An analysis of droughts in the Northeast District of Montana : their features, impact, monitoring and prediction

by Raya Hershenhorn

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Soils
Montana State University

Abstract:
This study considered characteristics of droughts in the Northeast District of Montana, evaluated the impact of drought and explored the possibility of predicting them.

The project was based upon about 100 years of historical data from four sources: 1. Palmer Drought Severity Index (PDSI) (monthly values); 2. Precipitation (daily totals); 3. Spring wheat, winter wheat and wild hay yield as well as range condition; 4. Normalized Difference Vegetation Index, derived from satellite data (weekly values). Statistical analyses were conducted on these four data sources.

Variability of the PDSI was greatest during the summer. There was a significant correlation between August PDSI and May PDSI. Probability charts of PDSI in August based on PDSI in May were developed. Chi Square tests indicated that precipitation for the entire season was significantly related to early season precipitation, especially in dry years. Spring wheat yield was most highly correlated with June PDSI, and range condition with June and July PDSI. PDSI in April, May and June was highly correlated with NDVI of the same month, with the highest correlation in May. August PDSI, spring wheat and winter wheat yield were highly correlated with NDVI in May.

PDSI characterizes drought conditions and revealed some of its features. The high correlation between August and May PDSI suggested the possibility of predicting August PDSI from May PDSI. The correlations concerning spring wheat suggested that the impact of drought on spring wheat yield could be estimated about two months prior to harvest. NDVI can be used to monitor the extent of drought in April, May and June, when the vegetation is green. NDVI in April and May can be used as a predictor for August PDSI, spring wheat and winter wheat yield as well as range condition.

The relations that were developed in this study should help to interpret and apply the variables that are being calculated in the drought monitoring system of Montana.

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ABSTRACT

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PDSI characterizes drought conditions and revealed some of its features. The high correlation between August and May PDSI suggested the possibility of predicting August PDSI from May PDSI. The correlations concerning spring wheat suggested that the impact of drought on spring wheat yield could be estimated about two months prior to harvest. NDVI can be used to monitor the extent of drought in April, May and June, when the vegetation is green. NDVI in April and May can be used as a predictor for August PDSI, spring wheat and winter wheat yield as well as range condition.

The relations that were developed in this study should help to interpret and apply the variables that are being calculated in the drought monitoring system of Montana.

INTRODUCTION

Drought indicates dryness or lack of water. It is variable, both temporally and spatially, and is very difficult to define (Wilhite and Nield, 1982). There are numerous definitions of drought.

In most dictionaries, drought is defined only in relative terms of temporary and unusual dryness (Roots, 1988). Palmer (1965) defined drought as "A period of months or years, in which the actual moisture supply is less than the climatology expected". A season (three months) of deficient precipitation has a large impact on soil moisture and streamflow in many areas of the world, and is considered the shortest period that can be identified as a drought (American Meteorological Society, 1990).

Roots (1988) characterized drought by three features:
1. Unusual: less moisture available to the biological and industrial systems, compared to normal conditions in the last several decades, in the same region and season.
2. Transient: period of dryness, long enough to influence human activity, but not too long to create a new arid climate condition. 3. A period of dryness which has a subjective negative effect on human activity.

Definition of drought is easier by designating its impact on particular sectors (Wilhite and Neild, 1982). In general, droughts can be divided into four categories: meteorological, hydrological, agricultural and socioeconomical (Wilhite and

Glantz, 1987).

In meteorological drought, precipitation decreases to less than 25% of normal (Venkateswarlu, 1987). When this drought is prolonged, it becomes a hydrological drought, with depletion of surface water and ground water levels. Agricultural drought occurs when the water is inadequate for crops during the growing season and productivity is reduced. Socioeconomical drought generally follows the other droughts a few months later (Venkateswarlu, 1987).

The Northeast District of Montana is prone to reoccurrence of droughts (Rosenberg and Katz, 1990). Both in the past and the present, agriculture in the region is sensitive to drought (Wilhite and Heim Jr. 1990), and the economic impact is often severe (Peters et al. 1991). Sensitivity to droughts in the past resulted from lack of agroclimatic knowledge, lack of technology and lack of financial reserves (Wilhite and Heim Jr. 1990). Droughts resulted in food shortage and starvation.

Sensitivity to droughts continues today. Intensive settlement in the last century caused much more demand of water on many economic sectors. Droughts can cause significant ecological damage, and it is not possible to withstand drought of several years without reducing the use of water (Godwin, 1988).

From agricultural stand point of view, availability of water is the primary limiting factor for crops in the Northeast District (Rosenberg and Katz, 1990). It is the leading district for spring wheat in Montana (Caprio and Williams, 1973). The importance of drought research in this region is enhanced by the fact that agriculture is the most important sector of the economy in Montana. The Northeast District is part of the Great Plains, a marginal agricultural area, which makes a large contribution to global food production (Hecht, 1983). Twelve to fifteen percent of the world's total wheat and 60-65% of the nation's wheat is produced in the Great Plains (Hecht, 1983).

To evaluate drought conditions in Montana, the state monitors several parameters each month, and the results are published by the Department of Natural Resources and Conservation (Montana State Department of Natural Resources and Conservation, 1992). The parameters are: 1. A weather summary for the last month, and weather forecasts for 6-10 days, 30 days and 90 days; 2. Snowpack measured at snowtel stations by the Soil Conservation Service (SCS); 3. Streamflow measured in gaging stations by the U.S. Geological Survey; 4. Reservoir status evaluated by the U.S. Bureau of Reclamation and the State of Montana; 5. Soil moisture estimated during the growing season by the Montana Agricultural Statistics Service.

These measurements are applied to estimate the following indices: 1. Surface Water Supply Index (SWSI) for individual river basins, especially for mountainous areas, estimated by the SCS; 2. Regional Palmer Drought Severity Index (PDSI) for each district calculated by the National Climatic Data Center, Asheville NC; 3. PDSI for many stations in each district, calculated by the State Climate Office, Montana State University. This study relates to the Montana drought monitoring system by researching the historical perspective of droughts and assessing their impacts. Its purpose was to contribute to a better understanding of the variables which are calculated in this system, with the major emphasis placed on the PDSI section of the monitoring system.

LITERATURE REVIEW

Studies of drought have concentrated on meteorological and agricultural drought, and less on hydrological and socioeconomical drought (Wilhite and Heim Jr. 1990). This study also concentrated on meteorological and agricultural droughts, which are discussed in the following literature review.

Meteorological Drought

Research on meteorological drought has been based primarily on three sources of information: Tree rings, PDSI and departure from normal precipitation.

Tree Rings

Tree rings were often used to analyze drought periods for the time before climatic records began. Climate records for the Great Plains go back to the 1800's (Wilhite and Heim Jr. 1990). Tree rings have been used to characterize the history of droughts, duration of drought periods and drought cycles. Mitchell et al. (1978) have found a cycle of 22 years for the western United States in data from 1700. This period was found to be related to solar magnetic effects.

Stockton and Meko (1975) studied the drought pattern for climatic divisions during the period 1700-1963. They correlated tree ring indices with PDSI of July for regions west of the Mississippi River in order to reconstruct a drought history. Although the correlation appeared poor for a few individual years, the agreement was good for any wet or dry periods lasting at least two years. In a later study, Stockton and Meko (1983), added four locations inside the Great Plains: Iowa, Oklahoma, southeastern Montana (Miles City) and eastern Wyoming. Their analyses of the actual and derived PDSI values showed clear clustering of drought years and non drought years. The clustering of drought was mainly in the 1750's and 1860's. The 1930's drought was mentioned for its intensity. Average of the four regions in the Great Plains revealed a drought cycle of 19 years (Stockton and Meko, 1983). On a regional basis, the cycle was much different, and for most western states, including Montana and Wyoming, it was a 58 year drought cycle.

Palmer Drought Severity Index

The Index. The PDSI is internationally the most used regional drought index (Alley, 1984; Thompson, 1990). It is published every other week during the growing season, and once a month during the rest of the year in the Weekly Weather and Crop Bulletin (1992). Some of the basic ideas and critical aspects of the index will be presented here. For more details, the reader can refer especially to Palmer (1965) and Alley (1984).

PDSI is a hydrological water balance model, based on the concept of a balance between moisture supply and demand (Doesken et al. 1983; Palmer, 1965). The index determines the duration and intensity of drought periods (Alley, 1984).

The water balance in the index is based on precipitation and temperature data, usually on a weekly or monthly basis (Palmer, 1965). These data are used to calculate several coefficients: evapotranspiration, runoff and soil moisture recharge or depletion in the topsoil and in the root zone. These coefficients define the normal conditions, and departures from the normal contribute to wet and dry periods.

Palmer defined two soil layers that may hold moisture. In the surface layer, 25 mm of water can be stored, and when it is saturated, water infiltrates to the bottom layer (Palmer, 1965). In the bottom layer, available water holding capacity is determined by soil characteristics. Runoff appears when both layers achieve their moisture capacity. Potential evapotranspiration (PET) is calculated by the Thornthwaite method. The index also takes into account the indexes of previous months (U.S. Bureau of Reclamation, 1990).

Palmer defined "Z" as a moisture anomaly index (Karl and Knight, 1985). The Z index represents the relative departure of weather, in a particular month and place, from the mean moisture conditions. The Z index was developed for PDSI's analogue between different months and locations.

The values of PDSI are negative for dry periods and positive for wet periods. The dry and wet periods are divided into the following categories:

	EXTREMELY WET	≥ 4.0
	SEVERELY WET	3.0 - 3.9
	MODERATELY WET	2.0 - 2.9
	SLIGHTLY WET	1.0 - 1.9
	INCIPIENT WET	0.5 - 0.9
NORMAL	CONDITIONS	0.5 - -0.5
	INCIPIENT DROUGHT	-0.5 - -0.9
	MILD DROUGHT	-1.0 - -1.9
	MODERATE DROUGHT	-2.0 - -2.9
	SEVERE DROUGHT	-3.0 - -3.9
	EXTREME DROUGHT	≤ -4.0

Alley (1984) discussed some of the PDSI's limitations. He stated that some people are against developing a drought index, as they believe that taking into account all the physical and biological effects is too complicated a task. He has some doubts about utilizing the water balance model for developing a drought index.

Palmer used some unknown terms and definitions in his method. He used several arbitrary rules, which have weak physical and statistical bases to quantify drought (Alley, 1984). Some of the variables were defined based on only a few comparisons and inappropriate periods of data.

Some of the variables which were arbitrarily defined include: soil water holding capacity, the relations between actual and potential evapotranspiration, estimation of runoff, designation of drought severity classes, the determination of onset and end of a drought period, and the Z index (Alley, 1984).

The Thornthwaite method for calculating PET ignores three major factors that affect evapotranspiration (ET): solar energy, humidity and sensible heat advection. Thus, this method underestimates PET (Rosenberg et al. 1983) and consequently PDSI underestimates drought severity (Peters et al. 1991).

The index does not consider availability of snowmelt runoff, reservoir storage and ground water resources (U.S. Bureau of Reclamation, 1990). Man-caused changes in local supply and demand, such as irrigation and water storage reservoirs, are not taken into consideration (Karl, 1986).

The importance of the PDSI is that no better regional index exists (Alley, 1984). This index characterizes spatial and temporal features of historical dry episodes over a large region (Alley, 1984). PDSI can be derived and updated in a timely and economical manner using the data generated by the national meteorological observation network (Stommen and Motha, 1987).

Applications. Karl (1983) related PDSI to anomalies of precipitation and to potential evaporation. He found that PDSI calculations reflected the real trend of drought. However, forecasts derived from PDSI values were not a significant improvement from what would have been obtained by using precipitation persistence forecasts.

In analysis of PDSI data for the years 1895-1980, Diaz (1983) and Karl (1983) found that extreme droughts (PDSI ≤ -4) lasted longer in the Great Plains than in the rest of the U.S. Diaz (1983) showed also that the Great Plains tended to be either too wet or too dry, i.e. it had anomalous moisture conditions.

Wilhite and Wood (1985) used the frequency of moderate to extreme drought (PDSI $\leq$ -2.0) to determine climatological divisions in the U.S. for the period 1931-1978. In 16 to 25% of all the months, moderate to extreme droughts existed in most of the Great Plains. Extreme drought persisted over the major part of the Plains 4 to 6% of the time.

