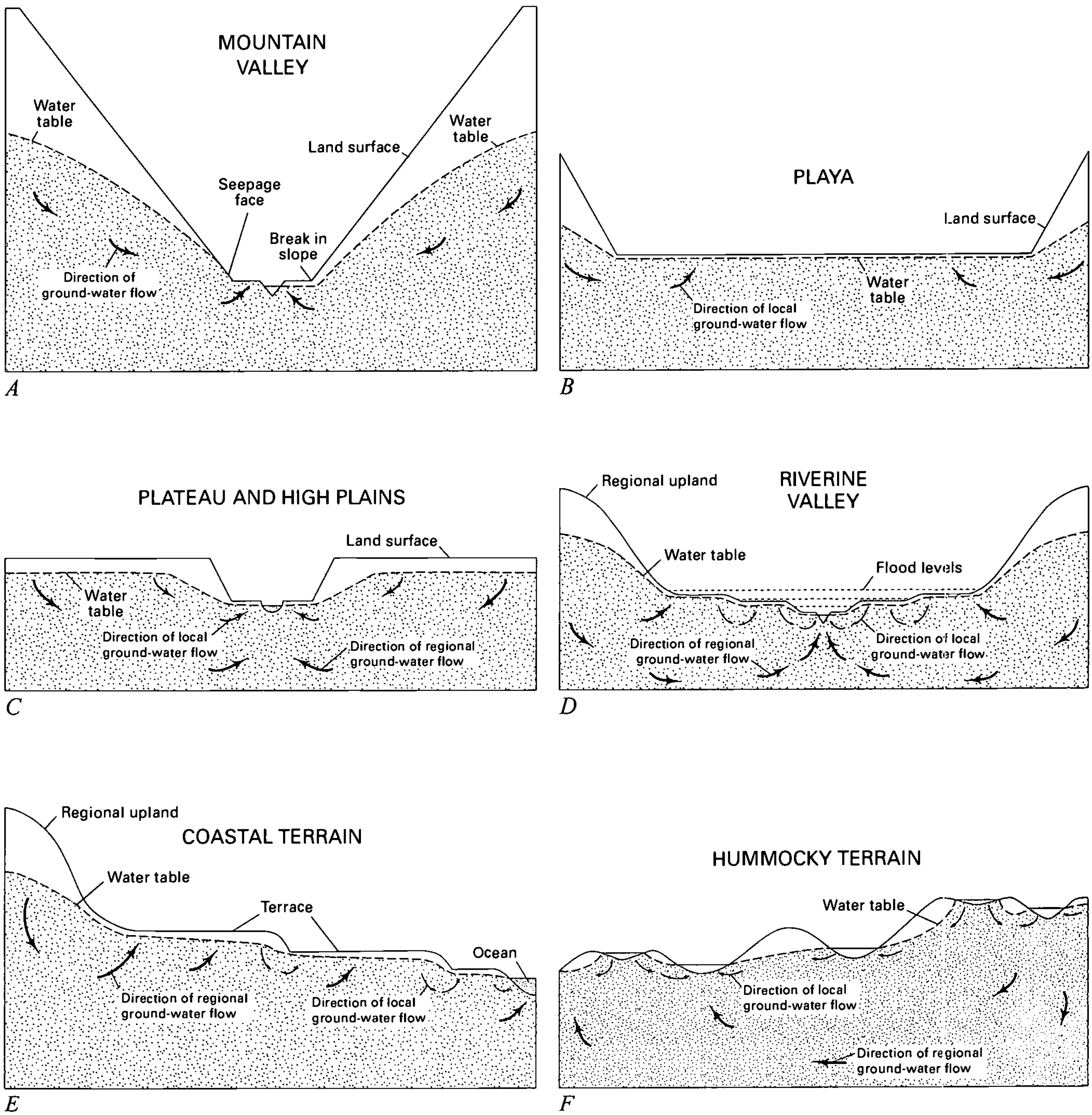


Figure 4. Generalized Hydrologic Landscapes: (A) Narrow Uplands and Lowlands Separated by a Large Steep Valley Side (mountainous terrain); (B) Large Broad Lowland Separated From Narrow Uplands by Steeper Valley Sides (playas and basins of interior drainage); (C) Small Narrow Lowlands Separated From Large Broad Uplands by Steeper Valley Side (plateaus and high plains); (D) Small Fundamental Hydrologic Landscape Units Nested Within a Larger Fundamental Hydrologic Landscape Unit (large riverine valley with terraces); (E) Small Fundamental Hydrologic Landscape Units Superimposed on a Larger Fundamental Hydrologic Landscape Unit (coastal plain with terraces and scarps); (F) Small Fundamental Hydrologic Landscape Units Superimposed at Random on Larger Fundamental Hydrologic Landscape Units (hummocky glacial and dune terrain).

slopes, hydraulic characteristics of geologic units, and climate in conjunction with geographic information system (GIS) methods to make maps of hydrologic landscapes. An example of using the hydrologic-landscapes concept to quantitatively define and map hydrologic-setting regions of the United States is provided by Wolock *et al.* (in review). It can also be used in a more qualitative way to develop hypotheses of water movement through various types of terrain. Furthermore, the concept of hydrologic landscapes can be applied, either quantitatively or qualitatively, through a nested approach at scales from national to local.

The hydrologic-landscape concept can be used at the scale needed to interpret data collected from specific localities. For example, the appropriate scale for understanding the chemistry of a ground-water sample taken from a deep aquifer in the high plains would be to consider the Rocky Mountains the upland and the Great Plains the lowland. All smaller hydrologic landscapes nested within this regional one could be ignored. However, if the water sample was taken from a shallower aquifer, it might be necessary to identify smaller-scale hydrologic landscapes within the Great Plains.

