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Changes in atmospheric circulation patterns affect midcontinent wetlands sensitive to climate

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Abstract

Twenty-seven years of data from midcontinent wetlands indicate that the response of these wetlands to extremes in precipitation—drought and deluge—persists beyond the extreme events. Chemical changes transcend such simple relations as increased salinity during dry periods because drought provides mechanisms for removal of salt by deflation and seepage to groundwater. Inundation of vegetation zones including rooted or floating mats of cattail (*Typha glauca*) can stimulate sulfate reduction and shift the anion balance from sulfate to bicarbonate dominance. Disruptions in the circulation of moisture-laden air masses over the midcontinent, as in the drought of 1988 and the deluge of 1993, have a major effect on these wetlands, which are representatives of the primary waterfowl breeding habitat of the continent.

The glaciated prairie of North America encompasses an area of nearly 800,000 km^2 (Luoma 1985) (Fig. 1) and contains lakes and wetlands that produce 50–80% of the continent's waterfowl (Batt et al. 1989). This prairie landscape contains a mosaic of fresh and saline wetlands whose plant communities vary with salinity (Stewart and Kantrud 1972), creating diverse habitat for waterfowl (Swanson and Duebbert 1989). The climate of the region is semiarid; annual evaporation is 30 cm more than annual precipitation as rain or snow (Winter 1989). Thus, timing and intensity of rainfall and amount of snowmelt affects the persistence and permanence of wetlands in the region (Eisenlohr et al. 1972). Moisture enters the region primarily from Pacific and Gulf of Mexico air masses. When major changes in the movement of rain-producing weather systems through the region occur due to changes in the jet stream, as in 1988 and 1993, drought or flood results (Trenberth et al. 1988; Rodenhuis et al. 1994).

A study begun in 1967 looked at the relation between chemical characteristics of wetlands and use by waterfowl in a region that included some of the wetlands in the Cottonwood Lake area of North Dakota (Fig. 1) (Swanson et al. 1988). Experience from that regional investigation indicated chemical and biological characteristics of the wetlands were related to hydrologic conditions. Furthermore, detailed hydrologic studies were needed to understand and quantify the relationship between hydrologic processes, chemical characteristics, and waterfowl use in these prairie wetlands. A detailed hydrologic study was begun in 1978 at the Cottonwood Lake area to understand the interaction of prairie wetlands with groundwater and atmospheric water (Winter and Carr 1980). During the course of this detailed study, drought and deluge occurred. Here we examine the effect of these extremes on hydrological and chemical characteristics of the wetlands. Three wetlands (P1, P8, and P11) were the focus of study because they were representative of the range of hydrological, chemical, and biological conditions present in semipermanent wetlands in the region. Seasonal wetlands are alternately wet and dry on a regular basis and during drought rarely contain water. Much less is known about how semipermanent wetlands respond to wet and dry periods, hence our focus on these semipermanent wetlands.

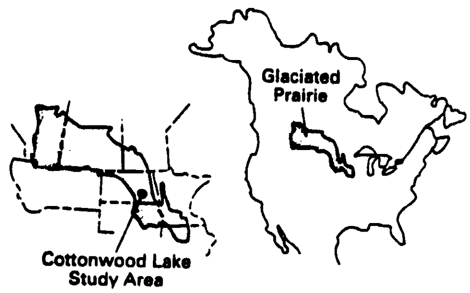

Fig. 1. Maps showing the glaciated prairie containing prairie wetlands and the Cottonwood Lake study area.

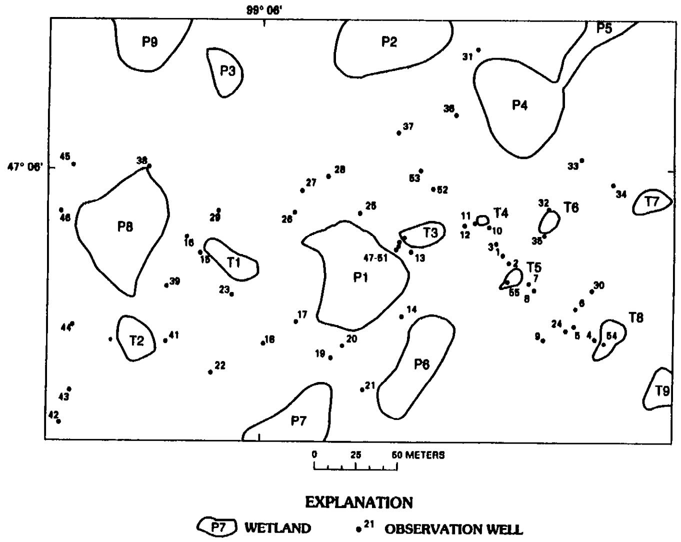

Fig. 2. Map of wetlands and observation wells in the principal study area. T—Wetlands originally classified as seasonal; P—Wetlands originally classified as semipermanent.

