A Conceptual Framework For Assessing Cumulative Impacts on the Hydrology of Nontidal Wetlands

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ABSTRACT / Wetlands occur in geologic and hydrologic settings that enhance the accumulation or retention of water. Regional slope, local relief, and permeability of the land surface are major controls on the formation of wetlands by surface-water sources. However, these landscape features also have significant control over groundwater flow systems, which commonly play a role in the formation of wetlands. Because the hydrologic system is a continuum, any modification of one component will have an effect on contiguous components. Disturbances commonly affecting the hydrologic system as it relates to wetlands include weather modification, alteration of plant communities, storage of surface water, road construction, drainage of surface water and soil water, alteration of groundwater recharge and discharge areas, and pumping of groundwater. Assessments of the cumulative effects of one or more of these disturbances on the hydrologic system as related to wetlands must take into account uncertainty in the measurements and in the assumptions that are made in hydrologic studies. For example, it may be appropriate to assume that regional groundwater flow systems are recharged in uplands and discharged in lowlands. However, a similar assumption commonly does not apply on a local scale, because of the spatial and temporal dynamics of groundwater recharge. Lack of appreciation of such hydrologic factors can lead to misunderstanding of the hydrologic function of wetlands within various parts of the landscape and mismanagement of wetland ecosystems.

Wetlands occur throughout the landscape in a wide variety of physiographic settings. Wetlands commonly occur in topographic lows, where water might be expected to accumulate, or adjacent to rivers or lakes, where periodic overflows might be expected. However, wetlands also occur in more unexpected localities, such as on hillslopes or on topographic highs. All wetlands are a result of a physiographic setting and water balance that favor the accumulation or retention of soil water and/or surface water for a period of time. To understand the occurrence and hydrologic function of wetlands, and ultimately, the effects of disturbance on their hydrologic balance, we must be aware of the wide range of physiographic and hydrologic environments in which wetlands form.

The purpose of this article is to (1) provide a generalized framework for the physical existence of nontidal wetlands, (2) discuss uncertainty in measurement and in understanding of hydrologic components as they relate to water balances of wetlands, and (3) discuss the effects of disturbance on the hydrology of wetlands. We do not intend to present a comprehensive literature review, but rather a conceptual model of the hydrologic system as related to nontidal wetlands, drawing on selected hydrologic literature.

KEY WORDS: Wetland hydrology; Groundwater and surface water interrelationships; Evapotranspiration; Surface runoff; Groundwater movement; Drainage; Reservoirs; Lakes; Geologic boundaries.

Physical Basis for the Existence of Wetlands

Physical Settings

Wetlands commonly occur in topographic depressions or in lowlands having minimal topographic slope. However, it is not uncommon to find wetlands on steep slopes, topographic highs, or drainage divides. Wetlands that occur in these latter terrains, and some that occur in flat areas, generally result from hydrologic processes such as groundwater discharge, related to breaks in topographic slope or to heterogeneity in the geologic units underlying or near the wetland (Winter and Woo 1988), or to extremely slow movement of subsurface water related to minimal hydraulic gradients and organic soils of low permeability (Daniel 1980).

Topographic Controls

Depressions in the land surface. Depressions are common in many types of terrain, but the most extensive region with large numbers of relatively small depressional wetlands is Wisconsinan-age glacial terrain, which occurs in the north-central and northeastern United States. This glacial drift has been deposited so recently that an integrated drainage network has not yet developed.

Other large regions that contain depressional wetlands include the Basin and Range province in the western United States and part of the southeastern coastal plain. The Basin and Range province contains

Environmental Management Vol. 12, No. 5, pp. 605–620

fewer depressional wetlands compared to glacial terrain, but they can be very large. Depressional wetlands on the Atlantic coastal plain, such as the Carolina Bays, are rarely >3 m deep, and are characterized by their distinctive oval shape. More than 500,000 Carolina Bays occur, largely in North and South Carolina and Georgia (Kaczorowski 1976).

Minimal land slope. Wetlands are common in areas of minimal land slope because drainage is slow and water can remain on the land surface or within the soil for considerable periods of time. Examples of areas of minimal land slope containing wetlands are southeastern coastal plains, river flood plains, and glacial lake plains. In some cases, such as the Carolina Bays and river flood plains, wetlands are actually in depressions, because the wetlands occur where surface-water flow is blocked by natural levees or other small topographic ridges. However, in other cases, such as pocosins or large northern peatlands, wetlands form largely because of slow natural drainage. In addition, coastal plains, flood plains, and glacial lake plains commonly (1) are underlain by a very shallow water table which is within reach of the roots of wetland plants, and/or (2) are areas of groundwater discharge.

Discontinuities in the slope of the water table and of land surface. In areas of steep land slopes, such as embankments or river valley walls, the water table sometimes intersects the land surface, and groundwater discharges directly to the land surface near the base of the slope (Figure 1A). Constant groundwater seepage at this seepage face keeps the soil saturated and permits the growth of wetland plants. The size of seepage faces can vary considerably depending on the local geology and dynamic characteristics of the groundwater source.

Modeling studies of groundwater movement have indicated that where the water table has an upward break in slope, groundwater moves upward toward the land surface in the part that has the lower slope. For example, where steeply sloping end moraines meet flatter glacial lake plains, till plains, or outwash plains, groundwater moves upward toward the water table in the plain, and the flow is concentrated near the valley side (Figure 1B). This same pattern of groundwater movement also occurs in flood plains, coastal plains, or lake basins that are adjacent to more steeply sloping valley or escarpment sides.

Geologic Controls

Two types of subsurface stratigraphy may have a role in forming wetlands: (1) the stratigraphy of the organic soils, if present, and the fine-grained fluvial silts and clays that usually underlie the organic soils, and (2) the stratigraphy of the underlying geologic deposits.

In many wetlands, the low permeability of the compacted and humified organic matter, if present, together with the underlying silts and clays, greatly restrict vertical movement of water either to or from the wetland. Many wetlands that hold water for short periods of time are the result of this type of local subsurface geologic boundary.

Subsurface stratigraphy within underlying geologic units also can affect groundwater movement, resulting in the formation of wetlands. In complex, heteroge-

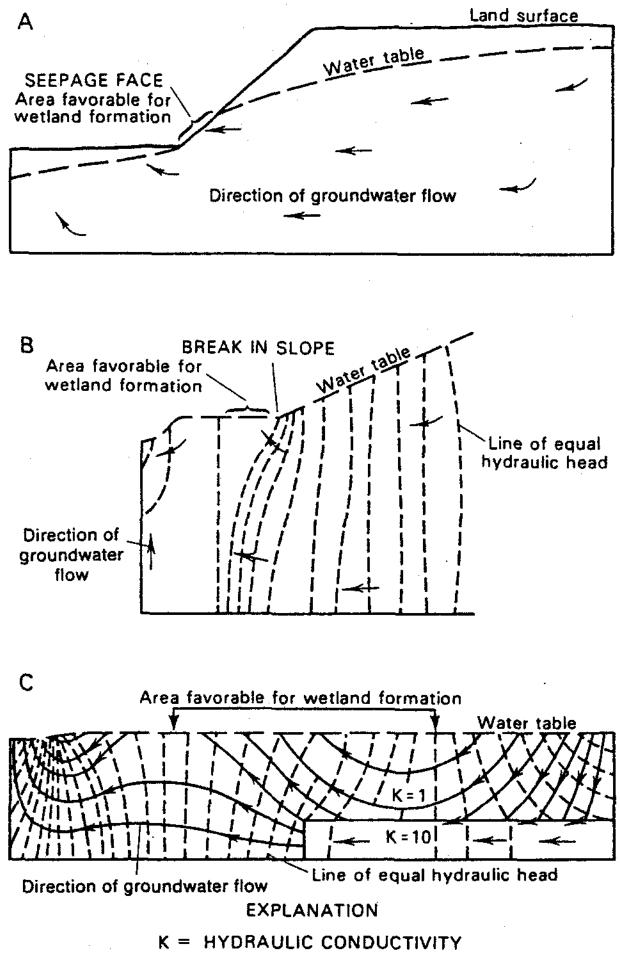

Figure 1. Geologic boundaries associated with the formation of some types of wetlands. **(A)** Development of a seepage face, caused by groundwater flow intersecting land surface. **(B)** Upward movement of groundwater associated with a break in slope of the water table. The upward movement occurs in the lower-slope segment near the break in slope. **(C)** Upward movement of groundwater associated with complex subsurface geologic boundaries. The upward movement occurs above the down-gradient half of aquifers of limited areal extent. (Data from Freeze 1969.)

