February 1995

Hydroclimatic Perspectives on Waterfowl Production in the North Dakota Prairie Pothole Region

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Great Plains Research 5 (February 1995):137-62

HYDROCLIMATIC PERSPECTIVES ON WATERFOWL PRODUCTION IN THE NORTH DAKOTA PRAIRIE POTHOLE REGION

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Abstract. *The North Dakota Prairie Pothole Region is one of the most unique and important wetland environments for waterfowl in North America. A water balance climatology is developed for this region for the period 1895-1990. A monthly water balance time series for the 96-year period was computed utilizing the Thornthwaite water balance methodology and a regional time series developed from area-weighted National Climate Data Center divisional data. Results illustrate the unique seasonal dynamics of the mean soil moisture regime, the frequency distribution of selected water balance variables over the period of record, and the large intra-annual and interannual variability which characterizes the hydroclimatic environment of the Northern Great Plains. Long-term analysis of the water balance variables revealed statistically-significant linear trends toward warming and increased soil dryness. The increased soil dryness trend, however, has been concentrated in the summer months after the peak waterfowl breeding and migratory period. Trends toward decreased precipitation and increased spring soil dryness, although suggested by the data, are not conclusive at the 0.05 level. Inferences related to waterfowl production, global warming, historic loss of wetlands, and resource management issues are noted.*

North Dakota is divided into three distinct physiographic regions. Along the eastern edge, comprising 10 percent of the state's total area, lies the Red River Valley, part of the lake bed of former glacial Lake Agassiz. To the south and west of the Missouri River lie the unglaciated uplands. This hilly terrain, accounting for 40 percent of the total area, escaped the effects of the Wisconsin glaciation. In the northwest and east-central portion of the state, covering approximately 50 percent of the total area, lies the Prairie Pothole Region (Fig. 1), which is composed of two subregions: the Missouri Coteau, an area of knob-and-kettle topography stretching along the Missouri River, and the Drift Plain, an area of gently rolling ground moraine to the east.

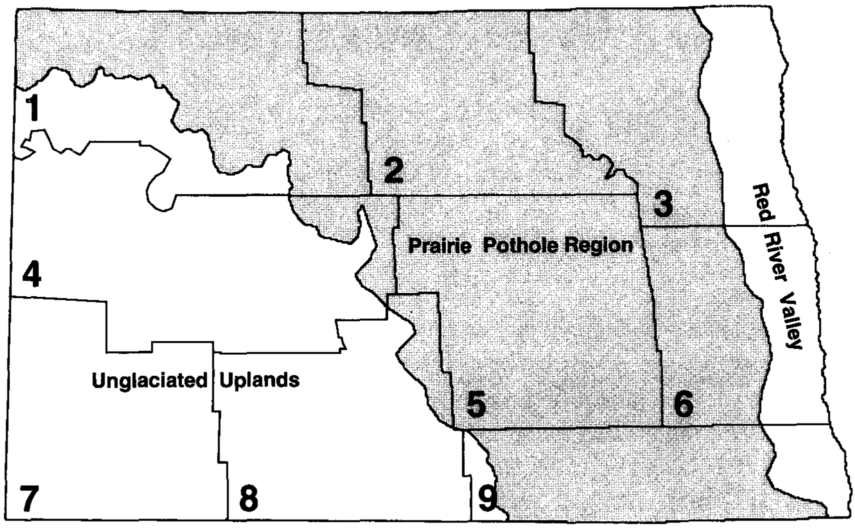

Figure 1. The Prairie Pothole Region of North Dakota (shaded). National Climatic Data Center climate divisions are shown and numbered.

The water table in the Prairie Pothole Region is a subdued image of the surface topography, and intercepts the surface to form innumerable wetland habitats, including ponds, lakes, and sloughs. The gentle surface terrain, shallow water table, and highly variable precipitation regime result in significant intra-annual and interannual variations in the number, size, permanence, and water quality of wetland habitats (Eisenlohr and Sloan 1968). The North Dakota Prairie Pothole Region is part of a larger wetlands complex which is North America's most valuable waterfowl breeding ground (Heimlich and Langner 1986), and the primary breeding ground for North American ducks (Stewart and Kantrud 1974).

The Prairie Pothole Region experienced a massive landscape transformation during the past century primarily as a result of the conversion of native semi-arid grasslands into a small grains agroecosystem by immigrant settlers (Riebsame 1990a). Agricultural expansion and intensification of dryland small grain production in the region continues to this day, despite

periodic setbacks due to drought and economic downturns. More than a century after the initial Great Plains sodbusting, controversy still exists over the most proper and sustainable use of this semi-arid grassland (Riebsame 1991; Popper and Popper 1987).

North Dakota is estimated to have experienced a 50 percent loss of wetlands, from 5 million acres in the 1780s, to 2.5 million acres in the 1980s (Dahl 1990). Until the signing of Executive Order 11990 in 1977, the U.S. Department of Agriculture provided direct support for wetland conversion through technical assistance and federal cost-sharing (Heimlich et al. 1989). Indirect government support for wetland drainage continued until 1985 in the form of farm program benefits and income tax deductions. Indirect support for wetland drainage was eliminated by the swampbuster provision of the Food Security Act of 1985, which denied all farm program benefits to producers who converted wetlands for the purpose of growing annual crops (Heimlich and Langner 1986). The 1990 Farm Bill amended this policy to include benefit denial to any producer who drained wetlands irrespective of whether or not the land was cropped.

The purpose of this study is to develop a profile of the hydroclimatic conditions facing waterfowl in the region, and to provide a climatological perspective on resource management issues in this complex and controversial habitat. The hydroclimatology will focus upon three major aspects of the region's water balance. First, the mean seasonal variation of the regional water balance will be examined in order to explain how this region, which has the most distinctly continental climate in the United States and which experiences an annual water supply deficit, can maintain its unique wetlands environment. Second, the interannual variability of the regional water balance will be studied. Alternating wet and dry periods resulting from the highly variable annual precipitation regime produce significant interannual variations in the number of wetlands containing surface water. This is a major contributing factor to the large year-to-year fluctuation in the statewide duck population reported by the North Dakota Game and Fish Department (1990) (Fig. 2). Annual fluctuations in pond abundance within the greater region have, in fact, been correlated with indices of waterfowl populations (Stewart and Kantrud 1974), mallard duck breeding activities (Krapu et al. 1983), annual productivity of lesser snow geese (Davies and Cooke 1983), and pintail duck breeding patterns (Smith 1970). Third, tests of selected water balance variables will be made to determine whether there have been systematic trends in the regional water balance over the study period. Numerous global climate modeling studies have raised the specter of

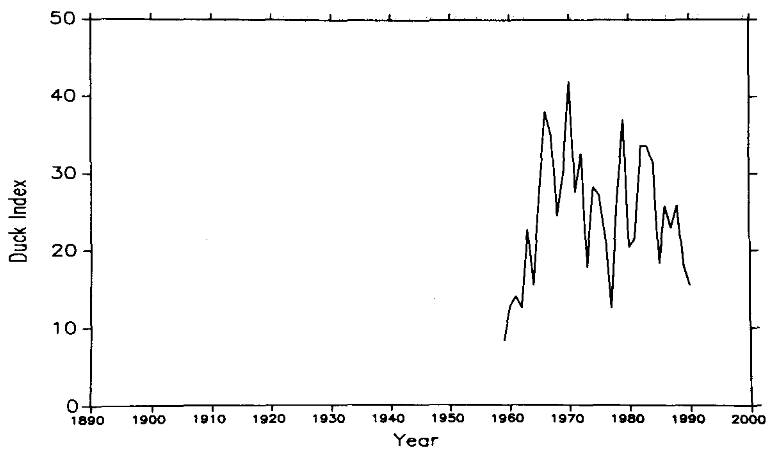

Figure 2. Time series plot of statewide duck index, 1959-1990.

increased summer soil dryness within continental interiors as a result of human production of trace gases (Manabe and Wetherald 1986; Kellogg and Zhao 1988), with probable deleterious impacts upon wetland habitats (Poiani and Johnson 1991), and agricultural production (Rosenzweig and Hillel 1993).