The study site

The Cottonwood Lake area is in a large glacial drift complex known as the Missouri Coteau (Winter and Carr 1980; Eisenlohr et al. 1972). Drift in the study area primarily consists of clayey, silty glacial till. This fine-grained material was derived from local bedrock containing mostly shale. Topography of the region, as well as of the study site, is hummocky and numerous wetlands occupy the depressions. Drainage is not integrated; streams are rare. The highest part of the principal study area (Fig. 2), in the vicinity of wetland T8, is ~25 m above the lowest part, in the vicinity of wetland P9. Another wetland of interest, P11, is ~2 km WNW and 33 m below the high point of the principal study area.

Two types of wetlands are found in the study area: seasonal and semipermanent. Wetland classification is based on the vegetation of the deepest, usually central, part of the wetland basin (Stewart and Kantrud 1971; Kantrud et al. 1989), which reflects the length of time water remains in these shallow (<2 m deep) water bodies. Seasonal wetlands are those with a central shallow-marsh zone in which midheight herbaceous vegetation (grasses, coarse sedges) is dominant. Semipermanent wetlands are those with a central deep-marsh zone in which tall, coarse herbaceous vegetation (cattail, bulrushes) is dominant. Water is present for a period of weeks to months in seasonal wetlands and throughout the year (for most years) in semipermanent wetlands. The distribution of seasonal and semipermanent wetlands and observation wells in this study is shown in Fig. 2.

Wetlands in the study area are representative of prairie wetlands found in the region based on size, chemical composition of wetland water, and hydrogeologic setting (Swanson et al. 1988). Cottonwood Lake area wetlands range in size from <1 to ~40 ha and are spaced from tens of meters to 2 km apart. Water salinity ranges from fresh to saline, and the relative abundance of major ions is not uniform among these wetlands (LaBaugh 1988). The watersheds are not connected by surface-water drainage, hence the water balance of each wetland is determined by rainfall, evapotranspiration, and interaction with groundwater. Seasonal wetlands commonly occur in areas of recharge to groundwater, and semipermanent wetlands usually occur in areas receiving groundwater discharge (LaBaugh et al. 1987). However, when groundwater recharge is minimal for a prolonged period, areas that once received groundwater discharge can become areas where semipermanent wetlands lose water by outseepage (Winter and Rosenberry 1995).

The hydrologic and physical settings of the three wetlands of principal interest are not uniform. Wetlands P1 and P8 are in areas receiving water from local, shallow groundwater flow, whereas wetland P11 is in an area likely to also receive groundwater from regional, deeper flow. Wetland P8 has an intermittent surface outlet, providing a way to lose water and solutes from the wetland not present in either P1 or P11. Wetlands P1 and P8 are similar in size and both are in relatively steeply sloped basins. Wetland P11 is much larger and lies in a less steeply sloped basin than either P1 or P8.

Methods

Beginning in 1967, vegetation and vegetation zones in selected wetlands, including P1, were recorded by aerial photography, and chemical characteristics of wetland water, including wetlands P1 and P8, were determined sporadically, once or more in a year, but not in every year (Swanson et al. 1988). Observation wells were installed at the site throughout the study area and adjacent to wetlands (Winter and Carr 1980; Winter and Rosenberry 1995). Staff gauges were installed in the wetlands to enable measurement of wetland water levels (Winter and Carr 1980; Winter and Rosenberry 1995). In the area shown in Fig. 2, beginning in 1979 and continuing through 1993, water levels in observation wells, water levels in wetlands, and chemical characteristics of wetland and groundwater were determined on a regular biweekly to monthly basis (Winter and Carr 1980; LaBaugh et al. 1987; Swanson et al. 1988). In wetland P11, water-level measurements began in 1981 and chemical determinations began in 1984.

