HYDROLOGY OF PRAIRIE POTHOLE WETLANDS DURING DROUGHT AND DELUGE: A 17-YEAR STUDY OF THE COTTONWOOD LAKE WETLAND COMPLEX IN NORTH DAKOTA IN THE PERSPECTIVE OF LONGER TERM MEASURED AND PROXY HYDROLOGICAL RECORDS

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Abstract. From 1988 to 1992 the north-central plains of North America had a drought that was followed by a wet period that continues to the present (1997). Data on the hydrology of the Cottonwood Lake area (CWLA) collected for nearly 10 years before, and during, the recent dry and wet periods indicate that some prairie pothole wetlands served only a recharge function under all climate conditions. Transpiration from groundwater around the perimeter of groundwater discharge wetlands drew water from the wetlands by the end of summer, even during very wet years.

Long-term records of a climate index (Palmer Drought Severity Index), stream discharge (Pembina River), and lake level (Devils Lake) were used to put the 17-year CWLA record into a longer term perspective. In addition, proxy records of climate determined from fossils in the sediments of Devils Lake were also used. These data indicate that the drought of 1988-92 may have been the second worst of the 20th century, but that droughts of that magnitude, and worse, were common during the past 500 years. In contrast, the present wet period may be the wettest it has been during the past 130 years, or possibly the past 500 years.

Keywords: wetland hydrology, Palmer Drought Severity Index, Devils Lake, Pembina River

1. Introduction

Concerns over the fate of aquatic resources resulting from changes in climate are widespread (Firth and Fisher, 1992; Cushing, 1997). The concerns are particularly pertinent to prairies because many prairie ecosystems have adjusted to conditions near warm/cold and (or) wet/dry extremes, and even small shifts in climate can have significant effects on water resources and aquatic ecosystems (Covich et al., 1997). Furthermore, water resources and aquatic ecosystems in the prairies have great economic importance for water supply, flood control, fisheries, and waterfowl breeding and habitat.

Climate in the Great Plains is affected by air masses from the Arctic, Pacific Ocean, and Gulf of Mexico. As a result of the great differences in the temperature and moisture content of these air masses, the prairie environment of the Great Plains is characterized by great variability in air temperature and moisture (Bryson and Hare, 1974). Determination of long-term trends that would signal changes in climate are confounded by this extreme natural variability of climate in the Great Plains. The need to distinguish natural variability from directional change in climate is one of the challenges in determining the fate of aquatic resources in the Great Plains.

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The glaciated prairie (Figure 1), which lies in the northern part of the Great Plains, is characterized by numerous small depressions that commonly contain wetlands called prairie potholes. The majority of these wetlands have no stream inlets or outlets and most are underlain by glacial till having low permeability, which restricts their interaction with groundwater. As a result of this physiographic setting, the water balance of prairie pothole wetlands is greatly dependent on exchange of water with the atmosphere -- precipitation is the largest source of water and evapotranspiration causes the largest loss of water. The entire glaciated prairie is characterized by a negative water balance with respect to the atmosphere. The amount that annual open-water evaporation exceeds annual precipitation ranges from 10 cm in Iowa to 60 cm in southwestern Saskatchewan and eastern Montana. This great dependence on atmospheric water makes prairie pothole wetlands particularly useful for evaluating the effects of climate variability on aquatic resources.

Recognizing the importance of understanding the hydrology of prairie pothole wetlands with respect to management of land and aquatic resources, a group of wetlands in the Cottonwood Lake area in North Dakota was selected in 1977 for long-term study and monitoring (Winter and Carr, 1980). Instruments were installed to measure wetland water levels and precipitation, calculate evaporation, and determine groundwater movement to and from the wetlands. During the past 20 years, the Cottonwood Lake area has been subjected to a drought (1988-1992) and a deluge of precipitation (1993-present).

The purpose of this paper is (1) to discuss the response of several different types of wetlands in the Cottonwood Lake area to extreme dry, extreme wet, and more normal climate conditions during the past 17 years, and (2) put these results into a longer term perspective by comparing them to long records of climate (Palmer Drought Severity Index, 1895 to present), streamflow (Pembina River at Neche, North Dakota, 1904 to present), and lake level (Devils Lake, North Dakota, 1860 to present). The interaction of Wetland P1 (Figure 1) and groundwater from 1979 to the middle of the drought was discussed in detail by Winter and Rosenberry (1995). That information is extended in this paper by including the last 2 years of the drought (1991-92) and the subsequent 4 years (1993-96) of very wet conditions.

2. Description of Study Sites

The Cottonwood Lake study area is situated on one of the higher parts of the eastern edge of the Missouri Coteau, a large topographic feature that was formed by glacial deposition. The study site (Figure 1) is 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