The following are examples of how various generic hydrologic landscapes might be described. In the case of mountainous terrain, a mountain valley having uniform geology might be considered to be a single hydrologic landscape, as shown in Figure 4A. However, different geologic units may be present in different parts of the valley that might result in different lengths of flow paths, different rates of ground water flow, and different interactions with streams. In such cases, the valley may be subdivided into several hydrologic landscapes based on the different geologic conditions. If a mountain valley has glacial moraines within it, the hydrologic landscape might consist of smaller FHLUs (the moraines) nested within the larger FHLU (the mountain valley). In this case, the moraine would not only be a smaller landform unit, but also the unconsolidated geologic deposits probably would have different hydraulic characteristics than the bedrock of the mountain valley.

In the case of riverine valleys, the hydrologic landscape might consist of a number of small FHLUs (terraces) nested within the larger FHLU (the river valley). In this case, the land slopes and/or geologic composition of the terraces might differ, resulting in different surface runoff as well as different ground water flow patterns in the different terraces. Also, the water table might be shallower in the lower terraces, resulting in different exchanges with the atmosphere, such as rapid infiltration of precipitation resulting in more efficient ground water recharge, or greater transpiration directly from ground water, compared to the higher terraces.

Perhaps the most complex hydrologic landscape to describe is glacial terrain. The complex topography and varying types and distribution of unconsolidated geologic materials in glacial terrain could result in hydrologic landscapes typified by FHLUs nested within one another from very small scales to entire morainal complexes. Such landscapes have complex ground water flow systems (Meyboom *et al.*, 1966; Lissey, 1971; Winter, 1999). Rivers running through glacial terrain could have substantially different interactions with ground water depending on whether they traverse till moraines, till plains, or outwash plains. In this case, the river would be part of different hydrologic landscapes depending on the geologic substrate it traverses. (See example of the Crow Wing River in Minnesota discussed later in this paper.)

Possible Uses of the Hydrologic-Landscape Concept

The concept of hydrologic landscapes is based on the assumption that certain common patterns of surface runoff, ground water flow, and interchange of surface water and ground water with one another and with atmospheric water can be associated with different variations or multiples of FHLUs. By making this assumption, hypotheses of the hydrologic processes taking place can be developed for any area of interest, regardless of scale. The hypotheses can then be tested by study of a particular area, or, they can be the foundation for plans of study, design and evaluation of data networks, syntheses of existing information, enhancing transfer value of information from well-studied to unstudied sites, or comparisons of research results from a wide variety of small research sites.

Data and information collected within a number of different study areas commonly needs to be synthesized into a broader picture of hydrologic or environmental information on regional or national scales. Although the study areas might be in many different geographic regions, they are likely to have some commonalities if viewed within the framework of hydrologic landscapes. For example, areas having similar land slopes, surficial geology, and climate will result in similar hydrologic flow paths regardless of the geographic location of the sites. Similarly, local ground water flow systems associated with terraces or small scarps probably will have similar characteristics whether they are in coastal areas, river valleys, or high mountain valleys containing glacial moraines.

By defining hydrologic landscapes using a common conceptual framework, comparison of seemingly different study areas would have a common foundation. Examples of the types of comparisons that could be made include: (1) runoff from given land slopes can be evaluated across variations in geologic substrate and/or climate; (2) the relative importance of discharge to streamflow from local versus regional ground water flow systems can be evaluated across variations in geologic framework and/or climate; (3) the effect of transpiration directly from ground water can be evaluated for all hydrologic landscapes that have shallow water tables, regardless if the hydrologic landscape is coastal, riverine, mountainous, or glacial and dune, and it can be compared across climate gradients; (4) the presence or absence of, extent of, and the effect of biogeochemical processes in the hyporheic or hypolentic zone beneath surface-water bodies can be evaluated across hydrologic-landscape types; and (5) the likelihood of small local ground water flow cells being associated with minor breaks in slope of the water table can be evaluated across hydrologic-landscape types.

APPLICATION OF THE HYDROLOGIC-LANDSCAPE CONCEPT

Two examples of the application of the hydrologic-landscape concept are given below. The examples use the concept in a qualitative way, primarily to indicate the thought process that goes into using the hydrologic-landscape concept. The first example describes how hydrologic landscapes can be viewed at different scales to understand streamflow in a drainage basin. The second example compares the chemistry of lakes in the context of ground water flow systems for four small research watersheds in glacial and dune terrain.

The Crow Wing River Watershed

The Crow Wing River watershed covers nearly 10,000 km^2 of glacial terrain in central Minnesota (Lindholm *et al.*, 1972) (Figure 5). The watershed divide is defined by high moraines on the north and northwest sides, lower moraines on the northeast and southwest sides, and a very low moraine on the southeast side (Figure 5A). More than 75 percent of the area is gently sloping (less than a few percent), and most of the gently sloping area is in lowlands. About 50 percent of the watershed has permeable outwash sands at the surface, and the remainder of the land surface is poorly permeable till (Figure 5B). The glacial deposits range in thickness from less than 30 m to more than 180 m, and they are underlain by crystalline bedrock. Precipitation is about equal to evaporation in this area, about 66 cm per year.

If a hydrologist or water manager is interested in understanding the average discharge of streams in the drainage basin, it is immediately noticeable that discharge is substantially greater in the northern part compared to the southern part (Figure 5B). Ground water, surface water and atmospheric water are the three basic components of the hydrologic system that define hydrologic landscapes. Therefore, one of the initial steps in using the approach is to conceptualize ground water flow systems, surface-runoff characteristics, and exchange of water with the atmosphere in different parts of the basin. The latter can be ignored in a basin of this size because it all is in the same climatic setting.