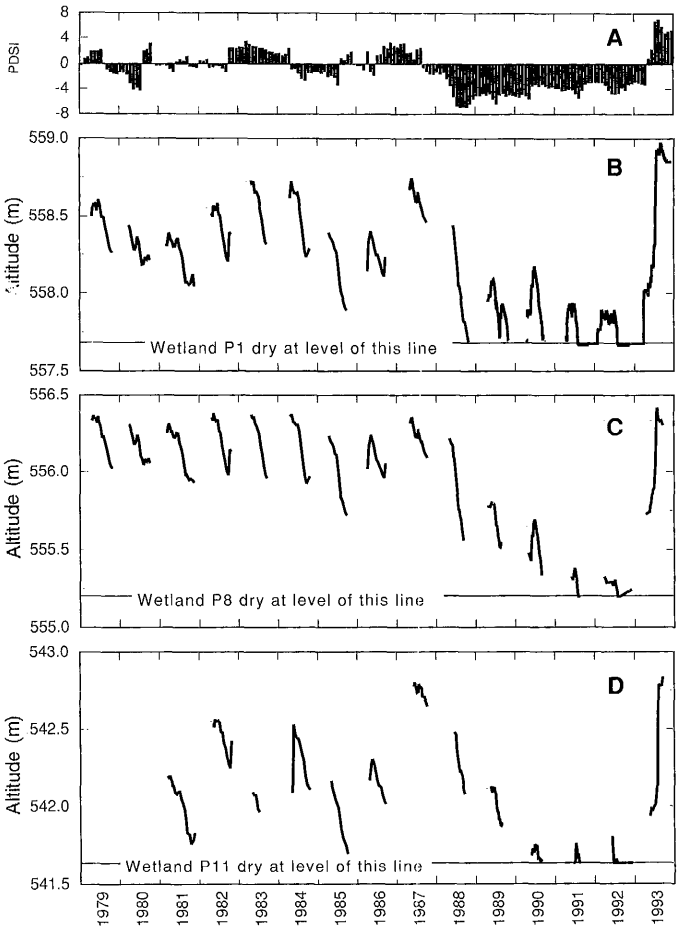

Fig. 3. A. Palmer drought severity index (PDSI) values for climate region 5 of North Dakota, 1979–1993. B, C, D. Wetland water levels in wetlands P1, P8, and P11, 1979–1993. Gaps between wetland water-level lines are periods when the wetlands were ice covered and water levels were not measured. Water levels were not measured in P11 before 1981.

Methods of chemical analyses are given by Swanson et al. (1988) for samples collected before 1983 and by Fishman and Friedman (1985) for samples collected between 1983 and 1992. Samples collected in 1993 were analyzed at the U.S. Bureau of Reclamation Laboratory in Bismarck, North Dakota, using similar procedures that provided data comparable to data from previous years. The measure of ions in solution used in our report is specific conductance, which is a general indication of salinity in wetlands according to the classification of Cowardin et al. (1979). Climatic data at the study site were collected with methods presented by Sturrock et al. (1987). Palmer drought severity index and precipitation values for climate region 5 of North Dakota for the period 1895 through 1993 were obtained from the National Climatic Data Center in Asheville, North Carolina.

Results and discussion

During the study period, wetland P1 varied between an open-water pond of moderate water depth (~1.5 m) containing little emergent vegetation in 1967 (a wet period) and a mudflat containing little or no water in 1974, 1977, and 1988 (dry periods). Photographs taken by G. Swanson of this wetland during extremes are found elsewhere in this issue (Poiani et al. 1996). Emergent vegetation that covered the mudflat of the wetland following dry episodes was not the same for each episode, with whitetop (*Scolochloa festucacea*) present in 1978 and hybrid cattail (*Typha glauca*) present in 1992. Wetland P8 changed from a pond with a floating mat of hybrid cattail around the edge encompassing an area of open water in the middle, known as the deep-marsh zone, to a mudflat surrounded by a fringe of senescent hybrid cattail at the height of the dry episode of 1988–1992. Vegetation, primarily hybrid cattail, germinated in the area of open water in wetland P8 at very low water levels during this dry episode and was partially submerged in 1993. Prior to the dry episode of 1988–1992, the open water of the deep-marsh zone in wetland P11 covered most of the area of the pond of the wetland, and within the deep-marsh zone sago pondweed (*Potamogeton pectinatus*) was abundant. As the deep-marsh zone dried, the former area of open water became a white saltflat across which little vegetation appeared. Thus, vegetation changes were dynamic but not uniform among these wetlands in relation to changing water levels.