Soule (1990a,b) examined the temporal pattern of drought during its first six months. Monthly values of the Palmer Moisture Anomaly Index (ZINX), PDSI, Palmer Hydrological Drought Index (PHDI) and the departure from the normal precipitation and temperature were used to describe the drought conditions. He found strong similarities in the patterns of the different indices for the same time, especially between PDSI and PHDI.

Precipitation

Compared to other factors, precipitation represents the largest contribution to drought (American Meteorological Society, 1990). However, it is difficult to define drought by precipitation records, since precipitation data are summed by state, month, season or year. Additionally, there is no commonly accepted departure from the mean precipitation definition for the onset of drought (Wilhite and Heim Jr. 1990).

The Australian Drought Watch System has been operational for the last twenty years and relies on rainfall deficiency (Coughlan, 1987). The system compares the observed precipitation for a three month period at a given location with its historical record (Janowiak et al. 1986). The criteria for drought was arbitrarily chosen to be the lowest ten percentile of the mean precipitation, for three or more consecutive months (French, 1987). It has proved to be an effective tool for detecting incipient drought conditions (Coughlan, 1987), and compares favorably with the PDSI (Janowiak et al. 1986).

Several studies of precipitation probabilities included stations from the Northeast District of Montana (Caprio, 1991b; Caprio et al. 1980; Gifford et al. 1967; Missouri Basin Inter Agency Committee, 1967). Caprio (1991b) found a high probability for a secondary precipitation maximum, from mid April to mid May at several locations in Montana.

In the Republic of South Africa, the eligibility of State Relief Schemes requires that affected areas are declared as being disaster drought stricken (Bruwer, 1990). A disaster drought condition is determined when over a period of two consecutive rain seasons, 70% or less of the average mean precipitation of the area has occurred.

In India, drought is declared if rainfall decreases by more than 30% from the mean (Venkateswarlu, 1992). In Brazil, drought is forecasted by a rainfall index called "normalized departure". It is obtained by dividing departures of the mean precipitation by the standard deviation (Hastenrath, 1987).

Agricultural Drought

Many different agricultural drought indexes are used all over the world. PDSI is used widely not only as a meteorological drought index, but also as an agricultural index, and is considered one of the best tools available (Wilhite, 1983). Doesken et al. (1983) applied PDSI to estimate dryland winter wheat yield in Colorado. They found the best correlations between yield, and June or July PDSI.

Palmer (1968) developed the regional Crop Moisture Index (CMI), as an outgrowth of the PDSI. CMI responds rapidly to changes in the soil moisture (Strommen and Motha, 1987), because it only includes the moisture anomaly of each successive month. Therefore its values indicate more favorable moisture conditions over a particularly wet or dry month, even in the middle of a serious long-term dry or wet period (Peters et al. 1991). The CMI is recommended for assessing short-term moisture deficiencies (Karl, 1986).

In Canada, the Forage Drought Early Warning System (FoDEWS) exists in the Prairie Provinces (Dyer, 1986). Soil moisture is calculated from daily rainwater and snowmelt, considering current and past years. The availability of soil moisture can limit daily plant water use, aimed for spring pasture for the beef industry.

NOAA (1973) designates drought as weather conditions that result in yields of 10% or more below yields realized under normal weather conditions. The probability of drought for wheat anywhere in the U.S. was found to be approximately 10% (NOAA, 1973).

The Food and Agriculture Organization (FAO) of the United Nations uses a water balance method to evaluate crop yields, as an early warning drought system (Frere and Propov, 1979). It is aimed mainly for developing countries with dryland agriculture, where the major constraint is inadequate availability of water for crop production. The method is a balance between precipitation received by a specific crop and the potential evapotranspiration, defined by Penman, as well as water reserves in the soil. Crop coefficients are also taken into account, based on the phenological stage during the growing season and the water requirements of the crop.

In New South Wales, Australia, agricultural drought is defined for a Pasture Protection District by a need for survival feeding of stock, in at least half of a district (Smith, 1989). Comparison on a district level with PDSI revealed that PDSI defined moderate drought in half of the months so defined by this method (Smith, 1989). At the state level, PDSI corresponded closely with the method.

There were not many studies that dealt with agricultural drought in the U.S. Great Plains (Wilhite and Heim Jr. 1990). Agricultural drought can be best analyzed in a specific region within the Great Plains, because it is influenced by crop type, soil type and management.

Pengra (1958) calculated the probability of drought days during the growing season in South Dakota on the basis of soil moisture deficits. A drought day was defined as a day when available soil water was less than 50% of field capacity. Unfortunately, timely and reliable measurements of soil water status were limited in spatial coverage (Wilhite and Heim Jr. 1990).

Pengra (1952) found that seasonal precipitation in the Great Plains was rarely sufficient to overcome a marked moisture deficiency at seeding time. Preseason precipitation (or soil moisture supply at seeding time) appeared to be at least as significant in the production of small grains, as was precipitation received during the growing season.

Wilhite and Neild (1982) studied wild hay in northcentral Nebraska. They used the McQuigg et al. (1973) and NOAA (1973) definition for drought year, as having 10% or more negative departure from the expected yield realized under normal weather conditions. Drought was classified as moderate drought (10-20%) and severe drought (>20%). The probability of drought occurrence in a single year was 5 to 15% in the North Crop Reporting District of Nebraska.

Normalized Difference Vegetation Index

The Normalized Difference Vegetation Index (NDVI) is an indirect measure of plant conditions, based on satellite data. It compensates for some of the weaknesses of the PDSI: the dearth of weather sampling stations, the generally irregular geographic pattern and the inherent time lag factors in reporting weather observations (Peters et al. 1991).

The index is based on data from the National Oceanic and Atmospheric Administration's Advanced Very High Resolution Radiometer (NOAA AVHRR) (Gallo, 1990; Goward et al. 1985). The radiometer measurements were previously obtained from the Meteorological Satellite NOAA-7 through 1985 and from NOAA-9 since 1985 (Tucker and Goward, 1987). The satellite has twice daily coverage and high radiometric resolution. Vegetation satellite derived indices are computed from a matrix of thousands of 1.1 km^2 pixels (Peters et al. 1991).

The vegetation indices are based on the different reflectance of plants in the red (RED) band and in the Near Infra Red (NIR) band (Tucker and Goward, 1987). The NOAA/NESDIS (National Environmental Satellite Data and Information Service) is providing drought early warning alerts and climate impact assessments to national and international agencies with one of its objectives being satellite crop assessments (Sakamoto and Steyaert, 1987).

Amongst the vegetation satellite derived indexes is the NDVI, which is defined as: NDVI = NIR - RED / NIR + RED

(Gallo, 1990; Lillesand and Kiefer, 1987). Vegetated areas with greater biomass have high reflectance in the NIR and low reflectance in the RED and therefore produce high values of the index (Goward et al. 1985; Peters et al. 1991). Bare soil and rock reflect similarly in both bands, and therefore tend to have indices near zero. Other features such as clouds, water and snow have high RED reflectance and low NIR, and produce negative index values.

Researchers seem to prefer the NDVI to other vegetation indices because it minimizes the effects of changing illumination conditions, surface slope, aspect and other extraneous factors, while emphasizing varying vegetation density (Goward et al. 1985; Roller and Colwell, 1986; Tucker and Goward, 1987).

One significant problem with this index is that it is difficult to precisely register or composite pixels from different dates, because they may not represent the same geographic area (Peters et al. 1991).

In an analysis by Peters et al. (1991) in Nebraska, the NDVI detected spatial and temporal drought conditions, specifying the accurate location of the geographic core of the 1988 drought.

Conclusively, research on drought in the U.S. relates to the entire country or to a specific region, such as a state or river basin (Wilhite and Heim Jr. 1990). It is difficult to extrapolate from one region to another, or to conclude from studies for the whole United States to a specific region.

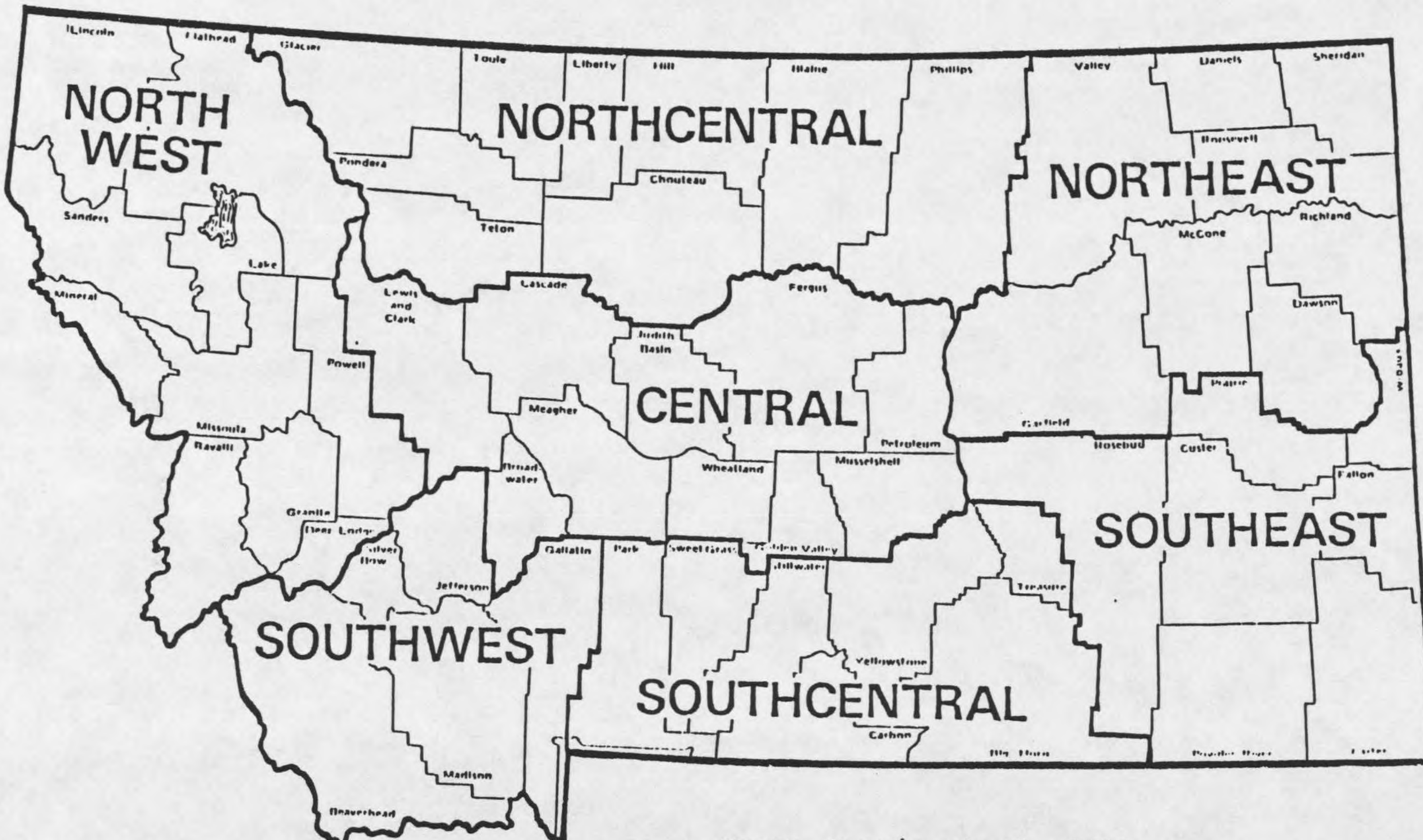
I believe that even though it has certain limitations, PDSI is an important tool of monitoring and characterizing drought. It is probably one of the best regional and agricultural drought indices that exist so far. Precipitation measurements can contribute to drought evaluation due to its largest contribution to drought, compared to other factors. The NDVI, which compensates for some of the weaknesses of the PDSI, may add information to the comprehensive assessment of drought.

The Study Area

The Northeastern District of Montana (Figure 1) is part of the Northern Great Plains physiographic province (Merritt et al. 1991). It is characterized by moderately dissected plains and small mountain ranges.

The climate has great variability (Rosenberg and Katz, 1990) and climatic extremes (Army and Hanson, 1960), which constitute one of the major problems in the region (Caprio and Eslick, 1961). Total mean annual precipitation is 13" and average annual temperature is 41.8°F (U.S. National Climatic Center, 1990). PET generally exceeds precipitation (Rosenberg and Katz, 1990), and actual annual ET is approximately 13" (Dightman, 1962).