Initially, the basin could be divided into two hydrologic landscapes based on the considerably different relief, landforms, and geology in the northern part compared to the southern part. Ground water flow systems in the northern part probably have a larger regional component than those in the southern part because topographic relief is greater and the glacial deposits are thicker. Furthermore, the streams in the northern part probably have greater baseflow compared to those in the southern part because the northern part has a much greater volume of permeable deposits directly in contact with the streams.

If needed for more detailed understanding of streamflow, the basin could be further subdivided into various hydrologic landscapes based on topographic and geologic characteristics of smaller areas. For example, the northern part of the basin could be divided into two areas, delineated primarily on the basis of geology. Although the high relief and thick glacial deposits are likely to favor the presence of regional ground water flow systems, the patterns and rates of flow are likely to differ markedly between morainal areas of till and areas of outwash. Surface runoff and ground water contributions to streams also is likely to differ between morainal areas of till and areas of outwash. If needed, these areas could be further subdivided on the basis of smaller-scale landforms and geology, nested within the larger features.

Interside Comparison of Lake Chemistry in Four Small Research Watersheds

Four sites in the north-central United States have been the focus of research on lake and wetland hydrology since the early 1980s (Figure 6). Three of the sites, the Trout Lake area in Wisconsin, the Williams Lake area in Minnesota, and the Cottonwood Lake area in North Dakota, are in glacial terrain. The fourth site, the Island Lake area in Nebraska, is in dune terrain. All of the sites contain closed lakes that lie within ground-water watersheds. Two questions might be easily addressed and compared among the four sites: (1) do the lakes become more mineralized in a down-gradient direction within their respective ground water flow fields? and (2) does the major-ion chemistry of the lakes reflect the mineralogy of their geologic framework?

The Trout Lake area (Figure 6B) lies within the north-central highlands in Wisconsin. Local relief in the Trout Lake area is about 35 m. The area is underlain by about 30 m of glacial deposits, which consist largely of relatively uniform sand. These deposits are composed largely of silica and contain few, if any, carbonate minerals. The glacial deposits are underlain by Precambrian crystalline bedrock. Precipitation exceeds evaporation by about 15 cm in the Trout Lake area.

The Williams Lake area (Figure 6A) is located on a small topographic ridge that extends south from the large, east-west-trending Itasca Moraine, in north-central Minnesota. Local relief in the Williams Lake area is about 25 m. The Williams Lake area is underlain by glacial deposits that are greater than 120-m thick. The deposits consist of thick alternating units of till and sand and gravel (Winter and Rosenberry, 1997). The surficial unit consists of sand and gravel that is as much as 22-m thick. The glacial deposits contain abundant carbonate minerals. The glacial deposits are underlain by Precambrian crystalline bedrock. Precipitation is about equal to evaporation in the Williams Lake area.

The Cottonwood Lake area (Figure 6D) is situated on one of the highest parts of the eastern edge of a large moraine, the Missouri Coteau, in east-central North Dakota. The study area lies about 120 m higher than the James River lowland to the east, and about 30 m higher than a small lowland within the Missouri Coteau about 3 km to the west. Local relief within the 80 ha that constitute the Cottonwood Lake area is about 33 m. The area is very hummocky and has many steep-sided closed depressions, most of which contain wetlands that have small surface-drainage areas. The glacial deposits in the Cottonwood Lake area are as much as 140-m thick and consist predominantly of clayey, silty till (Winter and Carr, 1980). The large clay content of the till causes it to crack upon drying, resulting in numerous fractures (Swanson, 1990) that affect water movement through the deposits (Winter and Rosenberry, 1995). A buried sand deposit is present in part of the southern part of the area. The glacial deposits contain abundant carbonate and sulfate minerals. The glacial deposits are underlain by shale bedrock. Evaporation exceeds precipitation by about 35 cm in the Cottonwood Lake area.

The Island Lake area (Figure 6C) is within the Crescent Lake National Wildlife Refuge, which lies within an extensive area of stabilized sand dunes in western Nebraska. The dunes were formed on a sandy aquifer that is about 40-m thick in the study area (Winter, 1986). The dune deposits contain abundant quartz and feldspar minerals. Evaporation exceeds precipitation by about 75 cm in the Island Lake area.

Previous studies of these four sites have presented information on the chemical characteristics of lakes with respect to ground water flow systems. For example, Kratz *et al.* (1997) discussed the Wisconsin site, and LaBaugh (1988) presented a comparison of the Minnesota, North Dakota, and Nebraska sites.

The following is a brief comparison of the four sites from the perspective of the hydrologic-landscape concept. Based on the three factors that define hydrologic landscapes, the four sites have some commonalities and some differences.

1. Land-Surface Form. They all have similar land-surface form; that is, relief of several tens of meters, and rolling uplands contiguous to lakes. There are no broad flat uplands, and the lakes (and associated wetlands) themselves cover most of the lowlands.
2. Geologic Framework. The upper part of the geologic framework is similar for the Wisconsin, Minnesota, and Nebraska sites; that is, permeable unconsolidated sand. However, the deeper surficial deposits differ; till is present at depth at the Minnesota site, but not at the Wisconsin and Nebraska sites. The bedrock is similar at the Wisconsin and Minnesota sites (crystalline), but different at the Nebraska site (sand). The geologic framework of the North Dakota site is completely different from the others, being a thick deposit of low-permeability glacial till overlying shale bedrock.
3. Climatic Setting. They all have different net exchange with atmospheric water.