The water-level response of the wetlands to changing hydrologic conditions is illustrated by data in Fig. 3. The largest decline in wetland water level in wetland P1 was in 1988 and the largest rise was in 1993 (Fig. 3). The general pattern of change in water levels in wetlands P8 and P11 were similar to those in P1 from year to year. The largest rise also occurred in wetlands P8 and P11 in 1993. There was a change to distinctly lower water levels from 1988 to 1992 in these three wetlands beginning with the large decline in 1988, which was most pronounced for wetlands P1 and P8. The study area is in climate region 5 of North Dakota, and annual precipitation in 1988 (283 mm) was the smallest amount in the region since 1936. Precipitation for the region in 1993 (694 mm, of which 443 mm fell in June and July) was the most that had fallen since records began in 1895 (Natl. Climatic Data Center pers. com.). A deluge of 105 mm on 15 July 1993 recorded at the site represented nearly a fourth of the average total precipitation for an average year.

Annual precipitation in the 4 yr after 1988 was similar to annual precipitation before 1988 (Fig. 4), yet wetland P1 consistently became dry each summer from 1988 through 1992. Near-average annual precipitation in 2 of the 4 yr from 1989 to 1992 was not effective in overcoming the extreme conditions brought on by the drought of 1988. Thus, the effect on hydrologic conditions in the wetlands of the extreme drought of one year persisted into subsequent years. Drought conditions during 1988–1992 (Fig. 3) were as persistent and severe as the drought in the mid-1930s, based on Palmer drought severity index (PDSI) values (Palmer 1965) for climate region 5 of North Dakota. The Cottonwood Lake area is near the center of climate region 5. The PDSI is based on precipitation, evapotranspiration, and soil moisture conditions. Values

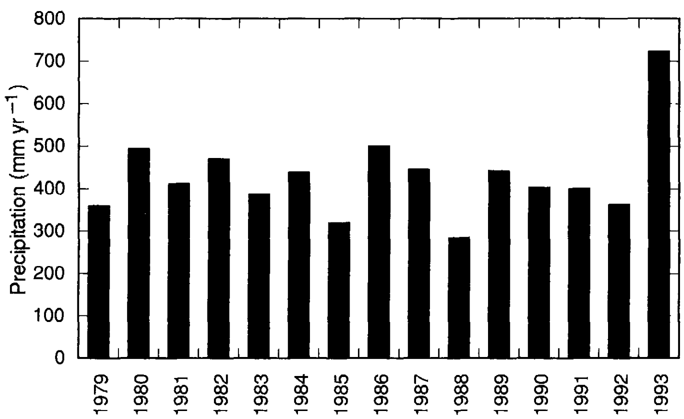

Fig. 4. Annual preciptiation at the study site for 1979–1993.

>0 indicate a wet period and values <0 indicate a dry period. The greater the value, the greater the degree of wetness or dryness. Severe drought is indicated by numbers from −3 to −4 and extreme drought is indicated by numbers <−4. Lack of effective recharge during the drought years is indicated by groundwater levels in an area of groundwater recharge at the study site (Fig. 5). Recharge from snowmelt and spring rain was insufficient to increase the level of groundwater from 1989 through 1992. Coincidently, seasonal wetlands located in areas of recharge were dry almost continuously through the 5-yr drought period. Semipermanent wetlands located in areas of groundwater discharge, such as P1, failed to contain water in midsummer from 1988 through 1992 because, in addition to loss of water by evaporation, transpiration directly from groundwater along wetland margins caused some wetland water loss, and interfered with groundwater discharge to the wetlands.

