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Abstract. *Wetlands in the prairie known as potholes or sloughs represent an ever-changing mosaic of surface waters interacting with the atmosphere, groundwater, and each other in a variety of ways. Studies of groups of adjacent wetlands in different parts of the glaciated North American prairie have enabled some connections to be made between hydrologic processes, biological communities, and use of these wetlands by wetland-dependent wildlife. Understanding controls on variability in water levels, water volume, and salinity in these wetlands sets the stage for understanding controls on biological communities utilizing these wetlands. The role that natural variability in water and salinity plays in making these wetlands an important resource for waterfowl will provide an important context for those who are responsible for artificially altering the variability of water and salinity in prairie wetlands.*

Prairie wetlands are spatially and temporally diverse (van der Valk 1989). This diversity may be responsible for the productivity of biota that are a valuable natural resource for the North American continent (Swanson and Duebbert 1989). Understanding the processes responsible for such diversity may benefit those who manage these natural resources (Robarts and Bothwell 1992). In addition, understanding the processes that affect wetlands' spatial and temporal variation may be useful to those who are intimately connected with the landscape through agricultural activity (Leitch 1989). Published studies in Canada and the United States have identified hydrologic processes and variability as important areas of study to improve understanding of prairie pothole wetlands (Meyboom 1963; Toth 1963; Lissey 1971; Eisenlohr et al. 1972; Swanson et al. 1988; Richardson et al. 1994; Winter and

Rosenberry 1995). The purpose of this report is to review existing hydrologic studies of prairie pothole wetlands and place their findings in the context of identifying the types of research that would be useful to advance our understanding of hydrologic processes in prairie wetland environments.

What a wetland does in relation to ground water, surface water, and atmospheric water defines a wetland's hydrologic functions. Prairie-pothole or slough wetlands are depressional wetlands that can store surface water, recharge ground water, be a source of water to the atmosphere, and provide an aquatic environment for wetland organisms. These all are examples of the hydrologic functions of prairie pothole wetlands. Other functions are storage of water received from ground-water discharge and water received from rainfall and snow. Questions related to these hydrologic functions are: how does the amount of surface water stored in a wetland change over time, how does a wetland interact with subsurface water, including soil water and ground water, and how does a wetland provide water to the atmosphere? Answers to these questions are provided by examination of hydrological processes. Thus, to understand the hydrologic function of prairie pothole wetlands it is important to focus on the processes that make those functions possible. Understanding hydrologic processes provides the foundation for understanding how wetlands receive, store, and release water. Because of the importance of hydrologic processes as determinants of the hydrologic function of prairie pothole wetlands, the emphasis of this report will be on hydrologic processes.

This report 1) provides an overview of the relation between hydrologic processes in prairie pothole wetlands and their chemical and biological characteristics, 2) examines how the hydrologic, chemical, and biological matrix in these wetlands changes in response to changing hydrologic conditions, and 3) identifies areas of study that could increase our knowledge of hydrologic processes that help define the function and value of these wetlands. Synthesis of literature from Canada and the United States will be used to meet these objectives. Although the examples used in this report primarily are from the glaciated prairie, the general hydrologic processes discussed herein are common to many physiographic settings in which closed-basin nontidal wetlands are found (Winter 1988).

Prairie Wetlands Represent a Wide Range of Hydrological, Chemical, and Biological Characteristics

The glaciated prairie (Fig. 1) contains many depressional wetlands in hummocky moraines or relatively flat outwash plains (Winter 1989). These

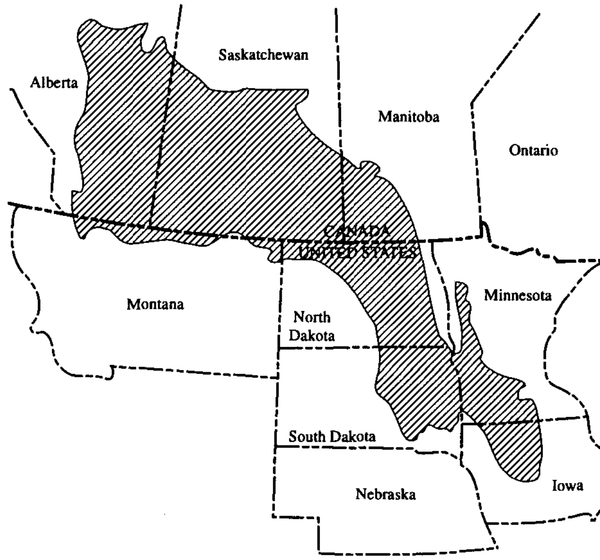

Figure 1. Location of glaciated prairie in Canada and the United States. (Adapted from Winter[1989]. Copyright Iowa State University Press; reprinted with permission.)

depressional wetlands are often referred to as sloughs in Canada and prairie potholes in the United States (Eisenlohr et al. 1972). Most of these depressional wetlands are not part of a naturally integrated drainage system; inflow and outflow of surface water in stream channels is not common (Winter and Woo 1990). The relative lack of naturally integrated surface drainage among depressions in the landscape is one of the reasons that runoff as spring snowmelt is retained in non-contributing areas (wetlands, ponds, and lakes) (Winter et al. 1984). Wetlands contain water after snowmelt for varied periods of time, some for only days, some for weeks or months, some throughout the year in all but the driest years, and others throughout the year even in the driest years (Stewart and Kantrud 1971). These differences in the length of time water is present in prairie pothole wetlands are reflected in the composition and distribution of vegetation within those wetlands (Kantrud et al. 1989).