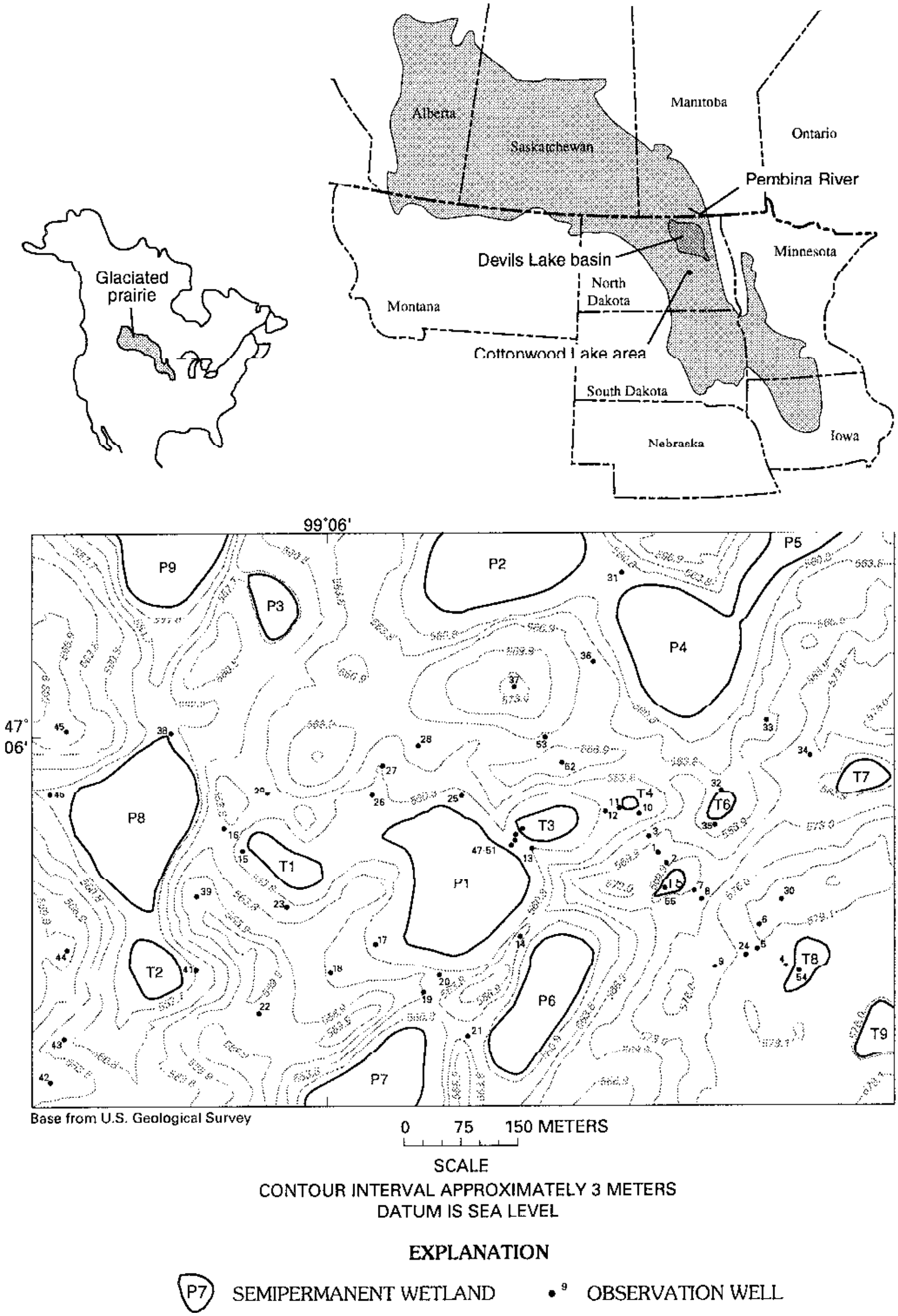

Figure 1. **Location of the Cottonwood Lake area within the glaciated prairie of North America, and topography, location of wetlands and observation wells in the Cottonwood Lake area in North Dakota.**

the 80 ha that constitute the Cottonwood Lake area is about 28 m. The area is very hummocky and has many closed depressions, most of which contain wetlands. The wetlands range in altitude from seasonal Wetland T9, about 577 m, to semi-permanent Wetland P9, about 550 m. Most glacial deposits in the study area consist of till, a heterogeneous mixture of clay through boulder-size rocks. However, sand and gravel deposits are buried within the till at several locations in the study area. Furthermore, because of the fine-grained texture of the till matrix, fractures are common, having an average spacing of about 10 cm (Swanson, 1990). The Cottonwood Lake area has not been cultivated or grazed for at least the past 30 years, and parts of it may be native prairie (Dr. G.A. Swanson, personal communication, 1997).

The Pembina River, a tributary of the Red River of the North, drains 8,830 km^2 of northeastern North Dakota and southern Manitoba upstream of the streamgage at Neche, North Dakota. The basin lies in the drift prairie, which is characterized by low land slopes and low topographic relief. The Pembina River has no control structures; therefore, it is largely a naturally flowing stream.

Devils Lake has no outlet; it is the lowest point of an inland drainage basin that covers 8,600 km^2 of northeastern North Dakota. The basin lies within the drift prairie; therefore, it also has very little topographic relief and stream gradients are low. The Devils Lake Basin also includes several lakes and numerous wetlands.

3. Methods

For the Cottonwood Lake area, the data used for this study are altitudes of water levels in water-table wells and in wetlands. The water-table wells were constructed by augering to about 2 m below the water table, placing well screen and pipe into the hole, placing a silica-sand pack around the screen, and backfilling with drill cuttings to land surface. The screens were 0.6- to 1.0-m long. Most holes, some of which were drilled as deep as 30 m, were drilled using a truck-mounted power auger, but a few holes less than 4-m deep were augered by hand using a soil auger. The well casings and screens are made of PVC; most are 5 cm in diameter, but a few are 3 cm in diameter. Staff gages consist of staff-gage plates attached to posts driven into the wetland bed. A continuously-recording gage was placed in Wetland P1. Water levels in the wells were measured using a steel tape. Measurements were made weekly during rapidly changing water levels in spring, biweekly during summer and fall, and monthly during winter. Staff gages were read on the same days the wells were measured during spring, summer, and fall. All staff gages and wells were surveyed to a common datum.

Computation of the PDSI, which is determined from precipitation, evapotranspiration, and soil moisture data, is relatively complicated and the explanation is beyond the scope of this paper. Details of the computation and assumptions are presented by Palmer (1965). The PDSI is determined for specific climatic divisions of States by the U.S. National Weather Service, and can be obtained from the National Climate Data Center in Asheville, North Carolina. For this study, the PDSI for Division 5 of North Dakota was used. Discharge data for the Pembina River and stage data for Devils Lake are from U.S. Geological Survey files.

4. Hydrologic Conditions at the Cottonwood Lake Area, 1979-1996

Climate conditions in the Cottonwood Lake area (CWLA) were relatively stable from 1979 to 1987. Using the water level of Wetland P1 as an integrator of hydrologic conditions at the site during this time (Figure 2), it can be seen that several wet-dry-wet cycles occurred. The first cycle extended

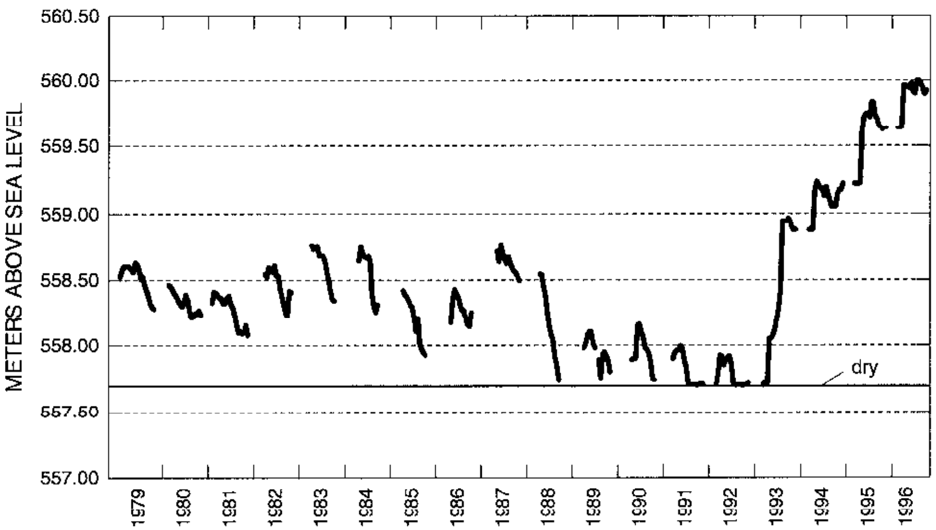

Figure 2. Altitude of the water surface of Wetland P1 for the open-water periods of 1979-1996.

from 1979 to 1983, and the second, which had a greater range of fluctuation, extended from 1984 to 1987. Climate conditions at the site changed significantly when a 5-year drought commenced during midsummer of 1987. During the summer of 1988, the wetland stage declined about 80 cm, and the wetland was dry by fall. From 1988 through 1992, the wetland dried each year, never having water more than half a meter deep. During the summer of 1993, record-breaking rainfall resulted in a sharp rise in the wetland water level. The magnitude of precipitation during the summer of 1993 can be seen from the following comparisons. Based on data from 1961-1990, average precipitation for May, June, and July was 61 mm, 92 mm, and 68 mm, respectively. For May, June, and July of 1993, monthly precipitation was 112, 157, and 264 mm, respectively, a 3-month total of more than half a meter. By late fall of 1993, water in Wetland P1 reached its highest level since monitoring began in 1979. In subsequent years, to the present, the level has steadily increased. Other semipermanent wetlands in the CWLA had similar patterns of fluctuation. However, Wetland P8, which is underlain by sand and which receives groundwater inflow from a more extensive buried sand aquifer, did not dry up until 1991 (LaBaugh et al., 1996).

