Red River Valley Climate Study
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On

Drought Frequency Investigations of the Red River of the North Basin

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Foreword

Droughts, naturally occurring events, have affected the northern Great Plains climate many times during the past 2000 years. Knowledge of when the next extreme drought will occur would allow critical time for the possible reduction of impacts. Given the importance of a reliable water supply for use in all aspects of daily activities, planning for the next extreme drought occurrence is not only wise for government planners, it is a responsibility.

The purposes of this study are to:

- Provide an overview of the present scientific knowledge on droughts in general and the understanding of notable droughts in the northern Great Plains in particular;
- Evaluate the effects of climatic cycles on streamflow within the Red River of the North Basin;
- Estimate recurrence probabilities for droughts of varying intensities; and
- Determine appropriate drought scenarios for future hydrologic consideration.

Drought is a normal part of the long-term water cycle, a counterpart to long-term wet periods and associated flooding. When defining drought, it is easiest to characterize it as a drier than normal period. However, this definition is too simplistic to identify the nature by which drought onset occurs. To clarify drought occurrence it is useful to divide drought onset into three phases – meteorological, agricultural, and hydrological.

The first phase, known as meteorological drought, is associated with weather factors that produce a period of lower than normal precipitation, especially during seasons when significant precipitation is expected to occur. The second drought phase, characterized by reduced soil and surface moisture, is agricultural drought. The final phase of drought is the development of hydrologic drought, which results in lower stream flow, lake and groundwater levels. Hydrologic drought is most frequently out of phase with the other phases of drought. The slower response of hydrologic drought to reduced precipitation is due in part to the time required to deplete existing hydrologic system water reserves including reduction of groundwater levels and upstream water reservoirs.

A very important factor to consider is that not all droughts are the same. Droughts not only vary by intensity and duration, but the development of dry conditions may occur for many different reasons and will not affect all areas in a given region the same.

The National Drought Atlas was used to construct the appropriate non-exceedance values necessary to identify precipitation thresholds associated with these drought levels. Using strong negative values of the Palmer Drought Severity Index as indicators of moderate, severe and extreme drought enabled a comparison of national and regional drought conditions since 1895 to present. It was found that there have been five significant droughts during the past century with four of these droughts affecting the Upper Missouri River and Red River of the North Basins. The most severe of these droughts was clearly the 1930's drought. Beyond the 1930's drought, the next significant drought was the late 1980's to early 1990's drought that was centered across the northern Great Plains.

Using the data and results of previous research on drought recurrence intervals, it was possible to estimate the recurrence intervals for the 1930's and late 1980's droughts. In general across all climate zones in North Dakota and the Red River of the North Basin, the recurrence intervals were significantly shorter for the 1980's drought as opposed to the 1930's drought indicating the lessening in drought severity for the 1980's drought relative to the 1930's.

The final activity of the study was the preparation of a drought scenario relating to precipitation for the purpose of future hydrologic consideration. The scenario chosen was based upon a severe sustained drought constructed as a modification of the 1930's drought. A range of precipitation shortages extending from the 1930's drought base to a drought more severe than the 1930's drought were generated for each climate zone in North Dakota over a ten year period.

It is only a matter of time before an extreme drought reoccurs across the Red River of the North Basin. Use of the 1930's drought as a representative extreme drought will provide necessary precipitation statistics to characterize a future drought over an extended drought period and of sufficient spatial extent to consider the impact on neighboring basins. Finally, the analyses of drought recurrence intervals indicate that the lack of a drought of the intensity of the 1930's drought suggests that there is a greater likelihood of such an extreme drought over time. Recent research indicates a strong probability of an extreme drought event occurring before 2050 AD.

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Executive Summary

Droughts, naturally occurring events, have affected the northern Great Plains climate numerous times during the past 2000 years. These droughts have occurred in short and long increments producing impacts that have resulted in reduced crop productivity, the desertification of soils and the inability to sustain organized human existence. Two of the most severe droughts to affect the northern Plains in the recent past occurred from 1988 to 1992 and during the “Dust Bowl” in the 1930s. Recent studies, though, have now shown that these two periods of intense drought are not a rarity in the northern Great Plains climatic history. Lake salinity and tree ring data reveal that a series of “Megadroughts” occurred prior to 1200 AD. These droughts encompassed decades and, in some instances, centuries at a time with very dry conditions.

With the natural occurrence of droughts, the question of when the next extreme drought is not focused so much on “if’ as it is upon “when” it will occur. Knowledge of when the next extreme drought will occur would allow critical time for possible mitigation. Given the importance of a reliable water supply for use in all aspects of daily endeavors, planning for the next extreme drought occurrence is not only prudent for government planners, it is a responsibility.

The purposes of this study are to:

- Provide an overview of the present scientific knowledge on droughts in general and the understanding of notable droughts in the northern Great Plains in particular;
- To evaluate the effects of climatic cycles on streamflow within the Red River of the North Basin;
- Estimate recurrence probabilities for droughts of varying intensities; and
- Determine appropriate drought scenarios for future hydrologic consideration.

The actions followed to satisfy the above objectives include:

- Conduct a literature search and review of previous studies, in academia and government research agencies, relating to drought in the northern Great Plains;
- Estimate the recurrence interval for extreme droughts, including the 1930’s and late 1980’s droughts;
- Estimate the severity (magnitude and duration) for 25-year, 50-year, and 100-year droughts; and
- Provide recommendations on appropriate drought scenarios for future hydrologic consideration.

Drought is a normal part of the long-term hydrological cycle, complementing long-term wet periods and associated flooding. When defining drought, it is easiest to characterize it as a drier than normal period. However, this definition is too simplistic to identify the nature by which drought onset occurs. To clarify drought occurrence it is useful to divide drought onset into three phases – meteorological, agricultural, and hydrological.