neous geologic terrane, upward movement of groundwater may occur where permeable rocks either pinch out (Figure 1C) or have a different dip compared to adjacent less-permeable rocks. Freeze (1969) and Winter (1976) provide several examples of groundwater movement toward the land surface as a result of these types of geologic boundaries.

Hydrologic Processes Important to Wetland Formation

Hydrologic processes are the primary reason for the existence of wetlands, because even if a physiographic and geologic setting favorable for the formation of a wetland exists, hydrologic conditions must be such that water will persist long enough for a wetland to form. To present the hydrologic processes in a consistent and unified way, the following discussion is organized according to the interaction of the hydrologic cycle with the landscape. Two aspects of the landscape that need to be considered are: (1) the shape and hydraulic characteristics of its surface that affect movement of surface water across it, and (2) the geologic boundaries and hydraulic characteristics of the rocks that affect subsurface flow systems. Several variations of a generalized landscape are used to help visualize the hydrologic concepts herein presented. The first generalized landscape consists of a regional topographic high (upland) and a regional topographic low (lowland), both of which have uniform minimal land slope. These are separated by a valley side with uniform land slope steeper than the upland or lowland (Figure 2A). A second generalized landscape is used that has the same regional upland and lowland, but also has local hummocky topography superimposed on it (Figure 2B).

These two landscapes are given as dimensionless because they are the two basic configurations on which there can be many variations. Examples of variations include:

(1) The width of the lowland, valley side, and/or upland can range from narrow to wide.
(2) The height of the valley side can range from small to large; that is, the upland can be only slightly higher than the lowland or it can be much higher.
(3) The slopes of any of the three surfaces can vary.
(4) Local hummocky topography can occur on any one individual, all, or in any combination of hummocky and uniform surfaces.
(5) Local relief of the individual hummocks can vary considerably.

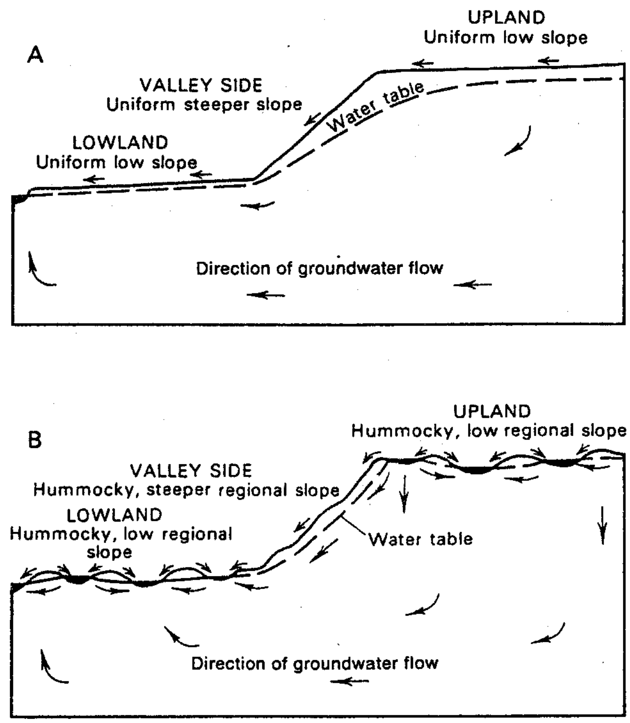

Figure 2. Schematic surface-water and groundwater flow systems that might be expected for generalized landscapes: (**A**) uniformly-sloping surface and (**B**) hummocky surface.

(6) The landscapes can represent any scale from small local sites to large regions.

Furthermore, these basic landscape configurations can exist as multiples; for example, in mountainous terrain steep valley sides commonly abut narrow lowlands in the alpine and subalpine zones, and these high valleys themselves are separated by a steep slope from lower, flatter parts of the same valley.

This generalized landscape concept, with its many variations, is considered to be applicable to nearly any landscape configuration. Examples include (1) high moraines adjacent to lower moraines and glacial lake plains, (2) uplands adjacent to river valleys, (3) high terraces adjacent to lower terraces, and (4) coastal scarps adjacent to lower coastal plains. The generalized landscape is used to address the interaction of surface water and atmospheric water and the interaction of surface water and subsurface water.

Surface water and atmospheric water. The land surface can gain water from the atmosphere by precipitation and can lose water directly to the atmosphere by evaporation and transpiration. Precipitation that falls on the land surface will flow over it, remain ponded in depressions, and/or infiltrate into the subsurface. The relative distribution of water involved in each of these

Table 1. Relative distribution of precipitation between surface runoff, ponding, and infiltration for different land-surface forms and permeability. Also listed are parts of the landscape and general type of terrain in which wetlands occur.

Land surface permeability	Land surface form[a]					
	High slope		Low slope		Hummocky	
Low	SR	H	SR	H	SR	L
	P	L	P	M	P	H
	I	L	I	L	I	M
	Landscape					
	Bottom of valleys adjacent to stream, mostly permanent		Throughout area, mostly temporary but some permanent		In depressions: Temporary wetlands in groundwater recharge depressions; Permanent wetlands in groundwater discharge depressions	
	Terrain most commonly found in					
	Mountains		Glacial lake plains; flood plains; Gulf of Mexico and Atlantic coastal plains		Glacial moraines consisting of till	
High	SR	M	SR	L	SR	L
	P	L	P	L	P	M
	I	M	I	H	I	H
	Landscape					
	Bottom of valleys adjacent to stream, mostly permanent		Throughout area, where shallow water table permits aquatic plants to grow		In depressions that are permanent groundwater discharge areas	
	Terrain most commonly found in					
	Mountains		Glacial outwash plains; flood plains; Gulf of Mexico and Atlantic coastal plains		Sand dunes; beach ridges	

[a] H = high percent; M = moderate percent; L = low percent; SR = surface runoff; P = ponding; and I = infiltration.

processes depends on the slope and permeability of the land surface.

In areas of steep uniform slope and low-permeability soils, most of the water will run off as surface water, and little or no water will be ponded (Table 1). In such areas, few wetlands will form in the uplands, but the generous supply of water to the lowlands adjacent to the rivers or lakes may result in wetlands along their margins. If permeability of the soil permits, the water that does infiltrate and that is not transpired will move downgradient in the subsurface and discharge in the lowlands near the streams or lakes. Therefore, in mountainous terrain, where the generalized landscape is characterized by nonexistent or narrow uplands, a large and steep valley side, and narrow lowlands, it is common to find narrow bands of wetlands in the valleys, directly adjacent to streams or lakes. These riparian wetlands receive water from both surface and subsurface sources.