Response of the groundwater system to these climatic conditions is more complex because the configuration of the water table reflects the constantly changing areal and temporal distribution of recharge and discharge. Nevertheless, hydrographs of the water-table altitude at most well locations in the study area had the same overall fluctuation patterns as those for Wetland P1. Furthermore, some characteristics of the configuration of the water table, and the resulting interaction of groundwater with wetlands in the study area, remained the same regardless of climatic conditions: for example, (1) The water table has sloped away from Wetland T8 (Figure 3) through all climate conditions, indicating that this wetland serves a groundwater recharge function whenever it holds water, (2) the water table had a complex configuration between Wetlands T8, T5, T3 and P1, and (3) groundwater moved from the east, south, and west into the valley occupied by Wetlands T2 and P8. Wetland P8 has a low spill point which results in frequent periods of surface-water outflow to Wetland P9 (Figure 1). While these characteristics of the water table in parts of the study area have been relatively consistent during the course of this study, water movement between some of the wetlands and groundwater commonly has reversed direction, as indicated below (Winter and Rosenberry, 1995; Rosenberry and Winter, 1997).

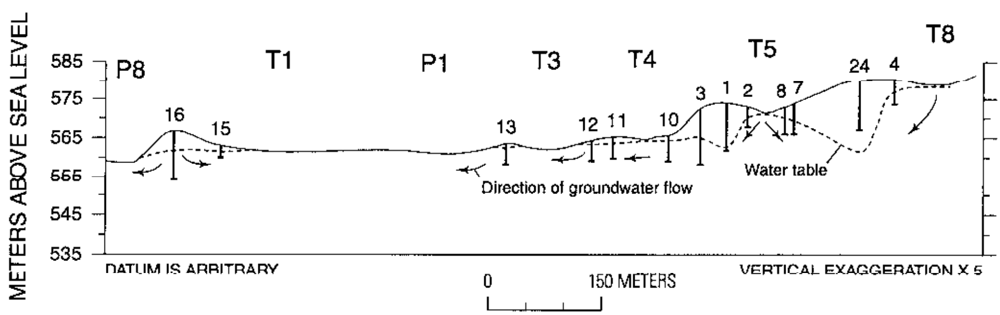

Figure 3. Hydrologic section through the Cottonwood Lake area showing the relationship of the water table to wetlands.

Long-term hydrographs of water levels in upland wells, such as wells 14, 19, 22, and 28, indicate that the altitude of the water table has been greater than the altitude of the water level in the Wetland P1 throughout the entire period of study (Figure 4). These data would indicate that Wetland P1 is perennially a groundwater discharge area. However, comparisons of the water level of Wetland P1 with the altitude of the water table at wells located in the lowland around the perimeter of the wetland, such as wells 13, 17, 20, 25, and 26 (Figure 5), indicate that flow direction between the wetland and groundwater has reversed many times. Withdrawal of water through the wetland bed is caused by transpiration of groundwater by plants around the wetland's perimeter.

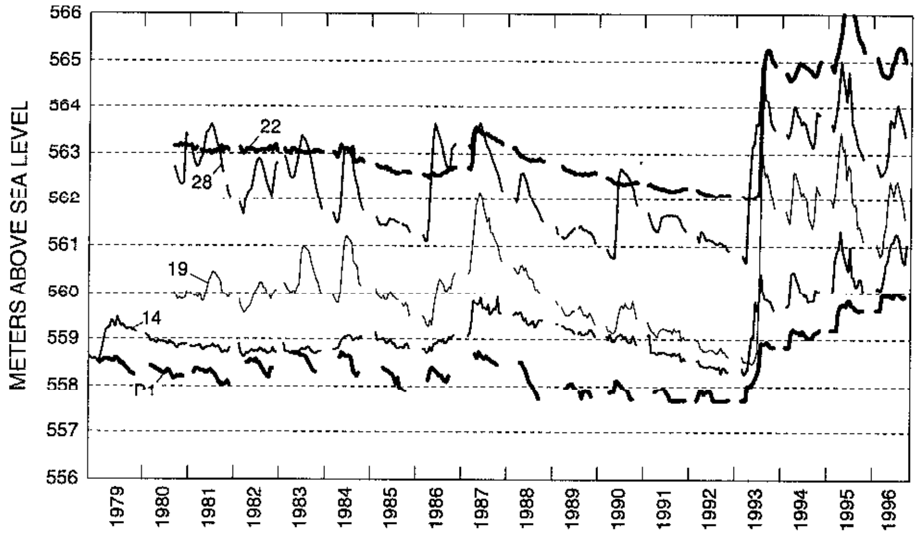

Figure 4. Water-table altitudes in selected upland wells relative to the altitude of the water surface of Wetland P1, 1979-1996.

The temporal complexity of the interaction of Wetland P1 with groundwater can be seen in hydrographs, such as Figure 5, but the spatial complexity needs to be shown by water-table maps representing a point in time. Examples of two greatly different water-table configurations near Wetland P1 prior to 1988 are for May 31, 1987 (Figure 6), which shows water-table gradients toward the wetland around its entire perimeter, and August 31, 1989, which shows water-table gradients away from the wetland around most of its perimeter (Figure 7).

The additional data from the past six years corroborate many of the general findings reported by Winter and Rosenberry (1995). For example, the water table was lower than Wetland P1 during most of the drought, as indicated by the examples of wells 25 and 26 (Figure 5). As the drought progressed the water table declined more and more each year, resulting in

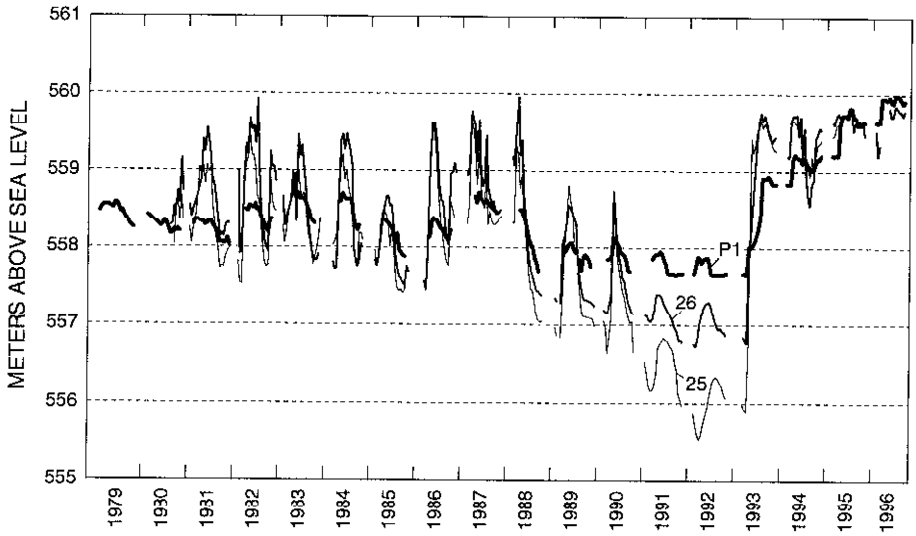

Figure 5. **Water-table altitudes in selected wells in the lowland surrounding Wetland P1 relative to the altitude of the water surface of Wetland P1, 1979-1996.**

increasingly steeper water-table gradients. Under these dry conditions the water-table configuration would be much like that shown in Figure 7. During the initial part of the wet period beginning in 1993, the water table was much higher than the wetland, resulting in a water-table configuration that would be much like Figure 6. As the wet period continued, the wetland water level continually rose to the point that it was similar in altitude to the water table at the nearby wells, such as wells 25 and 26. The water table could not continue to rise because the ground became fully saturated near the wells. Nevertheless, even under these wet conditions, transpiration from groundwater caused gradients from the wetland to develop during parts of 1994, 1995, and 1996 (Figure 5). Meanwhile, in the upland between the wetlands, the water table continued to rise higher each year, increasing the water table gradients toward the wetlands.