The first phase, known as meteorological drought, is associated with meteorological factors that produce a period of lower than normal precipitation, especially during seasons when significant precipitation is expected to occur. In addition to reducing precipitation, the loss of atmospheric water vapor results in less cloud cover. As water vapor provides a buffer against temperature extremes, the lowering of atmospheric water vapor results in a greater tendency for temperature extremes during meteorological drought.

The presence of meteorological drought produces the second drought phase characterized by reduced soil and surface moisture and formation of agricultural drought. The reduction in soil moisture is driven by the combination of higher temperatures and lower atmospheric water vapor. The lack of precipitation fails to restore the soil moisture and surface water resulting in a net water deficit.

The final phase of drought onset is the development of hydrologic drought, which results in lower stream flow, lake and groundwater levels. Hydrologic drought is most frequently out of phase with the other phases of drought. The slower response of hydrologic drought to reduced precipitation is due in part to the time required to deplete existing hydrologic system water reserves including reduction of groundwater levels and upstream water reservoirs.

In order to gain an understanding of the history of drought across the region, paleoclimatic (the climate during a past geological age) indicators must be used, as the instrumental climate record only dates back approximately 100 years. Such indicators include tree rings, lake sediment diatoms, and Bristlecone pine cones.

A very important factor to consider is that not all droughts are the same. Droughts not only vary by intensity and duration, but the development of dry conditions may occur for many different reasons and will not affect all areas in a given region the same. It has been concluded that wet and dry periods tend to last longer in the Great Plains than in other areas of the country. Changes in these regimes can be abrupt and may last for periods of several years or more.

Another factor to include is the fact that droughts are a part of the hydrologic cycle as a feedback mechanism. Considering this factor, a short period of very hot and dry conditions may dry soils sufficiently to cause drought conditions to develop. On the other hand, a brief, heavy rain event can increase soil moisture enough to fuel the development of additional rainfall, which may be a mechanism to end some droughts. Along this same premise, several strong feedbacks were produced when soil moisture was decreased across a region. Diminishing soil moisture resulted in an increase in surface temperature, lower surface pressure, increased ridging aloft, and a northward shift of the jet stream (indicating that surface conditions, even over land masses, can play an essential role in the circulation patterns of the upper atmosphere).

The use of sea-surface temperature anomalies to explain potential drought developments can be closely tied to their effects on atmospheric and moisture flows. Sea surface temperature anomalies create changes in evaporation rates, which in turn generate disturbances in atmospheric circulations because of the effect on precipitation and evaporation, due to latent heating. Significant disturbances of atmospheric circulation occurred over distant parts of the globe, resulting in areas of increased and decreased precipitation. It has been shown that soil-moisture anomalies do not play as much a part in short-term climatic fluctuations as do the sea surface temperature anomalies due to:

- the amount of area covered by the separate anomalies,
- land-surface anomalies are much shorter lived and less persistent, and
- the much greater volume of moisture available and the generally weak vertical stability over the oceans increases the chances of a global effect.

Coinciding with the identification of feedback mechanisms and hydrologic cycles, a reoccurrence interval has been suggested. Previous research has shown that droughts tend to occur at certain time intervals across much of the country. This is especially true of droughts in the Northern

Plains region. Through research included in this study, it has been found that 10- and 20-year precipitation fluctuations occur across the Great Plains, with strong climatic fluctuations being favored to occur during the summer months. In addition, a 400-year wet/dry cycle for the Northern Plains region has been identified, which is attributed to solar minima, which occur on the same time scale.

A major effort of the study performed was the identification of the severity for 25-, 50-, and 100-year droughts. The National Drought Atlas was used to construct the appropriate non-exceedance values necessary to identify precipitation thresholds associated with these drought levels. A table was prepared that can be used to identify the precipitation accumulation needed on a 1-, 2-, 3-, and 5-year formulation to identify the appropriate recurrence interval for a particular drought. Using these values, non-exceedance frequencies were assigned to precipitation occurring in geographically specific regions across the northern Great Plains.

The variability of drought conditions exist in space and time and are not considered highly ordered and regular. Although drought conditions may exist in one locale, the precipitation processes dictate that spatial inconsistencies will always exist, especially at short time intervals. Only in major drought events are coherent patterns present in the geographical distribution of drought where even spatial variability continues to limit the uniformity of the drought conditions. Therefore, providing scenarios that can be uniformly applied to the entire Red River of the North watershed and adjacent watersheds is not possible and should be avoided.

The work accomplished and cited in this report was the result of a comprehensive literature search and review of previous studies relating to drought in the northern Great Plains. The review of scientific literature identified appropriate metrics for estimating severity of droughts and how to apply these metrics to the 1930's and late 1980's droughts in the Red River of the North and Upper Missouri River Basins. Although many differing metrics exist that are better than the Palmer Drought Severity Index (PDSI) and the Palmer Hydrologic Severity Index (PHSI), the widespread historical use of these indices constrained this study to rely heavily upon their use. Using strong negative values of the PDSI as indicators of moderate, severe and extreme drought enabled a comparison of national and regional drought conditions since 1895 to present. It was found that there have been five significant droughts during the past century with four of these droughts affecting the Upper Missouri River and Red River of the North Basins. The most severe of these droughts was clearly the 1930's drought. Beyond the 1930's drought, the next significant drought was the late 1980's to early 1990's drought that was centered across the northern Great Plains.