In areas of low slope and low permeability, water moves across the surface very slowly, resulting in a time lag between precipitation and arrival of water at a stream or lake. If the time lag is long, water may remain in an area long enough to permit wetland plants to grow. This condition is common in large glacial lake plains (lowlands) underlain by lacustrine clays and in the Atlantic coastal plain. Most glacial lake plains and the Atlantic coastal plain are very broad lowlands that have been extensively ditched in order to make the land suitable for farming. The condition of low slope and low-permeability soils is also common in some areas of flood plains.

In contrast, in areas of low slope and high-permeability soils, high infiltration rates result in little opportunity for wetland formation by surficial ponding. In these areas, relatively large quantities of groundwater recharge may result in a shallow water table, particularly in lowland settings. Physiographic settings that have low slope and permeable soils include glacial outwash plains, which can be either uplands or lowlands, some areas of flood plains, and some areas of coastal plains, all of which usually are broad lowlands with uniform land slope.

In areas of hummocky topography and soils of low permeability, in uplands or lowlands, much of the precipitation runs into depressions. If the depression receives groundwater discharge, the surface runoff is added to the groundwater discharge, commonly resulting in a lake or wetland that is perenially flooded. Conversely, if the depression does not receive groundwater discharge, the surface runoff usually is not great enough to maintain a permanent body of water, resulting in formation of intermittently flooded wetlands. For wetlands that recharge groundwater, the ponded water enhances the potential for infiltration, but the poorly permeable soils inhibit the rate of infiltration, resulting in relatively small quantities of water that recharge groundwater. One of the largest regions of this type is the area of northern prairie wetlands in the north-central United States. Another large region of hummocky topography with more permeable soils is the high plains of west Texas.

In areas of hummocky topography and high-permeability soils, the depressions also affect hydrologic processes. Such areas are characterized by little surface runoff and high infiltration rates, regardless of topographic position. In this case, as will be discussed in the next section, the variable thickness of the unsaturated zone has a dynamic effect on the relationship of groundwater to wetlands. Regions of this type include areas of sand dunes and coastal shorelines, such as the Nebraska sandhills and some wetland areas in Florida. The only factor that decreases infiltration of water in this type of setting is the existence of sediments of low permeability that commonly underlie these depressions. However, even if sediments of low permeability are present, infiltration can be great around the periphery of the sediments.

Once water is on the land surface, the greatest loss of water at any given locality is back to the atmosphere through evaporation and transpiration. The longer surface water stays ponded or moves slowly in areas of low slope, the greater will be the water loss by open-water evaporation. Transpiration can vary greatly from season to season if the wetland is dominated by deciduous plants, or it can be relatively uniform if the wetland is dominated by evergreen plants. In either case, during the growing season most water that infiltrates does not do so past the root zone, but instead is transpired. Therefore, during the growing season much of the water loss from the landscape consists of atmospheric water that never becomes part of surface-water or groundwater flow systems. Evaporation and transpiration return groundwater to the atmosphere only in areas of groundwater discharge or where the water table is within reach of plant roots. Thus, the water returned to the atmosphere from a wetland in a groundwater recharge area is derived almost entirely from precipitation, whereas the water returned to the atmosphere from a wetland in a groundwater discharge area is derived from precipitation and groundwater.

In the context of Table 1, generalizations can be made about the relative quantities of water lost to evapotranspiration for the various combinations of land-surface form and permeability. For example, for areas of high slope and low permeability, evaporation would be expected to be low and transpiration low to moderate. For areas of low slope and low permeability, evaporation and transpiration would both be high. For hummocky terrain that has low permeability, evaporation would be high and transpiration moderate to high. For areas of high slope and high permeability, evaporation would be low and transpiration low. For areas of low slope and high permeability evaporation would be low and transpiration from the groundwater system could be moderate, because in these areas the water table commonly is close to land surface. In areas of hummocky topography and high permeability, evaporation and transpiration from lakes and wetlands could be moderate because of the relatively large contributions of groundwater to these surface-water bodies.

Surface water and subsurface water. The surface processes discussed in the preceding section are superimposed on, and interact with, water in the subsurface. Subsurface water consists of two general systems: (1) the unsaturated zone, including soil water; and (2) the saturated zone, which is groundwater. In most environments, only minimal quantities of water percolate through the unsaturated zone to recharge groundwater during the growing season. Larger quantities of water will percolate past the root zone if the water uptake capacities of the plants are met during extended rainy periods, or during the nongrowing season. In areas with high precipitation and where soil water does not freeze, such as the Pacific Northwest and parts of the southeastern United States, groundwater recharge is high beginning in the fall after plants become dormant. Where soil frost is common, such as in the north-central United States, the greatest quantities of groundwater recharge occur in spring, after the soil frost thaws and before the plants begin to grow.

Wetlands commonly occur where poorly permeable zones near the land surface restrict downward percolation of water. In these areas the soils are saturated for a sufficient length of time for wetland plants to become established. Generally the ponding or saturated-soil conditions are intermittent because there is not a persistent supply of water to the wetland area. However, in some cases precipitation may be sufficient throughout the year to maintain perennial wetlands. In either case, precipitation is sufficient during the growing season to maintain wetlands that are totally dependent on atmospheric input of water.

Water that percolates through the unsaturated zone recharges groundwater, and the hydrologic head associated with the recharge water becomes the driving force for groundwater flow systems. Because the water table is constantly changing in response to recharge, it is the most dynamic boundary of groundwater flow systems in both time and space. Groundwater recharge and its effect on groundwater movement relative to surface water has been studied using numerical modeling of generalized settings. One of the principal conclusions of these studies is that recharge commonly is localized where thickness of the unsaturated zone is small relative to contiguous points of the landscape.

Assuming the water table is relatively flat and the land surface is hummocky, the areas of minimal thickness of the unsaturated zone occur directly adjacent to the surface water or at depressions in the landscape (Figure 3). If water infiltrates uniformly it will reach the water table beneath the depression or adjacent to the surface water first, and initial recharge will be focused at these sites. The actual volume of recharge at a depression such as that shown in Figure 3 will be variable in space, depending on the size of the depression, permeability of the soil, and amount and type of vegetation that may transpire the water before it percolates past the root zone. With respect to scale, Figure 3 is dimensionless, and can be used to visualize multiple landscapes. For example, it can represent a sizeable depression surrounded by large uplands, or a small depression within an upland. The volume of recharge at a depression will also be highly variable in time, depending on the volume of precipitation, antecedent soil moisture conditions, and the transpiration potential of the vegetation.

An example of a simulated unsaturated–saturated flow system in a hypothetical interrelated groundwater and surface water setting is given in Figure 4.

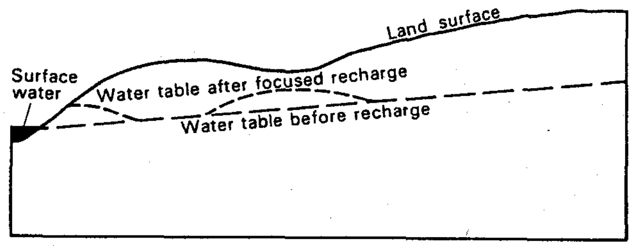

Figure 3. Formation of water-table mounds beneath land surface depressions and near surface water, as a result of focused recharge.