The lake water at the Wisconsin site is the least mineralized of the four sites, and all three lakes have calcium bicarbonate water (Figure 7B). Within the ground water flow system, Crystal Lake is the most upgradient, has little ground-water input, and has the least mineralized water. Allequash Lake is the most downgradient of the three, and it has the most mineralized water.

The lake water at the Minnesota site is the second least mineralized water of the four sites. Although the lakes all have calcium bicarbonate water (Figure 7A), the Minnesota lakes have relatively higher magnesium concentrations relative to calcium compared to the Wisconsin lakes. Within the ground water flow system, Crystal Lake is the most upgragient, has little ground-water input, and has the least mineralized water, although it is not much different than the chemistry of Williams Lake, the next lake downgradient. Shingobee Lake (not shown in Figure 6B) is the most downgradient of the three, and it has the most mineralized water.

The lake water at the North Dakota site is more chemically diverse than at the other three sites (Figure 7D). Wetland T8, the most upgradient in the ground water flow system, has no ground water

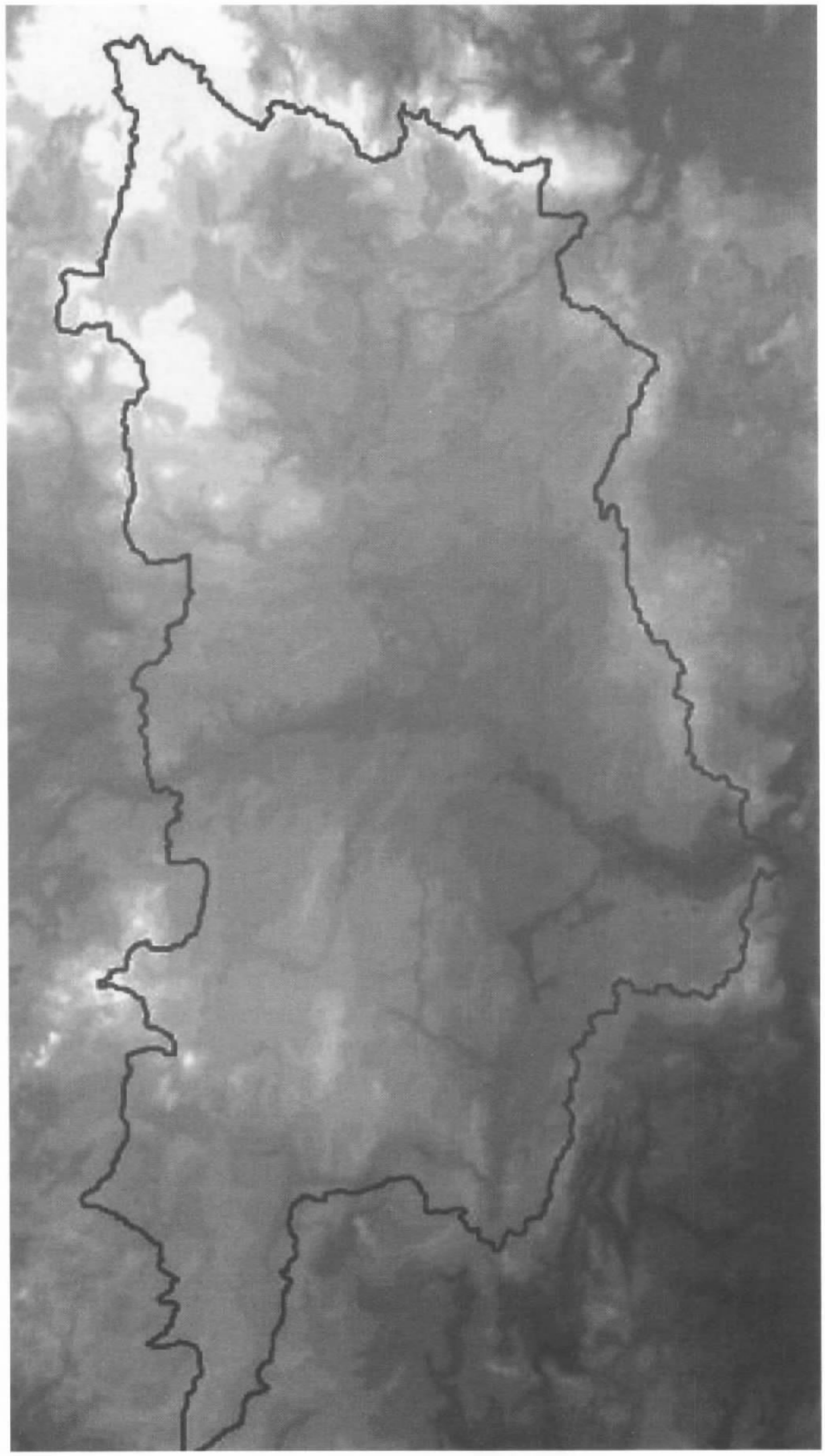


Figure 5A. Digital Elevation Model. Overall relief of the drainage basin is about 120 m. The interval of lines separating shades is about 13 m. The highest areas are white. The drainage divides on Figures 5A and 5B do not coincide precisely because the divide on the digital elevation model (Figure 5A) was drawn by computer using recent data and the divide on Figure 5B was drawn by hand on the topographic maps that were available in the late 1960s. In addition, the drainage area east of Pillager shown on Figure 5B is not included on the map shown in Figure 5A.