The variations in hydrologic conditions in the Cottonwood Lake area described above were the result of small and large variations in climate. The data indicate that a semipermanent wetland can dry up in one summer (1988) if not sustained by occasional rainfall during summer. Furthermore, if spring water levels are low, the wetland can continue to dry up even if it receives occasional rainfall during summer. These data indicate that a drought of only a few years duration can dry up semipermanent prairie pothole wetlands, even if, as in the case of Wetland P8, the wetland receives groundwater inflow from small sand aquifers. Conversely, a few years of abundant precipitation can fill these small wetland basins to the point where they coalesce with neighboring wetlands (Figure 8). Although much has been learned from hydrologic measurements made during extreme dry and wet periods at the Cottonwood Lake area, it is of interest to put this record in a longer-term perspective by comparing it to long-term records of other hydrologic features.

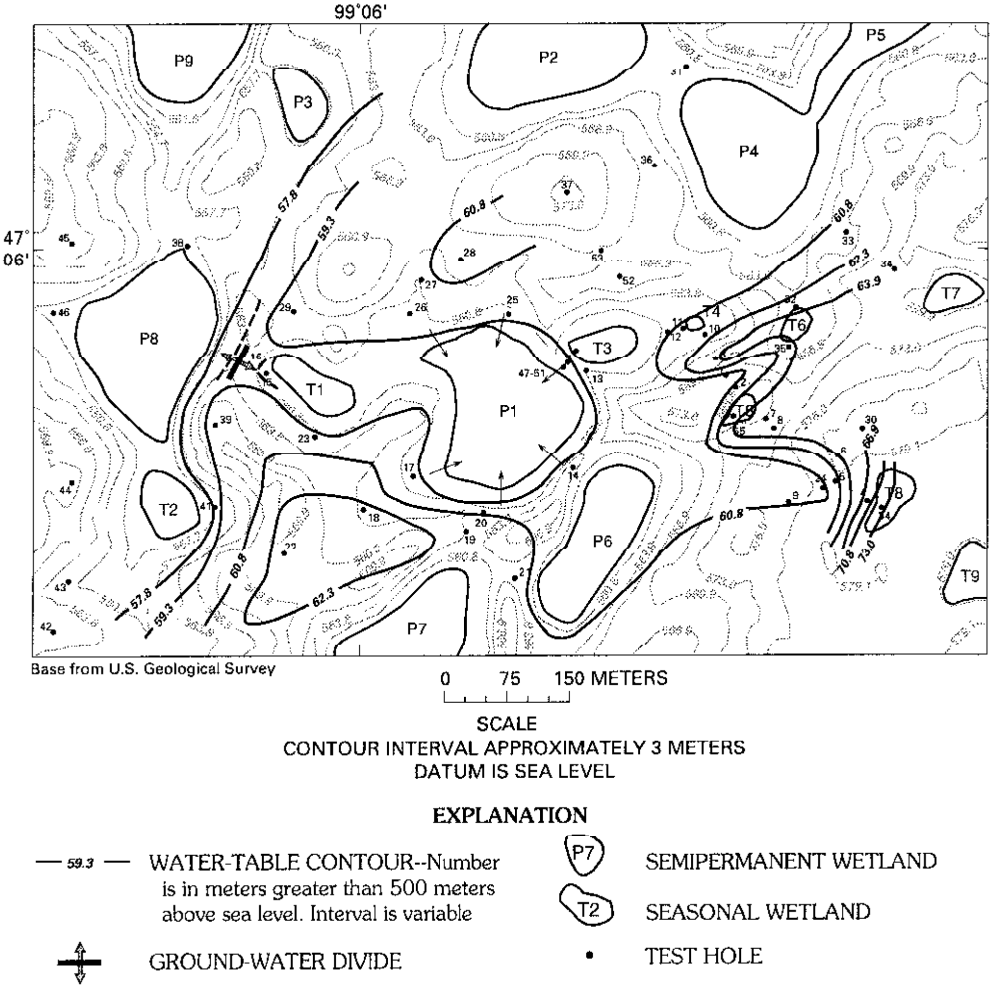

Figure 6. **Configuration of the water table in the Cottonwood Lake area, May 31, 1987, indicating that groundwater was discharging to Wetland P1 around its entire perimeter. (From Winter and Rosenberry, 1995.)**