Figure 1. Map of Montana showing the seven crop districts



From: Caprio et al. 1980

Winter weather is dominated by polar continental air masses, and summer weather by air masses from the Pacific Ocean or the Gulf of Mexico (Caprio, 1991a). Precipitation is greatest during the months of April to July, when 50 to 60% of the precipitation occurs (Caprio, 1991a). June is the month of greatest precipitation (Caprio and Eslick, 1961). At Culbertson in the Northeast district, 27% of precipitation received during the spring wheat fallow period was conserved in the soil (Aasheim, 1954).

The climate has some good features: ample solar radiation to power photosynthesis; usually calm, dry autumns that make harvesting easier; precipitation maxima during the growing season; winds that keep the growing crops well supplied with carbon dioxide and disperse pollutants; low humidity which diminishes the virulence of certain plant diseases and also makes crop drying less costly (Rosenberg and Katz, 1990).

Drought represents a recurring condition (Rosenberg, 1978). Among the important weather elements that influence agricultural production, inadequate precipitation is usually the major factor limiting the yield on non-irrigated land (Caprio and Eslick, 1961). This is particularly true for spring wheat yields, which tend to fluctuate directly with precipitation (Caprio and Eslick, 1961). The greatest difference between precipitation in good yield years and that in poor yield years was found to occur in March - April (Caprio and Eslick, 1961).

Climatic extremes are reflected in large yearly fluctuations in agricultural production (Army and Hanson, 1960). In dryland farming, severe loss of yields is common (Army and Hanson, 1960). Because moisture is the limiting factor for crop production, summer fallow is commonly practiced (Aasheim, 1954).

A total of 25" of precipitation usually satisfies crop moisture needs in Montana (Caprio and Williams, 1973). Army and Hanson (1960) found that precipitation between seeding and heading appeared to be more critical in relation to spring wheat yield than precipitation in the remainder of the growing season.

The growing season in the Northeast District is mostly encompassed within the period March to August (Caprio and Williams, 1973). The important agricultural crops are spring wheat, rangeland, wild hay, winter wheat and alfalfa. Livestock and livestock products have about twice the income of crops (Montana Agricultural Statistics, 1919 - 1990).

Spring wheat is generally seeded in April, headed approximately in July and harvested in August - September (Caprio, 1958). For rangeland, moisture in the autumn is important, which can be at least partially explained by the fact that some of this moisture is stored until the spring (Caprio and Williams, 1973). May - June moisture is also important because this is the time of maximum plant growth. Winter wheat is planted in September - October, headed in

June, and is generally harvested in August (Caprio, 1958).

Precipitation totals for the whole period of March through August in the Northeast District were found to be related to precipitation from the beginning of April until the end of May (Caprio and Williams, 1973). In a Chi Square analysis, dry years were characterized by fewer days with precipitation ≥ 0.05" from April 8 until May 27. The Chi Squares were higher from April 15 through May 13 within the above mentioned wider period.

High correlation was found between August range condition and wild hay yield. August also reflects moisture conditions that have built up before and during the growing season. August, therefore, was chosen as the critical month for agrometeorological analysis (Caprio and Williams, 1973).

In this research we analyzed the features of droughts in the Northeast District of Montana and assessed their impact. We also explored methods of monitoring droughts and the potential for predicting them.

MATERIALS AND METHODS

This study was based on historical data of the Palmer Drought Severity Index, daily precipitation totals, agricultural yields and the Normalized Difference Vegetation Index.

Palmer Drought Severity Index

The data source for the PDSI was the National Climatic Data Center (1991b). The data included monthly values of the index, one value for the Northeast District, for each of the years 1895-1991. First, the index values were classified as to drought and wet severity classes (Table 1).

Statistical Analyses

Statistical variables were calculated for the PDSI values for the years 1895 - 1990: mean, standard deviation, median, sum of the positive values, sum of the negative values, the number of positive and the number of negative values (Table 2).

The change in PDSI between two successive months was calculated by subtracting PDSI of the previous month from PDSI of the present month. For example, the change in PDSI between January and February was February PDSI minus January PDSI. The mean, standard deviation, median, the sum of positive values, the sum of negative values, the number of positive and the number of negative values were calculated for the change in

PDSI (Table 3).

Correlations

PDSI of August was correlated with PDSI for each of the 19 preceding months for the years 1895 - 1990 (Table 4). PDSI in August reflects the moisture conditions accumulated during the growing season, and the conditions near the time of harvest. The 19 months included 12 months of the previous year, and 7 months from the same year - all preceding the month of August. The PDSI value was for the end of each month, and included climate information for the entire month.

In order to find combinations with higher correlations, step wise up and down multiple regressions between August PDSI and PDSI of the 19 months preceding August were conducted (Table 5). The multiple regressions included multiple and triple months. The influence of each month separately, as well as the combined influences of several months, were examined. Month squared was introduced to determine whether the relations were curvilinear.

The change in PDSI between May and August was correlated with the change in PDSI between important moisture periods during the beginning of the growing season. The periods during the beginning of the growing season, which were the independent variables in the correlations, were chosen based on Caprio and Williams (1973). They were: April - May, March - April; April - May * March - April; April - May, March - May (note: [Month, month] represents the influence of each month separately, [Month - month] represents from month until month and [Month * month] represents the combined influence of both months).

Probabilities

To help in predicting August PDSI, probabilities of PDSI in August according to May PDSI were calculated (Table 6, 7, 8, 9). Probabilities were generated by MSUSTAT (Lund, 1991).

Precipitation

The precipitation data source, provided by the Montana State Climate Office (1990), was daily totals in inches for the period 1897 - 1988. Three representative stations in the district were chosen: Glasgow, Glendive and Poplar.

Correlations

Precipitation for the whole growing season was correlated with precipitation during the beginning of the growing season. The periods of precipitation and the daily amounts were determined according to Caprio and Williams (1973).

Precipitation during the beginning of the growing season included the number of days with precipitation ≥ 0.05", which distinguishes between dry and wet years (Caprio and Williams, 1973), and the total precipitation. The beginning of the growing season consisted of two precipitation periods, important for determining the precipitation for the entire season (Caprio and Williams, 1973): A broader period, April 8 - May 27 and a shorter, as well as more important period, April 15 - May 13. Precipitation for the whole growing season was calculated as the total precipitation for the period March 1 - August 26.

Correlations were conducted for the three stations separately, and for the mean and median (Table 12) values of these stations. The purpose of studying each location was to examine the spatial variability in the drought conditions.

The change in PDSI May → August was correlated with different periods of precipitation and PDSI in the beginning of the growing season. The precipitation and PDSI in the beginning of the growing season were, for example, a variable which included: PDSI May, total precipitation April 8 - May 27, the number of days with precipitation April 15 - May 13.

Chi Square Analyses

Chi Square analyses (Snedecor, 1953) were conducted between precipitation for the entire growing season as well as August PDSI, and precipitation in the beginning of the growing season (Table 13). Precipitation in the beginning of the growing season (April 26 - May 16) included the number of days with precipitation ≥ 0.01" and the number of days with precipitation ≥ 0.05"; both distinguish between dry and wet years (Caprio and Williams, 1973). Precipitation data were mean values of the three stations.

The sorted variable was total precipitation for the whole growing season (March 1 - August 26) and August PDSI. This variable was sorted to quartile dry years, half middle years and quartile wet years. The quartile dry and the quartile wet separately, were analyzed versus the half middle years.

Separate analyses were made for the period 1931 - 1970, which was identical to the period carried by Caprio and Williams (1973), and for the entire period of precipitation data, 1897 - 1988. These analyses included P values and PDSI, which were not included before.

Agricultural Yields

The source of the agricultural yield data was Montana Agricultural Statistics (1919 - 1990). Analyses were conducted on district yields of three crops: spring wheat, wild hay and range condition. The spring wheat data were in bushels per acre for the years 1919 - 1990. Wild hay was in tons per acre for the years 1944 - 1969. Range conditions were percentage estimates for the years 1928 - 1985. Agricultural yields were correlated with PDSI for each month during the growing season (Table 14).

A trend in yield data, due to technology, is characteristic for most of the grain crops in developed countries (Wilhite and Neild, 1982). Effects of technology on yield include: crop management, fertilizers, irrigation, farm machinery and equipment, herbicide and insecticide applications (Sakamoto, 1978). In order to concentrate on the influence of climate on yields, technology was held constant (Wilhite and Neild, 1982). The technology effects are time dependent, and therefore a time variable was introduced into the multiple regressions, as surrogate for the effects of technology. The time variable was used to determine the normal yield by the least squares method. Time squared was introduced in order to determine whether the technology effects were linear. The percentage of normal was the percentage departure of actual yield from normal yield.

Normalized Difference Vegetation Index

The data source of this satellite based index was the National Climatic Data Center (1991a), Asheville NC. The index values were bi-weekly, for the years 1985 - 1988. Each value was the mean of the indices of the many pixels in the district (Gallo, 1991, personal communication). In each pixel, the NDVI was based on the maximum value for the two weeks.

PDSI during the growing season, as well as spring wheat yield, winter wheat yield and range condition, were correlated with the NDVI at the end of each month in the growing season (Table 15).

RESULTS

The results include the following sections: Palmer Drought Severity Index, precipitation, agricultural yields and Normalized Difference Vegetation Index.

Palmer Drought Severity Index

This section contains classification of the index values into severity classes, calculation of statistical variables for the index values as well as for the change in the index between two successive months, and correlations for the PDSI values as well as for the change in PDSI between months.

Severity Classes

In order to characterize the features of droughts in the Northeast District, PDSI monthly values were clustered according to the drought and wet severity classes defined by Palmer (1965) (Table 1). Because of the large amount of data, only the more significant (moderate, severe and extreme) dry and wet spells were classified. For the same reason, moderate and severe spells were clustered together (see legend). (M.D., S.D and E.S. in Table 1 refer to moderate, severe and extreme drought, respectively. M.W., E.W. and S.W. refer to moderately, extremely and severly wet, respectively).

Table 1. PDSI values for each month in the years 1895-1991.

Month

Year \ Month	Jan / Jul	Feb / Aug	Mar / Sep	Apr / Oct	May / Nov	Jun / Dec
1895	0.70	1.03	1.36	1.10	0.79	1.11
	1.70	1.60	1.27	0.94	1.20	1.01
1896	1.20	1.09	1.32	2.11	3.22	2.64
	2.33	1.95	2.36	1.75	2.90	2.51
1897	2.36	2.63	3.01	-0.27	-1.52	0.85
	1.47	-1.01	-1.49	-1.55	0.56	-0.18
1898	-0.53	-0.53	0.55	0.45	0.83	1.22
	0.00	-0.28	-0.59	0.87	0.69	0.35
1899	0.35	0.37	0.67	0.73	1.90	1.85
	2.29	2.54	-0.54	-0.16	-0.62	-0.63
1900	-0.90	-0.85	-0.85	-0.43	-1.05	-2.38
	-3.19	1.05	1.83	-0.22	-0.34	-0.53
1901	-0.59	-0.71	-0.76	-0.79	-1.65	1.05
	1.13	-1.55	0.88	-0.68	-0.91	-0.55
1902	-0.90	0.31	0.60	0.47	1.78	2.04
	2.45	-0.33	-0.91	-1.26	0.01	0.08
1903	0.20	0.04	0.02	0.27	0.88	0.17
	1.48	2.30	2.51	1.72	1.59	1.60
1904	1.46	1.75	2.78	-0.27	-0.46	-0.84
	-1.14	-1.43	-2.13	-2.72	-3.04	-2.67
1905	-2.64	-2.60	-2.55	-2.55	-2.19	-1.14
	-0.90	-1.61	-1.99	-1.76	-1.29	-1.57
1906	-1.36	-1.39	-1.20	-1.51	1.56	2.74
	2.37	2.56	1.89	1.44	2.01	2.42
1907	2.95	2.88	3.24	3.39	3.87	**5.05**
	6.46	**7.72**	**7.38**	**6.20**	**5.40**	**4.79**
1908	**4.25**	**4.33**	**4.55**	3.96	**5.47**	**5.86**
	5.99	**6.00**	**5.62**	**6.08**	**5.52**	**4.87**
1909	**4.92**	**4.49**	**4.18**	**4.49**	**5.65**	**6.22**
	8.03	**7.82**	**7.83**	**6.81**	**6.47**	**6.42**
1910	**5.84**	**5.82**	**4.63**	3.51	2.93	2.15
	1.41	1.27	2.06	1.85	1.94	1.60
1911	1.81	1.80	1.05	1.15	1.51	1.55
	1.29	2.17	3.03	3.15	2.97	2.51
1912	2.18	1.64	1.47	1.59	2.68	1.55
	2.26	3.14	3.68	3.74	-0.24	-0.27
1913	0.27	-0.32	-0.08	-0.72	-0.93	-0.96
	-1.46	0.39	0.04	0.86	-0.18	-0.63
1914	-0.54	-0.41	-0.53	0.06	0.03	1.25
	-1.13	0.03	-0.13	0.48	-0.11	-0.28
1915	-0.57	-0.56	-0.78	-1.69	-1.94	1.45
	3.77	3.57	**4.20**	3.51	3.42	3.14
1916	3.49	3.35	3.51	3.20	3.41	**5.13**
	6.34	**6.45**	**6.32**	**6.07**	**5.39**	**5.45**

Legend:

-2 - -2.9: M. D.
-3 - -3.9: S. D.
≤ -4 : E. D.