Magnitude of water level fluctuations also is a determinant of the plant communities found within prairie pothole wetlands (Stewart and Kantrud

1972). Seasonal variation in rainfall, evaporation, and transpiration are reflected in water level fluctuations within wetlands (Sloan 1972; Eisenlohr and others 1972; Winter and Rosenberry 1995), but relation to groundwater can play a role in the length of time wetlands contain water (Sloan 1972; LaBaugh et al. 1987). Wetlands that contain water for weeks or months after snowmelt but are then dry are likely to be in areas receiving little if any groundwater discharge. Shjeflo (1972) found that rates of wetland water seepage to groundwater were greater in ephemeral and temporary wetlands, perhaps reflecting differences in weathering of the land surface. Wetlands that contain water throughout a year in most years are likely to be in areas receiving some groundwater discharge. Complexities in the geologic framework of the wetlands also plays a role in water level changes because wetlands with sandy zones at their margins can receive more discharge (Sloan 1972; van der Kamp 1988) and can contain water in years when adjacent wetlands are completely dry (LaBaugh et al. 1996). The importance of differences in geologic framework controlling chemical characteristics of water discharging to prairie lakes, and therefore of the chemical characteristics of those lakes, has been documented by Schwartz and Gallup (1978).

Plant communities in prairie pothole wetlands also reflect the salinity of wetland water (Stewart and Kantrud 1972). Water in these wetlands can be fresh, saline, or hypersaline according to the classification of Cowardin et al. (1979). Studies which have examined salinity in a variety of wetlands indicate salinity is variable throughout the prairie (LaBaugh 1989) (Fig. 2). Several studies of the chemical composition of groundwater in clayey-silty till indicate concentrations increase from areas of recharge to areas of discharge due to weathering of carbonate and sulfide minerals in the till (Rozkowski 1969; Cherry et al. 1971; Grisak et al. 1976; Hendry et al. 1986; Swanson 1990; Keller et al. 1991). Salinity of soil water also changes due to dissolution of these minerals in prairie soils (Arndt and Richardson 1989; 1992). As a result of the increase in the salinity of groundwater from recharge to discharge areas, prairie pothole wetlands that are areas of groundwater recharge are less saline and prairie pothole wetlands that receive groundwater discharge are more saline (Sloan 1972, LaBaugh et al. 1987). Wetlands in areas of glacial outwash tend to be more saline than wetlands in glacial moraine (Sloan 1972; Swanson et al. 1988). However, prairie pothole wetlands in glacial outwash and their relation to groundwater flow systems have not been studied in as much detail as wetlands in moraines (Rozkowski 1969; Sloan 1972; LaBaugh et al. 1987; LaBaugh and Swanson 1992; van der Kamp and Hayashi 1998).