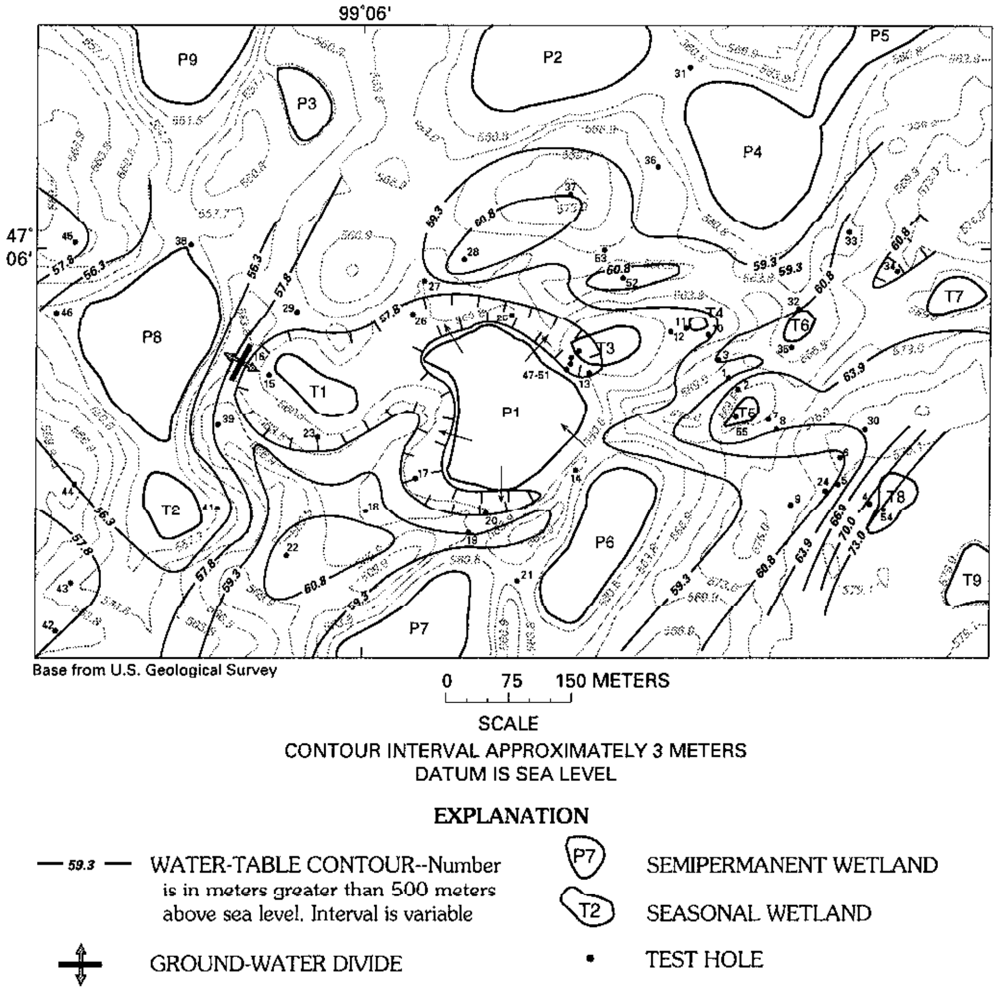

Figure 7. **Configuration of the water table in the Cottonwood Lake area, August 31, 1989, showing the water-table depression around much of the perimeter of Wetland P1 caused by transpiration directly from groundwater. (From Winter and Rosenberry, 1995.)**

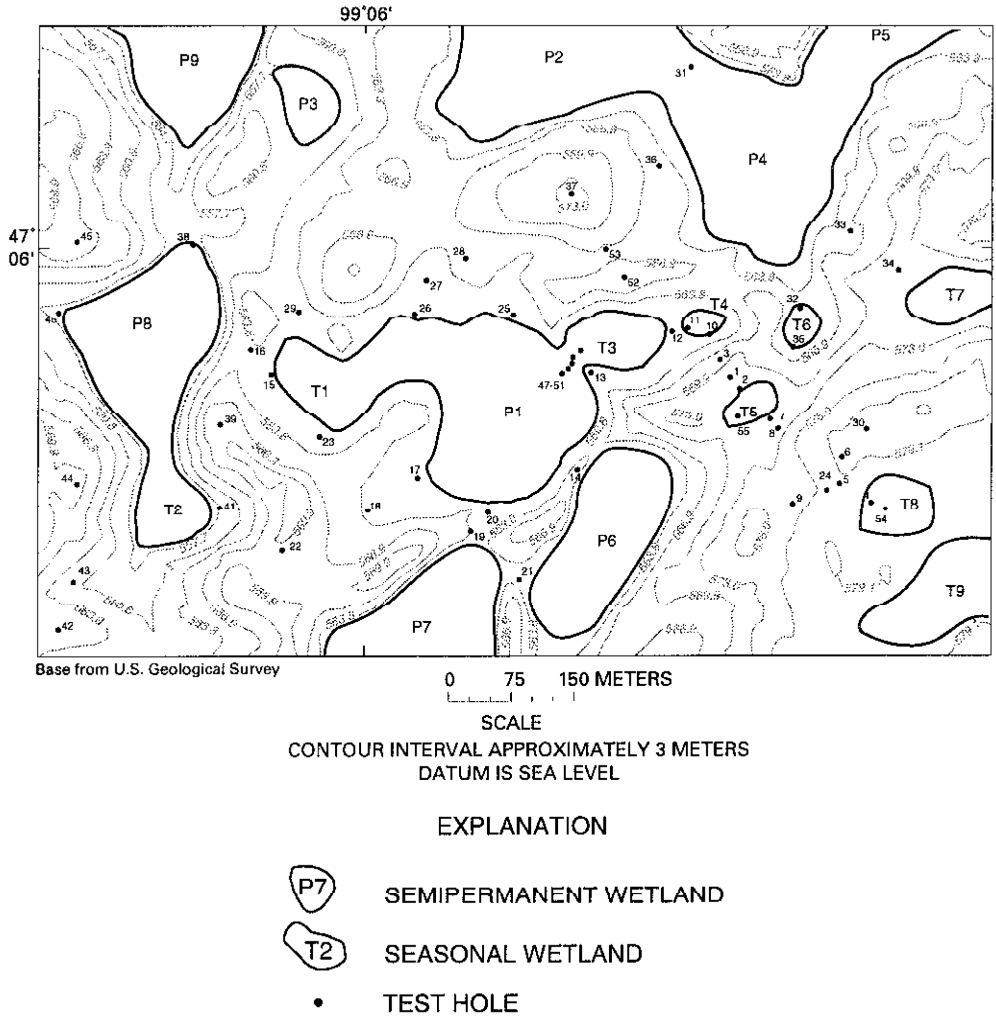

Figure 8. **Extent of open water in the Cottonwood Lake area in the fall of 1996. All wetlands are larger as a result of the wet period, and Wetland P1 has merged with Wetlands T1 and T3.**

5. The Recent Drought and Deluge with Respect to Longer Hydrological Records

Two types of long-term data are available that can be used to empirically extend insight gained from the 17-year Cottonwood Lake record into the effect of climate variation on aquatic resources of the northern prairies. These two types of data are direct measurement of hydrologic processes and indirect inferences of hydrologic processes from physical, chemical, and biological sediments in lakes and wetlands.

5.1. RECORDS OF DIRECT MEASUREMENTS

Three types of hydrologic information resulting from direct measurements have been collected for at least 95 years in the north-central prairies that are useful for evaluating the effect of climate variability on the hydrology of prairie pothole wetlands. These records are the Palmer Drought Severity Index (PDSI) for Division 5 in North Dakota, discharge of the Pembina River at Neche, North Dakota, and the stage of Devils Lake in North Dakota. Although these are all hydrologic records, each is representative of different scales of response time. Furthermore, even though they are in the same general region, they do not cover the exact same geographic area; therefore, exact correlations would not be expected.

The PDSI is calculated from climate and soil-moisture data; therefore, it can change sharply from month to month. River discharge integrates surface runoff and groundwater flow for entire drainage basins; therefore, it integrates a longer time frame of hydrologic conditions. The time frame of runoff is long for the Pembina River because the drainage basin has very low land slope. Closed basin lakes, such as Devils Lake are one of the best integrators of hydrologic conditions because, by having no outlet their water volume, chemistry, and biology can change markedly as climate and hydrologic conditions vary, and their sediments contain a record of those changes.