As precipitation is the signal carrier for drought, a comparison of the ten driest years on record across North Dakota and the Red River Basin proved useful in corroborating the identification of the 1930's and late 1980's droughts as the two most significant. Using the data and results of previous research on drought recurrence intervals, it was possible to estimate the recurrence intervals for the 1930's and late 1980's droughts. It was found that the length of observation data was an important factor in not only the identification of drought rankings, but also in the recurrence intervals of drought. Recurrence intervals ranging from less than 25 years to greater than 100 years were computed for the 1930's drought. In general across all climate zones in North Dakota and the Red River of the North Basin, the recurrence intervals were significantly shorter for the 1980's drought as opposed to the 1930's drought indicating the lessening in drought severity for the 1980's drought relative to the 1930's.

The final activity of the study was the preparation of a drought scenario relating to precipitation for the purpose of hydrologic consideration. Efforts were made to define a drought scenario that would provide precipitation estimations that were based both upon multiple years and geographical distributions across the Red River of the North Basin and the Upper Missouri River Basin (i.e., the remainder of North Dakota). The scenario chosen was based upon a severe sustained drought constructed as a permutation of the 1930's drought. A range of precipitation deficits extending from the 1930's drought base to a drought more severe than the 1930's drought were generated for each climate zone in North Dakota over a ten year period.

In conclusion, the presence of droughts is an expected by-product of variations in the global atmosphere-ocean-solar radiation exchange process. Evidence is compelling that the past several hundred years has been generally wetter across the northern Great Plains than the period prior to 1600. It is only a matter of time before an extreme drought reoccurs across the Red River of the North Basin. Planning and preparation for this drought is appropriate and prudent given the major impact it will have upon all facets of human existence in the region. Also, though the current above normal precipitation that has been present across the Red River Valley since the early 1990's is anticipated to continue through this decade, the possibility clearly exists for a sudden change to sustained significantly drier conditions for the majority of the twenty-first century.

Further, it is concluded that due to the possible wide variability in precipitation across a given climate zone, it is difficult to precisely adapt values from climate zone summaries for the climate zones that only partially intersect the Red River Basin. Of particular importance in the projection of future drought conditions for the Upper Missouri River Basin is the estimation of mountain snowpack. Since snowmelt is the primary water source for the Missouri River, and since any future availability of Missouri River water for the Red River will depend upon having adequate mountain snowpack, understanding the relationship of large-scale drought to mountain snow amounts will be important in future planning.

Results of this study indicate that a drought of the magnitude and intensity of the 1930's drought is a realistic and representative extreme drought in that it typifies the most extreme event anticipated until at least 2050. Utilization of the 1930's drought as a representative drought for reference for planning purposes will provide necessary precipitation statistics to characterize a future drought over an extended drought period and of sufficient spatial extent to consider the impact on adjacent basins. Finally, the analyses of drought recurrence intervals indicate that the lack of a drought of the intensity of the 1930's drought suggests that there is a greater likelihood of such an extreme drought with time. Recent research indicates a strong probability of an extreme drought event occurring before 2050 AD.

Introduction

Droughts, naturally occurring events, have affected the northern Great Plains climate numerous times during the past 2000 years. These droughts have occurred in short and long increments producing impacts that have resulted in reduced crop productivity, the desertification of soils and the inability to sustain organized human existence. Two of the most severe droughts to affect the northern Plains in the recent past occurred from 1988 to 1992 and during the "Dust Bowl" in the 1930s. Recent studies, though, have now shown that these two periods of intense drought are not a rarity in the northern Great Plains climatic history. Lake salinity and tree ring data reveal that a series of "Megadroughts" (Woodhouse and Overpeck, 1998) occurred prior to 1200 AD. These droughts encompassed decades and, in some instances, centuries at a time with very dry conditions.

With the natural occurrence of droughts, the question of when the next extreme drought is not focused so much on "if' as it is upon "when" it will occur. Knowledge of when the next extreme drought will occur would allow critical time for possible mitigation. Given the importance of a reliable water supply for use in all aspects of daily endeavors, planning for the next extreme drought occurrence is not only prudent for government planners, it is a responsibility.

Purpose and Methodology

As droughts are now seen as reoccurring events in climatology, there is a great need to evaluate the effects of climatic cycles leading to drought conditions on streamflow volumes across the northern Great Plains (especially within the Red River of the North Basin and the Upper Missouri River Basin), estimate recurrence probabilities for droughts of varying intensities, and determine appropriate drought scenarios in terms of previous drought conditions for hydrologic consideration of potential future significant, if not extreme, drought conditions.

The purposes of this study are to:

- Provide an overview of the present scientific knowledge on droughts in general and the understanding of notable drought in the northern Great Plains in particular;
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- Provide recommendations on appropriate drought scenarios for future hydrologic consideration.

It is important to note that the work conducted is primarily a research review and does not constitute a research investigation to create new knowledge on the subject of droughts. This limitation was required given the length of time permitted to conduct the study did not allow time for collection / formulation of ‘new’ data. Hence, the work performed was constrained to survey and assess existing research results. Further, the purpose of the study is to provide input to the Bureau of Reclamation on extreme drought potentials during the next 30 to 50 years. As part of this work, the study provides Bureau of Reclamation recommendations of future scenarios based upon the results of research review.

The following report presents information in seven parts beginning with a discussion on the foundation for drought. This section is followed by a description of methods to measure and characterize a drought. Then a discussion of a characteristic extreme drought is presented including an analysis of the 1930s and 1980s droughts and how they relate to 25-, 50- and 100-year droughts. The following section suggests how a characteristic extreme drought can be used to support hydrologic evaluation of future extreme drought scenarios including a depiction of precipitation expected during such extreme drought conditions. The final three report parts provide the report’s summary, conclusion and an extensive bibliography of literature cited within the report. A brief synopsis of each section is located at the end of each major section.