Methodology

A study of the interannual variability of the regional water balance ideally would be based upon some measure of hydrological drought, so as to characterize regional moisture conditions on the basis of the surface and/or subsurface hydrology (Wilhite and Glantz 1985). The U.S. Fish and Wildlife Service, in cooperation with Canadian authorities, has, in fact, been conducting aerial surveys of pond abundance every May since 1955, along standardized transects throughout 3.37 million km^2 of the pothole region of Canada and the United States. This database was used in studies by Smith (1970), Krapu et al. (1983), and Johnson and Shaffer (1987). The North Dakota Game and Fish Department also has made direct counts of spring pond numbers along fixed routes within the State since 1959 (North Dakota

Game and Fish Department 1990). Neither dataset were used in this study, however, because the short duration of both datasets limits their ability to identify long-term hydroclimatic trends, their lack of adequate temporal resolution obscures understanding of the seasonal dynamics of the wetlands environment, and there is inadequate correspondence between the transect routes and the study area.

The water budget methodology developed by Thornthwaite (1948) is adopted here. This technique can be used to examine ecological or agricultural drought, which links precipitation deficiencies to impacts upon ecological and agricultural systems (Wilhite and Glantz 1985). Analysis of the computed monthly water budget has proven to be an effective tool in understanding the nature, distribution, and extent of the water resources of an area (Mather 1991). Water budget analysis involves an accounting scheme, based upon the principle of conservation of mass, which determines the moisture availability within a soil zone of prescribed depth, on the basis of the atmospheric supply and demand of surface moisture. Examination of year-to-year variations in soil moisture storage during the peak waterfowl breeding season, as obtained from monthly water budget analyses, should provide an effective long-term measure of wetland conditions because of the close physical coupling between the unsaturated and saturated zones in the Prairie Pothole Region (Nielson and Biggar 1982).

Mather (1991) provides a history of the development of the field of hydroclimatology, with particular emphasis upon the water budget concept. The theory and methods of water budget analysis are reviewed in Muller and Thompson (1987), who also cite applications of the technique in studies of regional climatology and environmental systems. Previous applications of the water balance methodology within the region include Clark's (1989) long-term study of the effects of climate variability on the frequency of fire occurrence in northwest Minnesota, and Davies and Cooke's (1983) examination of the relationship between soil moisture storage and the annual productivity of lesser snow geese in southern Manitoba.

In recent years the Palmer Drought Severity Indexes have become the most widely used regional soil moisture indicators in the United States. Although the three Palmer indices provide an effective measure of relative drought for policy formulation and drought management, the indices suffer from numerous conceptual problems which limit their usefulness in climatological investigations. These theoretical and practical limitations are discussed in Alley (1984, 1985), Karl (1986) and Guttman (1991). The most serious problem is the fact that the Palmer indices are not interval or ratio

scale measures, a deficiency which severely constrains the types of statistical operations which can be performed appropriately. Measures obtained through Thornthwaite water budget equations, however, are true ratio scale values, which can be statistically analyzed using correlation, regression and other parametric statistical tools.

Data

Climate data were taken from a data tape prepared by the National Climatic Data Center (National Climatic Data Center 1989) of unweighted divisional average monthly temperature and precipitation. A monthly temperature and precipitation time series for the Prairie Pothole Region was developed for the period 1895-1990 by areally weighting data from the individual climate divisions which comprise the study area (Fig. 1). The WATBUG computer algorithm (Willmott 1977) was used to compute the monthly water budget for individual years for the long-term regional time series. Soil moisture storage was initialized by balancing the water budget for the first year of the climate record before computing the unbalanced water budgets for the entire 96-year period-of-record.

Climatic Water Balance, 1961-1990

The climatic water balance based upon 30-year normals (1961-1990) illustrates the average intra-annual variation of the regional water budget components (Fig. 3). The graphical pattern shown is typical of humid mid-continental regions in the mid-latitudes which are characterized by a seasonally dynamic water balance regime.

Annual potential evapotranspiration (PEA) totals 595 mm, with five winter months indicating potential evapotranspiration amounts of zero. Peak potential evapotranspiration is quite high during the short summer, however, due to the long days and warm air temperatures. Annual evapotranspiration (ETA) equals 458 mm and is confined to the seven warm season months. Monthly evapotranspiration (ET) equals or closely follows monthly potential evapotranspiration (PE) during the spring, but ET increasingly lags PE with the arrival of summer. Fall once again sees a merging of the monthly ET and PE values. The annual evapotranspiration ratio (RATA = ETA/PEA), which equals 0.77, is indicative of a climate which experiences a significant summer water deficit. Mean annual precipitation (PCPA) totals 446 mm and is highly concentrated as warm season rainfall, a pattern typical of humid

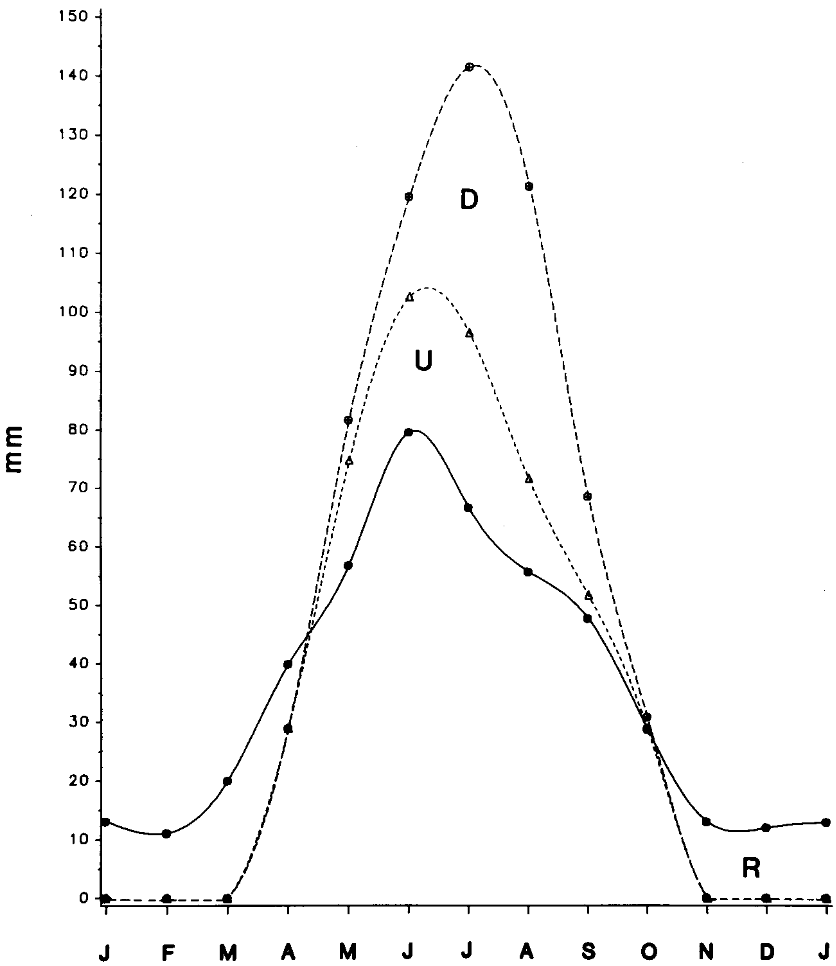

Figure 3. Climatic water balance for the North Dakota Prairie Pothole Region based upon monthly temperature and precipitation normals for 1961-1990. Solid line/ circles = precipitation; dashed line/circles = potential evapotranspiration; dashed line/triangles = evapotranspiration; D = soil moisture deficit; U = soil moisture utilization; R = soil moisture recharge.