2 - 2.9: M. W.
3 - 3.9: S. W.
≥ 4 : E. W.

Table 1 (continued)

1917	**5.09**	**5.02**	**4.74**	**5.06**	-0.35	-0.43
	-1.08	-1.70	-1.54	-1.15	-1.68	-0.91
1918	-0.63	-0.67	-0.91	-0.52	-0.55	-2.22
	0.17	1.22	1.18	-0.48	-0.38	-0.19
1919	-0.41	-0.13	-0.29	-0.93	-0.91	-2.56
	-3.42	-3.68	-3.90	0.84	0.99	0.92
1920	1.21	0.98	1.05	2.20	2.38	2.48
	2.85	2.81	-0.17	-0.51	-0.81	-0.92
1921	-1.07	-1.19	-0.88	-0.59	-0.73	-0.80
	-0.76	-1.61	-1.20	-1.87	0.36	0.27
1922	0.09	0.40	0.19	0.98	1.85	1.78
	2.50	2.32	1.43	1.09	1.44	1.56
1923	1.60	1.49	1.26	1.29	1.04	1.78
	2.57	2.62	2.52	0.04	-0.15	-0.24
1924	-0.41	0.04	0.17	0.30	-0.58	1.00
	-0.50	-0.72	-0.92	-0.81	-0.74	-0.70
1925	-0.72	-0.77	-0.60	-0.20	-0.94	-0.68
	-1.35	-1.80	0.90	1.74	-0.27	-0.37
1926	-0.56	-0.53	-0.88	-1.69	-2.32	-2.50
	-3.04	0.24	1.46	1.26	1.31	1.19
1927	1.08	1.01	0.80	0.95	**4.17**	3.72
	4.84	**6.51**	**6.38**	**6.08**	**6.22**	**6.06**
1928	**5.60**	**4.85**	**4.58**	**4.36**	3.02	3.65
	5.39	**5.95**	-0.60	-0.55	-0.68	-0.71
1929	0.08	0.03	0.33	0.31	1.01	-0.17
	-0.89	-1.96	-1.60	-1.51	-1.44	-0.78
1930	-0.94	-0.60	-0.65	-0.95	-1.49	-2.17
	-2.71	-3.43	-3.07	-2.20	-1.91	-2.08
1931	-2.30	-2.19	-1.86	-2.64	-3.84	-4.84
	-4.83	-5.16	-4.75	-4.88	-4.74	-4.30
1932	-4.15	-3.79	0.31	1.05	-0.73	-0.08
	-0.66	-0.07	-0.84	0.84	0.87	0.48
1933	0.36	0.13	0.02	0.60	1.16	-0.95
	-1.68	-1.18	-1.83	0.20	0.26	0.92
1934	-0.23	-0.56	-0.46	-1.36	-3.15	-3.37
	-4.33	-5.23	-5.13	-5.55	-5.43	-5.01
1935	-4.44	-4.35	-4.03	-3.68	-3.23	-3.20
	-2.25	-2.88	-3.73	-3.86	-3.30	-3.03
1936	-2.42	-1.82	-1.65	-1.83	-2.65	-4.27
	-5.01	-5.14	-5.59	-5.45	-5.12	-4.54
1937	-4.29	-4.18	-3.91	-3.95	-5.30	-6.18
	-6.04	-6.77	-6.37	0.75	0.37	0.21
1938	0.29	0.30	0.81	0.24	0.36	0.17
	0.67	0.38	0.31	0.64	0.83	-0.06
1939	-0.01	-0.24	-0.53	-0.93	-1.17	1.47
	-0.38	-0.80	-1.46	-1.34	-1.80	-1.36
1940	-1.58	0.11	0.18	1.87	1.55	1.77
	2.18	-0.72	-1.29	-1.01	-0.68	-0.91
1941	-1.10	-1.24	-1.23	-0.93	-1.18	-0.83
	-1.52	0.34	1.09	0.75	1.25	-0.32

Table 1 (continued)

1942	-0.67	-0.46	-0.58	-0.64	0.63	1.45
	-0.53	-0.46	-0.44	-0.54	-0.59	0.01
1943	0.72	-0.33	-0.13	-0.49	-0.93	2.25
	2.33	2.84	-0.83	-0.30	-0.41	-0.71
1944	-1.01	-1.02	0.34	0.36	-0.46	2.13
	1.53	2.04	-0.09	-0.95	-0.35	-0.68
1945	-0.66	-0.69	0.65	0.78	0.37	0.73
	-0.63	-0.97	-0.81	-0.94	0.59	0.76
1946	-0.28	-0.21	-0.83	-2.05	-2.34	-2.35
	1.48	0.71	1.63	2.35	2.15	2.12
1947	1.93	1.62	1.41	1.56	1.09	1.87
	1.65	3.59	2.82	2.04	1.98	1.76
1948	1.58	1.88	1.52	1.58	1.30	0.87
	1.88	1.85	-1.10	-1.70	0.47	0.85
1949	0.86	0.87	-0.21	-1.50	-2.21	-3.01
	-3.12	-3.79	-4.35	-3.44	-3.77	0.29
1950	0.70	0.66	0.83	1.49	1.12	2.42
	2.30	2.58	3.78	3.29	2.83	2.55
1951	2.55	2.75	2.50	2.79	-0.69	-0.94
	-1.69	0.93	1.42	1.58	1.25	1.37
1952	1.18	1.74	0.02	-1.15	-1.98	-2.65
	-2.13	-2.02	-2.64	-3.01	-3.00	-3.07
1953	0.10	0.06	0.08	1.18	3.50	**5.30**
	5.62	**5.72**	**4.69**	**4.78**	3.92	3.66
1954	3.78	3.51	3.87	3.77	3.53	3.52
	2.72	**4.32**	**5.13**	**4.94**	3.87	3.16
1955	2.89	2.79	2.28	2.83	3.27	-0.62
	0.59	-0.94	-1.64	-1.91	-1.62	-1.53
1956	-1.74	-1.83	-2.14	-2.30	-2.51	-3.49
	-3.46	-2.50	-3.09	-3.42	-3.11	-2.91
1957	-2.65	-2.51	-2.61	-1.69	-2.18	-2.35
	-2.61	-2.59	-2.67	-2.31	-2.22	-2.41
1958	-2.61	-2.32	-2.53	-2.69	-4.40	-4.45
	-4.71	-5.24	-5.65	-5.24	-3.81	-3.57
1959	-3.15	-2.79	-2.91	-2.98	-3.03	-2.73
	-3.76	-4.16	-2.46	-1.52	-0.91	-1.17
1960	-1.05	-1.01	-1.23	-1.05	-1.21	-1.69
	-2.81	-2.33	-3.28	-3.67	-3.43	-3.21
1961	-3.35	-2.79	-3.18	-2.49	-2.80	-4.44
	-5.04	-5.97	-4.13	-3.84	-3.83	-3.80
1962	-3.68	-3.33	-3.12	-3.78	0.75	0.73
	1.94	1.71	0.98	1.59	-0.68	-0.97
1963	-1.08	0.05	-0.14	0.72	0.63	1.52
	1.19	1.48	-0.84	-1.88	-2.04	-2.10
1964	-2.14	-2.25	-2.05	-2.24	-2.22	-1.60
	-2.14	-2.11	-2.54	-2.93	0.14	0.44
1965	0.62	0.37	0.08	0.21	2.29	2.62
	3.19	3.98	**4.44**	-0.66	-0.84	-0.94
1966	-0.81	-0.93	-1.28	-0.89	-0.96	-1.84
	-1.38	-0.73	-1.65	-1.65	-1.43	-1.52

Table 1 (continued)

1967	0.30	0.42	0.72	1.93	-0.40	-0.39
	-0.96	-1.95	-1.19	-0.79	-0.84	-0.72
1968	-0.75	-0.92	-1.64	-1.79	-2.44	-1.52
	-2.14	1.95	-0.58	-0.99	-1.02	0.39
1969	1.11	0.90	0.65	1.45	0.90	1.12
	2.42	-0.86	-1.59	0.57	-0.38	-0.28
1970	-0.09	-0.43	-0.58	1.75	2.08	1.75
	1.62	0.71	1.06	1.21	1.16	0.92
1971	1.56	-0.19	-0.11	-0.14	-0.59	-1.13
	-2.09	-3.21	0.05	1.72	1.31	1.31
1972	1.35	1.75	1.93	1.74	2.74	2.73
	3.18	3.59	-0.18	-0.27	-0.57	-0.35
1973	-0.76	-0.97	-1.45	0.91	-0.48	-0.37
	-1.29	-1.94	1.19	0.57	0.58	0.92
1974	0.59	0.43	0.59	0.15	1.53	-1.42
	-1.45	1.56	-0.66	-0.80	-0.75	-0.81
1975	-1.10	-1.29	0.51	1.83	2.10	2.42
	2.87	3.12	2.67	3.18	3.17	3.11
1976	2.78	2.25	2.02	1.72	0.85	2.24
	2.17	2.26	-0.77	-1.01	-1.08	-1.04
1977	-0.65	-0.84	-1.13	-2.23	-2.62	-3.72
	-4.45	0.06	1.22	0.86	0.92	1.46
1978	1.09	1.38	1.05	0.48	2.50	2.73
	3.31	2.53	**4.97**	**4.38**	**4.45**	**4.42**
1979	3.86	**4.15**	3.84	**4.34**	**4.37**	-1.04
	-0.96	-1.69	-2.37	-2.70	-2.65	-2.75
1980	-2.26	-2.30	-2.38	-3.44	-4.98	-5.63
	-6.59	-5.19	-4.83	-3.65	-3.51	-3.05
1981	-3.19	-3.25	-3.50	-4.24	-4.56	-4.21
	-4.59	-5.12	-5.54	0.53	0.46	0.26
1982	0.76	0.69	1.11	0.87	2.32	1.83
	1.45	1.33	1.37	1.81	1.30	1.71
1983	-0.25	-0.51	-0.30	-0.86	-0.89	-2.28
	-2.26	-3.34	-3.11	-3.37	-3.22	-3.00
1984	-2.74	-2.72	-2.70	-3.23	-4.18	-3.85
	-5.54	-6.28	-5.57	-5.17	-4.83	-4.26
1985	-4.27	-4.28	-3.79	-3.67	-3.85	-5.19
	-6.03	-4.77	-4.22	-3.24	-2.77	-2.50
1986	-2.40	-1.95	-2.63	-2.77	-2.15	-3.06
	-2.73	-3.33	2.99	3.20	3.38	-0.27
1987	-0.47	-0.66	0.72	-1.14	-0.77	-2.01
	1.34	0.01	-0.17	-0.73	-1.21	-1.55
1988	-1.53	-1.54	-1.72	-2.38	-3.49	-5.24
	-6.21	-6.72	-6.03	-5.94	-5.57	-4.95
1989	-4.16	-3.82	-3.70	-2.46	-1.96	-2.84
	-3.47	-3.23	-3.80	-3.20	-2.78	-2.40
1990	-2.40	-2.56	-2.52	-2.60	-2.75	-3.59
	-3.77	-3.98	-4.83	-4.87	-4.46	-4.17
1991	-4.08	-3.82	-3.60	0.79	0.90	2.46
	2.22	1.39	1.75	1.23	1.21	0.82

The significant features of drought and wet spells, as shown in Table 1, are: The lowest value for the 97 years was -6.77 in August, 1937 and the highest value was 8.03 in July, 1909. Drought months and wet months tended to cluster in batches of a year or several years. Short periods of drought and wet spells were few.