The series of diagrams indicate the spatial and temporal variability of recharge, the complex variations in flow direction as a result of the recharge, and the consequent changes in direction of seepage through the lakebed, for a single infiltration event. For example, Figure 4A shows conditions prior to the infiltration, where the water table slopes toward the lake beneath hill B and away from the lake beneath hill A. After 5 days of infiltration (Figure 4B), water-table mounds form where the unsaturated zone is thinnest, which is directly adjacent to the surface water. This early localized recharge causes complex local groundwater flow systems to form. In the case of water-table mound 2, flow directions reverse and groundwater seeps into the lake in the littoral zone, where water had been seeping out of the lake prior to the recharge event. With another five days of infiltration (Figure 4C), the local flow systems become even larger and, in the case of mound 2, completely stop seepage from the lake. Following the final 5 days of infiltration, the separate water-table mounds, 1 and 2, merge (Figure 4D), and the local flow systems extend the full depth of the groundwater system. With no additional recharge the water table gradually dissipates, resulting in the accompanying decrease in size of the local flow systems. Following seven months of redistribution, the local flow system associated with the lake is near the point where seepage from the lake will resume with any further lowering of the water table (Figure 4E).

In a hummocky landscape (e.g., Figure 2B), subsurface flow conditions such as those illustrated in Figure 4, can occur at a number of localities, all with variations in space and time throughout the landscape, whether in uplands or lowlands. These highly dynamic local flow conditions are superimposed on the larger regional groundwater flow systems. The regional systems are more stable than local flow systems, making it easier for hydrologists to justify steady-state analysis, as well as justify certain assumptions about groundwater movement with respect to surface water and/or wetlands. For example, it is fairly safe to as-

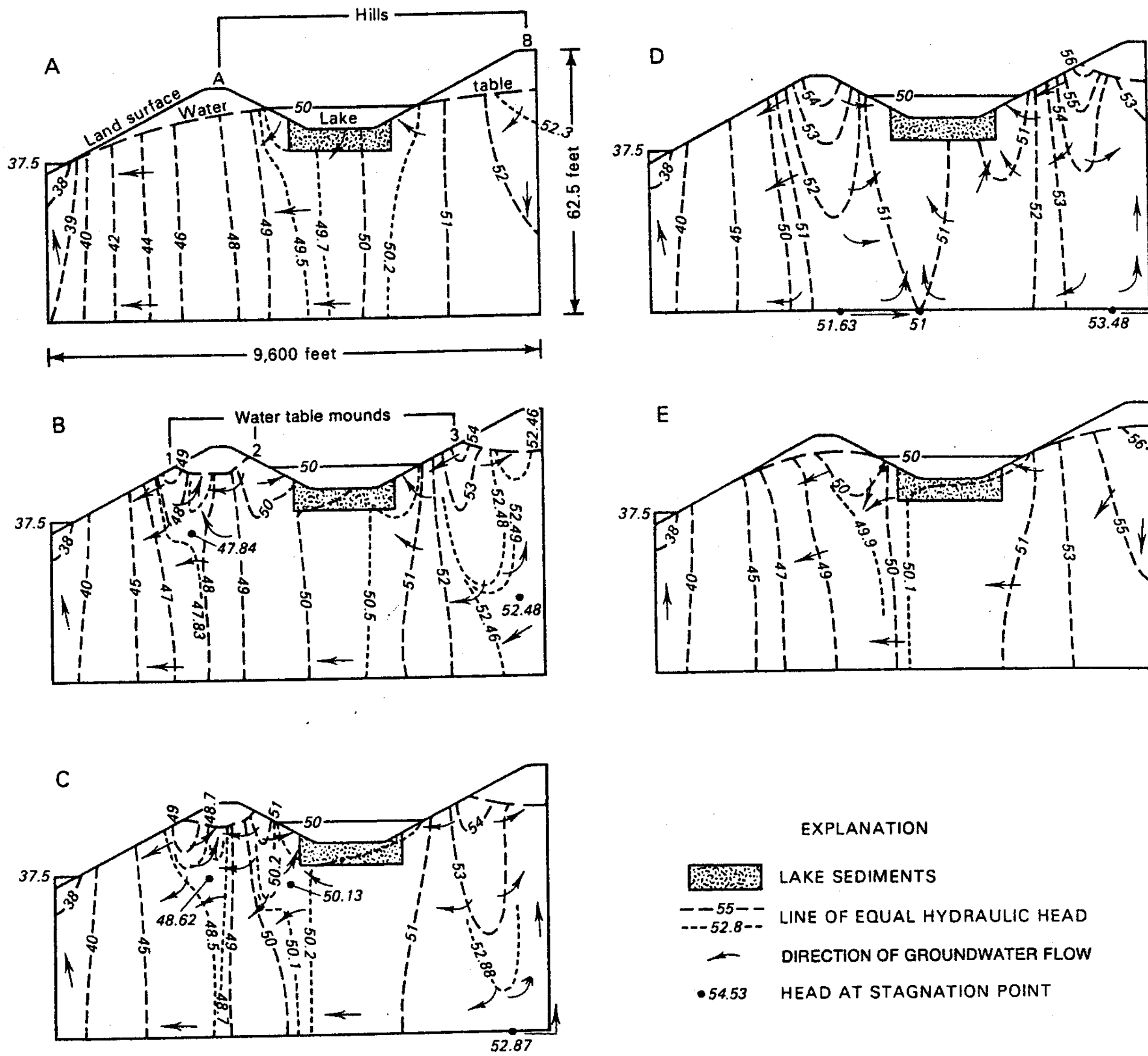

Figure 4. Distribution of hydraulic head and direction of groundwater flow for variably saturated porous media near a lake in a hypothetical basin. Anisotropy of the porous media is 500. Beginning with a steady-state water table (**A**), results are of conditions following five (**B**), ten (**C**), and 15 days (**D**) of infiltration from a saturated land surface. Effects on growth of water-table mounds and local groundwater flow systems can be seen. Conditions after seven months of redistribution (**E**) are also presented. Note that seepage from the lake is about to resume at this time. (Data from Winter 1983.)

sume that water-table highs underlie land-surface highs on a regional scale, but this is not a safe assumption on a local scale.

In the context of the generalized landscape (Figure 2) applied to the interaction of groundwater and surface water on a regional scale, the water table is certainly at a higher altitude beneath the upland than it is beneath the lowland, making the upland a regional groundwater recharge area and the lowland a regional groundwater discharge area. However, on a local scale, especially in hummocky topography, water-table highs may underlie land-surface highs at one scale (Figure 5, large hills A and C), but they may not underlie land-surface highs at other scales (Figure 5, small hills b–e, and large hill B). Furthermore, these conditions may change over space and time. Therefore, there is probably just as much groundwater involved in recharge and discharge in local flow systems in regional lowlands as in regional uplands.