continental climates. A small soil moisture deficit which begins in the late spring accumulates into a much more severe deficit by mid-summer. The annual cumulative soil moisture deficit (DEF) of 137 mm makes the region

best suited to small grains agriculture. Precipitation exceeds evapotranspiration by a small amount in late fall through winter, which results in continuous soil moisture recharge through early spring. No moisture surplus is generated in the climatic water budget. The annual moisture index for the region (Im) is -25.0, where Im = 100[PCPA/PEA-1]. This index, which was the basis for Thornthwaite's climate classification (1948), expresses how well the available moisture meets the climatic demand for water. A moisture index of -25.0 is classified as semi-arid/dry subhumid in the Thornthwaite classification.

Past studies of prairie pothole waterfowl productivity have normally selected May as the best indicator month of pond abundance (Smith 1970; Krapu et al. 1983; Johnson and Shaffer 1987; Johnson et al. 1989). Recharge normally peaks in May due to fall soil moisture recharge, winter snowmelt from snowdrift accumulations in pothole depressions, and spring rainfall. The resulting optimal soil moisture conditions occur well before the onset of peak evapotranspiration, creating a narrow window during April and May of optimal abundance and diversity of wetland habitats. Climatic water budget conditions in May are as follows: potential evapotranspiration (PE5) = 82 mm, evapotranspiration (ET5) = 75 mm, evapotranspiration ratio (RAT5) = 0.92, and soil moisture storage (ST5) = 100 mm. Mean cumulative January through May precipitation (PCP5) is 141 mm.

Frequency Distribution of Water Balance Parameters

Results obtained from water budget analyses based upon 30-year normals of monthly temperature and precipitation often fail to provide sufficient insight into intra-annual and interannual variability (Muller and Thompson 1987). The dominant role of precipitation variability in producing year-to-year fluctuations in the regional water budget is most effectively captured when historical monthly temperature and precipitation data is utilized. Consequently, frequency distributions of selected water balance parameters were developed for the complete 96-year period. The moisture index (Im) based upon the 1961-90 monthly normals (-25.0) was very similar to the mean moisture index (-23.0) derived from the continuous monthly time series (Fig. 4). Both values classify the region along the dry subhumid/semi-arid climate transition (Thornthwaite and Mather 1955). The distribution of the annual moisture index values illustrates the nature of transitional climatic regions. Twelve years are classed as arid (Im<-40), 42 years as semi-arid (-40<Im<-20), 40 years as dry subhumid (-20<Im<0), and

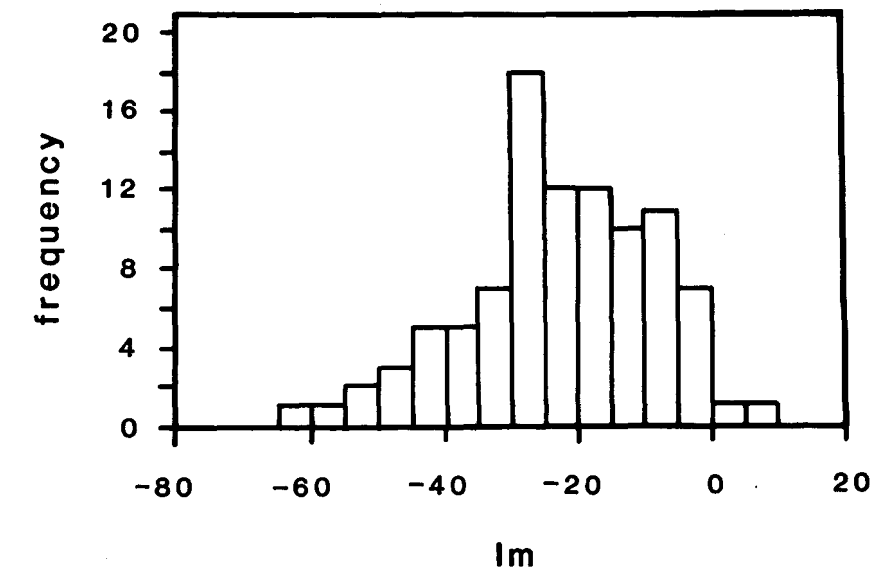

Figure 4. Moisture index frequency distribution based upon continuous monthly water budget analyses, 1895-1990.

2 years as moist subhumid (0<Im<20). Semi-arid and dry subhumid years occur in nearly equal frequency. The statistical properties of the moisture index time series document the highly variable moisture regime (Table 1), with a particularly large coefficient of variation (CV), and a distribution skewed toward negative values.

More detailed information on the regional hydroclimatology can be obtained by examining the frequency distribution of selected annual and May water budget components (Fig. 5), as well as the statistical properties of the complete water budget time series (Table 1).

Annual precipitation (PCPA) averages 448 mm and shows substantial interannual variability. Although PCPA is nearly normally distributed, there is a small negative skew to the frequency distribution, indicating a tendency for dry years to occur regularly throughout the time series. In contrast, January-May precipitation (PCP5) averages 22 percent of annual precipitation, has an even larger CV, and a weak positive skew. The distribution of annual soil moisture deficit (DEF) is indicative of dry subhumid/semi-arid

TABLE 1
SUMMARY OF DESCRIPTIVE STATISTICS FOR WATER BALANCE VARIABLES BASED UPON CONTINUOUS MONTHLY ANALYSES

(a) Annual Variables, N = 96

	TAA (C)	PCPA (mm)	PEA (mm)	ETA (mm)	DEF (mm)	RATA (frac)	Im (index)
$\bar{x}$	4.1	447.6	585.3	437.5	147.9	0.751	-23.0
s	1.0	71.7	37.5	52.5	69.7	0.106	14.0
CV	24.6	16.0	6.4	12.0	47.1	14.1	60.8
skew	0.16	-0.49	-0.06	-0.88	1.5	-0.859	-0.45
kurtosis	0.39	0.34	-0.19	0.70	1.37	0.658	3.10
r_1	0.238	-0.032	0.243	0.080	0.194	0.172	0.055
$Q_{1.0}$	7.2	610.0	677.0	536.0	384.0	0.925	6.4
$Q_{.75}$	4.8	499.5	615.5	476.5	189.0	0.825	-13.3
$Q_{.50}$	4.1	454.0	588.0	450.0	136.0	0.770	-23.4
$Q_{.25}$	3.4	412.0	558.5	405.0	99.0	0.694	-30.7
$Q_{.00}$	1.7	237.0	476.0	278.0	41.0	0.427	-63.6