Foundation for Drought

Drought is a normal part of the long-term hydrological cycle complementing long-term wet periods and associated flooding. When defining drought, it is easiest to characterize it as a drier than normal period. However, this definition is too simplistic to identify the nature by which drought onset occurs. To clarify drought occurrence it is useful to divide drought onset into three phases – meteorological, agricultural, and hydrological.

The first phase is associated with meteorological factors that produce a period of lower than normal precipitation, especially during seasons when significant precipitation is expected to occur. The first manifestation of drought during low precipitation periods, known as meteorological drought, results in decreased atmospheric water vapor from surface water sources and from evapotransporation. In addition to reducing precipitation, the loss of atmospheric water vapor results in less cloud cover. As water vapor and clouds provide a buffer against temperature extremes, the lowering of atmospheric water vapor and reduction in cloudiness results in a greater tendency for temperature extremes during meteorological drought. During winter, this results in colder than normal temperature while summer temperatures are warmer than normal. The presence of extreme summer temperatures and lower atmospheric water vapor are related and represent a feedback mechanism of drought conditions (Namias, 1966). The interrelationship between temperature, atmospheric water vapor and precipitation reflect the central concept of meteorological drought as one of a water deficit (Wilhite & Glantz, 1985). The presence of a water deficit found within long-term precipitation records are investigated by climatologists to provide insight into the relationship between drought severity and its geographical distribution across the United States. Using the Palmer Drought Severity Index (Palmer, 1965), one of many indices that have been developed over the past several decades to estimate drought existence and perseverance, investigators at the National Drought Mitigation Center have constructed a map depicting the percentage of time every climate zone in the conterminous United States have experienced drought over the past century (Figure 1). The figure clearly shows that drought is a frequent occurrence and the more displaced from coastal waters where water vapor is more prevalent, the more often drought is experienced.

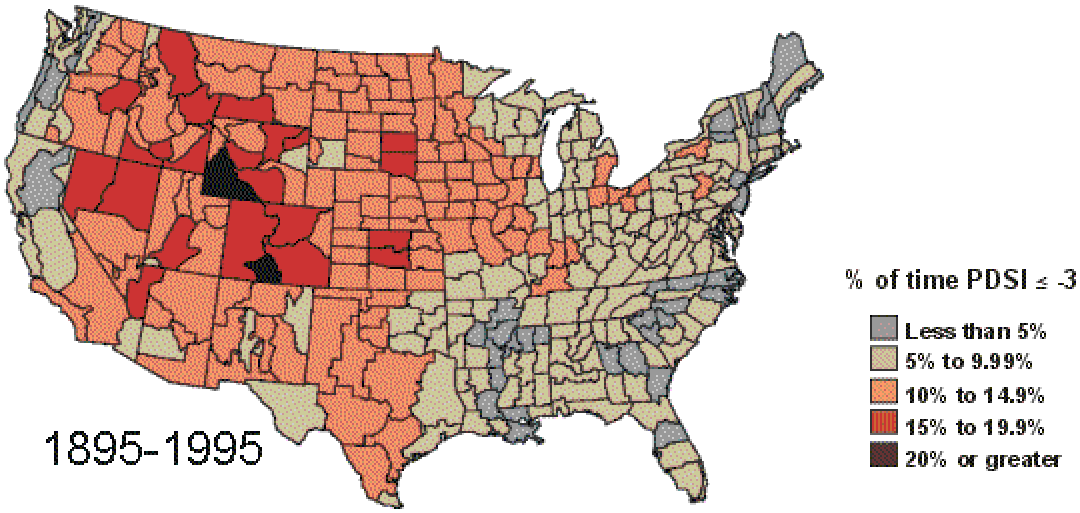

Figure 1: Percentage of time a climate region experienced drought conditions between 1895 and 1995. ***Source: Drought Mitigation Center, University of Nebraska-Lincoln.***

The presence of meteorological drought often produces a secondary drought condition, known as agricultural drought, characterized by reduced soil and surface moisture and formation of agricultural drought. The reduction in soil moisture is driven by evaporation and evapotranspiration promoted by the combination of higher temperatures and lower atmospheric water vapor. The lack of precipitation fails to restore soil moisture and surface water resulting in a net water deficit.

The final form of drought involves the development of hydrologic drought, which results in lower streamflow, lake and groundwater levels. Hydrologic drought is most frequently out of phase with the other forms of drought. The slower response of hydrologic drought to reduced precipitation is due in part to the time required to deplete existing hydrologic system water reserves including reduction of groundwater levels and upstream water reservoirs. The relationship of the three drought phases is presented in Figure 2 showing progressive degeneration of water resources over time.

Recovery from drought requires excessive precipitation during periods of normal dry (low precipitation) seasons with a return to normal to above normal precipitation during normal higher precipitation seasons. The spatial distribution of precipitation must be sufficiently large to provide general moistening of soil conditions and recharge of shallow and eventually deep groundwater systems.

A common characteristic of the three forms of drought described is the importance of precipitation as a carrier of the drought signal. Hence, an understanding of the variability of precipitation and its dependence upon climatic characteristics and variation are crucial to understanding the frequency and strength of drought episodes.