Severe wet periods were in 1907 - 1910, 1915 - 1917, 1927 - 1928, 1953 - 1955, 1978 - 1979. Drought developed in this area every decade. Severe dry spells were in the 1930's (1931 - 1932, 1934 - 1935, 1936 - 1937), in the end of the 1950's (1958, 1961), and in the 1980's (1980 - 1981, 1984 - 1985, 1988 - 1990).

Dry periods started in different months without any typical starting month. Entering into dry conditions was usually a gradual process. There was no typical dry season in the entire year. Ending dry spell was usually a sharp process, many times in the beginning of the winter.

Several times a wet spell preceded a dry spell (wet spell in 1927 preceded dry spell in 1931; wet in 1953 - 1954 preceded dry in 1956; wet in 1978 preceded dry in 1979).

Dry periods lasted five years in the 1930's, six years in the 1950 - 1960's and nine years in the 1980 - 1990's. The last decade had the highest number of dry months: 88 out of 120 months were dry (PDSI ≤ -1).

Statistical Variables

The following statistical variables for each month, 1895 - 1990, were calculated from the PDSI data for the Northeast District: mean, standard deviation (S.D.), median (Medi), sum of positive values, sum of negative, number of positive values and number of negative values (Table 2).

Table 2. Mean, standard deviation, median, sum of (+), sum of (-), no. of (+) and no. of (-) for PDSI in each month.

	Mean	Medi.	S.D.	Sum(-)	Sum(+)	#(-)	#(+)
Jan	-0.05	-0.28	2.22	-83	78	52	43
Feb	-0.04	-0.24	2.12	-78	74	51	44
Mar	0.01	0.02	2.04	-73	74	47	48
Apr	-0.03	0.06	2.12	-83	80	47	48
May	-0.10	-0.46	2.42	-100	91	51	44
Jun	-0.16	-0.17	2.75	-116	102	49	46
Jul	-0.17	-0.53	3.16	-133	117	50	45
Aug	-0.09	-0.07	3.30	-131	122	48	47
Sep	-0.25	-0.59	3.14	-131	107	56	39
Oct	-0.14	-0.48	2.81	-111	98	52	43
Nov	-0.12	-0.34	2.58	-99	88	53	42
Dec	-0.11	-0.28	2.37	-90	80	54	41

The drought characteristics monitored in Table 2 were as follows: The mean and median of all the months were around zero, to slightly negative. The highest standard deviations were for the summer months: August (3.30), July (3.16) and September (3.14). The standard deviations decreased gradually from August towards March, which had the lowest standard deviation (2.04).

The summer months had the highest sum of negative values: July (-133), September (-131) and August (-131). The sum of the negative values decreased gradually from July towards the lowest negative value (-73) in March.

The summer months had also the highest sum of positive values, August (122), July (117) and September (117). The positive values declined gradually towards March (74).

September had the highest number of negative values (56), and March and April the lowest (47). The highest number of positive values were in March and April, and the lowest in December.

The pattern of entering and ending dry spells that was found in the classified data (Table 1), inspired the calculation of statistical parameters for the change in PDSI between two successive months. The mean, standard deviation, number of times the change was greater than +2 PDSI units, number of times the change was less than -2 units, maximum positive and negative change between every two successive months in the year are presented in Table 3.

Table 3. Mean, standard deviation, no. of changes > 2 PDSI units, no. of changes < -2 units, max (+) change and max (-) change in PDSI of 2 successive months.

	Mean	S.D.	# > 2	# < -2	Max(+)	Max(-)
Jan → Feb	0.01	0.40	0	0	1.69	-1.75
Feb → Mar	0.05	0.65	1	0	4.10	-1.72
Mar → Apr	-0.04	0.84	2	2	2.36	-3.28
Apr → May	-0.07	1.26	6	3	4.53	-5.41
May → Jun	-0.07	1.31	6	4	3.39	-5.41
Jun → Jul	-0.02	1.03	4	1	3.83	-2.38
Jul → Aug	0.08	1.34	6	5	4.51	-3.28
Aug → Sep	-0.17	1.57	6	11	6.32	-6.55
Sep → Oct	0.11	1.40	5	3	7.12	-5.10
Oct → Nov	0.02	0.84	4	3	3.07	-3.98
Nov → Dec	0.01	0.68	1	1	4.06	-3.65
Dec → Jan	0.02	0.55	1	0	3.17	-1.96

The important drought features shown in Table 3 were as follows: The mean change between two successive months for all the months was around zero. The fall had the highest negative and positive mean change: August → September (-0.17) and September → October (0.11).

The standard deviation for the change was the highest in the fall: August → September (1.57) and September → October (1.40). The lowest standard deviation was in the winter: January → February (0.40).

The number of positive changes greater than 2 PDSI units was the highest in the spring and summer-fall: April → May (6), May → June (6), July → August (6) and August → September

(6). The lowest was in the winter: January (0). The highest number of negative changes smaller than -2 PDSI units was in the fall: August → September (11). The lowest number was in the winter: December → March (0).

The maximum positive change was between September and October (7.12), and the minimum positive change was between January and February (1.69). The maximum negative change was between August and September (-6.55) and the minimum was between February and March (-1.72).

An interesting point was noticed when analyzing the statistical variables of the change in PDSI (Table 3) together with the classified data (Table 1). Most of the maximum positive and negative changes occurred when the change was from extreme conditions back toward normal.

Correlations

PDSI of August was correlated with PDSI in 19 preceding months. R and P values of these correlations are presented in Table 4 and in Figure 2. The correlations started a positive buildup 16 months preceding August - from the previous April (Table 4, Figure 2). The correlations increased as the independent variable month approached August. They were significant at the 1% level for all 14 months preceding August.

There was a sharp increase in the correlations from April to May (Table 4, Figure 2). The August vs. May correlation was

Table 4. R and P values of the correlations between August PDSI and PDSI in preceding months (X).

X: Month	R	P value
[a]PJan	0.199	0.053
PFeb	0.195	0.059
PMar	0.165	0.110
PApr	0.135	0.193
PMay	0.236	0.022
PJun	0.376	0.000
PJul	0.353	0.000
PAug	0.385	0.000
PSep	0.449	0.000
POct	0.525	0.000
PNov	0.542	0.000
PDec	0.559	0.000
Jan	0.617	0.000
Feb	0.607	0.000
Mar	0.647	0.000
Apr	0.673	0.000
May	0.813	0.000
Jun	0.887	0.000
Jul	0.915	0.000

a: Pmonth means month in the previous year

0.813. The close relation of PDSI between August and May for each year from 1895 until 1990 is presented in Figure 3 (1895 - 1940) and Figure 4 (1940 - 1990).

Figure 2. R and P values for Aug PDSI correlated with PDSI in preceding months

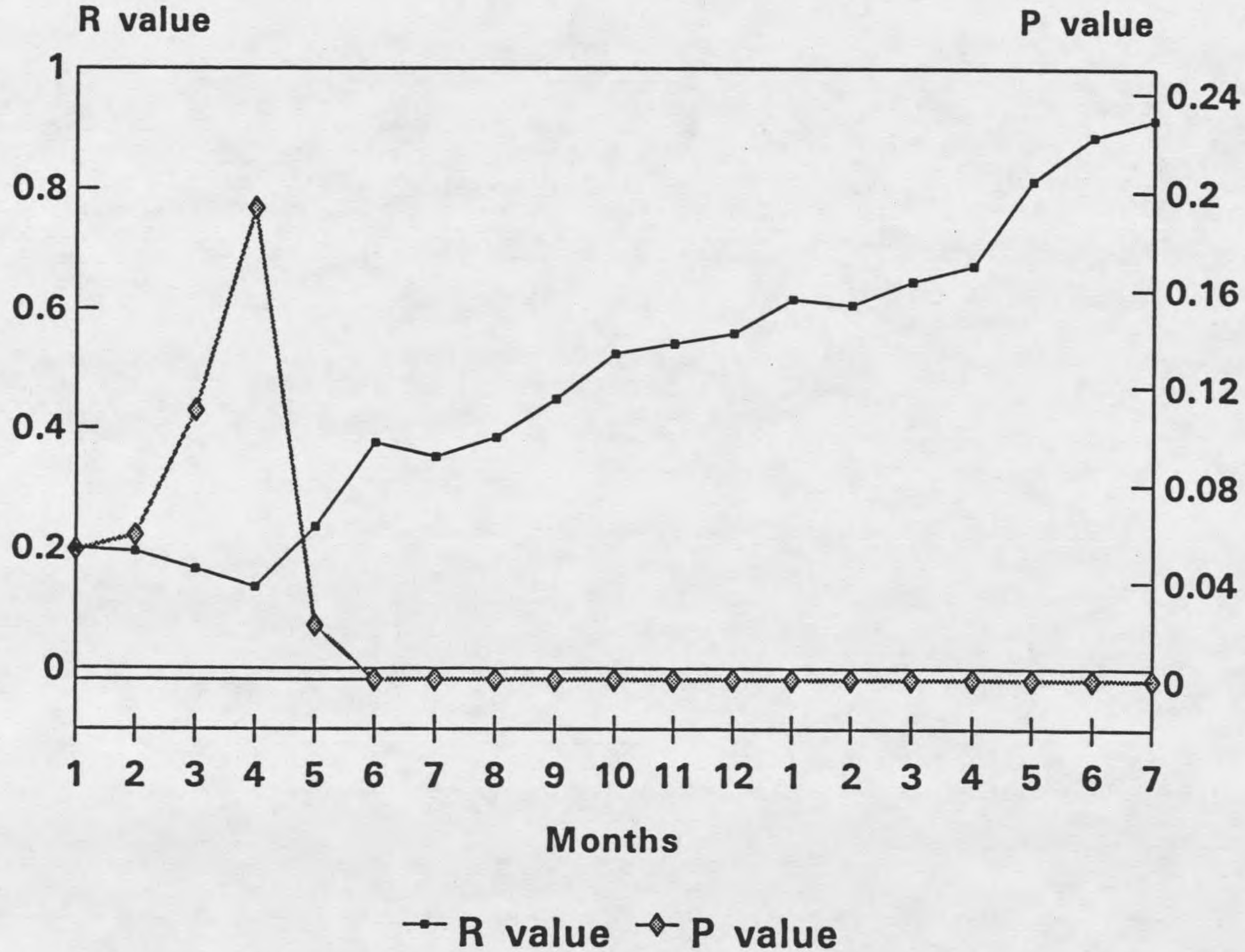


Figure 3. Relations between PDSI in August and May (1895-1940)