(b) May Variables, N = 96

	TA5 (C)	PCP5 (mm)	PE5 (mm)	ET5 (mm)	ST5 (mm)	RAT5 (frac)
$\bar{x}$	12.2	137.9	79.0	69.0	100.1	0.886
s	2.1	41.4	14.1	12.2	32.4	0.136
CV	17.1	30.0	17.8	17.7	32.4	15.4
skew	0.17	0.63	0.21	-0.03	0.00	-1.588
kurtosis	0.11	1.58	0.16	-0.04	-0.90	5.561
r_1	0.054	-0.151	0.056	0.041	-0.086	-0.068
$Q_{1.0}$	17.8	300.0	118.0	96.0	150.0	1.000
$Q_{.75}$	13.6	159.0	88.5	76.0	124.0	1.000
$Q_{.50}$	12.3	136.5	80.0	69.0	99.0	0.947
$Q_{.25}$	10.7	106.0	68.5	61.0	75.0	0.814
$Q_{.00}$	6.4	40.0	40.0	40.0	30.0	0.351

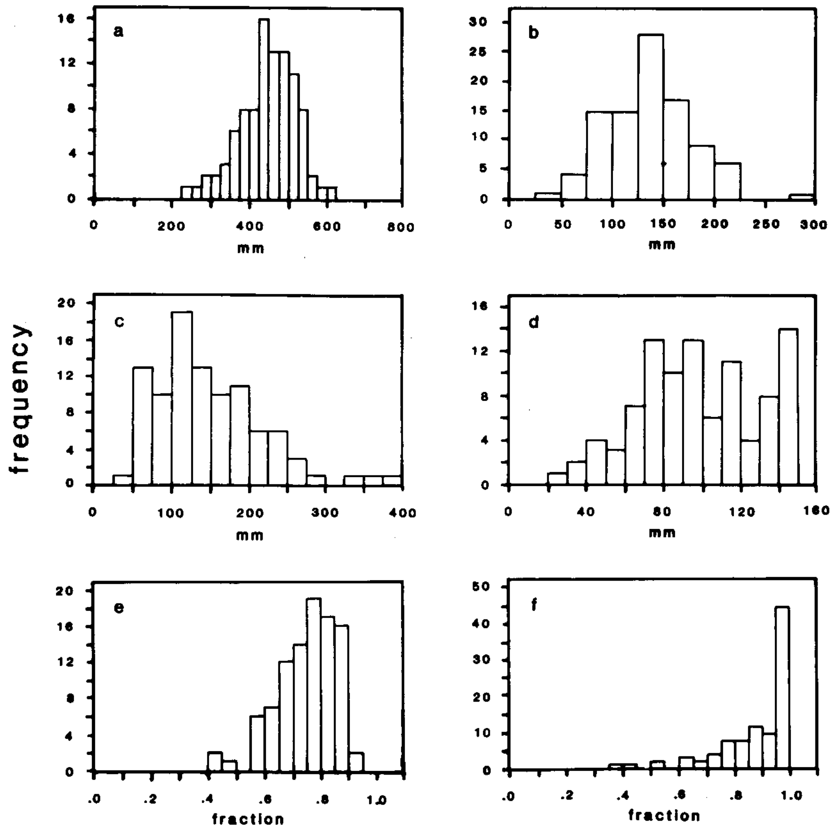

Figure 5. Frequency distribution of selected water balance components based upon continuous monthly water budget analyses, 1895-1990. a) annual precipitation (PCPA); b) January-May precipitation (PCP5); c) annual soil moisture deficit (DEF); d) May soil moisture storage (ST5); e) annual evapotranspiration ratio (RATA); f) May evapotranspiration ratio (RAT5).

environments, with a large mean deficit (148 mm), high year-to-year variability, and a large positive skew, reflecting the regular occurrence of years with extreme soil moisture depletion. May soil moisture storage (ST5) is bimodally distributed, with separate peaks in frequency between 70-100 and 140-150 mm. Although ST5 displays a substantial degree of interannual variability, as indicated by the large CV, only a weak tail toward extremely

low values is evident in the graph and, in fact, the skew value is zero. As previously noted, the May evapotranspiration ratio (RAT5) is appreciably larger than the corresponding annual total (RATA). The CV for both evapotranspiration ratios are comparable in magnitude, and indicative of a moderate degree of variability. Both parameters also display the negatively skewed distribution characteristic of dry subhumid and semi-arid climates. The negative skew, however, is much more pronounced in the May evapotranspiration ratio distribution.

Muller and Thompson (1987) state that mean annual totals of water budget variables determined from climatic normals may be less representative of environmental conditions than mean annual totals of water budget variables based upon continuous monthly analyses. For the North Dakota Prairie Pothole Region, the water budget totals based upon 30-year normals were very comparable to the mean values obtained from the complete 96-year time series. The minor differences can be explained on the basis of the different sampling periods for the two datasets. The 30-year normal period (1961-90) is an adequate representation of the long-term magnitude and seasonal variation of the precipitation and atmospheric demand regimes. Interannual variation in the atmospheric demand is constrained by the continental nature of the climate and the computational dependence of the potential evapotranspiration estimate upon latitude.

In general, the coefficient of variation for May water budget variables was actually larger than the CV for the corresponding annual variables. This was particularly evident for the estimates of potential evapotranspiration, evapotranspiration, and the evapotranspiration ratio, but less so for precipitation. The more reliable spring soil moisture condition, however, is indicated by the smaller coefficient of variation for ST5 than for DEF. Lack of significant hydroclimatological persistence is also evident in the numerical results (Table 1). With the exception of precipitation, the lag-1 autocorrelation coefficients (r_1) for the May water budget variables are consistently less than for the annual values. Correlations for longer lags were not examined.

Interannual Variability of Water Balance Parameters

The great variability in the precipitation regime of the Prairie Pothole Region results from the variable moisture content, path of movement, and instability of the maritime tropical and maritime polar air masses which supply the region's moisture (Rosenberg 1986). Mock (1991) summarizes the available information on precipitation fluctuations in the region during

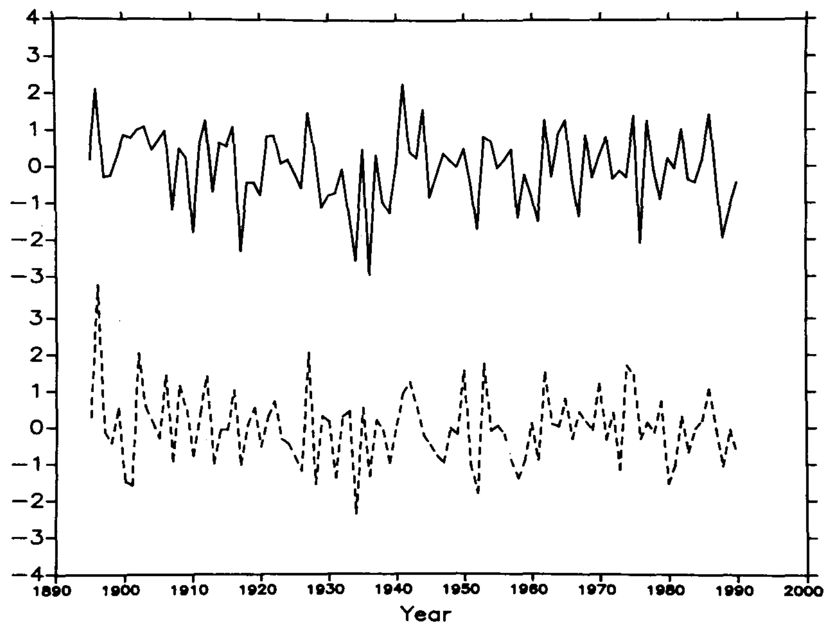

Figure 6. Normalized time series plots of mean annual (PCPA - solid) and May (PCP5 - dashed) precipitation, 1895-1990.

