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

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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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by

Raya Hershenhorn

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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.

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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 $\leq$ -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 ≤ -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
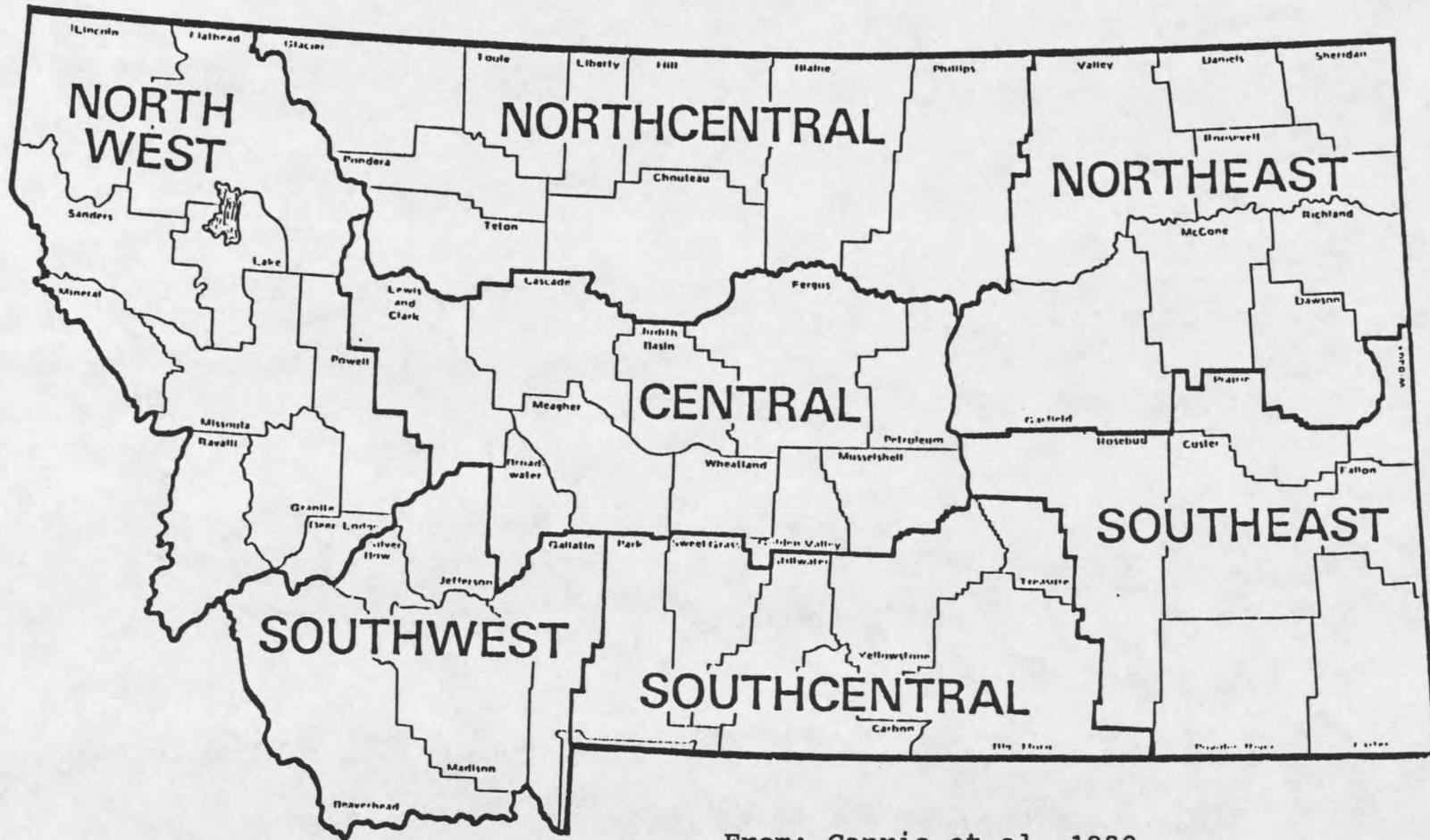
From: Caprio et al. 1980

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 $\geq$ 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 $\geq 0.05"$, 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).