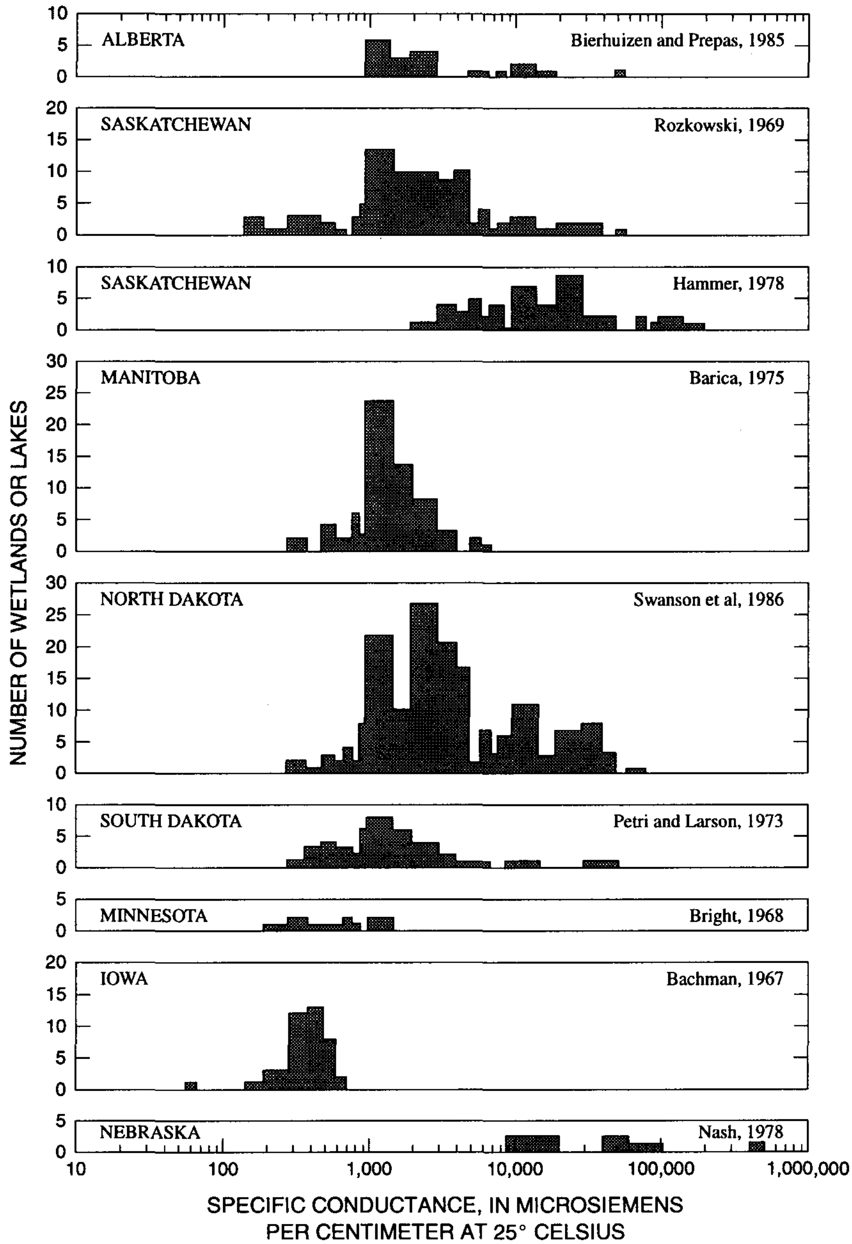

Figure 2. Frequency distribution of specific conductance for prairie wetlands and lakes in the northern prairie of North America from selected regional studies. (From LaBaugh [1989]. Copyright Iowa State University Press; reprinted with permission.)

Prairie Wetlands Have Different Hydrologic Functions

Existing studes of hydrologic processes in prairie wetlands have found that atmospheric deposition, evaporation and transpiration are the major components of the water balance of the wetlands (Millar 1971; Eisenlohr and others 1972; Sloan 1972; Winter and Rosenberry 1995; Parkhurst et al. 1998). Although groundwater may have a small role in the water balance of these wetlands, interaction with groundwater helps to define the hydrologic function of these wetlands (Winter 1992). Studies of groundwater interaction with depressional wetlands indicate the wetlands can be areas of recharge to groundwater and areas where groundwater discharges to the surface (Lissey 1971; Sloan 1972). Prairie pothole wetlands can also be areas where groundwater seepage to a wetland and wetland seepage of water to groundwater occur concurrently (through flow) in the same wetland (Sloan 1972).

Theoretical analysis of groundwater flow in the prairie of Alberta by Toth (1963) indicated that most shallow groundwater was part of local flow systems that could overlie intermediate and regional flow systems. Recharge at topographic highs and discharge at topographic lows in these flow systems were at scales consistent with the size of the flow system. Thus on a large scale, topographically high areas could be recharge areas for intermediate or regional flow systems (Fig.3), yet contain local-scale recharge and discharge areas relative to local groundwater flow systems (Winter and Carr 1980; Swanson et al. 1988). Vertical heterogenity in hydraulic conductivity also plays a role in defining the scale of flow systems interacting with prairie pothole wetlands; local-scale flow systems are related to the fracture permeabilty of tills and clays near land surface (van der Kamp and Hayashi 1998).

Prairie pothole wetlands that are areas of groundwater recharge are less saline and wetlands that receive groundwater discharge are more saline (Sloan 1972; LaBaugh et al. 1987). However, the relation between topographic position and salinity, where salinity is used as a indicator of hydrologic function, across numerous wetland basins, is not statistically significant (Swanson et al. 1988). Thus, one needs to know more about the hydrogeologic setting of wetlands than altitude to understand how the wetlands are related to groundwater flow systems.