5.1.1. *Palmer Drought Severity Index*

Monthly PDSI values for Division 5 of North Dakota, from 1979 to 1996, indicate a strong relationship to water levels of wetlands in the Cottonwood Lake area (Figure 9). Therefore, the PDSI can be used to make inferences about past hydrologic functions of the wetlands. Monthly PDSI values from 1895 to 1996 (Figure 10) indicate that the drought from 1988-1992 was the second worst drought during the past 100 years; it was nearly as pronounced as the drought of the 1930s. The drought of the 1930s was slightly longer overall, and it had more values consistently less than -4 compared to the more recent drought; however, PDSI values less than -6 were about the same for the two droughts. The deluge since 1993 has resulted in the highest PDSI values

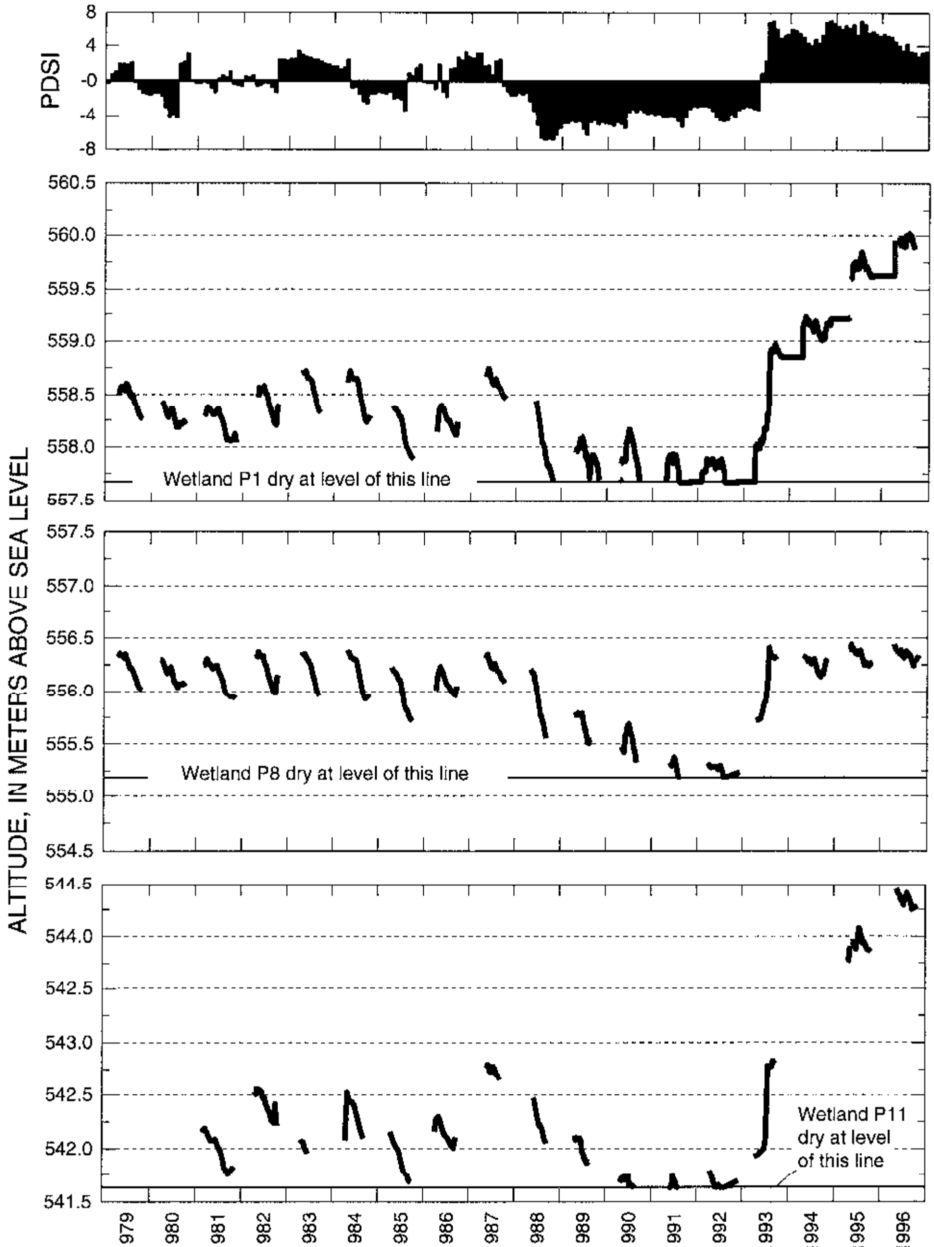

Figure 9. Comparison of the Palmer Drought Severity Index with water levels in Wetlands P1 and P8 in the Cottonwood Lake area, and Wetland P11, which is at a lower altitude 3 km west of the Cottonwood Lake area. Period of record is 1979-1993. (Modified from LaBaugh et al. 1996.)

of the past 100 years, the period of time the index has been determined for this region. A wet period extended through most of the first decade of the 20th century, but the magnitudes of PDSI values were less that those determined for the recent wet period, which is continuing. Therefore, from the perspective of the PDSI record, the hydrologic conditions measured at the Cottonwood Lake area during the past 10 years provide some idea of how these wetlands function under relatively extreme climatic conditions on the scale of a century.

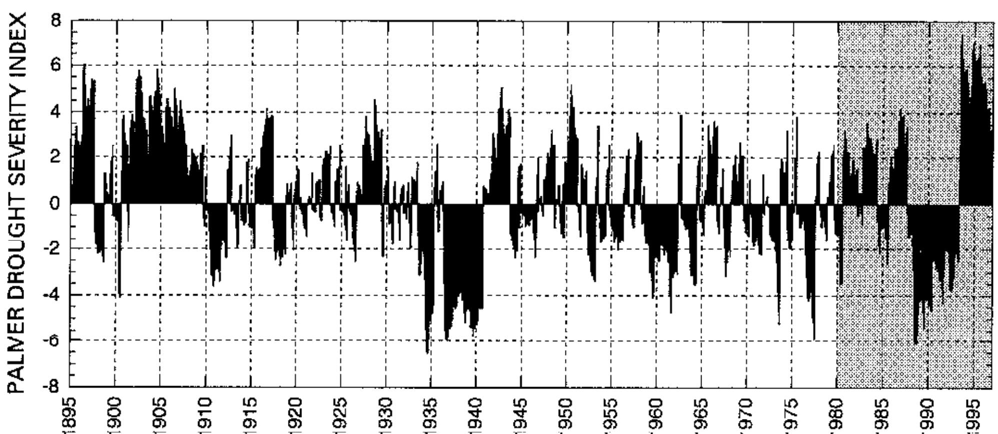

Figure 10. Palmer Drought Severity Index for Division 5 of North Dakota, 1895-1996.

5.1.2. *Discharge of the Pembina River at Neche, North Dakota*

Although the Pembina River does not lie within Division 5 of North Dakota, annual discharge of the Pembina River since 1904 has a pattern similar to the PDSI for Division 5 in some respects. For example, streamflows were very low during the drought of the 1930s, but streamflow was relatively low during much of the 1920s also (Figure 11). Based on the streamflow record, the drought of 1988-1992 was not unusual for the 20th century. The drought of the 1930s clearly resulted in the most extended period of low discharges. However, in agreement with the PDSI, the drought from 1988-1992 resulted in the second most extended period of low discharges during the 20th century, although it does not appear to be much worse than the period of low discharges during the 1920s. In contrast, the present wet period resulted in the highest continuous discharge of the 20th century. The lag time of runoff from such a flat basin is clearly seen for the past few years where much of the very high precipitation input to the basin that began in 1993 resulted in relatively high discharges only by 1995.