Drought can concentrate solutes in lakes (Schindler et al. 1990) and change acid-base characteristics due to decreased input from groundwater (Webster et al. 1990). Changes in chemical concentration in response to drought were not uniform for the semipermanent wetlands in the Cottonwood Lake area. In wetland P8, specific conductance increased as water levels declined throughout the drought (max specific conductance was 6,030 μS cm^{-1} in 1992) (Fig. 6). However, in wetland P1 the same pattern of increased specific conductance as water levels declined ceased in middrought (max specific conductance was 7,300 μS cm^{-1} in 1989). The margin of P1—the perimeter of the pool of water in the wetland—was primarily an area of groundwater inseepage before the drought but primarily an area of outseepage during the drought. We determined these changes in seepage patterns based on comparisons of wetland water levels with water levels in sets of wells along transects radiating away from the edge of the wetland; details are provided by Winter and Rosenberry (1995). Low water levels in spring in wetland P1 were associated with very different concentrations during

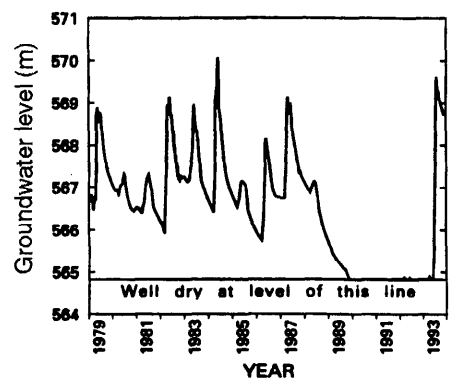

Fig. 5. Groundwater levels in well 2–18 (observation well 2, Fig. 2), located in an area of groundwater recharge, 1979–1993.

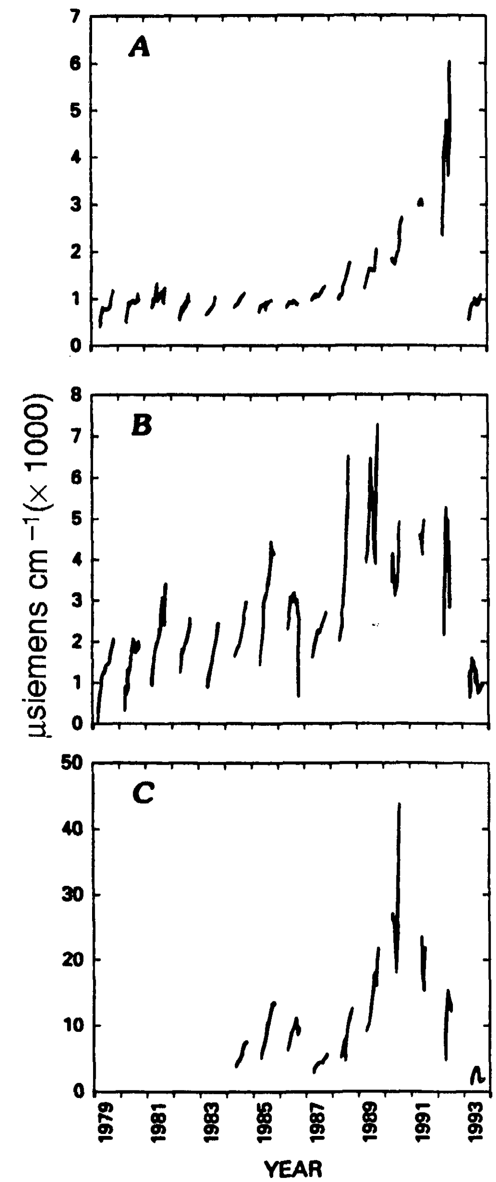

Fig. 6. Specific conductance of water in wetland P8 (A), P1 (B), and P11 (C). Gaps between lines are periods when the wetlands were ice covered. Chemical analysis of water in wetland P11 was not done before 1984.

dry periods of different duration (7,700 $\mu S\ cm^{-1}$ in 1977 and 2,180 $\mu S\ cm^{-1}$ in 1992). This difference reflects the interaction of the wetland with groundwater, which is affected by antecedent hydrological conditions. Outseepage during the drought provided the mechanism for removal of dissolved salts from wetland water in wetland P1 such that maximum specific conductance values were less in 1990–1992 than in 1988 and 1989 (Fig. 6) despite the fact wetland water levels were progressively shallower (Fig. 3).