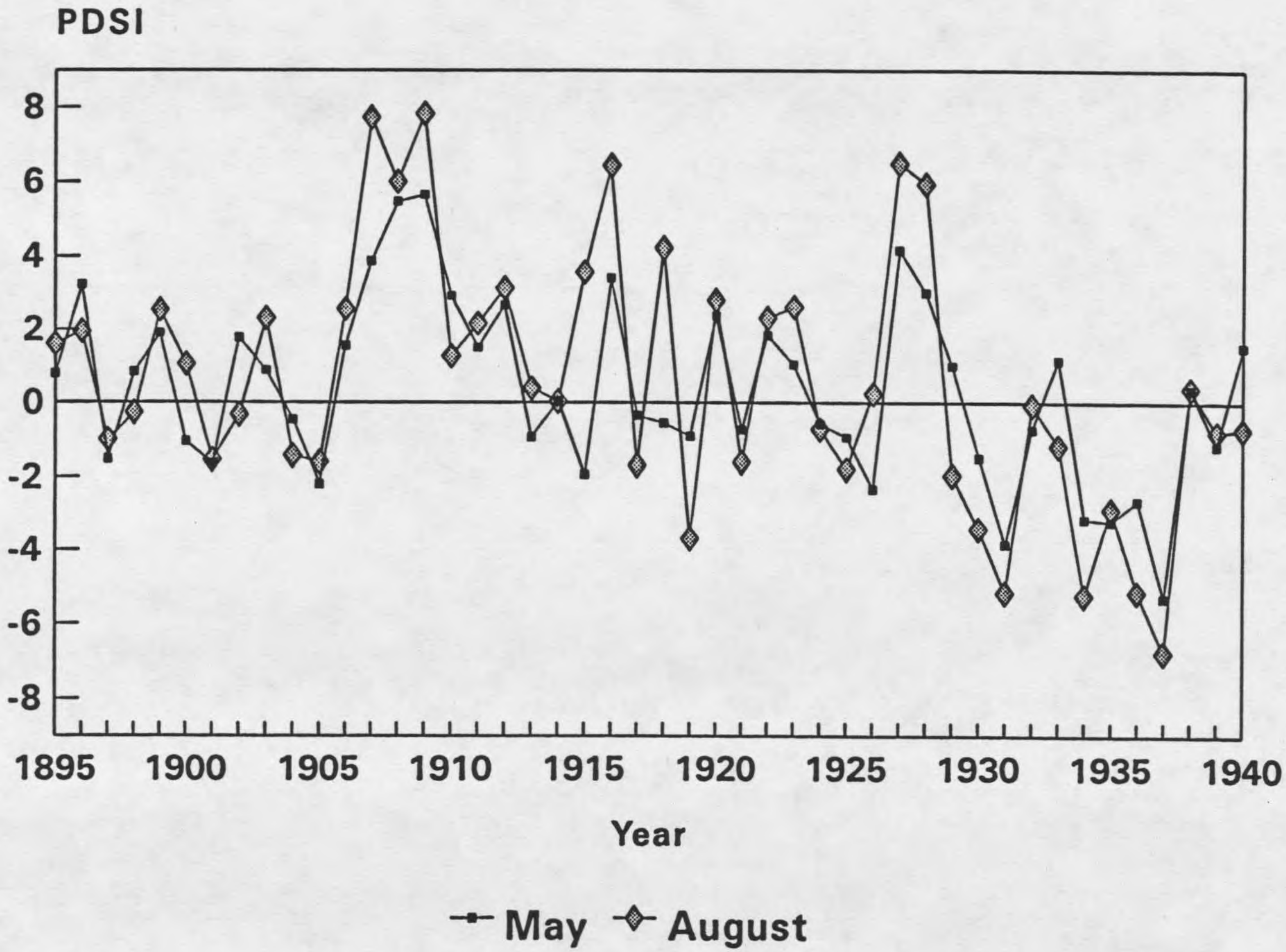
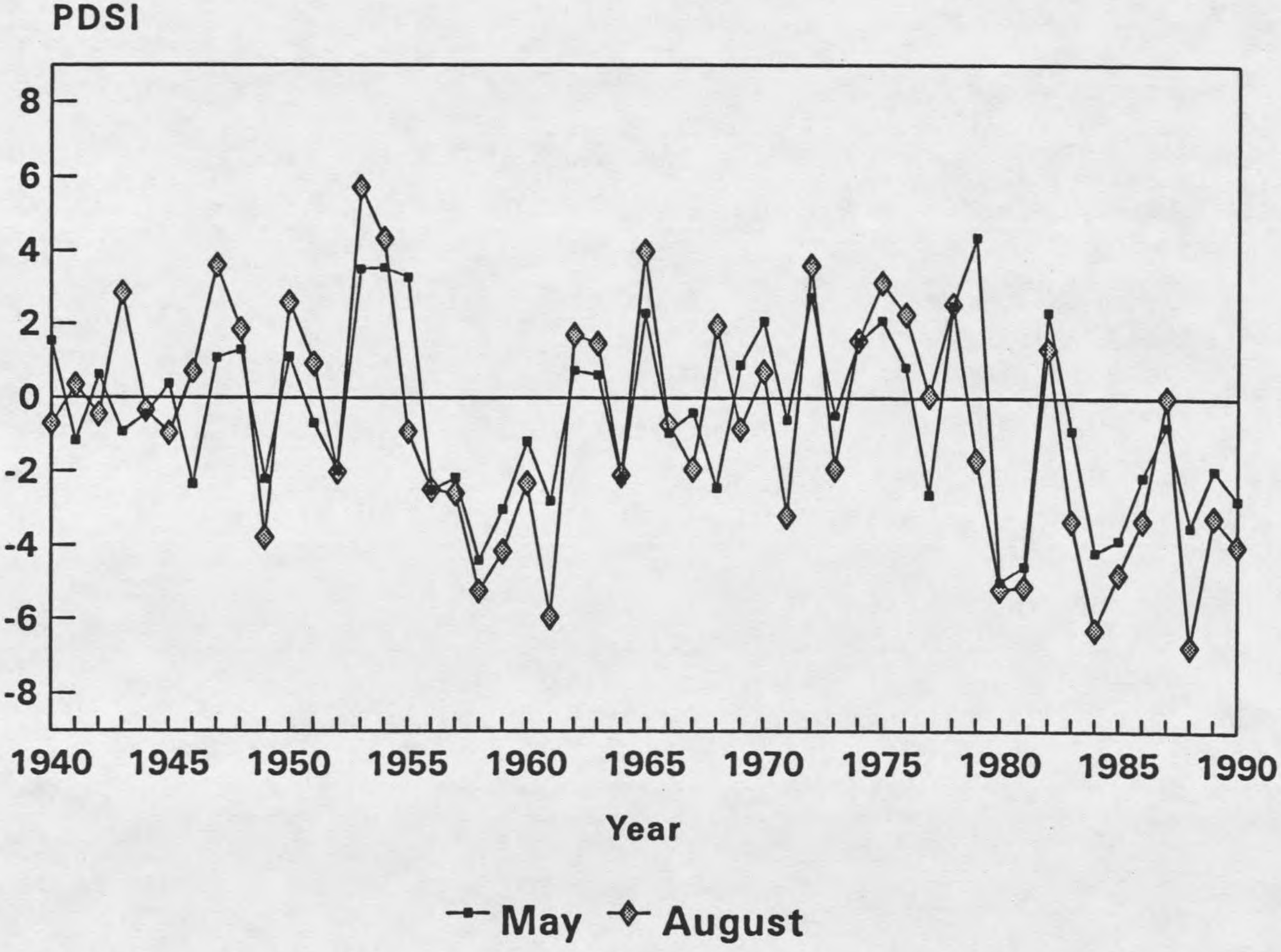


Figure 4. Relations between PDSI in August and May (1940-1990)



In order to detect higher correlations, stepwise up and down multiple regressions were conducted. From these regressions, those with the highest correlations between August PDSI, and individual months and periods of months, were chosen. R and P values of the chosen correlations are presented in Table 5.

Table 5. R and P values of the multiple regressions between August PDSI and PDSI in different periods of the year (X).

X: Period	R	P value
PAug[a], Oct-Nov[b], Jan-Feb	0.631	0.000
PJan-Mar	0.727	0.000
PJan-Apr	0.740	0.000
May, May^2	0.813	0.000
Jan, May	0.815	0.000
PJun, Jan, May	0.815	0.000
Jan, May, Jan*May[c]	0.817	0.000
PJun, Jan, May, Jan*Jun	0.818	0.000
PJan-May	0.849	0.000
Jan-Jul	0.924	0.000
PJan-Jul	0.929	0.000

a: [Month, month] means each month influences separately.
b: [Month - month] represents from month until month.
c: [Month * month] represents the combined influence of both months.

All these correlations were significant at the 1% level. The regressions had only slightly higher R values (Table 5) compared to the previous correlations (Table 4). For example, R = 0.849 when the independent variable was PDSI from previous January until May (PJan - May) (Table 5), compared to $R = 0.831$ when the independent variable was May PDSI (Table 4).

May and May^2 (May, May^2) as independent variables did not have higher correlation than May alone (Table 5). When May and May^2 were the independent variables, the significance of May was greater than 1%, and May^2 had very low significance ($P=0.571$). These facts suggested that the relations between August PDSI and PDSI in preceding months were linear.

Correlation coefficients were higher than 0.8 only when the three closest months to August (May, June, July) were part of the independent variable. These step wise up and down multiple regressions did not reveal more significant relations between August PDSI and PDSI in preceding months (Table 5).

The change in PDSI between May and August was correlated with the change in PDSI at the beginning of the growing season. The R values of these correlations ranged between 0.123 to 0.592, with the P values from 0.220 to 0.738. The change in PDSI between May and August was found not to be significantly related to the change in PDSI in any preceding period.

Probabilities

In order to predict August PDSI, probabilities of PDSI in August in relation to PDSI in May were calculated. The probabilities are presented in Tables 6, 7, 8, 9. PDSI values ranged from -8 to +8 at half unit intervals.

Table 6. Probabilities of ≤ August PDSI according to PDSI in May (-8.0 ≤ May PDSI ≤ -4.5, each half unit).

Aug PDSI ↓	May PDSI →							
	-8.0	-7.5	-7.0	-6.5	-6.0	-5.5	-5.0	-4.5
-8.0	.324	.238	.166	.110	.069	.041	.023	.012
-7.5	.432	.334	.247	.173	.115	.073	.043	.024
-7.0	.546	.443	.345	.256	.181	.121	.077	.046
-6.5	.655	.557	.455	.355	.265	.188	.127	.081
-6.0	.754	.666	.568	.466	.366	.275	.196	.133
-5.5	.834	.762	.676	.579	.477	.377	.284	.204
-5.0	.896	.841	.771	.686	.591	.489	.388	.294
-4.5	.936	.901	.848	.780	.696	.601	.500	.399
-4.0	.966	.942	.906	.855	.788	.706	.612	.511
-3.5	.983	.968	.945	.910	.861	.796	.716	.623
-3.0	.992	.984	.970	.948	.915	.867	.804	.726
-2.5	.996	.992	.985	.972	.951	.919	.873	.812
-2.0	.996	.997	.993	.986	.974	.954	.923	.879
-1.5	.999	.999	.997	.994	.987	.976	.957	.927
-1.0	1.000	1.000	.999	.997	.994	.988	.977	.959
-0.5	1.000	1.000	1.000	.999	.997	.995	.989	.979
0.0	1.000	1.000	1.000	1.000	.999	.998	.995	.990
0.5	1.000	1.000	1.000	1.000	1.000	1.000	.999	.998
1.0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	.999
1.5	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2.0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2.5	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
3.0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
3.5	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
4.0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
4.5	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
5.0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
5.5	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
6.0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
6.5	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
7.0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
7.5	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
8.0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

If, for example, May PDSI = -6.5, the probability to have August PDSI ≤ 0 was 100% (Table 6).

Table 7. Probabilities of ≤ August PDSI according to PDSI in May (-4.0 ≤ May PDSI ≤ -0.5, each half unit).

Aug PDSI ↓	May PDSI → -4.0	-3.5	-3.0	-2.5	-2.0	-1.5	-1.0	-0.5
-8.0	.006	.003	.001	.001	.000	.000	.000	.000
-7.5	.013	.007	.003	.001	.001	.000	.000	.000
-7.0	.026	.014	.007	.003	.002	.001	.000	.000
-6.5	.049	.028	.015	.008	.004	.002	.001	.000
-6.0	.085	.052	.030	.016	.008	.004	.002	.001
-5.5	.139	.090	.055	.032	.017	.009	.004	.002
-5.0	.212	.145	.095	.058	.034	.019	.010	.005
-4.5	.304	.220	.152	.099	.062	.036	.020	.010
-4.0	.406	.314	.229	.159	.104	.065	.038	.021
-3.5	.523	.421	.324	.238	.166	.110	.069	.041
-3.0	.634	.534	.432	.334	.247	.173	.115	.073
-2.5	.735	.645	.545	.443	.345	.256	.180	.121
-2.0	.820	.744	.655	.557	.454	.355	.265	.188
-1.5	.885	.827	.753	.666	.568	.466	.366	.274
-1.0	.931	.890	.834	.762	.676	.579	.477	.377
-0.5	.962	.935	.896	.841	.771	.686	.590	.489
0.0	.980	.964	.938	.901	.848	.780	.696	.601
0.5	.996	.991	.983	.968	.945	.910	.861	.796
1.0	.998	.996	.992	.984	.970	.948	.915	.867
1.5	.999	.998	.996	.992	.985	.972	.951	.919
2.0	1.000	.999	.999	.997	.993	.986	.974	.954
2.5	1.000	1.000	.999	.999	.997	.994	.987	.976
3.0	1.000	1.000	1.000	1.000	.999	.997	.994	.988
3.5	1.000	1.000	1.000	1.000	1.000	.999	.997	.995
4.0	1.000	1.000	1.000	1.000	1.000	1.000	.999	.998
4.5	1.000	1.000	1.000	1.000	1.000	1.000	1.000	.999
5.0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	.999
5.5	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
6.0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
6.5	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
7.0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
7.5	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
8.0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

If, for example, May PDSI = -2.5, the probability to have August PDSI ≤ 0.0 was 90% (Table 7).