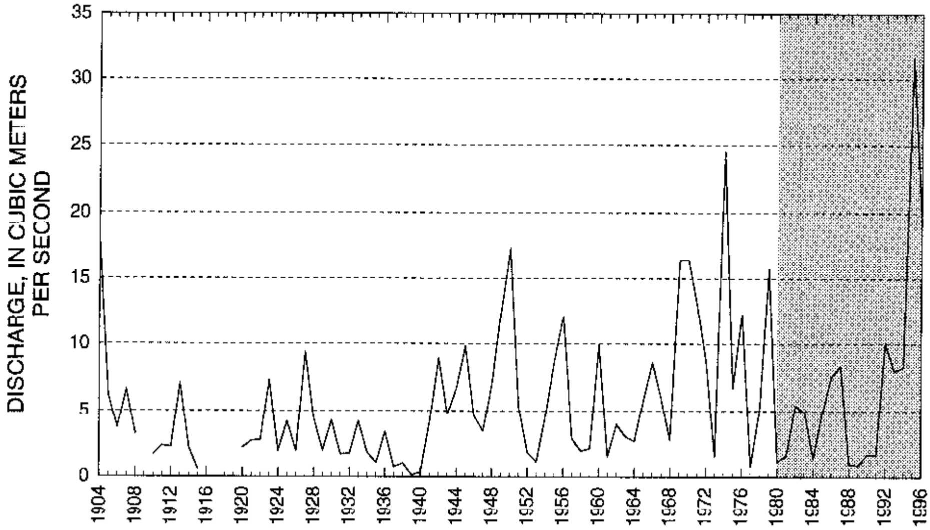

Figure 11. **Annual mean discharge of the Pembina River at Neche, North Dakota. Period of record is 1904-1996.**

5.1.3. *Stage of Devils Lake, North Dakota*

A continuous record of the stage of Devils Lake has been collected since 1901, but infrequent notes on its stage were made during the 1800s (Figure 12). Similar to the Pembina River basin, the Devils Lake drainage basin also is very flat. However, the stage of Devils Lake responds quickly and significantly to variations in climate. For example, the steepest rates of lake-level decline were during the drought of the 1930s, a dry period from the mid-1950s to mid-1960s, and the recent drought from 1988-1992. Even though the rates of lake-level decline were similar during these three periods, the recent drought had less affect on lake level because it had the shortest duration of the three drought periods. The dry period from the mid-1950s to mid-1960s also can be seen in the PDSI (Figure 10), but it does not appear as significant for the PDSI as it does for the stage of Devils Lake. The stage of Devils Lake is especially sensitive to precipitation input. The most significant increases in stage were in 1950 and during the current wet period. The sharp rise in lake level the past few years is unprecedented for the entire period of record.

These data indicate that the PDSI and the Devils Lake record are better indicators of hydrologic conditions in the Cottonwood Lake area than is discharge of the Pembina River. From these comparisons, it can be concluded that the drying up of semipermanent of prairie pothole wetlands that were documented for the recent drought probably were exceeded by even worse drought conditions only once or twice during the past century. Furthermore, the rise in water levels recorded in recent years has resulted in a lake stage that is as high as it has been during the past 130 years (Figure 12).

The sharp inflection from declining to increasing water level in Devils Lake about 1940, and the increase in discharge of the Pembina River at about this same time is not clearly corroborated by the PDSI for Division 5. The lack of corroboration could indicate that the inflection of lake stage and river discharge is not related to climate change, but instead perhaps to changes in land management in the two drainage basins. However, there is no historical evidence that land-management practices changed abruptly in these two basins in 1940. The major land-management changes in these areas were the advent of ditching and draining during the 1960s and 1970s. Furthermore, other major rivers in the north-central United States also had increases in discharge about 1940. The lack of corroboration also may be due to one or both of two factors: (1) The PDSI was calculated for the Cottonwood Lake area, not for the region covering the Devils Lake and Pembina River Basins, and (2) the PDSI is calculated from climate and soil-moisture data and essentially has little memory of antecedent conditions; whereas, the stage of Devils Lake and discharge of the Pembina River both integrate hydrologic conditions over relatively large watersheds.

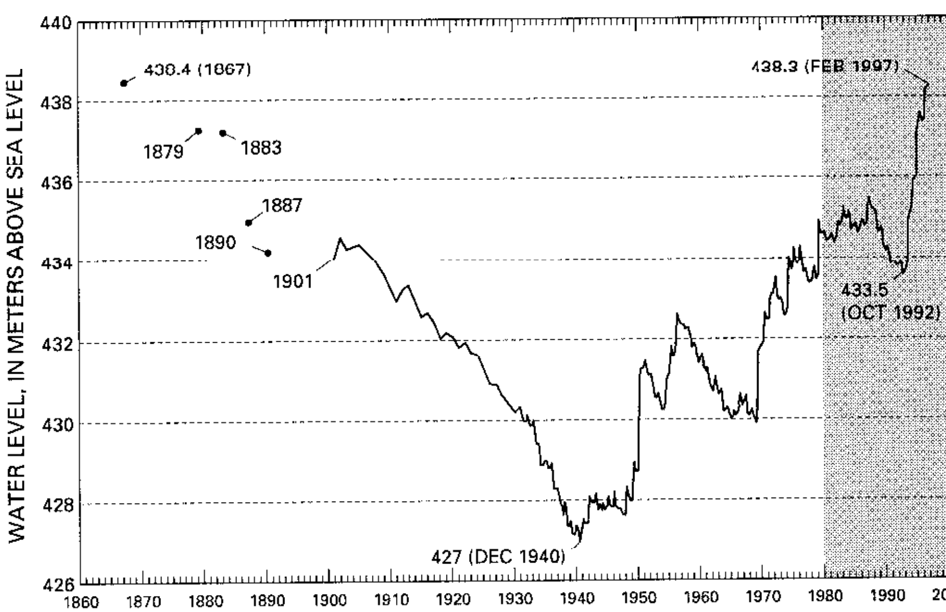

Figure 12. Stage of Devils Lake, North Dakota, 1830-1996 (Modified from Wiche, et al., 1997.)

5.2. HYDROLOGICAL RECORDS INFERRED FROM FOSSILS IN LAKE SEDIMENTS

The remains of many types of organisms that live in lakes are deposited in the sediments. The gradual accumulation of these remains provides a record of past limnological conditions, which reflect the hydrological and climatic processes that affected the lakes (Winter and Wright, 1977; Fritz, 1996). The remains of diatoms and ostracodes are particularly useful as indicators of environmental conditions in lakes because they incorporate chemicals in their shells that reflect the water chemistry at the time they were living. Because of its location in the prairies and its relative permanence, the sediments of Devils Lake are particularly attractive for studies of paleolimnology because they contain a relatively complete record of the lake's history for at least the past 10,000 years (Haskell et al. 1996).

To calibrate present conditions to the sediment record, Fritz (1990) developed a transfer function that relates salinity of lake water, as inferred from diatom remains, to the stage of Devils Lake. Similarly, Engstrom and Nelson (1991) compared salinity of lake water, as inferred from trace metals in fossil ostracodes, to the stage of Devils Lake. By developing these relationships of fossil indicators to the stage of Devils Lake for the past 100 years, inferences could be made about changes in the stage of Devils Lake, and the climate that caused those changes, for much of its history. For example, from the diatom and ostracode remains in the sediments of Devils Lake, Fritz et al. (1994) determined that the lake has been relatively saline during much of the past 500 years (Figure 13). The salinity varied widely during this time until the later part of the 1800s when it became less variable, which was also a time of relatively high lake levels (Figure 12). Since about 1940, the lake level generally has been rising and the diatom-inferred salinity has decreased to the least it has been during the past 500 years.