Topic of Further Study: Existing studies of wetland complexes that have included detailed hydrologic processes represent only part of the diverse hydrogeologic setting of the prairie (Winter and Rosenberry 1995;

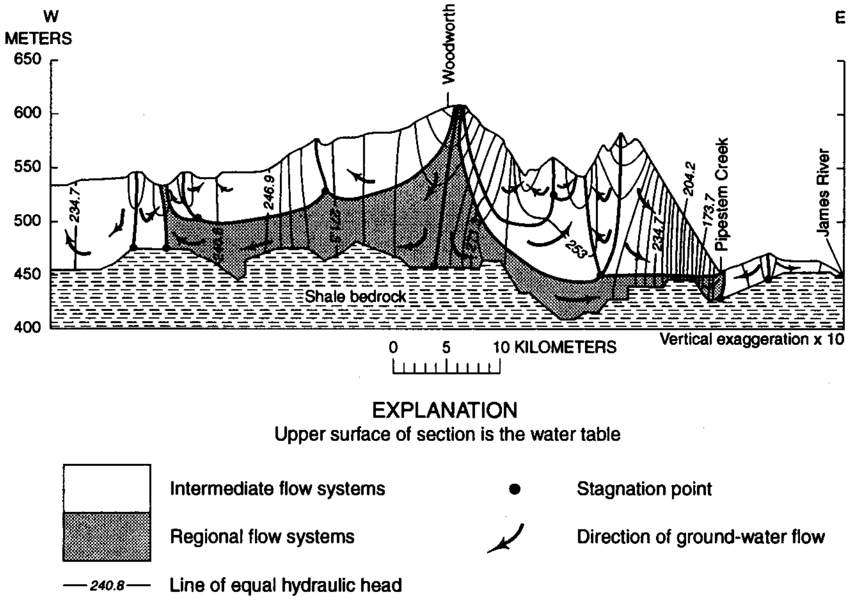

Figure 3. Numerical simulation of regional groundwater flow systems along a vertical section through northern Stutsman and Kidder Counties, North Dakota (From Winter and Carr, 1980).

van der Kamp and Hayashi 1998). Similar detailed investigations need to be done in areas of glacial outwash and areas of regional discharge. Comparative studies across the hydrogeologic spectrum of the prairie should indicate how hydrologic functions relate to the geologic framework. Knowing how hydrologic functions are related to particular geologic settings will be useful in understanding controls on vegetation and other biological communities.

Hydrologic Functions of Prairie Wetlands Can Change in Response to Variable Climate

A major factor contributing to the dynamic hydrologic conditions in prairie pothole wetlands is the location of the glaciated prairie in areas where

annual average evaporation exceeds annual average precipitation (moisture from rain and snow) (Fig. 4). Long-term annual averages of evaporation and precipitation help explain spatial differences in aridity at a large scale. However, at a local scale, evaporation from prairie wetlands changes both seasonally (Eisenlohr et al. 1972) and annually (Parkhurst et al. 1998). Rain and snowfall are also quite variable (Eisenlohr et al. 1972; Winter and Rosenberry 1995) reflecting the continental climate of the glaciated prairie (Winter 1992). As the relation between rainfall and evapotranspiration changes annually due to natural variability, water levels change in prairie wetlands (LaBaugh et al. 1996; Winter and Rosenberry 1995). Yet, water level changes in response to the same local imbalance between evapotranspiration and precipitation are not uniform (Fig. 5). The lack of uniformity in change of water level to the same climate 'signal' has been related to variations in wetlands' interaction with groundwater (LaBaugh et al. 1996).

Variability in water levels in response to wet and dry episodes translates into plant community changes within wetlands over time (Eisenlohr et al. 1972; van der Valk 1981; Kantrud et al. 1989; Poiani et al. 1996). When these episodes are viewed in the context of wetland function in relation to groundwater, the main reasons for variety in the plant communities of the prairie pothole wetlands are revealed. Salinity of wetland water can increase many-fold during dry episodes and decrease many-fold when deluges occur (LaBaugh et al. 1996). Within the salinity range spanning wet and dry periods, plant species can wax and wane according to individual species' tolerance for salinity (Stewart and Kantrud 1972). Localized conditions of fresh water spring discharge to wetlands can maintain salt intolerant plants in saline waters (Sloan 1972), and such zonation due to heterogeneity in discharge can maintain heterogeneity within plant communities of a single wetland throughout wet and dry episodes (Swanson 1987). While the relation of plant communities to changes in water level and salinity are documented to some extent, far less is known about the relation between water level fluctuations, salinity fluctuations and animal communities. However, the variety in salinity and water permanence in these prairie wetlands contributes to the abundance of food resources needed by waterfowl (Swanson and Duebbert 1989).