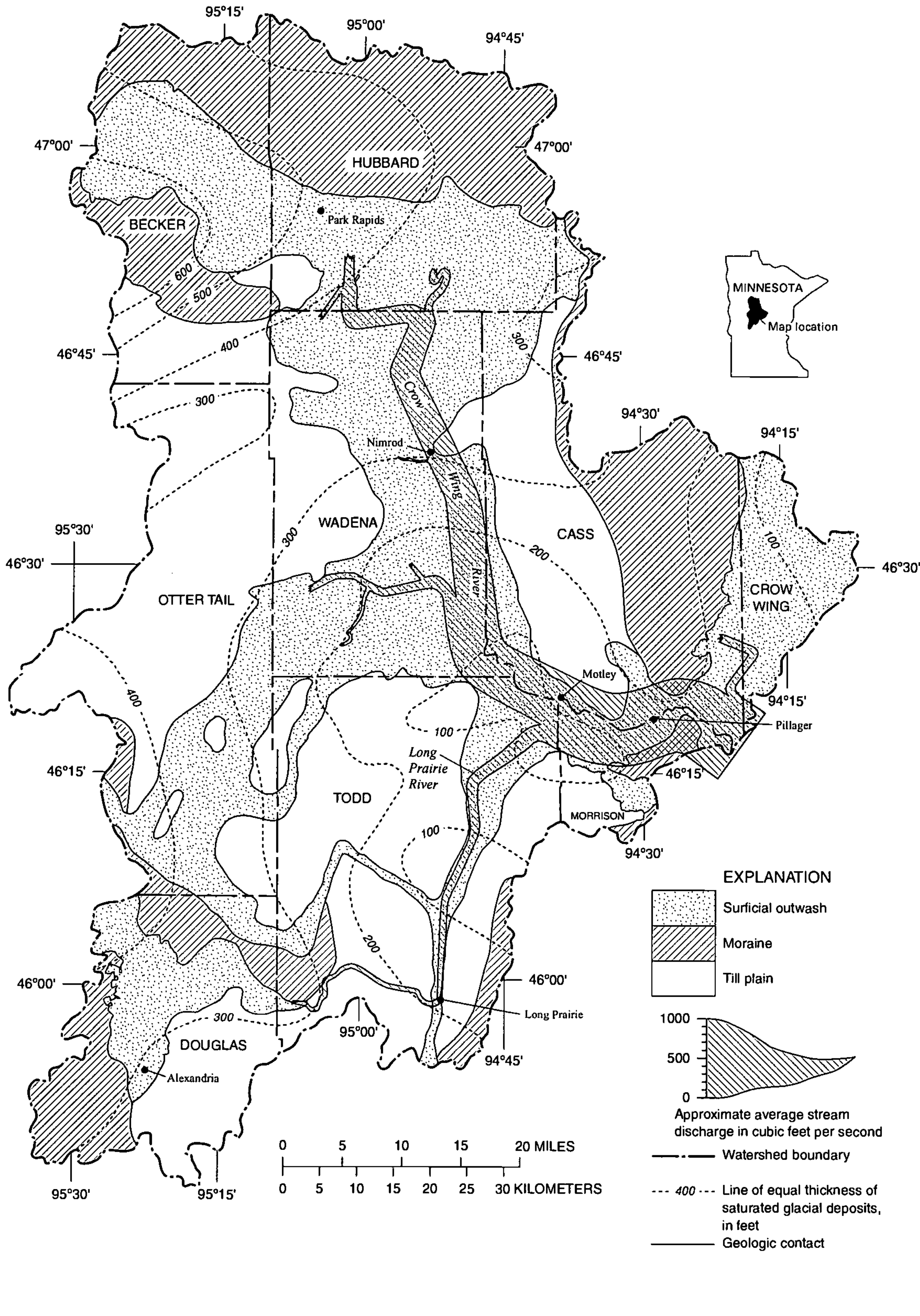


Figure 5B. Surficial Geology and Average Discharge of Streams in the Crow Wing River Drainage Basin in Minnesota (modified from Lindholm *et al.*, 1972). The drainage divides on Figures 5A and 5B do not coincide precisely because the divide on the digital elevation model (Figure 5A) was drawn by computer using recent data and the divide on Figure 5B was drawn by hand on the topographic maps that were available in the late 1960s. In addition, the drainage area east of Pillager shown on Figure 5B is not included on the map shown in Figure 5A.