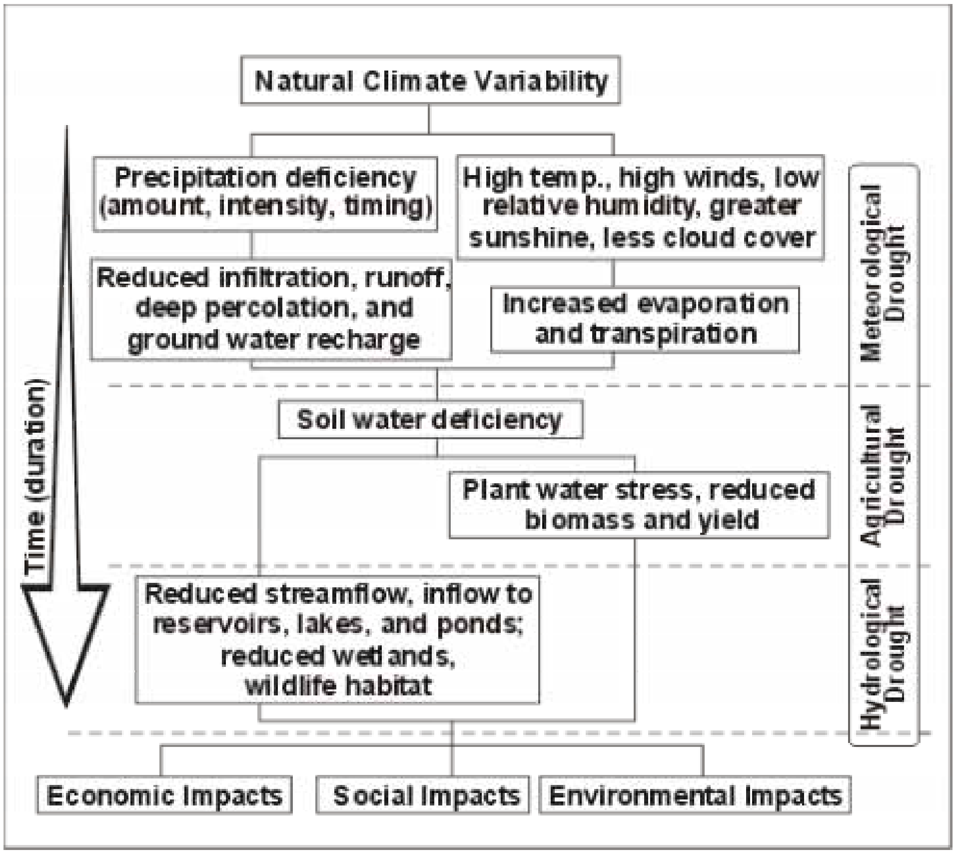

Figure 2: Progression of drought stages driven by climate variability. Adapted from: *National Drought Mitigation Center, University of Nebraska – Lincoln.*

Climate of the Northern Great Plains

The Red River of the North Basin encompasses approximately 45,000 square miles extending from eastern North Dakota, extreme northeastern South Dakota, northwestern and west central Minnesota and southern Manitoba including the 3,800 square mile closed basin of Devils Lake. The lakes in this region are extremely responsive to climate variability.

The location of the Red River Basin, near the center of the North American Continent, has a great influence on its climate response to global forcing. The Koeppen Modified system of climatic classification, which is based upon seasonal characteristics of temperature and precipitation, classifies the Red River Basin as a humid continental, cool summer climate. The region characteristically has large fluctuations in daily, annual, diurnal temperatures. This is also true for precipitation amounts from one year to the next.

The Upper Missouri River Basin in North Dakota encompasses approximately 34,000 square miles. This basin constitutes roughly eighty percent of the total streamflow in North Dakota, which is fed predominantly by snowmelt from the Rocky Mountains from northern Wyoming through Montana and into extreme southern Saskatchewan. Adjacent to the western boundary of the Red River of the North Basin, the Upper Missouri River Basin becomes progressively drier westward across North Dakota and into central Montana until encountering the foothills of the Montana Rockies. The increase in terrain heights associated with the Rocky Mountains results in higher wintertime precipitation and the resulting winter snowfall that provides eventual snowmelt that is the principle water source feeding the Missouri River system. Otherwise, the limited precipitation across the North Dakota and Montana prairie averages generally below fourteen inches of water, or about forty percent less than is found across the Red River of the North Basin.

Due to the northern Great Plains' geographical location, the majority of moisture (i.e. water vapor) for storm systems comes from the Gulf of Mexico. It is difficult for the extratropical cyclones originating over the Pacific Ocean to maintain large amounts of precipitable water from their point of origin because of the passage over the Rocky Mountains. As an air mass passes over the Rockies, it is lifted and moisture is removed, resulting in warm dry air descending down the leeward eastern slopes. As the polar jet stream takes on a more meridional regime, polar air masses are allowed to extend into lower latitudes and warm moist tropical air masses are extended into higher latitudes ahead of the cyclone, where it gets lifted, condenses and precipitates. The orientation of the polar jet in a southwest to northeast direction promotes a greater supply of low-level moisture into the region. Due to the origination of extratropical storms along this southwest-northeast trajectory, they produce more precipitation. However, these systems occur less frequently than under a more westerly regime where frequent, fast moving, zonal systems produce small contributions to the total precipitation but bring a change in temperature and cloud cover.

The same low-level moisture source for the Red River of the North Basin from the Gulf of Mexico provides the predominant source of moisture for precipitation across the Upper Missouri River Basin. Slight movements of synoptic and global weather patterns result in significant variations between precipitation patterns from the Rocky Mountains eastward to the Great Lakes. Given the predominant westerly flow in the mid-levels of the atmosphere across the northern Great Plains, eastern portions of the northern Great Plains experience a greater period of moisture availability that results in higher average precipitation across the Red River of the North Basin as compared to the Upper Missouri River Basin.