Studies designed to examine the interaction of wetlands and groundwater have been conducted at a limited number of sites throughout the glaciated prairie (Meyboom 1966; Rozkowski 1969; Eisenlohr et al. 1972; LaBaugh et al. 1987; Matheney and Gerla 1996; van der Kamp and Hayashi 1998), all in glacial moraine, but only a few of sufficient duration to include

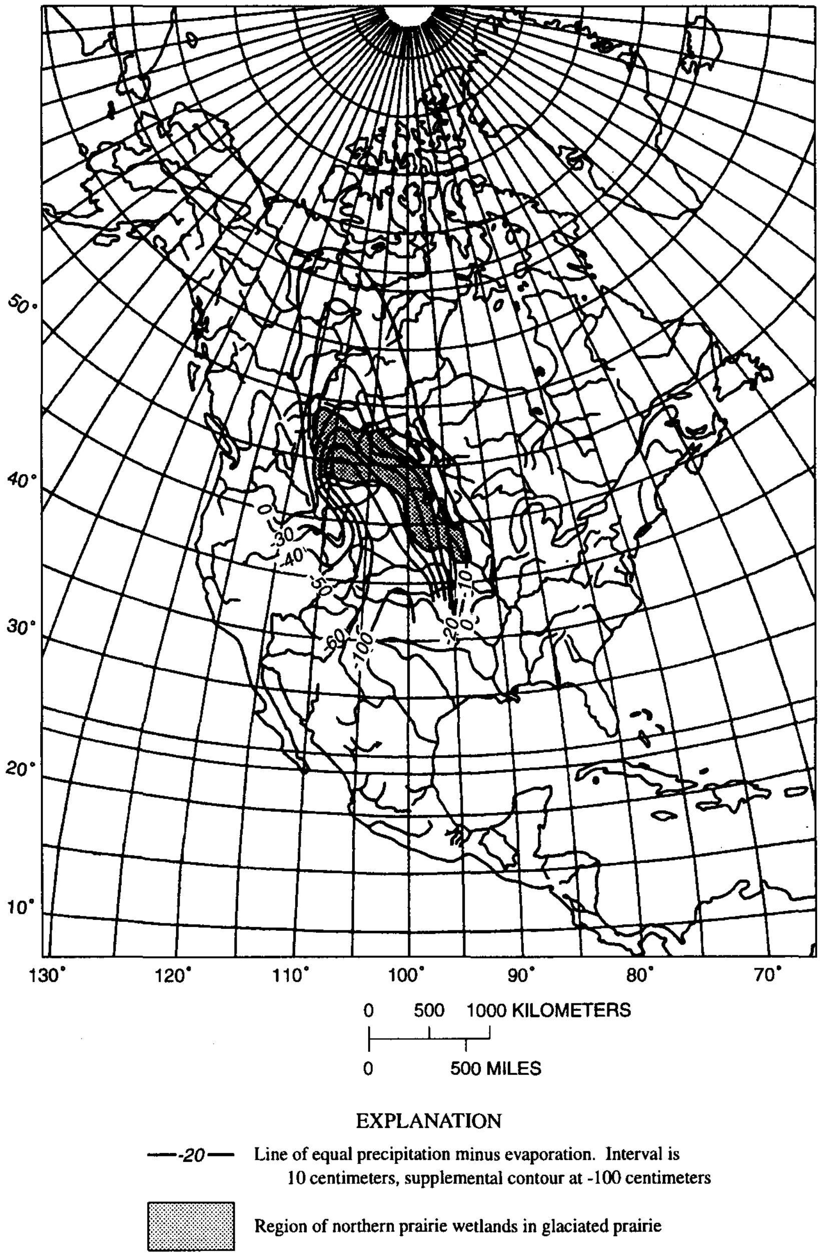

Figure 4. Precipitation minus evaporation in the northern prairie region (modified from Winter [1989]. Copyright Iowa State University Press; reprinted with permission).