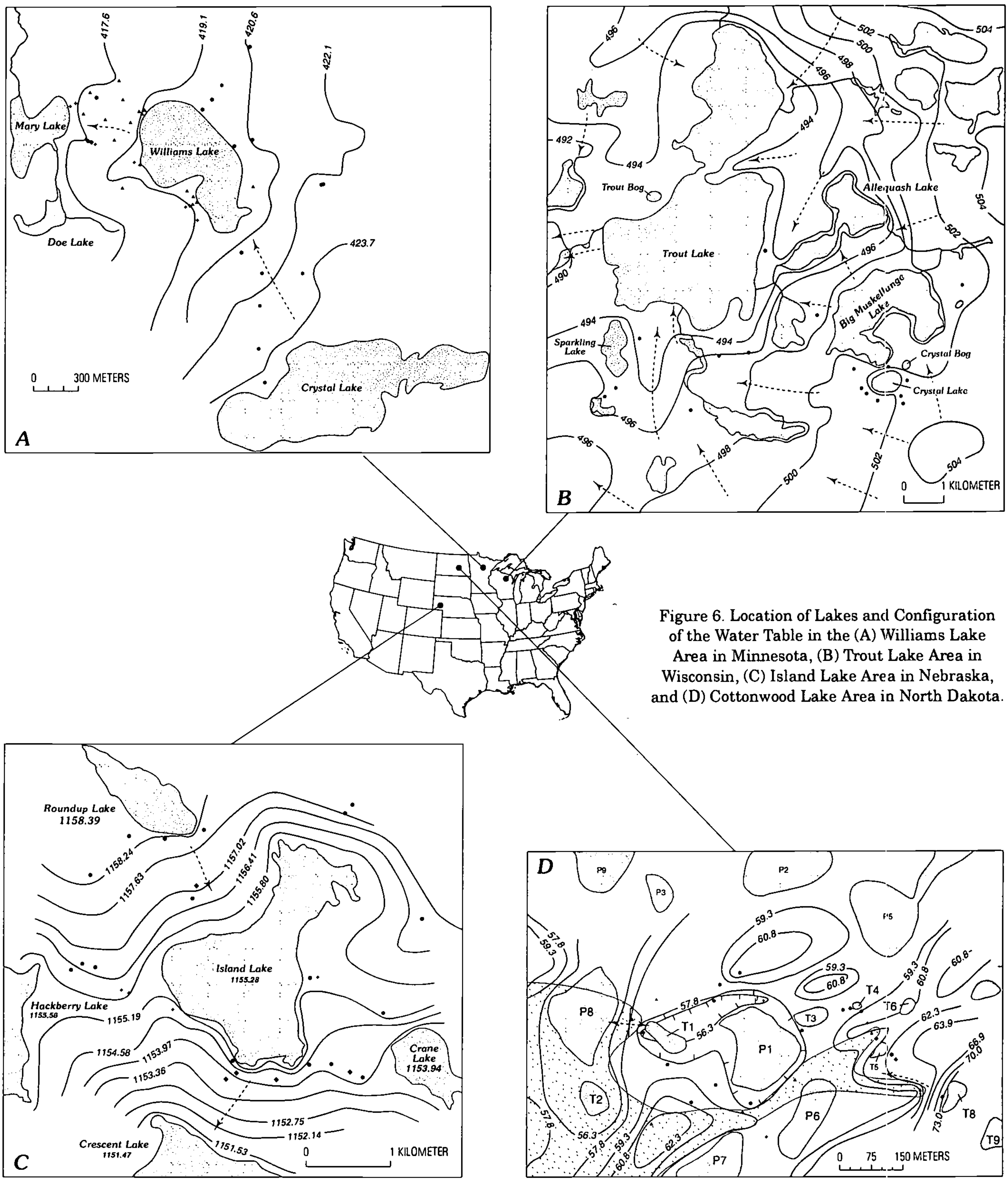


Figure 6. Location of Lakes and Configuration of the Water Table in the (A) Williams Lake Area in Minnesota, (B) Trout Lake Area in Wisconsin, (C) Island Lake Area in Nebraska, and (D) Cottonwood Lake Area in North Dakota.

EXPLANATION:

Lake or wetland

59.3 — **Water-table elevation contour** shows altitude of the water table in meters above sea level

Direction of ground-water flow

● ◆ ▲ + **Observation well**

Buried sand deposit—At surface near wetlands T2 and P8 (Panel D)