Atmospheric Features Supporting Extreme Drought

The extreme drought that affected the United States and Canada during 1988 resulted from the persistence of a large-scale atmospheric circulation anomaly. Droughts are associated with enduring anomalous atmospheric circulations persisting for months or seasons (or longer), which create little or no precipitation, and do not demonstrate any immediately discernible unique characteristic within the daily circulation patterns. A multi-layered inspection of atmospheric circulation patterns at any particular instant does not demonstrate unique individual features of a drought; rather the averaging over a time span of one or more months is required to demonstrate certain anomalies when compared to climatological averages.

Namias (1983) concluded that, in general, droughts are caused by initial abnormalities in the upper-level wind flow as blocking patterns develop to inhibit sources for precipitation. Across the northern Great Plains this develops as an abnormally strong ridge situated over the mountain regions of the United States and Canada, along with deep troughs along the eastern Pacific Ocean and eastern North America, which generates an atmospheric flow consistent with a recurrent movement of dry air from Canada southward into the central United States. This push of air from Canada, combined with a lack of atmospheric flow and moisture from the Gulf of Mexico (inhibited by the deep trough over eastern North America), results in descending air which inhibits precipitation. In addition, costal troughs accompanied by southern anticyclones create an inhibition to precipitation through the blocking of colder air from moving southward from Canada. With this lack of advection of cooler air during a warm season, destabilizing air means frontal showers occurred less frequently than usual.

These conditions result in decreased soil moisture and snow cover, which create a positive drought feedback by reducing the amount of evaporative moisture to replenish the lower atmosphere. Namias (1983) also showed that droughts in the northern Great Plains are correlated with upper-level troughs along the East and West coasts of North America, with a ridge in place across the Northern Plains. This pattern was shown to be the result of ridging developing in the central Pacific and Atlantic Oceans, which were likely influenced by sea surface temperatures in both ocean basins. Ting and Wang (1997) showed that correlations exist between Tropical and North Pacific sea surface temperatures (SST's) and precipitation in the northern Great Plains region of the United States. Summer precipitation in this area is driven by the transport of Gulf of Mexico moisture into the region, but this moisture transport is highly dependent on the atmospheric circulation present across North America. Warm North Pacific SST's weaken the Pacific jet stream, which lessens the intensity and frequency of storm systems tracking across North America. The transport of Gulf of Mexico moisture into the region is limited when fewer storm systems track across the northern Great Plains.

During the 1977 drought, a strong ridge over the West Coast, associated with descending air over the western United States (creating an inhibition of precipitation), as well as storm tracks moving northward to Alaska instead of the typical southerly track towards California, developed a west-east flow. This west-east flow created a southerly atmospheric circulation pattern that is believed to have increased the high pressure zone over the coast of California, while the low pressure area located in the central North Pacific was enhanced. This gradient produced and maintained the strong ridge located along the West Coast. The SST anomalies created changes in evaporation rates, which in turn generated disturbances in atmospheric circulations because of the effect on precipitation and evaporation, due to latent heating. Significant disturbances of atmospheric circulation occurred over distant parts of the globe, resulting in areas of increased and decreased precipitation.

Due to the fact that droughts during the 1980's occurred more recently and better datasets were collected during this event, extensive research into the forcing mechanisms for this drought has been conducted. Trenberth and Guillemot (1996) showed that SST's in the Tropical Pacific were a major factor in the development and maintenance of the 1988 drought across the central United States. Cooler than average SST's in the central and eastern Tropical Pacific (La-Niña conditions), coupled with a strong Inter-Tropical Convergence Zone (ITCZ) and above-average SST's to the north of the cold pool led to a breakdown of the ridge along the West Coast of the United States and the development of a ridge across the northern Great Plains. In an earlier paper by Trenberth and Branstator (1992), it was shown that the position of the jet stream was much more important than the position of surface cyclones/anticyclones in the development and maintenance of drought conditions in 1988. On the other hand, Kumar et al. (2001) showed that below-average SST's in the Central and Eastern Tropical Pacific were present while this drought was taking place, but could not be significantly linked with a physical process that would lead to the dry conditions across the central United States. The results from analysis of the droughts in the late 1970's and the 1980's demonstrate that not only are the characteristics of the SST anomaly in question, but also the season and the disturbances present in which the anomaly develops (Voice and Hunt, 1984).

Seasonal anomalies in upper-level flow across the Northern Hemisphere have also been linked with the development of drought conditions across the central United States. Namias (1982) showed that the summer drought conditions in the summer of 1980 were caused from unstable anomalies in the springtime flow pattern across North America. The westerlies were displaced southward during the spring of 1980, but this pattern was unstable once stronger heating of the surface began by late spring. The instability of the pattern favored the development of a threecell pattern of troughs on both coasts and a ridge across the central United States. Namias also showed that during the last week of May 1980, the rapid development of a Central Pacific ridge amplified the West Coast trough, which intensified the ridge across the central United States and allowed heat and drought to develop quickly across the area.

Chang and Smith (2001) related summertime drought conditions in the Great Plains region to synoptic patterns. In their analysis, severe drought conditions were shown to correlate with a weakened wave train over the North Pacific, with the jet stream taking a position north of its climatological mean. Hu and Feng (2001) found similar results when summer drought in the central United States was correlated with synoptic patterns and Pacific SST's. In addition, above-average sea-level pressure was shown to be present over New Mexico, the North Atlantic and central North America. Sinking motion under the ridge over the central United States was very important in maintaining high insolation and a dry atmosphere. Other interesting characteristics included the formation of a heat low centered over South Dakota as the North-South temperature gradient reversed itself over the North American continent and a westward displacement of the Bermuda High, which allowed an enhancement of low level hot air flow into North and South Dakota.