The relationship of Devils Lake stage to diatom-inferred salinity has been questioned by Wiche et al. (1996) on the basis of historical information. Observations of Devils Lake stage (Figure 12) and flow in the Red River of the North indicate that the early to mid 1800s was a relatively wet period; therefore, the diatom-inferred salinity for Devils Lake should be as low for that time as it is at present. Instead, the diatom-inferred salinity reaches some of its highest values during that time, which indicates that lake levels were low. However, the value for about the 1850s is the second lowest, only the more recent values are lower. To put the comparison into perspective, it needs to be noted that both methods of reconstructing historical records have limitations. Visual observations are not specific measurements, and they reflect the experience of the observer. Discrete samples of sediment cores generally integrate sediments deposited over a period of several years; therefore, they

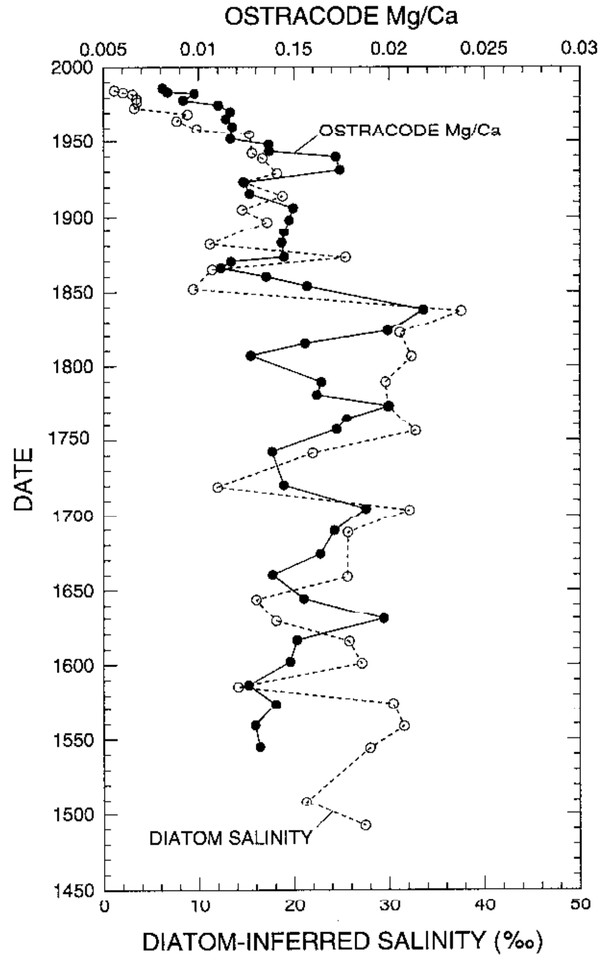

Figure 13. Stratigraphic profiles for two paleosalinity proxies in sediments from Devils Lake, North Dakota. Diatom salinity was quantitatively inferred from fossil diatoms by a transfer function constructed by analysis of salinity measurements and modern diatom assemblages from 66 regional lakes. Ostracode Mg/Ca, which represents the elemental composition of calcite shells of *Candona rawsoni*, is a direct correlate of salinity. (Modified from Fritz et al., 1994.)

cannot be interpreted for shorter time frames. Furthermore, the actual lake level data shown in Figure 12 is very sparse before 1900, and, based on the large changes recorded during the 1900s, it is reasonable to assume large stage changes took place during the 1800s also.

Despite the controversy over the relationship of diatom-inferred salinity to the stage of Devils Lake, the relationship can be used with caution to indicate general climate conditions during the past 500 years, and perhaps during the past thousands of years (Haskell et al., 1996). The data indicate that climate in eastern North Dakota has had numerous periods much drier than the drought of 1988-1992 and the drought of the 1930s. Conversely, the present wet period has been exceeded by wetter periods far fewer times. According to geologic evidence (Bluemle 1996), Devils Lake has risen to a natural spill elevation at least twice during the past 4,000 years. The lake is presently about 5.8 m from spilling again, and it has risen about 4.3 m during just the past 4 years.

6. Discussion

Wetlands in the Cottonwood Lake area have been subjected to wide variations in climate during the past 17 years, the period of time that the hydrology of several wetland types has been measured. During the drought of 1988-1992, all the semipermanent wetlands in the area dried up. One semipermanent wetland that is underlain by low-permeability till and that is at an intermediate topographic position in the landscape (Wetland P1) dried up the first year of the drought (Figure 9). Another semipermanent wetland that is at an intermediate topographic position in the landscape but is underlain by sand (Wetland P8) had decreasing water levels each year of the drought until it became dry the fourth year of the drought. A semipermanent wetland that is underlain by low-permeability till and that is at a low topographic position in the landscape (Wetland P11) had decreasing water levels until it dried up the third year of the drought. As the drought progressed, groundwater levels also declined each successive year (Figures 4 and 5).

Semipermanent wetlands generally are areas of groundwater discharge. However, data from the Cottonwood Lake area indicate that groundwater inflow to semipermanent wetlands underlain by low-permeability till is a small part of their hydrologic budget. The wetlands will contain water throughout minor dry periods, such as from 1980-1981 and 1985-1986 (Figure 2), but they have little chance of containing water throughout droughts lasting several years.

Using longer term instrument and proxy hydrologic records to extend the information obtained from the studies at Cottonwood Lake, it is likely that, during the 20th century, these wetlands were affected more severely than they were during the recent drought only by the drought of the 1930s. However, with respect to the proxy climate records obtained from Devils Lake sediments, it is likely that the wetlands in the Cottonwood Lake area dried up often prior to 1800. Conversely, the proxy climate record obtained from Devils Lake sediments indicates that the present wet period is the wettest it has been in 130 years, and perhaps in 500 years. Therefore, the hydrologic processes being measured presently at the Cottonwood Lake area are representative of the hydrologic function of these wetlands under unusually wet conditions.

The significant hydrologic response of prairie pothole wetlands to variations in climate have important implications for their water chemistry and biological characteristics. LaBaugh et al. (1996) indicated that the major ion chemistry of semipermanent wetlands can change as a result of drought and deluge. Wetland P1, which usually contains sulfate-type water, changed to a bicarbonate-type water following the deluge in 1993. Conversely, Wetland P8, which usually contains bicarbonate-type water, changed to a sulfate-type water by the second year of the 1988-92 drought.

The significant changes in the hydrologic conditions during the past decade resulted in major changes in the aquatic vegetation in Wetland P1. Before the recent drought, the wetland had open water in the center, which was surrounded by a broad rim of cattail and bullrush. During the drought, the wetland bed dried up each summer and cattail moved progressively each summer into the open area, to the extent that it covered the wetland bed by the end of the drought. The large rise in water level as a result of the deluge completely drowned out all emergent aquatic vegetation in the wetland, to the extent that it presently is completely an open-water lake. A wetland vegetation model was calibrated to the hydrologic and vegetation changes of Wetland P1 (Poiani et al., 1996). This modeling approach promises to be a useful tool in predicting variations in wetland hydrology and vegetation resulting from variations and changes in climate.

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