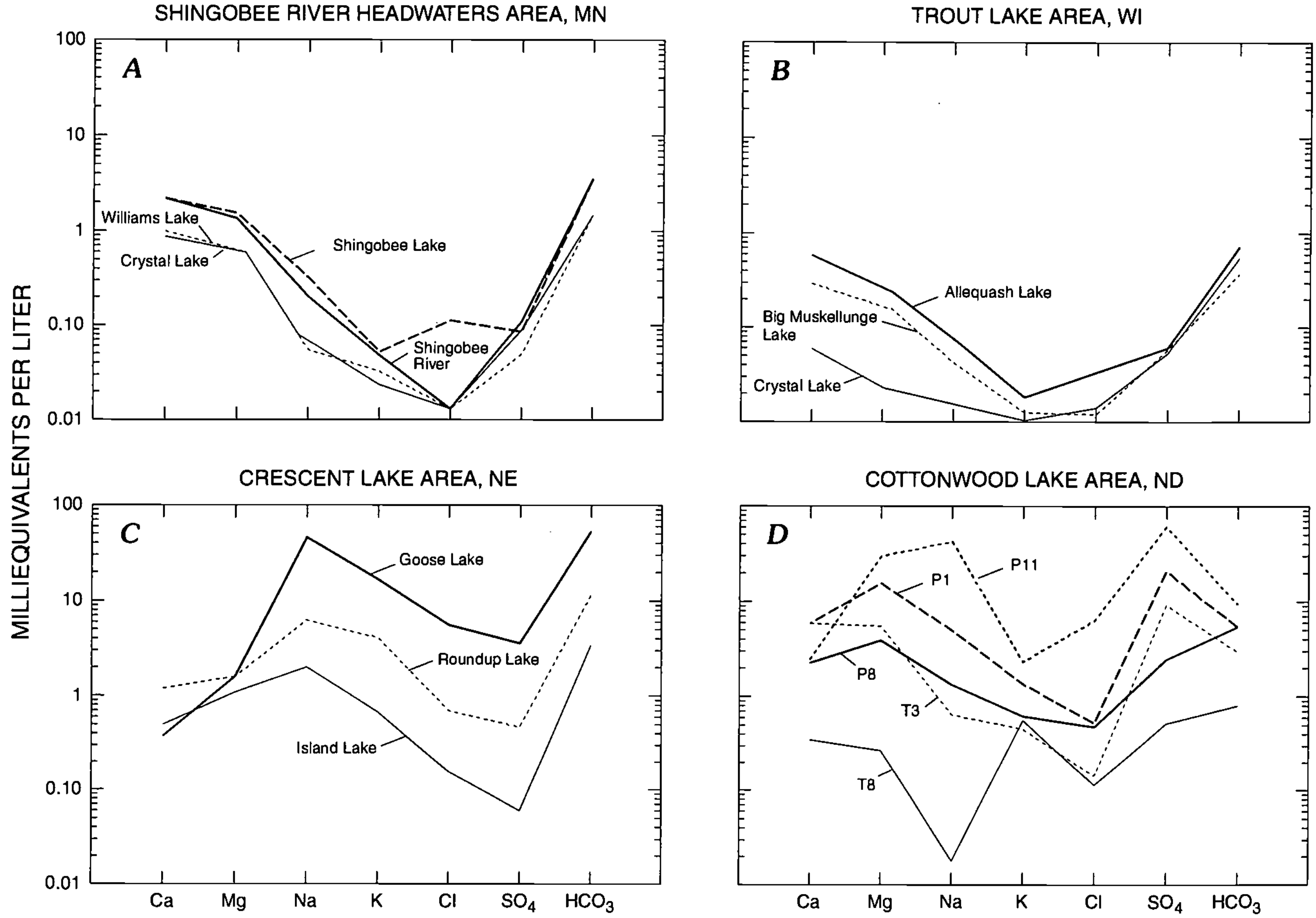


Figure 7. Average Major-Ion Chemistry of Selected Lakes in the (A) Williams Lake Area in Minnesota, (B) Trout Lake Area in Wisconsin, (C) Island Lake Area in Nebraska, and (D) Cottonwood Lake Area in North Dakota.

inflow, and it has potassium bicarbonate water. Wetland T3 is downgradient from Wetland T8, and it has calcium-magnesium sulfate water. Wetland P1, which is only about a meter lower than Wetland T3 has magnesium sulfate water. Wetland P8, which is topographically lower than Wetland P1, has magnesium bicarbonate water, but unlike the others, Wetland P8 receives some of its ground-water input from a small sand aquifer (Figure 6D). Wetland P11 (not shown on Figure 6D) lies in a regional topographic low about a km west of Wetland P8. Wetland P11 is a discharge area for local and regional ground water flow systems, and it has sodium sulfate water.

The lake water at the Nebraska site is all sodium bicarbonate water (Figure 7C). Unlike the other three sites, the most mineralized water is in the most upgradient lake (Goose Lake) and the least mineralized water is in the most downgradient lake, Island Lake. Goose Lake (not shown on Figure 6C), is about one km north (upgradient) of Roundup Lake.

Commonalities and differences in the chemistry of the lakes between the four sites can be determined with respect to: (1) differences in their position within ground water flow fields, (2) the mineralogical composition and permeability of their geological substrate, and (3) climate. At the Minnesota and Wisconsin sites, the lakes become more mineralized, but they maintain a common major-ion water type, as they are positioned increasingly downgradient in their respective ground water flow fields. In addition, the major-ion water type is calcium bicarbonate at both sites. In contrast, at the Nebraska site, the lakes become less mineralized as they are positioned increasingly downgradient in their respective ground water flow fields. However, similar to the Minnesota and Wisconsin sites, the lakes maintain their major-ion water types throughout the ground water flow field. Thus, a commonality of these three sites is that they all maintain their major-ion chemistry within their respective ground water flow fields.

The North Dakota site is more complex. Similar to the Minnesota and Wisconsin sites, most of the wetlands are more mineralized as they are positioned increasingly downgradient in their respective ground water flow fields. However, the chemistry of several wetlands are unique because of local geologic or biological characteristics. For example:

1. Wetland P8, although downgradient of Wetland P1, is less mineralized and has a different major-ion water type because it has inflow from a small sand aquifer and an intermittent surface outlet.
2. The major-ion water type of Wetland T8 is different than the others because it holds water only seasonally. The high potassium content of water in this wetland results from decomposition of the aquatic plants during the dry season and the resolution of potassium when the wetland is rewetted in the spring.
3. The major-ion water type of Wetland P11 is different than the others because it is a major ground-water discharge area, and it has no surface-water or ground-water outflows.

To summarize, at the Wisconsin, Minnesota, and North Dakota sites, the lakes most downgradient have the most mineralized water. Although it is tempting to assume the reason for this is that as water flows from lake to lake through the ground water flow system the entire lake/ground-water system becomes more mineralized. However, if this was a general process, the same should be true for the Nebraska site. A more likely explanation is that inflow to the lakes is a combination of shallow and deeper ground water. Where the lowest lakes have greater mineralization relative to higher lakes, it is likely that inflow from deeper ground water is greater than inflow from the ground water freshly recharged in the shallowest part of the ground-water system between the lakes. In the Nebraska case, it is likely that inflow from the freshly recharged ground water in the shallowest part of the ground-water system between the lakes is greater than inflow from deeper ground water.

This comparison of the degree of mineralization of lake water and major-ion chemistry of lakes is just one example of how the hydrologic-landscape concept can be used as a framework for gaining understanding of the commonalities and differences between hydrologic systems within a given type of landscape, in this case glacial and dune terrain. By gaining insight through this type of comparison, it is likely that qualitative assessments could be made of similar landscapes simply by knowing something about land-surface form, geologic framework, and climatic setting. Similar evaluations of physical, chemical, or biological characteristics can be made using the perspective of hydrologic landscapes for all types of terrain.