Soil-moisture anomalies do not play as much a part in short-term climatic fluctuations as do the SST anomalies. Three factors are provided by Walsh et al. (1985) which limit the effect of land-surface anomalies versus sea-surface anomalies. The first factor deals with the amount of area covered by the separate anomalies. With soil-moisture and snow-cover, the area of impact is much smaller than an ocean born SST anomaly. The second factor, pertaining to persistence, shows that land-surface anomalies are much shorter lived and less persistent than SST anomalies. Finally, with the much greater volume of moisture available and the generally weak vertical stability over the oceans for an SST anomaly, the potential for redistribution of the SST anomaly throughout the atmosphere increases the chances of a global effect due to the SST anomaly.

A decrease in relative humidity during droughts extends through all levels of the atmosphere that contain substantial water vapor. Namias (1966, 1978) and Spar (1968) present several case studies showing that the relative humidity at less than 500 millibars is less during droughts than during non-drought periods.

Huff and Changnon (1963) conclude that, during summer droughts in Illinois, the decreased relative humidity is not well correlated to the absolute quantity of water in the atmosphere; that is, the increased temperature is the primary factor in causing the decrease in relative humidity. Namias (1966), however, presents some evidence that the decrease in relative humidity also can be caused by a lack of water vapor. The absolute-humidity values from the land surface to 10,000 feet during the drought were about 10 to 20 percent less than the values for the normal period during all seasons. At least in this case study, the air during the drought was drier throughout the lower atmosphere not only because the temperatures were higher but also because there was less water vapor in the atmosphere.

Possible Impacts Due to Global Climate Change

Scientific evidence has established the fact that concentrations of carbon dioxide, methane, and chlorofluorocarbons have increased due to human activities over the past two centuries (IPCC, 2001). The increases in greenhouse gases have been used by scientists to model the potential increase in global temperatures in coming decades and the possible impacts on the frequency of extreme events of droughts and floods. With an increase in global atmospheric temperatures it is expected that an enhancement in atmospheric moisture content will occur. This rise in atmospheric moisture may result in enhance precipitation and precipitation rates at many locations. While it is expected that climate change will produce more frequent extreme weather events, unfortunately these models do not provide regional detail sufficient to indicate whether there is a preferred occurrence of droughts or floods for a specific location (OTA, 1993). This leaves uncertainty as to whether climate change will produce a greater or less likelihood of extreme drought across the northern Great Plains. Should climate change produce more frequent extreme droughts across the northern Great Plains, the recurrence interval of droughts similar to the "dust bowl" drought of the 1930s would be shortened and would lead to dramatic sustainability issues. Furthermore, the anthropogenic influence on natural streamflows are important factors since the rate of withdrawal changes over time and can alter the relationship of natural flows to climatic cycles. However, the review of anthropogenic impacts on natural flows was not a part of the study conducted.

Synopsis

Hydrologic droughts are the final form of a trio of drought types beginning with meteorological and agricultural. Whether a drought becomes a hydrological drought depends upon duration and magnitude sufficient to deplete groundwater and soil moisture leading to reduced streamflow. The presence of drought in the northern Great Plains depends upon atmospheric factors associated both with global-scale and regional-scale circulations. In either of these a sustained atmospheric climate pattern is required to provide the magnitude and duration needed to result in a hydrologic drought. Further, the climate of the northern Great Plains, stretching from central Montana to northwestern Minnesota is one that changes from semi-arid in the west to semi-humid in the east. The location of the northern Great Plains in the center of the North American continent and away from readily available water vapor sources places it in a geographic region that promotes great variability in climate regimes.

Measurement of Drought

In order to gain an understanding of the history of drought across the Red River of the North and Upper Missouri River Basins, paleoclimatic (the climate during a past geological age) indicators must be used in addition to the observed climate record. Paleoclimate indicators are required as the observed climate record, those recorded by instrumented observations, only dates back approximately 100 years. Such indicators include tree rings, lake sediment diatoms, and Bristlecone pine cones[1]. Tree rings can be problematic across the region, as much of the area of investigation is not covered by trees. In addition, old-growth trees are difficult to find. Some research has used tree rings to reconstruct climate over the last several hundred years for the Upper Missouri and Red River of the North Basins. Fritts (1965) conducted an analysis of tree ring data from western North America to determine growing-season precipitation patterns, although he questioned how well tree ring data correlates with summertime precipitation patterns. Temperature becomes a more significant issue during the summer, so he concluded that the data was a better measure of spring and fall precipitation trends. His research showed that dry periods in the western United States occurred from 1576-1590, 1626-1635, 1776-1785, 1841-1850, 1871-1880, and 1931-1940. This research did not include most of the Upper Missouri/Red River Basins, but it still is useful in describing past climate regimes in the region. LaMarche and Fritts (1971) also analyzed tree ring data across the western United States for the 1700-1930 time

[1] Bristlecone pines were singled out specifically for their extreme longevity and ability to withstand heat and drought. Since strip-bark morphology sustains the Bristlecone, cones are sometimes used for carbon dating as the tree's youth rings may have been entirely eroded through this process of death and re-growth.

period. The magnitude of wet and dry periods experienced during the 1931-1962 time period was compared to the tree ring data. The authors concluded that droughts of similar magnitude and duration experienced during the latter time interval also occurred during the 18th and 19th centuries. These patterns are likely to be repeated in the future.

A study that included the entire Northern Plains region was conducted by Stockton and Meko (1983). This investigation used tree ring data from Iowa, Oklahoma, eastern Wyoming and near the Montana/North Dakota/South Dakota border to reconstruct long-term precipitation trends for the Great Plains. These reconstructions showed that droughts occurred in the late 1750's, early 1820's, early 1860's, mid 1890's, mid 1930's and during the 1950's. In addition, it was shown that the drought of the 1930's was milder than those that occurred in the 1750's, 1820's and the 1860's. Similar findings were shown by Meko et al. (1993) in a climate reconstruction for the United States and Southeastern Canada generated from tree ring data. Briffa et al. (1992) used tree ring data from western North America to reconstruct growing season mean temperatures, which could be used to generate precipitation patterns with the use of a temperature/precipitation relation.