From the perspective of wetland hydrology and chemistry, however, there may be significant differences between wetlands in uplands compared to those in lowlands because of the effects of surface runoff and because of the position of the wetland relative to

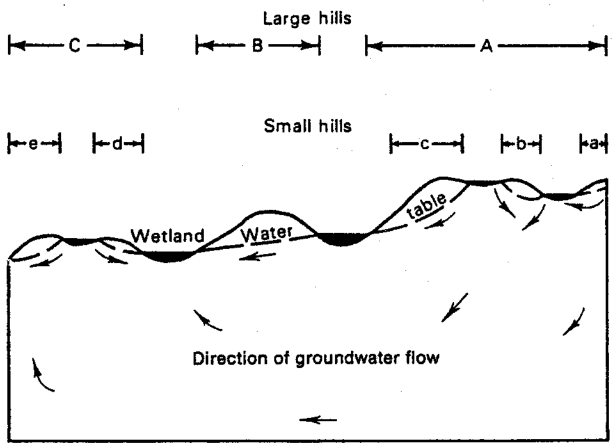

Figure 5. Water-table highs underlying land-surface highs on a large scale (hills A and C), but not on a small scale (hills b, c, d, and e).

regional groundwater flow systems. Wetlands that have no surface-water inlets and outlets, and that have the water table slope away from them, receive the bulk of their water input from precipitation, and lose water by evaporation and seepage to groundwater. The difference between the two regional settings for this type of recharge wetland is that wetlands in lowlands are much more likely to be flooded by surface runoff from contiguous uplands than are wetlands in uplands. Wetlands in lowlands that are primarily groundwater discharge areas may receive discharge from large intermediate and regional flow systems as well as from their immediate local flow system. In the uplands, depressional wetlands that are groundwater discharge areas may receive water from small intermediate flow systems, but are more likely to be the discharge areas for local flow systems only.

In general, in hummocky landscapes local groundwater flow systems dominate the interaction of wetlands and groundwater, regardless of regional topographic position. Thus, wetlands that recharge groundwater, have flow-through relative to groundwater, or discharge groundwater can occur anywhere in the landscape. These processes are highly dynamic on a local scale, and reversals of these functions can occur on a seasonal and/or annual basis. However, in lowlands, where some wetlands discharge water from regional flow systems, the discharge process is much more stable. These wetlands commonly contain water with relatively high dissolved solids because of the steady supply of chemicals over a long period of time. This is especially evident in wetlands in arid and semiarid climates. Because of the wide variety of flow system configurations, however, it is not unusual or unexpected that in lowlands, freshwater wetlands receiving groundwater discharge from local flow systems only may occur adjacent to more saline wetlands receiving groundwater discharge from local and regional flow systems. Or conversely, that wetlands receiving relatively highly mineralized groundwater from intermediate flow systems may occur in upland areas.

Uncertainty in Measurement and in Understanding of Wetland Hydrology

The information presented in the first section of this article is a general summary of hydrologic concepts as related to wetlands. In this section, a perspective is given on the adequacy of the scientific foundation upon which present understanding of wetland hydrology is based. For some components of the hydrologic system, the basic hydrologic understanding has been developed for any system, and the results can be applied to wetlands. For example, extensive research on precipitation measurement, regionalization, and analysis can be applied to determining atmospheric input to a wetland landscape. For other components, such as evaporation and transpiration, comprehensive process-oriented research specific to wetland vegetation has been minimal. The following is a brief evaluation of how well hydrologic processes are understood and how accurately they can be measured for each component of the hydrologic system as related to wetlands.

Atmospheric Water

Studies of precipitation and the accuracy with which it can be measured have been conducted for many years and at many localities; the published literature base is extensive (Winter 1981). As a result of this research, it is possible to measure precipitation accurately provided accurate gauges are used, the density of gauges is commensurate with project accuracy goals, the gauges are properly positioned and properly maintained, and the data are analyzed using appropriate regionalization methods.

However, research on evaporation and transpiration from wetlands has been minimal. Evapotranspiration from wetlands is determined by examining (1) differences in the water budget; (2) evaporation pan data; (3) evaporimeters and lysimeters; or (4) by any of several empirical formulas.

If pans are used, large errors in the calculated evapotranspiration are common because the open-water evaporation from a pan is not a surrogate for transpiration by plants. Studies of evapotranspiration using evaporimeters and lysimeters containing wetland vegetation are not common (Carter 1986).

If empirical formulas, such as those of Penman (1948, 1963) and Blaney and Criddle (1950), are used to estimate evapotranspiration, the sensors that provide the data commonly are not located at the site of interest, but at the nearest weather station. In some cases, on-site sensors have been used. For example, Eisenlohr and others (1972), Allred and others (1971), and Meyboom (1967) used the mass-transfer method to determine evaporation from northern prairie wetlands. Although the studies were primarily of open-water evaporation, Eisenlohr and others (1972) also attempted to determine evapotranspiration. Errors associated with use of various formulas, together with different configurations of sensor placement, have not been determined in a systematic way for a wide variety of settings. Therefore, errors associated with various empirical methods of calculating evapotranspiration are largely unknown.

In the general context of wetland hydrology, there have not been comprehensive studies of evapotranspiration, based on on-site measurement of the transpiration process in a wide variety of wetland settings. Therefore, a database does not exist upon which adequate understanding or accurate measurement of evapotranspiration from wetlands can be based.

Surface Water

As the only component of the hydrologic system that is usually a delineated, observable body of water, the discharge of channelized surface water can be measured very accurately (Rantz and others 1982). Using the best measurement techniques, surface-water discharge can be measured to an accuracy of 3%–5% (Winter 1981). However, it should not be assumed that all surface-water discharge measurements are made within this degree of accuracy. If flow characteristics are changing, other environmental conditions vary, or short cuts are taken in the measurement, errors can be as great as 10%–30% (Dickinson 1967, Carter 1973). Nevertheless, in the context of conducting hydrologic studies of wetlands, it is possible to accurately measure channelized surface-water fluxes to and from the site of interest.

However, one of the major concerns of wetland scientists is the role of wetlands in surface runoff; specifically, the storage capacity of wetlands to reduce flood peaks and the effect of wetland drainage on streamflow characteristics. Studies to address these concerns are generally based on statistical analysis of existing data (Moore and Larson 1979, Novitzki 1979, Ogawa and Male 1985) or rainfall-runoff models (Moore and Larson 1979). Most of these studies indicate that drainage basins containing wetlands have different runoff characteristics than drainage basins that do not contain wetlands.

For example, Novitzki (1979) concluded that throughout Wisconsin, in basins with 40% lakes and wetlands compared to basins with no lakes and wetlands, flood flows are 80% lower, spring streamflows are 40% higher, and fall base-flows are 40% lower. Daniel (1980) indicated that pocosins also attenuate peak flows by providing retention storage. On the other hand, Verry and Boelter (1979) indicated that if wetlands are already saturated, they may have little capacity to store additional water. This is true not only of depressional wetlands but also of upland wetlands, such as pocosins (Daniel 1980).

The preceding are a few examples of the types of studies done on the relationship of wetland storage and drainage to streamflow. Although such statistical studies are useful for the specific data set, they are not fundamental, process-based analyses, and the results are difficult to apply on a general basis.

Groundwater

The difficulty in determining groundwater flow directions and groundwater fluxes has been discussed by Winter (1981) in terms of the difficulty and expense of defining flow-system boundaries, dynamics of recharge and discharge, hydraulic gradients, and permeability distribution. Most of the concepts upon which present understanding of wetland and groundwater interaction are based have been developed through field studies of selected wetlands with minimal development of general principles, or through modeling of hypothetical settings with minimal field verification. The groundwater flow-system modeling studies by Toth (1963), Freeze (1969), and Winter (1976, 1978) are mostly of steady-state, generalized systems and are most appropriate for understanding regional flow systems. Applications can be made to nearly any landscape where uplands are adjacent to lowlands, such as glacial terrain, river valleys, and coastal areas. Even though the flow-system configurations are theoretically sound, in only a few areas have regional flow systems been mapped from actual data (Meyboom and others 1966, Swanson and others 1988). Furthermore, few studies have considered the highly dynamic characteristics of the local flow systems that are superimposed on, and interact with, the regional systems.