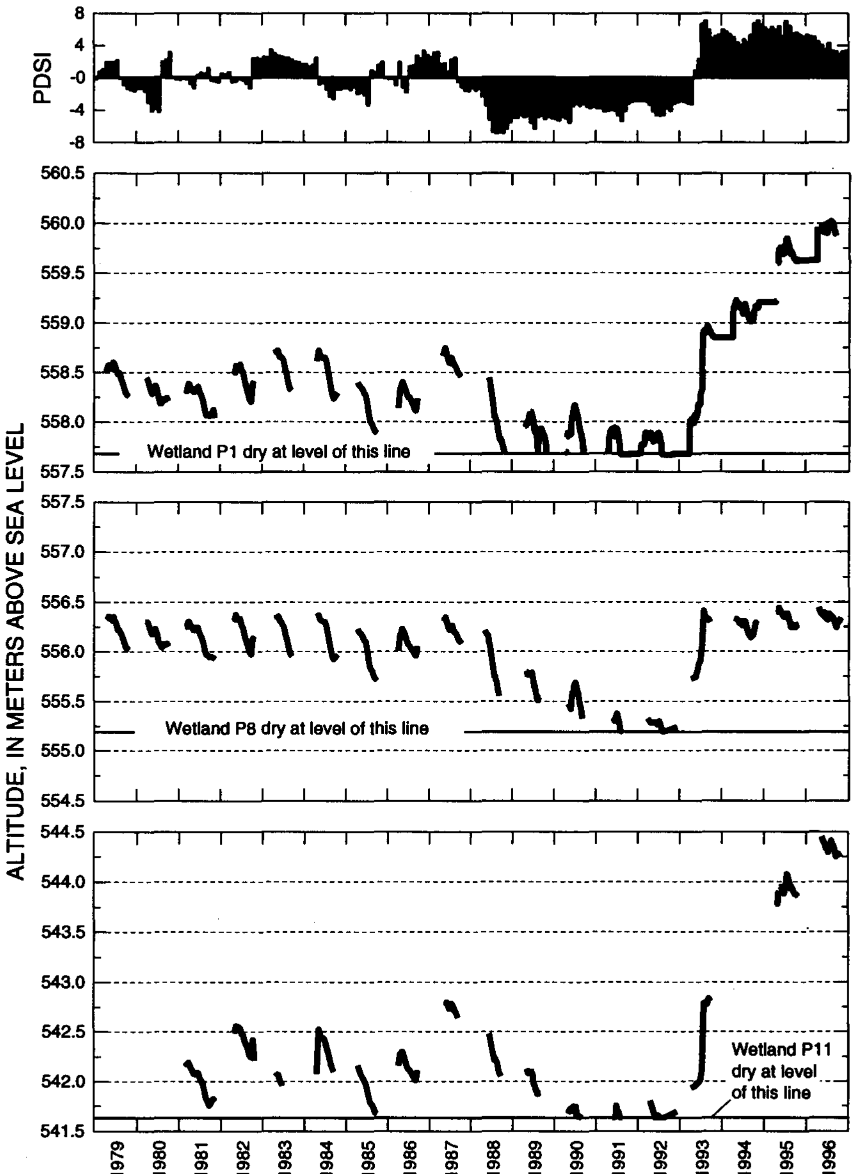

Figure 5. Wetland water levels in wetlands P1, P8, and P11, 1979-1996 (Modified from LaBaugh et al. [1996]. Copyright American Society of Limnology and Oceanography, Inc.; reprinted with permission).

major natural wet and dry episodes. In one of the few cases to examine wetland hydrologic functions for many years, wetlands that were in ground-water discharge areas during wet periods lost water and salts in dry periods due to wetland water seepage induced by transpiration at wetland margins (Winter and Rosenberry 1995; LaBaugh et al. 1996). Dry periods also can lead to removal of salts by wind erosion (deflation) of dried wetland sediments. Wet and dry episodes can alter the salinity of wetland water as hydrologic function of prairie wetlands in glacial moraine changes (Winter and Rosenberry 1995). However, changes in hydrologic function of wetlands in glacial outwash in reponse to variable climatic conditions are undocumented.

Studies such as those by Eisenlohr and others (1972), LaBaugh et al. (1996), Winter and Rosenberry (1995), and van der Kamp and Hayashi (1998) indicate that wet and dry episodes are a characteristic of the prairie region. In view of recent concern about variability in climate and inland water resources (McKnight et al. 1996) it is useful to examine the historical frequency of wet and dry episodes. Interest in wet episodes is related to occurrence of floods (Winter et al. 1984). Changes in drainage patterns in the prairie landscape due to human activity have been thought to contribute to increased flooding in recent years, but the relation between changes in the landscape and severity of flooding is not clear (Winter et al. 1984). One of the longer-term records of changing hydrologic conditions in the glaciated prairie comes from measurements made of the lake level in Devils Lake, North Dakota, U.S.A. (Wiche 1996) (Fig.6).

The wet periods of the early 1950s and mid 1990s, reflected in large rises in Devils Lake (Fig. 6), were also periods of high water in prairie potholes in North Dakota (Eisenlohr and others 1972; LaBaugh et al. 1996). The mid 1990s were also a period of increased water levels at the St. Denis wetland complex in Saskatchewan (van der Kamp and Hayashi 1998). Wet and dry episodes evident in the Devils Lake record since 1930 are superimposed on a general rise in lake level to heights similar to those last recorded in the mid 1800s. Thus, using the Devils Lake record as a proxy for hydrologic conditions in the glaciated prairie of North Dakota, the recent wet episode may have brought wetland water levels to heights not encountered for 130 years. Unfortunately, there are no recorded measurements made by humans available for preceding centuries that allow us to put recent episodes into longer context. However, wetlands and lakes in the prairie have been recording these events through deposition of sediments. Collection of sediment cores from wetlands and lakes for examination of past climate as