Table 8. Probabilities of ≤ August PDSI according to PDSI in May (0.0 ≤ May PDSI ≤ 4.0, each half unit).

Aug PDSI ↓ \ May PDSI →	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0
-8.0	.000	.000	.000	.000	.000	.000	.000	.000	.000
-7.5	.000	.000	.000	.000	.000	.000	.000	.000	.000
-7.0	.000	.000	.000	.000	.000	.000	.000	.000	.000
-6.5	.000	.000	.000	.000	.000	.000	.000	.000	.000
-6.0	.000	.000	.000	.000	.000	.000	.000	.000	.000
-5.5	.001	.000	.000	.000	.000	.000	.000	.000	.000
-5.0	.002	.001	.000	.000	.000	.000	.000	.000	.000
-4.5	.005	.002	.001	.000	.000	.000	.000	.000	.000
-4.0	.011	.006	.003	.001	.001	.000	.000	.000	.000
-3.5	.023	.012	.006	.003	.001	.001	.000	.000	.000
-3.0	.043	.024	.013	.007	.003	.001	.001	.000	.000
-2.5	.077	.046	.026	.014	.007	.003	.002	.001	.000
-2.0	.127	.089	.049	.028	.015	.008	.004	.002	.001
-1.5	.196	.133	.085	.052	.030	.016	.008	.004	.002
-1.0	.284	.204	.139	.090	.055	.032	.017	.009	.004
-0.5	.388	.294	.212	.145	.094	.058	.034	.019	.010
0.0	.500	.398	.304	.220	.152	.099	.062	.036	.020
0.5	.716	.623	.523	.421	.324	.238	.166	.120	.069
1.0	.804	.725	.634	.534	.432	.334	.246	.173	.115
1.5	.873	.812	.735	.645	.545	.443	.344	.256	.180
2.0	.923	.879	.819	.744	.655	.556	.454	.355	.265
2.5	.957	.927	.885	.827	.753	.666	.568	.466	.366
3.0	.977	.959	.931	.890	.834	.762	.676	.579	.477
3.5	.989	.979	.962	.935	.895	.841	.771	.686	.590
4.0	.995	.990	.980	.964	.938	.900	.848	.779	.696
4.5	.998	.995	.990	.981	.966	.942	.905	.855	.788
5.0	.998	.995	.990	.981	.966	.942	.905	.855	.788
5.5	.999	.998	.996	.991	.983	.968	.945	.910	.861
6.0	1.000	.999	.998	.996	.992	.984	.970	.948	.915
6.5	1.000	1.000	.999	.998	.996	.992	.985	.972	.951
7.0	1.000	1.000	1.000	.999	.999	.997	.993	.986	.974
7.5	1.000	1.000	1.000	1.000	.999	.999	.997	.994	.987
8.0	1.000	1.000	1.000	1.000	1.000	1.000	.999	.997	.994

If, for example, May PDSI = 0.0, the probability to have August PDSI ≤ 1.0 was 80% (Table 8).

Table 9. Probabilities of ≤ August PDSI according to PDSI in May (4.5 ≤ May PDSI ≤ 8.0, each half unit).

Aug PDSI ↓ \ May PDSI →	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0
-8.0	.000	.000	.000	.000	.000	.000	.000	.000
-7.5	.000	.000	.000	.000	.000	.000	.000	.000
-7.0	.000	.000	.000	.000	.000	.000	.000	.000
-6.5	.000	.000	.000	.000	.000	.000	.000	.000
-6.0	.000	.000	.000	.000	.000	.000	.000	.000
-5.5	.000	.000	.000	.000	.000	.000	.000	.000
-5.0	.000	.000	.000	.000	.000	.000	.000	.000
-4.5	.000	.000	.000	.000	.000	.000	.000	.000
-4.0	.000	.000	.000	.000	.000	.000	.000	.000
-3.5	.000	.000	.000	.000	.000	.000	.000	.000
-3.0	.000	.000	.000	.000	.000	.000	.000	.000
-2.5	.000	.000	.000	.000	.000	.000	.000	.000
-2.0	.000	.000	.000	.000	.000	.000	.000	.000
-1.5	.001	.000	.000	.000	.000	.000	.000	.000
-1.0	.002	.001	.000	.000	.000	.000	.000	.000
-0.5	.005	.002	.001	.000	.000	.000	.000	.000
0.0	.010	.005	.002	.001	.000	.000	.000	.000
0.5	.041	.023	.012	.006	.003	.001	.001	.000
1.0	.073	.043	.024	.013	.007	.003	.001	.001
1.5	.121	.077	.046	.026	.014	.007	.003	.002
2.0	.188	.127	.081	.049	.028	.015	.008	.004
2.5	.274	.196	.133	.085	.052	.030	.016	.008
3.0	.376	.284	.204	.139	.090	.055	.032	.017
3.5	.488	.387	.294	.212	.145	.094	.058	.034
4.0	.601	.500	.398	.303	.220	.152	.099	.061
4.5	.706	.612	.511	.409	.313	.229	.159	.104
5.0	.706	.612	.511	.409	.313	.229	.159	.104
5.5	.796	.716	.623	.522	.420	.324	.237	.166
6.0	.867	.804	.725	.634	.534	.432	.334	.246
6.5	.919	.873	.812	.735	.644	.545	.443	.344
7.0	.954	.923	.879	.819	.744	.655	.556	.454
7.5	.976	.957	.927	.885	.827	.753	.665	.568
8.0	.988	.977	.959	.931	.890	.834	.762	.676

If, for example, May PDSI = 5.5, the probability to have August PDSI ≤ 3.0 was 20% (Table 9).

For readability of the probability tables, they were reduced to PDSI values from -6 to 6 and for each one unit. These probabilities are presented in Table 10 (negative values), and Table 11 (positive values). The probabilities are for equal or less August PDSI.

Table 10. Probabilities of ≤ August PDSI according to PDSI in May, for negative values (-6 ≤ PDSI ≤ 0, each one unit).

Aug PDSI ↓ May PDSI →

	-6.0	-5.0	-4.0	-3.0	-2.0	-1.0	0.0
-6.0	.366	.196	.085	.030	.008	.002	.000
-5.0	.591	.388	.212	.095	.034	.010	.002
-4.0	.788	.612	.410	.229	.104	.038	.011
-3.0	.915	.804	.634	.432	.247	.115	.043
-2.0	.974	.923	.820	.655	.454	.265	.127
-1.0	.994	.977	.931	.834	.676	.477	.284
0.0	.999	.995	.980	.938	.848	.696	.500

If May PDSI = -2.0, the probability of August PDSI ≤ -4.0 was 10% (Table 10).

Table 11. Probabilities of ≤ August PDSI according to PDSI in May, for positive values (0 ≤ PDSI ≤ 6, each one unit).

Aug PDSI ↓ May PDSI →

	0.0	1.0	2.0	3.0	4.0	5.0	6.0
0.0	.500	.304	.152	.062	.020	.005	.001
1.0	.804	.634	.432	.246	.115	.043	.013
2.0	.923	.819	.655	.454	.265	.127	.049
3.0	.977	.931	.834	.676	.477	.284	.139
4.0	.995	.980	.938	.848	.696	.450	.303
5.0	.998	.990	.966	.905	.788	.612	.409
6.0	1.000	.998	.992	.970	.915	.804	.634

If May PDSI = 0.0, the probability of August PDSI ≤ 1.0 was 80% (Table 11).

Precipitation

To ascertain drought occurrences in the Northeast District, precipitation data were examined together with the PDSI. The relation between August PDSI and the total precipitation for the whole growing season (March 1 - August 26) is presented in Figure 5. Negative August PDSI tended to develop when precipitation for the whole growing season was lower than 10 inches (Figure 5).

The relation between August PDSI and the number of days with precipitation $\geq 0.05"$ during the beginning of the growing season (which distinguish between dry and wet years), is presented in Figure 6. Low daily precipitation in the beginning of the growing season was not always related to negative August PDSI.

The relation between August PDSI and precipitation totals during the beginning of the growing season (April 26 - May 16) is presented in Figure 7. Negative August PDSI usually followed when the amount of precipitation in the beginning of the growing season was low (Figure 7). However again, low precipitation amounts in the beginning of the growing season was not always related to negative August PDSI.

Figure 5. Relations between Aug PDSI and total precipitation 3/1-8/26 (1897-1988)