CONCLUSION

Hydrologic landscapes can be described objectively in terms of land-surface form, hydraulic properties of their geologic framework, and their climatic setting. The concept of hydrologic landscapes provides a logical and convenient framework for developing hypotheses of water movement in watersheds. In turn, the movement of water in watersheds is fundamental to many water-supply, water-quality, and environmental issues. Thus, this hydrologic foundation can become the framework for evaluating any number of physical, chemical, or biological issues related to natural or human-induced processes, including design of studies and data-collection networks, syntheses of information, and comparison of process research across study sites.

ACKNOWLEDGMENTS

Data for the Wisconsin site were obtained from the chemical limnology data base of the North Temperate Lakes Site, Long-Term Ecological Research Program, National Science Foundation. The site is administered by the Center for Limnology, University of Wisconsin-Madison.

LITERATURE CITED

Chorley, R. J., A. J. Dunn, and R. P. Beckinsale, 1964. The History of the Study of Landforms, Vol. 1, Geomorphology Before Davis. Methuen, London, England.

Chorley, R. J., S. A. Schumm, and D. E. Sugden, 1984. Geomorphology. Methuen, London, England.

Duff, J. H., F. J. Triska, A. P. Jackman, and J. W. LaBaugh, 1997. The Influence of Streambed Sediments on the Solute Chemistry of Ground-Water Discharge in the Upper Shingobee River. U.S. Geological Survey Water-Resources Investigations Report 96-4215, pp. 143-147.

Freeze, R. A. and P. A. Witherspoon, 1967. Theoretical Analysis of Regional Ground Water Flow; 2. The Effect of Water-Table Configuration and Subsurface Permeability Variation. Water Resources Research 3:623-634.

Heath, R. C., 1984. Ground Water Regions of the United States. U.S. Geological Survey Water-Supply Paper 2242.

Kratz, T. K., K. E. Webster, C. J. Bowser, J. J. Magnuson, and B. J. Benson, 1997. The Influence of Landscape Position on Lakes in Northern Wisconsin. Freshwater Biology 37:209-217.

LaBaugh, J. W., 1988. Relation of Hydrogeologic Setting to Chemical Characteristics of Selected Lakes and Wetlands Within a Climate Gradient in the North-Central United States. Verhandlungen Internationale Vereinigung Limnologie 23:131-137.

Leopold, L. B., M. G. Wolman, and J. P. Miller, 1964. Fluvial Processes in Geomorphology. Freeman, San Francisco, California.

Lindholm, G. F., E. L. Oakes, D. W. Ericson, and J. O. Helgesen, 1972. Water Resources of the Crow Wing River Watershed, Central Minnesota. U.S. Geological Survey Hydrologic Investigations Atlas HA-380.

Lissey, A., 1971. Depression-Focused Transient Ground Water Flow Patterns in Manitoba. *In:* Geological Association of Canada Special Paper 9:333-341.

Meinzer, O. E., 1923. The Occurrence of Ground Water in the United States, With a Discussion of Principles. U.S. Geological Survey Water-Supply Paper 489.

Meyboom, P., R. O. van Everdingen, and R. A. Freeze, 1966. Patterns of Ground Water Flow in Seven Discharge Areas in Saskatchewan and Manitoba. Geological Survey of Canada Bulletin 147.

Omernik, J. M., 1995. Ecoregions: A Spatial Framework for Environmental Management. *In:* Biological Assessment and Criteria: Tools for Water Resource Planning and Decision Making, W. Davis and T. Simon (Editors). Lewis Publishers, Boca Raton, Florida, pp.49-62

Swanson, K. D., 1990. Chemical Evolution of Ground Water in Clay Till in a Prairie Wetlands Setting in the Cottonwood Lake Area, Stutsman County, North Dakota. MS Thesis, University of Wisconsin, Madison, Wisconsin.

Tóth, J., 1963. A Theoretical Analysis of Groundwater Flow in Small Drainage Basins. Journal of Geophysical Research 68:4795-4812.

Triska, F. J., J. H. Duff, and R. J. Avanzino, 1993. Patterns of Hydrological Exchange and Nutrient Transformation in the Hyporheic Zone of a Gravel-Bottom Stream: Examining Terrestrial-Aquatic Linkages. Freshwater Biology 29:259-274.

Winter, T. C., 1986. Effect of Ground-Water Recharge on Configuration of the Water Table Beneath Sand Dunes and on Seepage in Lakes in the Sandhills of Nebraska. Journal of Hydrology 86:221-237.

Winter, T. C., 1999. Relation of Streams, Lakes, and Wetlands to Groundwater Flow Systems. Hydrogeology Journal 7:28-45.

Winter, T. C. and M. R. Carr, 1980. Hydrologic Setting of Wetlands in the Cottonwood Lake Area, Stutsman County, North Dakota. U.S. Geological Survey Water-Resources Investigations 80-99.

Winter, T. C. and D. O. Rosenberry, 1995. The Interaction of Ground Water With Prairie Pothole Wetlands in the Cottonwood Lake Area, East-Central North Dakota, 1979-1990. Wetlands 15(3):193-211.

Winter, T. C. and D. O. Rosenberry, 1997. Physiographic and Geologic Characteristics of the Shingobee River Headwaters Area. U.S. Geological Survey Water-Resources Investigations Report 96-4215, pp. 11-17.

Wolock, D. M., T. C. Winter, and G. McMahon, G. (In Review). Delineation of Hydrologic Setting Regions in the United States Using Geographic Information System Tools and Multivariate Statistical Analyses. U.S. Geological Survey Water-Resources Investigations Report, Reston, Virginia.