the late nineteenth century. The annual and January-May precipitation time series for the study period (1895-1990) are characterized by large interannual fluctuations (Fig. 6). The PCPA and PCP5 time series are more characterized by high variability on a year-to-year basis than by multiple-year wet and dry periods. For the PCPA time series, only five runs of three or more years with annual precipitation below the long-term mean occur: 1917-20, 1924-34, 1958-61, 1972-74, and 1987-90. Five such runs are found in the PCP5 time series: 1913-15, 1923-26, 1944-49, 1956-59, and 1987-90. Interestingly, these two sets of multiple-year drought occurrences only coincide during the most recent drought episode, which continued through 1991. There is little evidence of significant persistence in either time series. Several investigators have suggested possible linkages between regional precipitation and the Pacific-North American, North Pacific Oscillation, North Atlantic Oscilla-

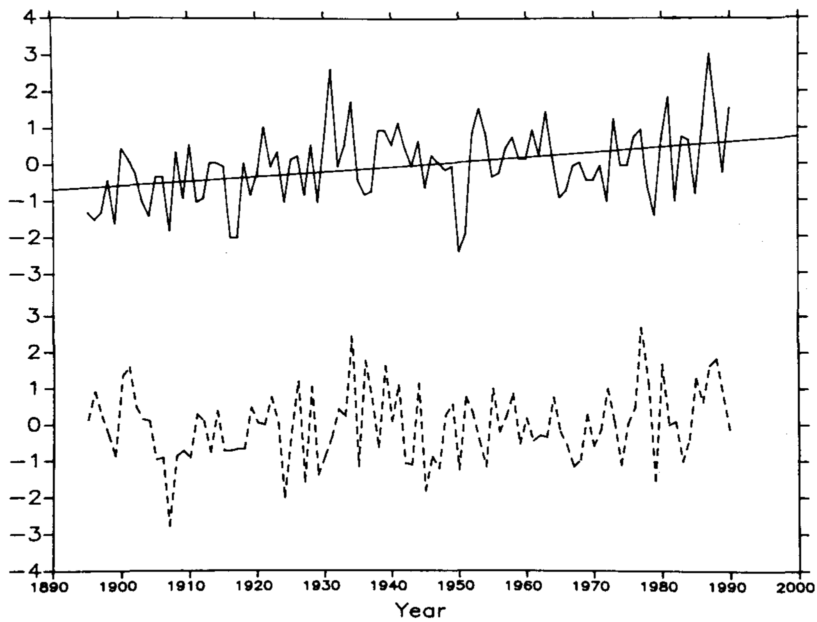

Figure 7. Normalized time series plots of mean annual (TAA - solid) and mean May (TA5 - dashed) air temperature, 1895-1990. A linear trend line is drawn through the TAA data (P = 0.01).

tion, and Southern Oscillation teleconnection patterns (Trenberth et al. 1988; Namias 1991; Knox and Lawford 1990). However, such relationships remain speculative, since a systematic synoptic climatology of Great Plains drought has not yet been developed (Mock 1991).

The annual and May air temperature time series (Fig. 7) provide some indication of the magnitude and intra-annual and interannual variability of the evaporative demand. TAA and TA5 are also characterized by large variability and weak-to-no persistence. An insignificant inverse relationship exists between the annual precipitation and air temperature time series (r=0.139).

The cumulative annual soil moisture deficit time series (Fig. 8) reveals the regular occurrence of severe agricultural drought that has played such a prominent role in the economic history of the Great Plains (Borchert 1971).

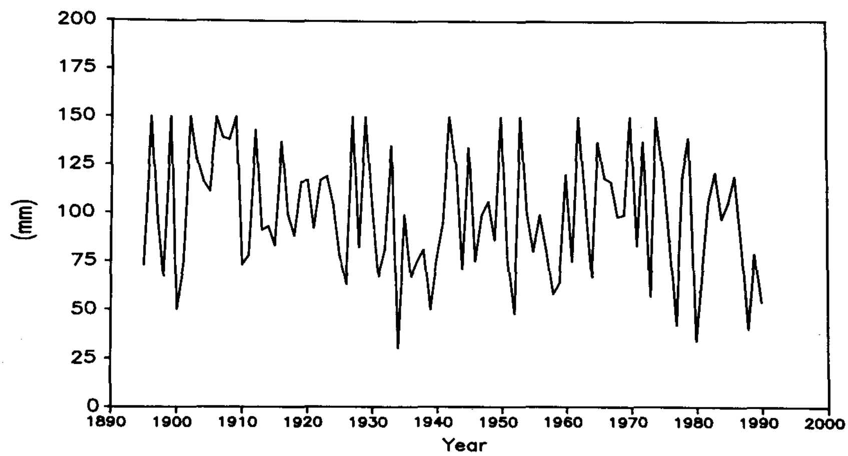

Figure 8. Time series plot of annual cumulative soil moisture deficit (DEF), 1895-1990. A linear trend line is drawn through the data (P = 0.01).

The time series is marked by abrupt transitions between years, with DEF values less than 100 mm and greater than 200 mm. The data exhibit weak persistence (r_1=0.194), often a characteristic of hydrological systems. One major run stands out in this record of agricultural drought, namely the Dust Bowl Era of the 1930s. During the twelve year period from 1929 to 1940, only one year experienced a DEF total less than the long-term mean of 148 mm. This period of extreme drought was primarily caused by persistent deficient moisture supply (nine of twelve years from 1929-40 had annual precipitation totals less than the long-term mean), and was exacerbated by increased levels of evaporative demand (Figs. 6 and 7). Shorter runs of DEF totals greater than the long-term mean occurred in 1917-19, 1958-61, and 1987-90. The soil moisture drought of 1988, which reached 384 mm, was the most severe single event in the study period, exceeding even the Dust Bowl Era peak of 374 mm in 1936.

The simulated ST5 values (Fig. 9) also demonstrate considerable interannual fluctuation between high and low soil moisture storage. Thirteen years displayed ST5 totals of 150 mm, although the last year to do so was 1974. Runs of three or more years with ST5 totals below the long-term mean

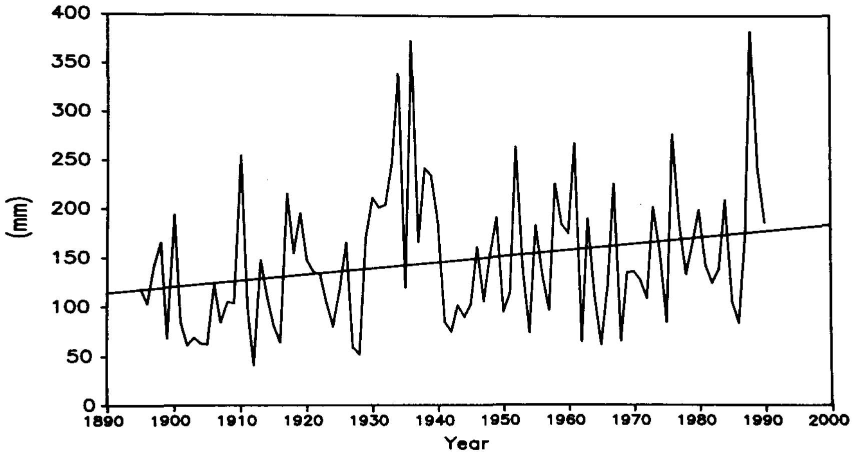

Figure 9. Time series plot of May soil moisture storage (ST5), 1895-1990.

of 100 mm occur in 1913-15, 1934-41, 1955-59, and 1987-90. These significant runs of ecological drought for prairie pothole waterfowl show only partial correspondence to the agricultural drought runs identified in the DEF time series. The ST5 time series exhibits no evidence of hydrological persistence.