The few field studies of local flow systems associated with depressional wetlands (see Meyboom 1966, Lissey 1971) were of only a few wetlands in the Canadian prairie, and they usually did not involve mapping the entire groundwater watershed of the wetlands.

These studies commonly resulted in generalized interpretations applied to a much broader region, and the concepts were, to some extent, in conflict. For example, the conceptual flow systems for the Moose Mountain area (Meyboom 1966) assumed groundwater was recharged at land surface highs. However, Lissey (1971), also working in the Canadian prairie, indicated that groundwater was recharged at land surface depressions. By studying several entire contiguous watersheds in North Dakota, LaBaugh and others (1987) have indicated that the difference in perception about the relationship between land surface configuration and groundwater recharge probably depends on scale, as shown in Figure 5.

Modeling studies of groundwater movement by Winter (1983) and studies of the capillary fringe above the water table by Gillham (1984) have resulted in modified approaches to field study of the interaction of wetlands and groundwater. However, these studies have begun only recently, and there has been minimal field verification of models of transient flow conditions.

Because of the general lack of comprehensive long-term studies of groundwater movement near wetlands, it must be concluded that the field verification needed for understanding the interaction of wetlands and groundwater is minimal. Most knowledge is based on theoretical studies. The field studies that have been done are generally short-term and do not include the entire watershed of the wetland. The complexity of spatial and temporal changes in water movement, together with the impropriety of making generalized assumptions, is documented by LaBaugh and others (1987) for a group of prairie wetlands in North Dakota (Figure 6), and by Winter (1986) for lake–wetland complexes in the Nebraska sand hills (Figure 7).

Cumulative and Offsetting Effects of Disturbances on the Hydrology of Wetlands

From the above analysis, it is apparent that the scientific foundation for understanding wetland hydrology is very weak. The topic has not attracted the attention of many hydrologists; therefore, field studies have been few and most have not been comprehensive. Most hydrologic information relative to wetlands has been based largely on theoretical studies of generalized settings, on scattered field studies, and on hydrologic intuition. With this rather inadequate information base to draw upon, the following discussion of impacts of disturbances is intended to be very general and is based largely on hydrologic intuition. The disturbances considered herein are: (1) weather modification, (2) alteration of plant communities, (3) storage of surface water, (4) road construction, (5) drainage of surface water and soil water, (6) alteration of groundwater recharge and discharge areas, and (7) pumping of groundwater. These are discussed with respect to the generalized landscape (Figure 2).

Weather Modification

Weather modification refers principally to inducing precipitation through cloud seeding. This practice is most common in the arid western United States because of the desire to increase the water supply to selected parts of the landscape. However, a tradeoff of this practice is that the additional water applied in one area results in less water available in downwind areas. In general, any increased or decreased precipitation has the potential to affect formation and persistence of wetlands.

The principal effect of increased precipitation in upland areas, such as mountainous terrain, would be to increase runoff because of the steep valley sides, and to increase subsurface flow, which would supply greater quantities of water to riverine lakes and wetlands within the mountain valleys. The increased water would possibly benefit wetlands by increasing their size, but the increased water depth might also drown existing wetland plants. In addition, the readjustment of the size and shape of wetlands could affect riparian landowners.

Wetlands not along rivers in the lowland regions of decreased precipitation downwind of the mountains could be adversely affected because of the decreased supply of atmospheric water, as well as decreased groundwater inflow. However, if increased precipitation in uplands results in increased streamflow to the lowlands, the additional water may enhance formation of riparian wetlands.

Alteration of Plant Communities

Evapotranspiration from a wetland may be altered by altering the wetland vegetation. If plants are removed from a wetland, such as by logging, the loss of water by evapotranspiration may change (Heikurainen 1975), thereby changing the quantity of water available for surface-water flow or groundwater recharge. However, it is conceivable that removal of one species might not alter the total evapotranspiration at all. Although not related exclusively to evapotranspiration, Daniel (1980) discusses the effect on hydrology of changing vegetation in a pocosin wetland in North Carolina from natural forest to agriculture. Total destruction of wetland plants by herbicides or plant disease would have a significant impact on the other hy-

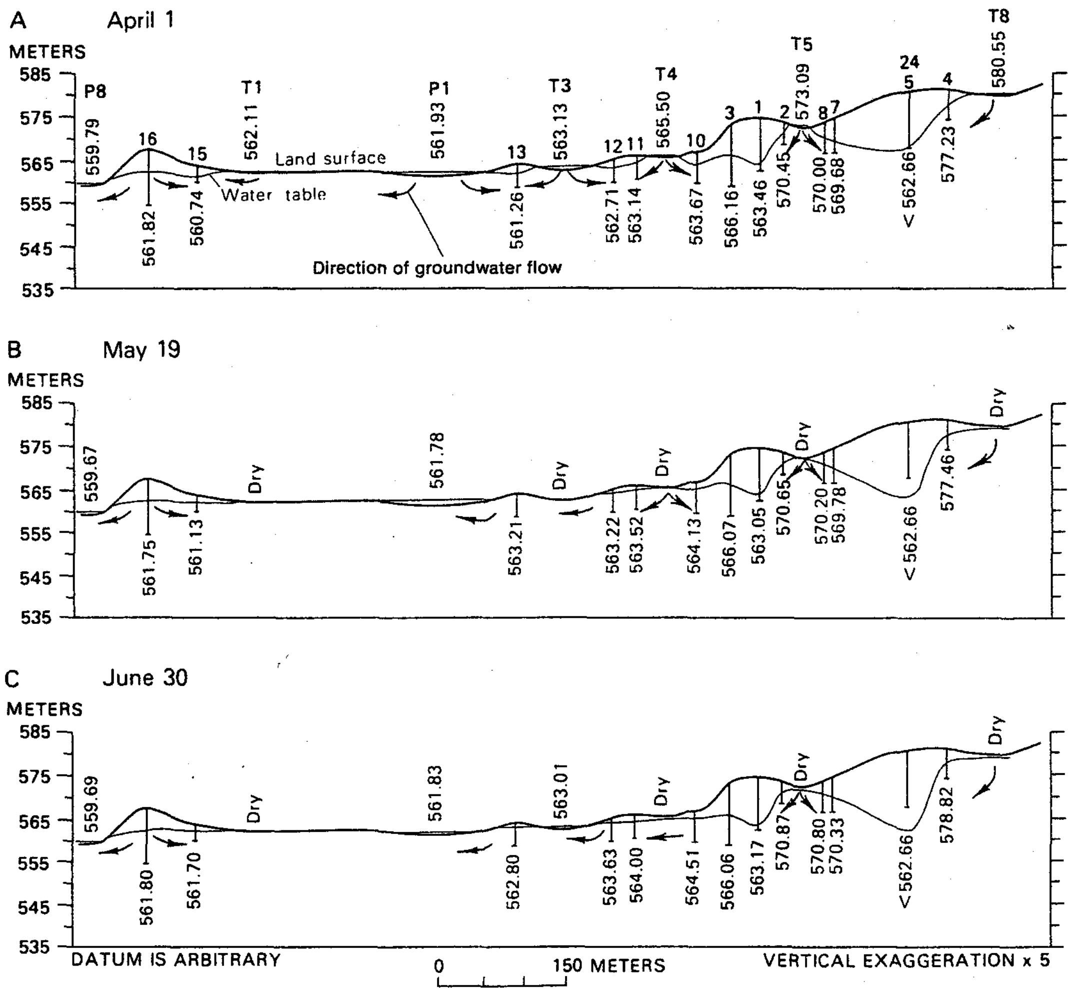

Figure 6. Altitudes of wetland water levels and water-table levels for (**A**) 1 April, (**B**) 19 May, and (**C**) 30 June 1980 in the Cottonwood lake area, North Dakota. Wetlands T8 and T5 are groundwater recharge areas. Beneath the hills between these two wetlands, water-table highs do not underlie land-surface highs. Reversals in flow between wetlands and groundwater occur from early to late spring in the area between well 10 and wetland P1. A water-table high always underlies the land-surface high near well 16. (Data from LaBaugh and others 1987.)

drologic components. Complete removal of the transpiration process, which usually accounts for the greatest loss of water from wetlands, could result in considerably more water available for surface runoff and/or groundwater recharge.