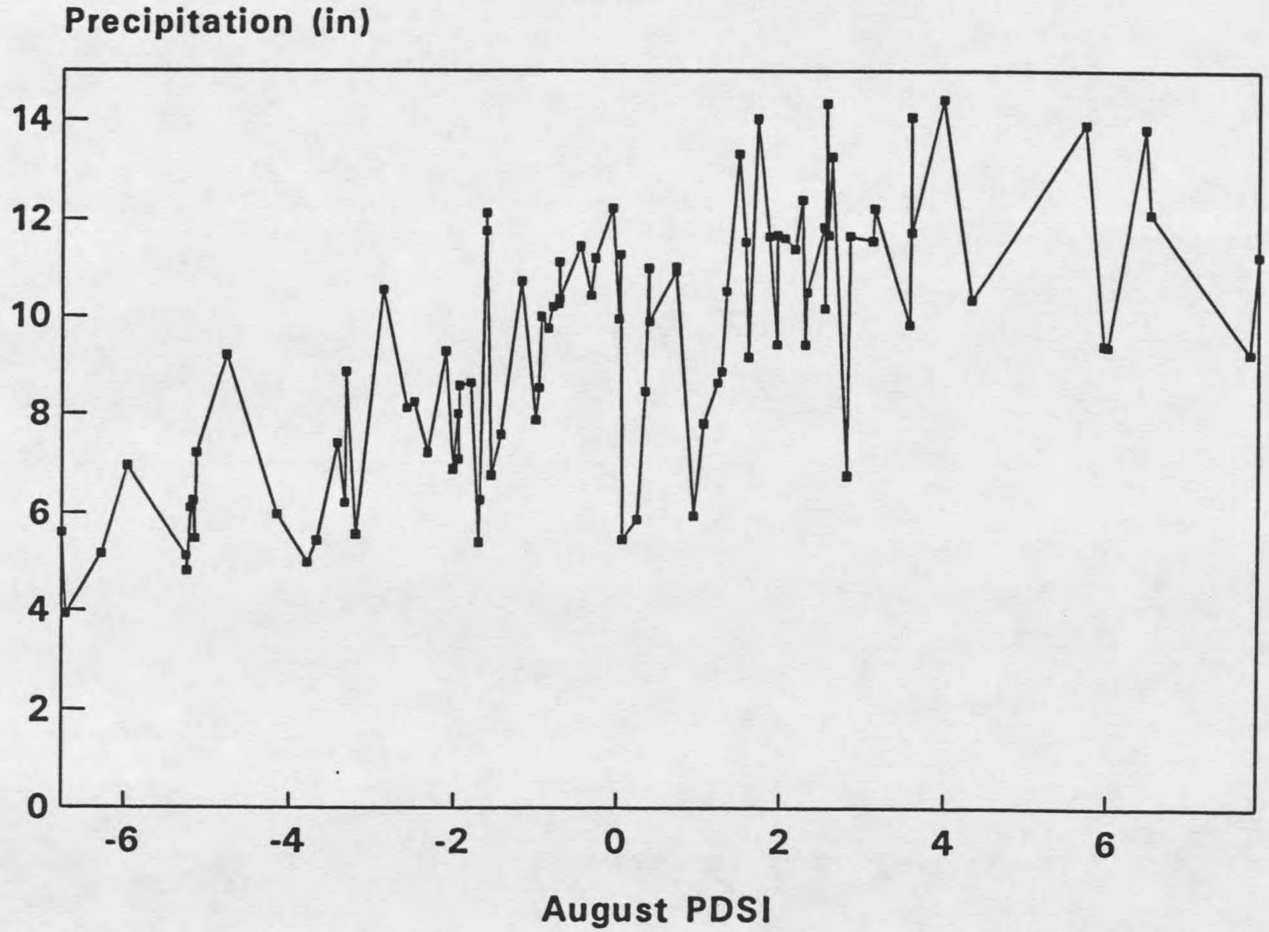
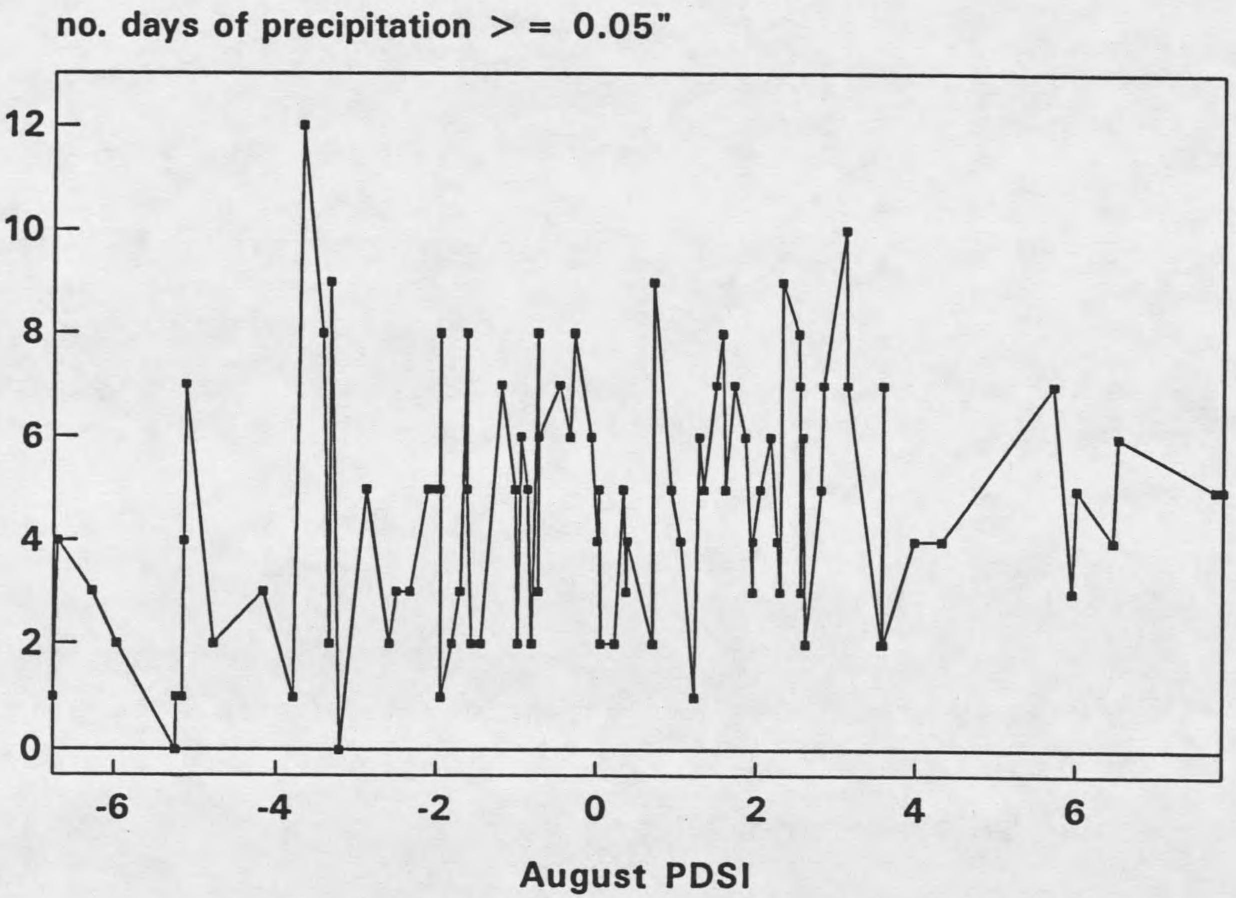
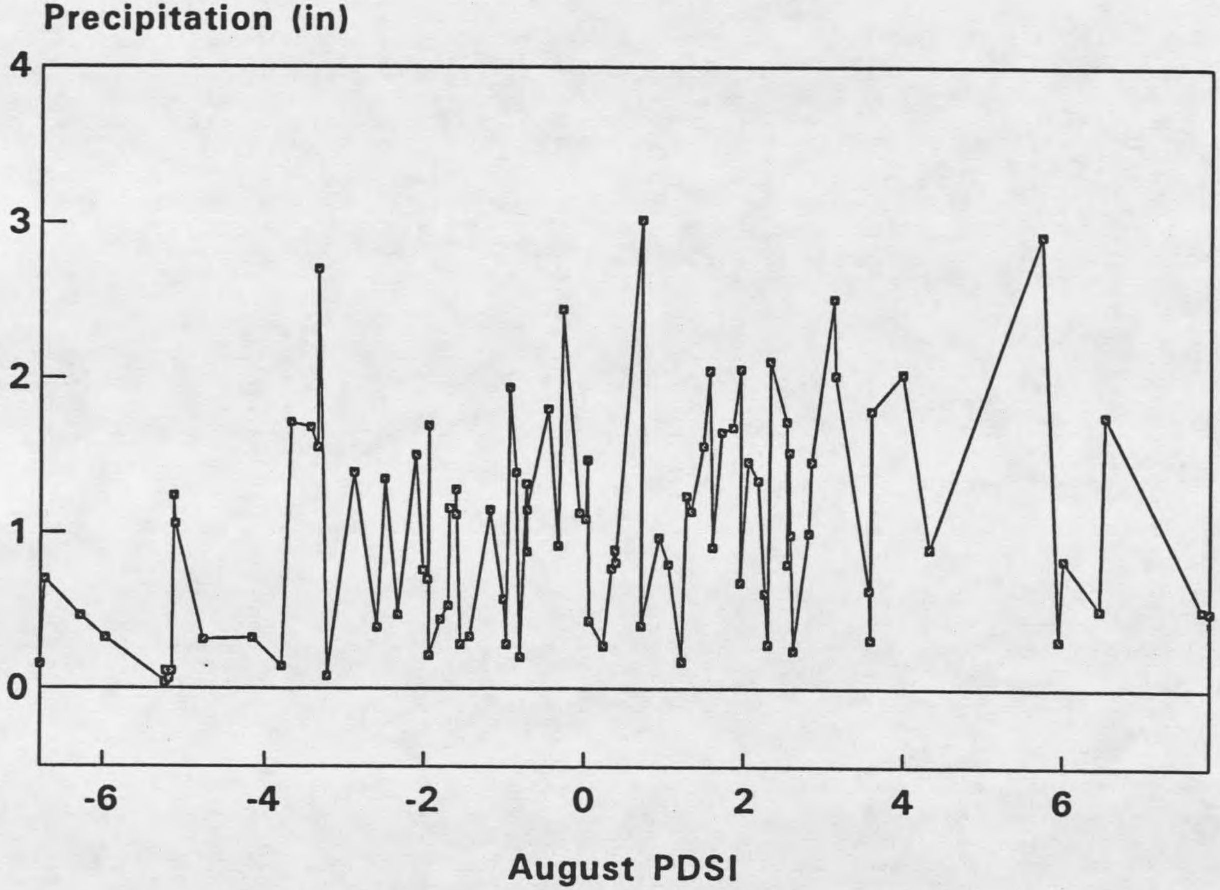


Figure 6. Relations between Aug PDSI and no. days of prec. > = 0.05" for 4/26-5/16



note: prec. = precipitation

Figure 7. Relations between Aug PDSI and total prec. 4/26 - 5/16 (1897-1988)



note: prec. = precipitation

Correlations

Precipitation for the whole growing season was correlated with precipitation in the beginning of the growing season, for the years 1897 - 1988. Precipitation in the beginning of the growing season was for two different periods. These two periods were found previously to be related to precipitation amounts for the entire season (Caprio and Williams, 1973): April 8 - May 27 and April 15 - May 13. Early season precipitation included the number of days with precipitation ≥ 0.05" and the total precipitation. Precipitation for the whole growing season was the total for the period March 1 - August 26.

The correlations of each station were similar to the correlations of the mean and median of the three stations together. The R and P values of the correlations for the median value, are presented in Table 12.

The R values ranged between 0.464 and 0.658 (Table 12). They were all significant in the 1% level. The correlations were higher for the April 8 - May 27 period compared to the shorter April 15 - May 13 period. Total precipitation in the beginning of the growing season (total) had higher correlations than the number of days with precipitation ≥ 0.05".

Table 12. R and P values for the correlations between precipitation for the whole growing season (3/1-8/26) and precipitation in the beginning of the growing season (X).

X: Period	X: Parameter	R	P
April 8 - May 27	#days≥0.05"	0.595	0.000
	total	0.643	0.000
	#days≥0.05"*total[a]	0.639	0.000
	#days≥0.05", total[b]	0.658	0.000
	#days≥0.05", total, #days≥0.05"*total	0.658	0.000
April 15 - May 13	#days≥0.05"	0.464	0.000
	total	0.528	0.000
	#days≥0.05"*total	0.492	0.000
	#days≥0.05", total	0.532	0.000
	#days≥0.05", total, #days≥0.05"*total	0.533	0.000

a: [Parameter * parameter] represents the combined influence of both parameters.
b: [Parameter, parameter] means each influences separately.

The change in PDSI May → August was correlated with different combinations of precipitation parameters and PDSI early in the season (No. of days with precipitation ≥ 0.05" and total precipitation for 4/8 - 5/27 and 4/15 - 5/13, April PDSI and May PDSI). Correlation coefficients ranged between 0.084 to 0.223 and P values between 0.106 to 0.699. This indicated that the change in PDSI May → August was not significantly related to precipitation or PDSI in the beginning of the growing season.

Chi Square Analyses

Chi Square analyses were conducted between precipitation for the whole season (March 1 - August 26) as well as August PDSI and precipitation during the beginning of the growing season (April 26 - May 16). Precipitation data were mean of the three stations (Glasgow, Glendive and Poplar). The quartile wet years were analyzed versus the half middle years, and the quartile dry years were also analyzed versus the half middle years. The results of the Chi Square analyses are presented in Table 13.

Table 13. Chi Square values for the total precipitation for the whole growing season (3/1-8/26) as well as August PDSI, and the number of days with precipitation in the beginning of the growing season (4/26-5/16).

# Days Prec.[a] ≥	1/4 Wet[b] Chi Sqr	1/2 Mid P value	1/4 Dry Chi Sqr	1/2 Mid P value	Sorted	Years
0.05"	1.007	0.316	9.560	0.002	Total prec.	1931-1970
0.01"	1.521	0.218	10.140	0.001	Total prec.	1931-1970
0.05"	4.917	0.027	8.813	0.003	Total prec.	1897-1988
0.01"	5.296	0.021	6.466	0.011	Total prec.	1897-1988
0.05"	0.747	0.388	5.756	0.016	Aug PDSI	1895-1988

a: prec. = precipitation
b: The sorted variable was ranked to 1/4 wet years, 1/2 middle years and 1/4 dry years. The 1/4 dry and the 1/4 wet separately, were analyzed vs. the 1/2 mid.

For the drier years (1/4 dry vs. 1/2 mid), precipitation for the whole growing season as well as August PDSI was found to be related to early season precipitation (Chi Sqr = 5.756 - 10.140). (note: Chi Sqr greater than 4 is significant at about the 5% level) (Table 13). The relation precipitation - precipitation (Chi Sqr = 6.466 - 10.140) was more significant than the relation PDSI - precipitation (Chi Sqr = 5.756).

The significance of the analyses was greater for the shorter period (1931 - 1970) (P = 0.001 - 0.002) than for the longer period (1897 - 1988) (P = 0.003 - 0.011), particularly for 0.01" daily precipitation (P = 0.011) (Table 13).

Agricultural Yields

Agricultural yields for three crops were compared to parameters for predicting droughts: spring wheat, wild hay and range condition. R and P values of the correlations between different agricultural yields and PDSI as well as effects of time are presented in Table 14.

All the correlations were significant at the 1% level (Table 14). The correlation between spring wheat yield and time, $time^2$ (R = 0.546) was not significantly higher than the correlation between spring wheat yield and time (R = 0.537), suggesting that the relation was linear (Figure 8).