The evapotranspiration ratio plots (Fig. 10) provide an alternative measure of long-term environmental conditions in the Prairie Pothole Region. RATA totals are always less than 1.0 (maximum=0.925) because of the large summer soil moisture deficit experienced by dry subhumid/semi-arid climates. Because of normally favorable spring soil moisture conditions, RAT5 usually is greater than RATA. Twenty-six years (27% of total) featured a May evapotranspiration ratio of 1.0. Spring soil moisture conditions were not always more favorable than summer conditions, however, for during ten years RAT5 values were actually less than the corresponding RATA values. These years were: 1900-1, 1925, 1928, 1934, 1951-52, 1964 and 1980-81.

Interannual Hydroclimatic Variability and Waterfowl Production

The most distinguishing characteristic of the North Dakota Prairie Pothole Region water balance is the large interannual variability of all

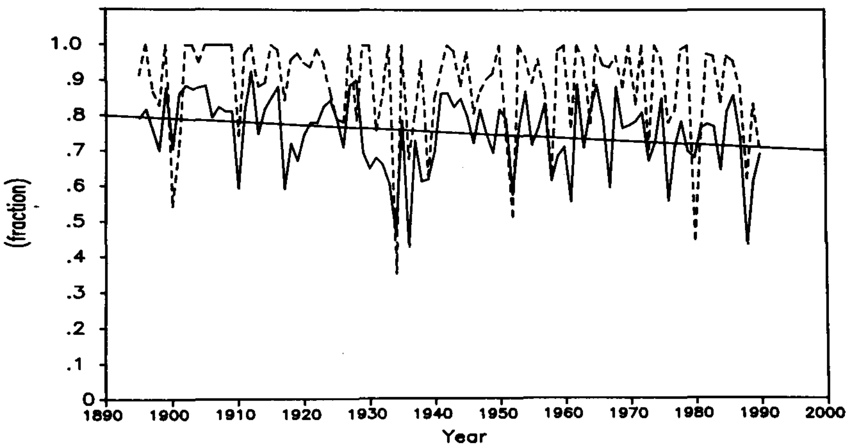

Figure 10. Time series plots of mean annual evapotranspiration ratio (RATA - solid) and May evapotranspiration ratio (RAT5 - dashed), 1895-1990. A linear trend line is drawn through the RATA data (P = 0.05).

hydroclimatological parameters. This variability is most apparent on a year-to-year basis rather than as multiple-year runs of wet and dry periods. Wet years occur on a frequent and random basis throughout the study record, and are even interspersed among what are clearly recognized as dry decades. Evidence of significant hydroclimatological persistence, often cited for the Central and Southern Great Plains (Barry 1983), is not clearly recognizable in this Northern Great Plains data set. Past investigations may have overstated hydroclimatological persistence due to the computational inertia of the Palmer Drought Severity Index (Alley 1985), which may obscure drought patterns of the Northern Great Plains (Karl and Koscielny 1982).

Populations of breeding waterfowl reflect this climatic instability, since their numbers fluctuate considerably due, in large part, to yearly variations in the number and quality of wetlands habitats (Steward and Kantrud 1974). Prairie ducks appear to have evolved within an environment marked by alternating water abundance and scarcity (Cowardin et al. 1983). For example, Mallard ducks have several reproductive strategies which make them well-suited for maximizing production under the variable water conditions experienced in the North Dakota Prairie Pothole Region. These include (1) large initial clutch sizes, (2) increased nesting effort during wet years, (3) toleration of high feeding and nesting densities under favorable conditions,

(4) a tendency to return to past successful nesting locations, and (5) the ability to select predator-free nesting sites (Krapu et al. 1983). These traits result in a high reproductive potential under favorable habitat conditions, provided the ducks are relatively protected from predators. Their long-lived nature and the variable regional water conditions ensure the regular occurrence of wet years which enable long-term population numbers to be successfully maintained.

Pintail ducks also show adaptations to the region's hydroclimatology, including a preference for habitat that is subject to seasonal and interannual instability, and the displacement to nesting sites north of the Arctic Circle during prairie droughts (Smith 1970). Grassland bird populations in the general region also appear to be able to recover quickly from short-term drought conditions (George et al. 1992).

Intra-annual Hydroclimatic Variability and Waterfowl Production

Hydroclimatic instability also occurs on an intra-annual time scale. Some indication of this is given in Table 2 which shows the correlation of annual and May water balance variables for the period-of-record. The total variance of an annual parameter explained by the paired May parameter ranged between 9 and 38 percent (r^2). In particular, January-May precipitation accounted for only 33% of the variance in annual precipitation, and variation in May soil moisture storage explained only 30% of the variance in the annual soil moisture deficit. May soil moisture conditions show only a weak-to-moderate relationship with annual conditions. Because of the high evaporation demand in summer, initially moist spring soil moisture conditions can be followed by much drier conditions if summer rains are deficient. Conversely, initially dry spring soil moisture conditions can be quickly ameliorated by summer precipitation because of the accompanying reduced temperatures and increased cloudiness.

Dry periods in the Northern Great Plains are typically associated with a quasi-stationary mid-tropospheric ridge centered over the western plains states and Canadian provinces (Dey 1982). These ridges result in the northward displacement of the jet stream which effectively blocks migratory lows and maritime polar air from entering the region. These mid-tropospheric ridges normally alternate with a mid-tropospheric trough or zonal flow circulation on a one-to-two week time scale. Persistent mid-tropospheric ridges result in decreased frequency of migratory low pressure systems, and an accompanying reduced frequency of frontal activity. Droughts occur

TABLE 2
CORRELATION COEFFICIENTS OF PAIRED ANNUAL-MAY
WATER BALANCE VARIABLES

Variable Pairs			r	r^2
TAA	-	TA5	.300	0.09
PCPA	-	PCP5	.577	0.33
PEA	-	PE5	.618	0.38
ETA	-	ET	.452	0.20
DEF	-	ST5	-.552	0.31

when a stationary mid-tropospheric ridge becomes established over the region, which can persist for a month or longer.

Transitions between ridge-, trough-, and zonal flow-dominated circulation patterns can be abrupt, as indicated by the weak-to-moderate correlations shown in Table 2. These marked variations in Prairie Pothole Region water conditions produce major intra-annual changes in food availability for waterfowl (Krapu et al. 1983), which influences waterfowl production by impacting nesting effort and predation rates.