The basin of wetland P1 is a small steep-sided depression that provides protection from the wind. In contrast, wetland P11 is a larger basin whose sides offer less protection from the wind. Salts on the dry mudflat of P11 were removed by wind (deflation) and blown onto the upland and beyond, particularly after the wetland became dry in 1990 (Fig. 3), something not observed in either P1 or P8. Single deflation episodes resulted in a measurable loss of 1 cm from the saltflat surface near the staff gauge of the 40-ha wetland. Such episodes changed the albedo of the entire saltflat surface from white to gray due to removal of salt, some of which was deposited tens of meters from the edge of the saltflat to a depth that covered upland vegetation. The change in albedo indicated that the veneer of salt was removed from the entire saltflat. Loss of at least 1 cm from the entire saltflat surface of wetland P11 during a single deflation episode represented a loss of 400 m^3 of salt. In wetland P11, specific conductance increased as water levels declined, as recorded by staff gauge measurements, until middrought (max specific conductance was 43,600 $\mu S\ cm^{-1}$ in 1990). However, as the drought continued and salts were lost from P11 by deflation, specific conductance did not continue to increase as water levels declined. Thus, because of deflation (as in P11) and increased seepage loss of solutes as wetland-groundwater interaction changes (as in P1), changes in wetland water level cannot be assumed to be inversely related to changes in salinity as these wetlands increase and decrease in depth and area with changing climate conditions.

Changes in vegetation and the relative abundance of major ions in wetland water accompanied changes in hydrological conditions in the wetlands. Groundwater discharging to the semipermanent wetlands is sulfate-rich (LaBaugh 1991). Bicarbonate was the most abundant anion in wetland P8 before the drought and in P1 only in 1967 and 1993 but was never the most abundant anion in P11 (Fig. 7). Sulfate was the most abundant anion in wetlands P1, P8, and P11 during the drought. Before the drought, a floating mat of hybrid cattail fringing wetland P8 provided a zone of anaerobic conditions that resulted in loss, most likely due to sulfate reduction, of some of

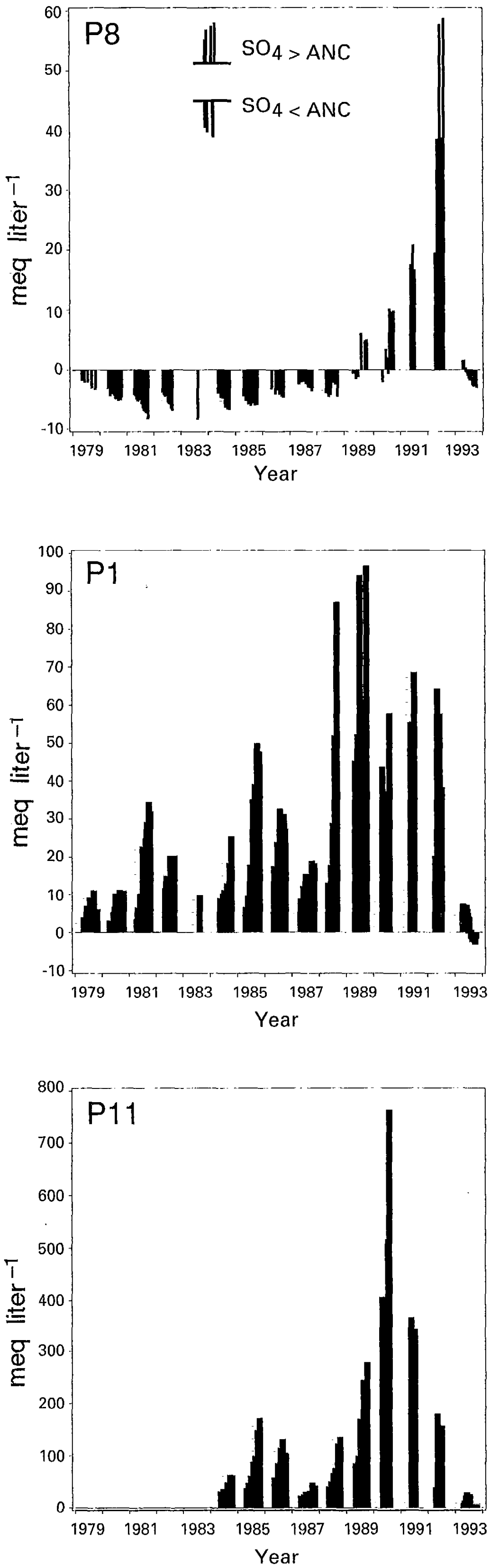

Fig. 7. The difference between sulfate and acid-neutralizing capacity (ANC) in wetlands P8, P1, and P11, 1979–1993. Maximum values for sulfate (meq liter^{-1}): P8—70.7, P1—104, P11— ←