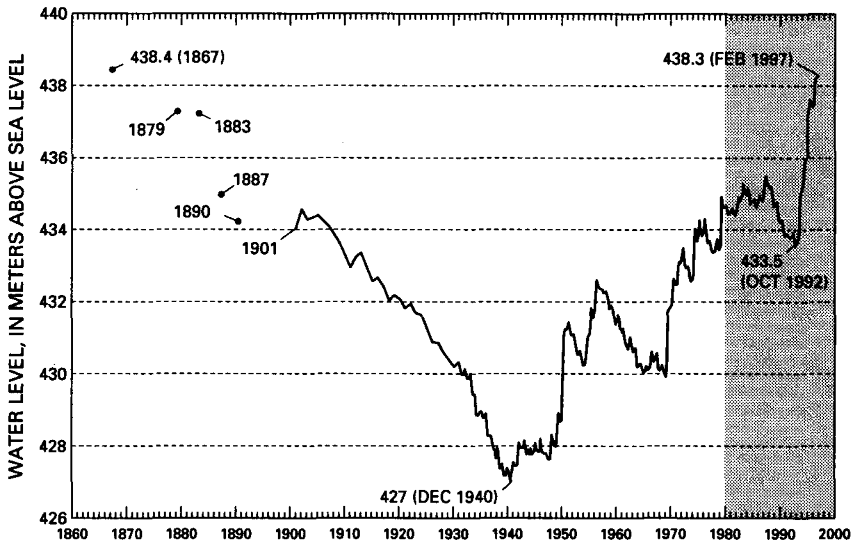

Figure 6. Historic water-level data for Devils Lake, North Dakota (Modified from Wiche [1996]).

recorded by fossils and other evidence is a useful technique (Watts and Winter 1966; Smith 1991; Laird et al. 1996; Xia et al. 1997). Prairie pothole wetland sediments could be used to determine how such wetlands responded not only to wet and dry episodes of a decadal nature, but also if past wet and dry periods were of longer duration.

Topic of Further Study: Recent hydrologic events in parts of the North American prairie indicate how variable climate is in this semi-arid region. Available historic record indicates such changes are common. To place events of the past 200 years in context requires examination of evidence from paleoclimatological records. Understanding the fact that variability is common, and determining how hydrologic processes contribute to that variability, is important information for those who manage prairie wetlands and those who make a living from agricultural activity in the prairie landscape. Also of interest is the relation of the extent of nonintegrated drainage to

storage of runoff in noncontributing areas, particularly in wet periods. Examination of the sediment record in these wetlands might enable us to answer questions such as 1) are recorded hydrologic extremes in the prairie similar to extremes in recent millennia, and 2) Is the frequency of recorded episodicwet and dry periods similar to the frequency of wet and dry periods of recent millennia?

Processes at the Margins of Wetlands Can Affect Hydrologic Function

Our current understanding of the relation of groundwater to prairie wetlands comes from measurements made at sites where detailed instrumentation, including observation wells, have been installed for the purpose of studying hydrologic processes. Such studies led to the discovery that loss of water by transpiration can exceed loss due to open-water evaporation (Eisenlohr and others 1972) and transpiration can cause flow reversals at the margins of wetlands ringed by willow trees (Fig. 7) (Meyboom 1966). In Meyboom's study, groundwater flow to the wetland from uplands was intercepted and removed by transpiration before the water could discharge to the ponded water within the wetland. Also, water leaving the wetland in reponse to the gradient caused by transpiration did not recharge groundwater but was lost from the ground by transpiration. Transpiration-induced flow reversals are not peculiar to wetlands fringed by trees, such reversals are common even in prairie wetlands with grass and herb-dominated uplands (Winter and Rosenberry 1995; Rosenberry and Winter 1997). Although the effect of transpiration has been documented in discharge wetlands (Meyboom 1966; Rosenberry and Winter 1997), transpiration also is important in recharge wetlands (van der Kamp and Hayashi 1998) where changes in vegetation in adjacent uplands can determine whether or not the wetlands will contain water at all. Even in the few detailed, published water balance studies of wetlands (LaBaugh 1986), quantification of the transpiration potential of different upland and wetland plants is lacking. Such knowledge is needed to relate vegetation dynamics to water loss by transpiration and open-water evaporation as well as to changes of water movement into and out of wetlands at their edges.

Transpiration also affects wetlands and their margins through effects on soils (Stolte et al. 1992; Arndt and Richardson 1993). Movement of water and salts due to the action of transpiration helps explain hydric soil morphology and chemical characteristics at wetland edges (Arndt and Richardson 1992; Richardson et al. 1994). Transpiration allows for the deposition of