Long-term Hydroclimatological Trends

Standard linear regression techniques were applied to the water balance variables to test for evidence of long-term hydroclimatic trends. Results for the annual variables (Table 3) indicate statistically significant trends for four variables - TAA, PEA, DEF and RATA. Annual air temperature has increased at a rate of 1.33°C during the past century. Annual potential evapotranspiration, which is a function of air temperature in the Thornthwaite equation, has increased at a rate of 42.7 mm over the same period, indicating a trend toward increased atmospheric demand. Although annual precipitation decreased over the past century, the linear regression coefficient was not significant at the 0.05 level. These changes in atmospheric demand and moisture supply over the past century have produced a

TABLE 3
SUMMARY OF LINEAR TREND ANALYSIS OF WATER BALANCE VARIABLES, 1895-1990

		B	P
	(a) Annual Variables		
TAA	(C)	0.0133	<.01
PCPA	(mm)	-0.3306	.21
PEA	(mm)	0.4270	<.01
ETA	(mm)	-0.2143	.27
DEF	(mm)	0.6449	.01
RATA	(fraction)	-0.0009	.02
	(b) May Variables		
TA5	(C)	0.0123	.11
PCP5	(mm)	-0.1404	.36
PE5	(mm)	0.0840	.11
ET5	(mm)	0.0223	.62
ST5	(mm)	-0.1867	.12
RAT5	(fraction)	-0.0007	.20

trend toward increased soil moisture dryness, as evidenced by statistically significant trends toward increased annual soil moisture deficit and decreased annual evapotranspiration ratio. Since annual evapotranspiration also showed a negative trend, although the relationship was at a lower level of significance, the trend toward increasing soil dryness can primarily be attributed to increased atmospheric demand, with decreasing precipitation also providing a contributing role.

Long-term May water balance variable trends are less conclusive. None of the trends were significant at the 0.05 level. However, the May trends toward increased air temperature and potential evapotranspiration, and decreased precipitation, soil moisture storage, and evapotranspiration ratio are consistent with the patterns in the corresponding annual variables. Only the

regression coefficients for the trend of annual and May actual evapotranspiration are opposite in sign.

Such regional trends are consistent with the findings of Clark (1989) who found evidence of twentieth century warming and drying, in comparison to the mid-nineteenth century, at Itasca, Minnesota. Additional results from Minneapolis, Minnesota (Clark 1989), indicate a shift from a strongly positive annual water balance (Im>>0.0) during the mid-nineteenth century, to a subhumid twentieth century soil moisture regime (Im=0.0). Regional warming has also been inferred from geothermal gradient data in the northern Great Plains (Gosnold and LeFever 1991).

The observed annual air temperature and simulated summer soil moisture trends occurring within the North Dakota Prairie Pothole Region during the secular period are consistent with global climate model warming scenarios resulting from anthropogenic trace gas emissions (Manabe and Wetherald 1986). Most state-of-the-art climate models show increased warming and increased summer soil dryness for the North American continental interior with a doubling of the equivalent CO_2 concentration of the atmosphere (Kellogg and Zhao 1988). However, there is considerable variation among the model projections, and a high degree of uncertainty is associated with global climate model precipitation simulations. Thompson (1992) also reported decreased summer soil moisture for the central Great Plains when climate model scenarios were coupled to the Thornthwaite water balance methodology.

Caution must be exercised, however, in attributing such regional trends to human origin rather than to natural climate variability. Hanson et al. (1989) have found no evidence of a statistically significant warming trend for the contiguous United States, based upon climate division data for 1895-1987. Climatic trends in the northern Great Plains during the study period are consistent with global warming projections, although a cause and effect linkage has not been positively established.

Conclusions

The past two decades have witnessed a rapid increase in the perceived values of wetlands (Heimlich et al. 1989), largely driven by concern over a possible recent decline in waterfowl populations (Johnson and Shaffer 1987). Native prairie grasslands and wetlands continue to be lost via agriculture, grazing, burning, mowing, sedimentation, and drainage (Poiani and Johnson 1991). This ongoing intensification of land use has been suggested as the

probable cause of decreased nesting success and declining duck populations in the North Dakota Prairie Pothole Region (Cowardin et al. 1983). Consequently, resource managers have focused upon land use considerations in formulating wetlands preservation policy.

Past analyses of the effectiveness of the swampbuster provision of the current Farm Bill in conserving wetlands have focused upon such factors as:

(1) degree of producer participation in the farm program,
(2) effectiveness of economic incentives,
(3) economic factors such as conversion and production costs and market prices,
(4) exemptions allowed by the legislation,
(5) degree of producer compliance, and
(6) uncertainties regarding implementation (Heimlich and Langner 1986; Heimlich et al. 1989).

Although the swampbuster provision has been effective in reducing wetland losses, innovative approaches are still needed to protect remaining wetlands (Jones 1988). Three swampbuster exemptions are particularly germane relative to the hydroclimatology of the North Dakota Prairie Pothole Region. First, farm operators can retain farm program eligibility and still maintain drainage projects at depths which either existed or were planned prior to December 23, 1985. Second, wetlands may be cropped if production is possible in the wetland's natural state. Third, crop production on wetlands is permitted if they become workable due to natural conditions such as drought (Heimlich and Langner 1986).

The current Farm Bill provides an example of how environmental policy for climate-sensitive natural environments is often formulated without adequate consideration of the impact of climate variability (Morrisette 1988). Environmental managers have generally ignored the natural variability of climate in resource management decisions, particularly within subhumid, semi-arid, and arid regions (Morrisette 1988). The Prairie Pothole Region is an environment which is closely adjusted to the natural variability of the North American continental interior. Natural resource policy for the region must be similarly adapted to the natural variability of this critical environment.

The existing swampbuster exemptions have been developed without adequate consideration of the natural hydroclimatic variability of the Prairie Pothole Region. The sustainability of this natural system is predicated on the

fact that regeneration of wetlands during moist periods is able to compensate for wetlands deterioration during dry periods. This is true with respect to both the number and quality of wetlands. Allowing crop producers to maintain drainage projects at depths which existed as of December 23, 1985, places an upper limit upon the extent of potential wetland regeneration and, in effect, prohibits the positive effects of wet years from fully compensating for the negative impacts of dry years. Similarly, the frequency of occurrence of dry years is relatively high, as is the probability of a multiple-year dry period.

Temporary deterioration or loss of wetlands due to environmental desiccation is a natural component of the system. Allowing crop producers to cultivate such lands during dry cycles thereby ensures the progressive deterioration and eventual loss of wetlands. These potential negative impacts upon Prairie Pothole wetlands arise due to the natural hydroclimatic variability of the region, and are in addition to potential negative impacts which may arise from climatic warming of either natural or human origin (Poiani and Johnson 1991).

Riebsame (1990b) has called for a new paradigm of natural resources planning which accommodates natural climatic variability and the threat of global warming. Rather than assume a constancy of basic environmental conditions, he argues that environmental planners should assess the sensitivity of natural resource systems to changing climate, and develop flexible management practices which are adapted to the variability of climate and can respond to a changing climatic regime (Riebsame 1990b). The future sustainability of waterfowl habitat and populations in the North Dakota Prairie Pothole Region will require such a new paradigm.

References

Alley, W. M. 1984. The Palmer Drought Severity Index: Limitations and assumptions. *Journal of Climate and Applied Meteorology* 23: 1,100-1,109.

Alley, W. M. 1985. The Palmer Drought Severity Index as a measure of hydrologic drought. *Water Resources Bulletin* 21:105-14.

Barry, R. G. 1983. Climatic environment of the Great Plains, past and present. *Transactions of the Nebraska Academy of Science* 11:45-55.