811; minimum values: P8—0.74, P1—1.7, P11—10.5. Maximum values for ANC (meq liter^{-1}): P8—12.2, P1—11.0, P11—48.7; minimum values: P8—1.65, P1—1.51, P11—0.39. Data are for periods when the wetlands were not covered by ice.

the sulfate seeping in from groundwater. Eh values consistent with conditions needed for sulfate reduction have been measured in the sediments at the study site by Biondini and Arndt (1993). Detailed information on the importance of sulfate reduction in hydric prairie soils was presented by Arndt and Richardson (1992). As water levels declined, the edge of the pool of water in the wetland and the zone of groundwater seepage to wetland water moved beyond the cattail fringe and sulfate became the most abundant anion in wetland water (Fig. 7). As wetland P8 dried, as recorded by staff gauge measurements, hybrid cattail germinated across the entire mudflat of the wetland. When cattail became inundated during wet conditions and the deluge in 1993, the edge of the pool of water in the wetland and the zone of groundwater seepage to wetland water again were in an area of anaerobic conditions, and bicarbonate replaced sulfate as the most abundant anion in wetland water. Decomposition of inundated vegetation, including hybrid cattail that had germinated in P1 during the drought, also was accompanied by a shift in relative abundance of the major anion from sulfate to bicarbonate in midsummer 1993. In contrast, when the whitetop that germinated across the mudflat of P1 in 1977 was inundated, sulfate remained the dominant anion. The saltflat of wetland P11 was not colonized by large amounts of vegetation during the drought and sulfate remained the most abundant anion after the 1993 deluge.

It is difficult to translate the effects of global phenomena to effects at the scale of individual watersheds. For example, changes in atmospheric circulation patterns that bring moisture to the northern prairie have been linked to El Niño–Southern Oscillation phenomena (Trenberth et al. 1988; Rodenhuis et al. 1994), yet the event of 1982–1983 (Rasmusson 1985; Quinn et al. 1987) was not associated with extreme dry or wet conditions in the study area. Both the dry year of 1988 and the wet year of 1993 have been associated with decreased or increased movement of moisture-producing weather systems into the midcontinent (Trenberth et al. 1988; Rodenhuis et al. 1994). Such changes are common if past hydrologic conditions in wetlands near the Cottonwood Lake area are used as an indicator. For example, wetlands in the nearby James River basin were noted as being dry in 1959 (Eisenlohr et al. 1972). Also, wetland C1, a permanent wetland that was part of a previous study near the Cottonwood Lake area, was dry in August 1961 and increased to its highest level in 1966 (Eisenlohr et al. 1972). The commonality of such wet and dry episodes in the past 25 yr is clearly demonstrated by data from wetland P1, which was dry in 1974, 1977, and 1988–1992, whereas water levels were highest in 1967 and 1993.

Data from the Cottonwood Lake area indicate that effects of precipitation extremes are not limited to the season or years in which they occur. Extremes set the stage for subsequent years through their effect on wetland and groundwater levels. Responses of the wetlands to extremes in precipitation, resulting in shifts in major ion abundance and uncoupling of salinity-wetland water-level relations, have not been considered in previous attempts to determine controls on chemical composition of wetlands in the region (Gorham et al. 1983) or to determine empirical relations between major ion abundance and species composition (Fritz et al. 1993) because few studies have documented what happens in these wetlands when extremes occur. Winter and Rosenberry (1995) indicated that the timing of changes in precipitation due to changes in atmospheric circulation patterns is critical to understanding the consequences for these wetlands and the waterfowl that use them; a dry year based on annual precipitation may not be a dry year for the wetland, depending on the amount of precipitation that fell in October–April. Also, record precipitation reversed the hydrological effects of multiyear drought on wetland water levels in the Cottonwood Lake area. The changes noted here may be useful in reconstructing climate changes from the fossil record or in analyzing seed banks preserved in lake and wetland sediments to determine changes in species resulting from changes in salinity or major ion composition (Forester 1986; Fritz et al. 1991; Smith 1991; Poiani and Johnson 1993). These changes may also be useful in examining the potential impact of climate-induced alterations in hydrologic regime and chemical composition of wetland water on invertebrate communities that serve as important food sources for waterfowl (Driver 1977; Murkin et al. 1982).

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