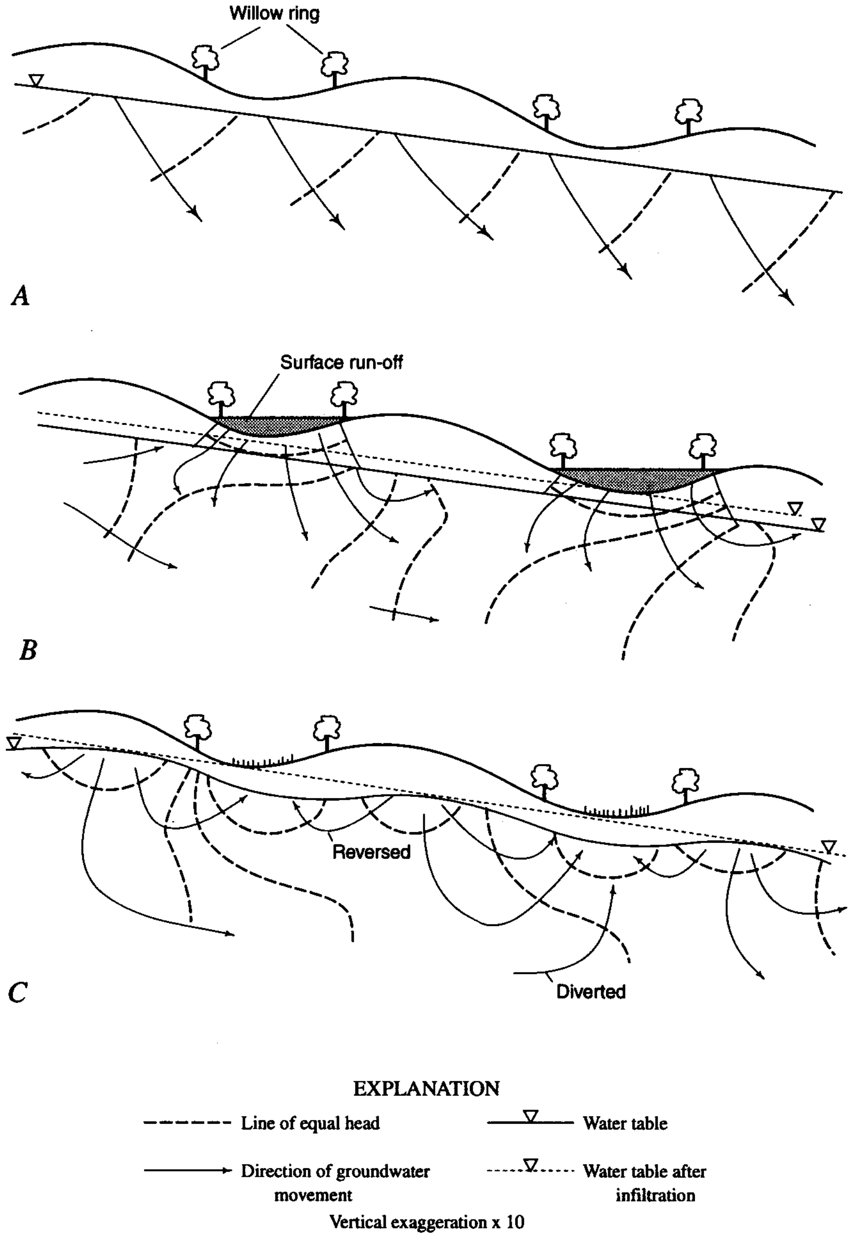

Figure 7. Generalized sequence of flow conditions near a willow ring in Saskatchewan (Adapted from Meyboom [1966]. Copyright Elsevier BV; reprinted with permission).

carbonate and sulfate minerals, which can constitute the bulk of soil materials at the edge of some prairie wetlands (Biondini and Arndt 1993; Arndt and Richardson 1993). This edge effect relating water movement to soil development occurs in a variety of soil environments (Richardson et al. 1992). The presence of carbonate and sulfate minerals at the edge of prairie pothole wetlands receiving groundwater discharge provides a source of readily weathered material that can contribute to the salinity of water discharging to the wetlands (Mills and Zwarich 1986; Arndt and Richardson 1989; Arndt and Richardson 1993). One effect of wet and dry cycles is to move the wetland-groundwater margin above or below zones of salinized soils. Little is known about how such changes in the position of groundwater flow into wetlands alters the salinity of these systems.

Topic of Further Study: Transpiration effects on movement of water into and out of wetlands noted by Meyboom occur during wet and dry periods across a variety of vegetation types. Quantification of the transpiration potential of different plants that exist at the fringe of standing water in wetlands is lacking. Such knowledge is needed to relate vegetation dynamics to water loss by transpiration and open-water evaporation as well as to changes of water movement into and out of wetlands at their edges. The relation between hydrologic processes at the edge of wetlands and soil and vegetation dynamics has only begun to be explored.

Conclusions

Many studies of prairie wetlands in the glaciated prairie have been done in Canada and the United States in the past 60 years. Wetlands have been examined from many perspectives by hydrologists, geologists, soil scientists, chemists, biologists, limnologists, and ecologists. Each has contributed to our understanding of these wetlands, but the timing, duration, and spatial extent of such studies have rarely overlapped. Yet, collectively, findings from these studies identify gaps which need to be filled and opportunities for collaborative work in the future. Gaps include: lack of detailed studies in glacial outwash and area of regional discharge to compare with concurrent detailed studies in glacial moraine, absence of studies of wetland sediments to place current hydrologic variability in historical perspective, and paucity of information about the importance of transpiration. Finally, more needs to be done to translate an increased understanding of processes in these wetlands to advancing knowledge of wetland functions.

Acknowledgments

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