Borchert, J. R. 1971. The Dust Bowl in the 1970s. *Annals of the Association of American Geographers* 61:1-22.

Clark, J. S. 1989. Effects of long-term water balances on fire regime, northwestern Minnesota. *Journal of Ecology* 77:989-1,004.

Cowardin, L. M., A. B. Sargeant, and H.F. Duebbert. 1983. Problems and potentials for prairie ducks. *Naturalist* 34:4-11.

Dahl, T. E. 1990. *Wetlands Losses in the United States 1780s to 1980s*. Washington, DC: U.S. Department of the Interior, Fish and Wildlife Service.

Davies, J. C. and F. Cooke. 1983. Annual nesting productivity in snow geese: prairie droughts and arctic springs. *Journal of Wildlife Management* 47:291-96.

Dey, B. 1982. Nature and possible causes of droughts on the Canadian Prairies: Case studies. *Journal of Climatology* 2:233-49.

Eisenlohr, W. S., Jr, and C. E. Sloan. 1968. Generalized hydrology of prairie potholes on the Coteau du Missouri, North Dakota. U.S.G.S. Circular 558.

George, T. L., A. C. Fowler, R. L. Knight, and L. C. McEwen. 1992. Impacts of a severe drought on grassland birds in western North Dakota. *Ecological Applications* 2:275-284.

Gosnold, W. D., Jr., and R. D. LeFever. 1991. Comparison of climate record with bore hole temperatures in the central United States. *EOS* 72:69.

Guttman, N. B. 1991. A sensitivity analysis of the Palmer Hydrologic Drought Index. *Water Resources Bulletin* 27:797-807.

Hanson, K., G. A. Maul, and T. R. Karl. 1989. Are atmospheric "greenhouse" effects apparent in the climatic record of the contiguous U.S. (1895-1987)? *Geophysical Research Letters* 16:49-52.

Heimlich, R. E., M. B. Carey, and R. J. Brazee. 1989. Beyond swampbuster: A permanent wetland reserve. *Journal of Soil and Water Conservation* 44:445-50.

Heimlich, R. E. and L. L. Langner. 1986. *Swampbusting: Wetland Conversion and Farm Programs*. AER-551. Washington, DC: Economic Research Service, U.S. Department of Agriculture.

Johnson, D. H., A. B. Sargeant, and R. J. Greenwood. 1989. Importance of individual species of predators on nesting success of ducks in the Canadian Prairie Pothole Region. *Canadian Journal of Zoology* 67:291-97.

Johnson, D. H. and T. L. Shaffer. 1987. Are mallards declining in North America? *Wildlife Society Bulletin* 15:340-45.

Jones, L. A. 1988. Implementing swampbuster: A view. *Journal of Soil and Water Conservation* 43:30.

Karl, T. R. 1986. The sensitivity of the Palmer Drought Severity Index and Palmer's Z-Index to their calibration coefficients including potential evapotranspiration. *Journal of Climate and Applied Meteorology* 25:77-86.

Karl, T. R. and A. J. Koscielny. 1982. Drought in the United States: 1895-1981. *Journal of Climatology* 2:313-29.

Kellogg, W. W. and Z-C Zhao. 1988. Sensitivity of soil moisture to doubling of carbon dioxide in climate model experiments. Part I: North America. *Journal of Climate* 1:348-66.

Knox, J. L. and R. G. Lawford. 1990. The relationship between Canadian Prairie dry and wet months and circulation anomalies in the mid-troposphere. *Atmosphere-Ocean* 28:189-215.

Krapu, G. L., A. T. Klett, and D. G. Jorde. 1983. The effect of variable spring water conditions on mallard reproduction. *The Auk* 100:689-98.

Manabe, S. and R. T. Wetherald. 1986. Reduction in summer soil wetness induced by an increase in atmospheric carbon dioxide. *Science* 232: 626-28.

Mather, J. R. 1991. A history of hydroclimatology. *Physical Geography* 12:260-73.

Mock, C. J. 1991. Drought and precipitation fluctuations in the Great Plains during the late nineteenth century. *Great Plains Research* 1:26-57.

Morrisette, P. M. 1988. The stability bias and adjustment to climatic variability: The case of the rising level of the Great Salt Lake. *Applied Geography* 8:171-89.

Muller, R. A. and R. C. Thompson. 1987. Water budget analysis. In *The Encyclopedia of Climatology*, ed. J.E. Oliver and R.W. Fairbridge, 914-21. *Encyclopedia of Earth Sciences*, Volume XI. New York: Van Nostrand Reinhold Company.

Namias, J. 1991. Spring and summer 1988 drought over the contiguous United States: Causes and prediction. *Journal of Climate* 4:54-65.

National Climatic Data Center. 1989. *Time Biased Corrected Divisional Temperature-Precipitation-Drought Index: TD-9640 Tape Documentation*. Asheville, NC: National Climatic Data Center.

Nielson, D. R. and J. W. Biggar. 1982. Implications of the vadose zone to water-resource management. In *Scientific Basis of Water-Resource Management*, 41-50. Washington, DC: National Academy Press.

North Dakota Game and Fish Department. 1990. *Waterfowl Breeding Ground Survey, 1990*. Report 859. Bismarck, ND: North Dakota Game and Fish Department.

Poiani, K. A. and W. C. Johnson. 1991. Global warming and prairie wetlands. *Bioscience* 41:611-18.

Popper, D. E. and F. J. Popper. 1987. The Great Plains: From dust to dust, a daring proposal for dealing with an inevitable disaster. *Planning* 53:12-18.

Riebsame, W. E. 1990a. The United States Great Plains. In *The Earth as Transformed by Human Action*, ed. B. L. Turner et al., 561-75. Cambridge, UK: Cambridge University Press.

Riebsame, W. E. 1990b. Anthropogenic climate change and a new paradigm of natural resource planning. *The Professional Geographer* 42:1-12.

Riebsame, W. E. 1991. Sustainability of the Great Plains in an uncertain climate. *Great Plains Research* 1:133-51.

Rosenberg, N. J. 1986. Climate of the Great Plains region of the United States. *Great Plains Quarterly* 7:22-32.

Rosenzweig, C. and D. Hillel. 1993. The Dust Bowl of the 1930s: Analog of greenhouse effect in the Great Plains? *Journal of Environmental Quality* 22:9-22.

Smith, R. I. 1970. Response of pintail breeding populations to drought. *Journal of Wildlife Management* 34:943-46.

Stewart, R. E. and H. A. Kantrud. 1974. Breeding waterfowl populations in the Prairie Pothole Region of North Dakota. *The Condor* 76:70-9.

Thompson, S. A. 1992. Simulation of climate change impacts on water balances in the Central United States. *Physical Geography* 13:31-52.

Thornthwaite, C. W. 1948. An approach toward a rational classification of climate. *Geographical Review* 38:55-94.

Thornthwaite, C. W. and J. R. Mather. 1955. The water balance. *Publications in Climatology* 8:9-86.

Trenberth, K. E., G. W. Branstator, and P. A. Arkin. 1988. Origins of the 1988 North American drought. *Science* 242:1,640-45.

Wilhite, D. A. and M. H. Glantz. 1985. Understanding the drought phenomenon: The role of definitions. *Water International* 10:111-20.

Willmott, C. J. 1977. WATBUG: A FORTRAN IV algorithm calculating the climatic water balance. Publications in Climatology Vol. XXX, No. 2.