Alteration of plant communities in the drainage basins of wetlands may have various effects on wetlands because of changing water regime and sedimentation. For example, logging in upland areas results in modification of surface runoff and subsurface flow systems as well as increased sediment transport (Megahan 1981). Wetlands associated with the altered surface-water and groundwater flow regimes may enhance, change, or destroy existing wetlands, depending on how the flow regime is altered. However, the increased sedimentation would almost certainly have harmful effects on existing wetlands.

Storage of Surface Water

Surface water can be stored in reservoirs along the main stem of rivers (on-channel storage) in lowlands (Figure 2), or in reservoirs off the main stem (off-channel storage). Because wetlands commonly occur in flood plains of major rivers, on-channel storage obliterates the wetlands drowned by the reservoir. In addition, storage of water commonly has a negative impact on riparian wetlands downstream from the dam because the natural flow regime upon which many wetlands were formed and maintained is altered. Bedinger (1979) discusses the effect of regu-

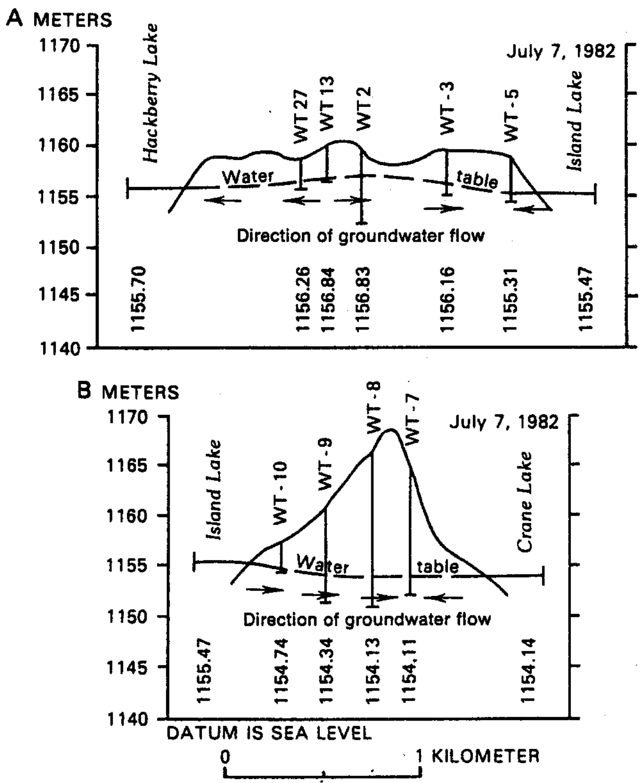

Figure 7. Configuration of the water table beneath sand dunes in the southwestern part of the sand hills, Nebraska: **(A)** water-table mounds occur beneath some hummocky dunes, and **(B)** water-table troughs occur beneath sharp-crested dunes. (Data from Winter 1986.)

lated river flows on riverine wetlands containing bottomland hardwood forests in Arkansas. The study indicates that flooding is the dominant hydrologic factor affecting distribution of wetland tree species, and it compares the lower White River with the Ouachita River. It is conceivable that reservoirs could have a positive impact on downstream wetlands if the reservoir were managed to enhance wetland formation and maintenance. Few, if any, dams were constructed for this purpose, except in some wildlife management areas.

On-channel reservoirs affect groundwater moving toward the river valleys by inducing bank storage (Simons and Rorabaugh 1971), which is the movement of water from the reservoir to the groundwater system. In addition, the increased stage of the reservoir relative to pre-reservoir stream level provides a different base level for discharge from groundwater flow systems (van Everdingen 1968); that is, the higher level of the discharge area decreases groundwater gradients toward the river valley, thereby decreasing groundwater discharge and increasing groundwater storage. Wetlands commonly are created directly downstream from reservoirs because the high hydraulic head provided by the reservoir water level can cause seepage around the dam as well as diversion of groundwater moving toward the reservoir to the valley below the dam.

Off-channel reservoirs can be constructed anywhere on the landscape. If off-channel reservoirs are constructed on an upland, they usually are small and shallow because they have small drainage areas and high topographic position. Shallow surface water enhances the formation of wetlands, but is subject to increased water loss through evaporation. In addition, topographically high lakes and wetlands have a great probability of losing water as seepage to groundwater.

Off-channel reservoirs in lowlands can be large because of potentially large contributing drainage areas. They also commonly are shallow, which enhances the formation of wetlands. Lowland reservoirs and associated wetlands can have seepage losses to groundwater, but because they are likely to be in regional groundwater discharge areas the water losses are likely to be less than the seepage from upland reservoirs. The largest seepage losses would probably occur as bank storage during periods of high reservoir water levels.

Reservoirs can be managed to favor wetland processes, but most are managed for other purposes. In shallow, off-channel reservoirs, the pools themselves commonly are rimmed by wetlands. But large, deep reservoirs that have large fluctuations in water level commonly have barren or weed-covered flats at low water level.

Road Construction

Because wetlands have low land values, and have shallow water or areas of wet soils, it commonly is more cost effective to build roads across, rather than around them. This practice can have significant effects on the wetland, because the roadbed serves as a dam to water movement, even if culverts are used to connect the separated areas of wetland. It is not unusual to find dead vegetation on one side of a road and a living viable wetland on the other side. However, even the side with living plants undergoes change to adjust to the new condition of water flow.

In the case of wetlands interacting with surface water, it is relatively easy to visualize obstruction of natural water flow by roadbeds. However, wetlands without surface water inlets and outlets and with interactions with groundwater also can be significantly affected by road construction. In the Crystal Springs area, Stutsman County, North Dakota, a prairie wetland with open water has been divided into eight parts by interstate, state, and county highways, as well as by a railroad. In its native condition, the wetland received groundwater inflow on one side and had seepage losses to groundwater on the other side. Furthermore, the lake had uniform chemical composition. As a result of the subdivision by roadbeds, individual water bodies presently range in specific conductance from 2,000–29,000 μS/cm (Swanson and others 1988). Those areas with specific conductance of 2,000 μS/cm continue to receive groundwater inflow as before, but those with specific conductance of 29,000 μS/cm are farthest downgradient and receive little groundwater inflow.

Drainage of Surface Water and Soil Water

Drainage of water is a common practice in regions of flat and/or hummocky topography. Because ponded water or slowly moving water enhance formation of wetlands, removal of water from a wetland is detrimental. Wetlands that have little or no groundwater inflow can be completely destroyed by drainage. These wetlands are particularly vulnerable in upland settings. Wetlands that receive groundwater discharge have a better chance to withstand drainage, because drainage does not eliminate inflow. Drainage lowers the hydraulic head at the wetland site, initially increasing groundwater gradients, which increases groundwater discharge to the site. However, over a long period of time groundwater levels generally decline with drainage, as evidenced by drainage of pocosins in North Carolina (Daniel 1980).

Drainage of any area can affect wetlands downstream. Drainage of uplands results in increased delivery of water to lowlands, streams, and lakes. This increased volume of water, if it results in flooding, could drown and destroy or alter existing riparian wetlands. However, the increased delivery of water to lowlands could enhance the formation and persistence of wetlands in the lowlands by providing additional water. Bedinger (1979) points out that wetland species in riverine bottomlands along the White and Ouachita Rivers depend to some extent on flooding. Furthermore, flooding of lowlands supplies water for groundwater recharge, provided the water table is not already at land surface in the flooded area.

Alteration of Groundwater Recharge and Discharge Areas

Recharge to local groundwater flow systems occurs throughout the landscape, whether in regional uplands, regional slopes, or regional lowlands. Alteration of a recharge area refers to any practice that would add or remove potential recharge water. Construction of an off-channel reservoir on any part of the landscape, although beneficial to wetlands, would also enhance the potential for groundwater recharge. Because recharge to regional groundwater flow systems occurs primarily in uplands, construction of off-channel reservoirs in these areas enhances recharge to regional flow systems.

Detrimental effects of altering recharge are caused by removal of water. Increasing the efficiency of water removal from areas of flat slope by ditching, such as in pocosins, or any area of minimal slope, reduces recharge to groundwater. Not only is less water available because of the drainage, but the resulting lowered water table reduces the hydraulic head that provides the driving force for recharge. In hummocky topography, wetlands that are groundwater recharge areas are those that are relatively high topographically. Because the water source is largely atmospheric water or periodic surface water, recharge wetlands usually hold water only intermittently. These wetlands are also the smallest and easiest to drain. If a depressional wetland that recharges groundwater is drained, the recharge function is lost. If a recharge wetland is adjacent to a groundwater flowthrough or groundwater discharge wetland, these adjacent wetlands will receive less groundwater inflow. In addition, the lack of recharge will cause the water table to decline to the next level of potential recharge, which is the next lowest wetland, formerly a wetland receiving groundwater. Thus, drainage of small seasonal wetlands will eventually lower the water table enough to change the hydrologic function of lower wetlands, changing them from groundwater flowthrough or groundwater discharge wetlands to recharge wetlands. The end result will be a lower water table throughout the entire area.

The impact of wetland drainage on regional flow systems is not as great as it is for local flow systems. For upland areas, some of the water that seeps from recharge wetlands serves as recharge to regional flow systems. Whether or not the recharge point shifts from one local depression to another in uplands makes little difference to the total regional recharge process. Similarly, in lowlands, wetlands that receive discharge from regional groundwater flow systems will continue to receive that discharge even if the wetland depression in the upland is drained. In lowlands, the removal of the recharge function of a small, topographically high wetland will have less effect on lowering the overall water table because of the relatively constant supply of regional groundwater discharge to the lower adjacent wetlands.

Drainage is not the only practice that will decrease the quantity of water available for recharge. Other modifications to the landscape that will have the same effect include paving or building over extensive areas with the attendant urban storm sewering. Other modifications to the landscape that could affect groundwater recharge, and, ultimately, the wetlands that receive that groundwater as discharge, include forest clearing, tillage, and other modifications to vegetative cover.

Modification of groundwater discharge areas generally has less significant impact on wetlands than modification of recharge areas. For example, if water is added to the landscape in a groundwater discharge area, the resulting recharge will be added to the groundwater discharge. This water may temporarily reverse groundwater flow directions, but with a lowering of surface-water level, the water will return to the surface. Draining water from groundwater discharge areas initially increases groundwater discharge because the hydraulic head gradients are increased. A detrimental impact that is likely to result is that the increased gradients could increase seepage rates from nearby wetlands, and, ultimately, cause a regional lowering of the water table. It is also probable that the plant communities would change in a groundwater discharge wetland that is drained.

Pumping of Groundwater

Groundwater development, mostly by pumping but occasionally by artificial recharge, can have an impact on surface water and wetlands. Groundwater pumping causes a lowering of hydraulic head within an aquifer that results in a cone-shaped depression of hydraulic head centered on the well. In the case of unconfined aquifers, the water table itself takes the shape of a cone centered on the well. If the cone of depression extends areally to intersect a wetland, the lowered hydraulic head can cause seepage from the wetland (Figure 8A).

The shape of the cone of depression, that is, its areal extent and curvature, depends on the permeability of the porous media. In permeable media the cone of depression is generally shallow and extensive (Figure 8B), whereas in media of low permeability, it is steep and restricted in areal extent. The same principle applies to ditches that intersect the groundwater system. In media of low permeability the effect of the lowered water table caused by a ditch will create a line of hydraulic-head depression that has less areal extent than in media of high permeability.

From the perspective of groundwater development, the practice of pumping groundwater near wetlands is beneficial, because water that would be used to sustain plants is available to the well instead. This practice is commonly referred to by hydrologists as "salvaging evapotranspiration." From the perspective of wetland ecology, of course, groundwater pumping specifically at the expense of the wetland is extremely detrimental. But even if not specifically designed to impact the wetland, groundwater pumping anywhere within the flow field may impact surface water. Decreasing the hydraulic head by pumping, even some distance away from a wetland, will change the flow field configuration, in some cases enough to decrease groundwater discharge to the wetland or even to induce seepage from it.

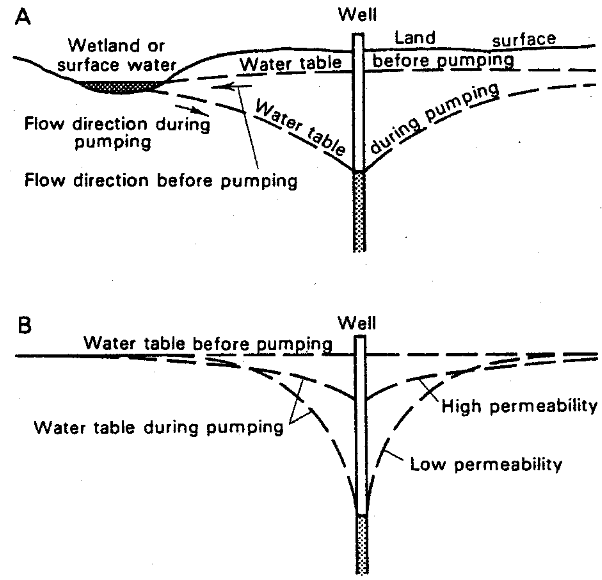

Figure 8. Effects of pumping on water-table configuration: **(A)** a cone of depression intersects surface water or wetland, causing seepage from the surface water or wetland; **(B)** differences in the shape of the cone of depression are related to differences in permeability of the porous media.

Conclusion

Because the hydrologic system is a continuum, any modification of the continuum will impact contiguous parts. Therefore, modification of the hydrologic system is a self-perpetuating process, because the solution to one problem generally creates a problem for the contiguous area, which in turn must be modified. The seriousness of the impact commonly is related to scale. One well or one landscape modification generally has only local effects, but multiple modifications or development can have extensive impacts. The most serious drawbacks to effective management of the hydrologic continuum are (1) inadequate understanding of hydrologic processes such as the interactions of the atmospheric water, surface water, and groundwater components, and (2) lack of consideration of the uncertainties in measuring these components.

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