Lake sediment diatoms can also be used to describe past climate regimes. Leavitt et al. (2000) used lake sediment diatoms from Moon Lake, North Dakota to generate historical salinity values for this terminal lake. Salinity can be converted to a measure of wet/dry conditions as higher salinity indicates drier conditions while lower salinity shows an influx of fresh water into the lake, thus indicating a wetter period. From the salinity record, a comparison of drought conditions during the last century can be compared to those experienced at earlier times to generate a recurrence interval for these droughts as well as indicate how the magnitudes and durations of previous dry periods relate to the more recent droughts.

Drought Indices

The use of drought indices provides a consistent method of comparing place-based measures of drought across spatial and temporal domains. The most commonly used drought index is the Palmer Drought Severity Index (PDSI), developed by W.C. Palmer in 1965. Hayes (2003) provides an in-depth explanation of the attributes of the PDSI, as well as the advantages and limitations in using the PDSI. The index is a measure of departure from an average water supply for a given region. The water balance equation forms the basis for the PDSI. Factors such as soil recharge, runoff, moisture loss, and evapotranspiration are considered, but human impacts (such as irrigation) are not. The PDSI provides a straightforward method to compare dry and wet conditions both spatially and temporally. Although the PDSI has been adopted as the most common drought index, the index has been found to have its limitations, as noted in Table 1. Despite these limitations, many governmental agencies use this index to determine the severity and duration of drought conditions across the United States.

Hayes (2003)	Alley (1984)
• Values used to determine intensity, as well as beginning and ending of droughts, were arbitrarily selected.	• Reliance on the 1931-1960 climate period.
• Two soil layers used for the water balance may not represent a given location.	• Only includes an analysis for a few areas in Kansas and Iowa.
• Lag for snowmelt is not included as all precipitation is calculated as if it falls in the form of rain.	• Assumes the top layer of soil must be fully saturated before runoff occurs.

Hayes (2003)	Alley (1984)
• Calculation of potential evapotranspiration uses the Thorthwaite method which is only an approximation.	• Assumes that the soil water holding capacity is consistent in all areas.
• Lag between precipitation and resulting runoff is not considered.	

Table 1: PDSI limitations as denoted by Hayes (2003) and Alley (1984).

Akinremi et al. (1996) studied how well the PDSI worked for the Canadian Prairie region. They found that the PDSI was only able to explain 33% of the trend in historical data for that area. This calls into question how well the PDSI works for both the Upper Missouri River and the Red River of the North Basins. Another potential problem results when the PDSI is used in reconstructions of past climates, as it is susceptible to precipitation totals which may have resulted from one intense heavy rain event. A single event would not end drought conditions across an area if dry conditions continued after the event, but the PDSI may show this as an end to a drought due to its heavy reliance on the quantity of precipitation for a region.

Many other indices have been proposed to measure and correlate wet and dry periods over a broad region.

- Byun and Wilhite (1999) proposed the Effective Precipitation (EP) index, which includes a moisture budget (with particular emphasis on soil moisture) and drought periods are defined by the length of time that the moisture budget is less-than-average. This index was tested for the period 1960-1996 across the Plains and was shown to provide a better measure of drought intervals in the region for this time.

- McKee et al. (1993) developed the Standardized Precipitation Index (SPI), an index based on the probability of precipitation for any time scale, plus information on groundwater, reservoir storage, soil moisture, snowpack, and streamflow. Used by the state of Colorado, the SPI allows for a simple determination of drought duration and intensity, in addition to operationally monitoring conditions across the state. It is also used for climate considerations by the National Drought Mitigation Center and the Western Regional Climate Center.

- The state of Colorado also uses an index called the Surface Water Supply Index (SWSI) to complement the Palmer Index. Developed by Shafer and Dezman (1982), the SWSI incorporates both hydrological and climatological information into a single index. The major limitation of this index is that it must be calibrated for each area, so inter-basin comparisons are difficult to make.

- Palmer (1968) also developed the Crop Moisture index (CMI), which measures short-term moisture supply in agricultural regions. This index responds rapidly to changing conditions, so it is not a reliable measure of drought conditions.

These are just a few of the many indices that have been developed to measure moisture characteristics and drought magnitude and duration. Likely additional indices will be added in the future as drought research evolves. However, to be applicable in comparing droughts across a broad time domain it is necessary to apply the indices consistently for all times considered. It is this lack of a broad temporal application of most drought indices that has resulted in the selection of the PDSI as the principle index in this study as it represents a more commonly used index over time.

Drought Intensity/Variability

One important factor to consider is that not all droughts are the same. Drought intensity and variability are essential to this study, as the intensity of droughts in the 1930's and late 1980's are compared. Droughts not only vary by intensity and duration, but the development of dry conditions may occur for many different reasons and will not affect all areas in a given region the same.

Klugman (1978) conducted a localized analysis of drought conditions for the Upper Midwest encompassing the time period 1931-1969. During this time, the droughts of the 1930's and 1950's impacted the region. Klugman found that the drought conditions of the 1930's began across the western High Plains and spread eastward through the decade. Drought conditions in the 1950's spread into the Upper Midwest from the south and southwest, but periods of above-average precipitation were still experienced. Diaz (1983) showed that droughts are favored to initiate in the north-central United States in late spring/early summer (May or June) and also during the fall (October or November). Karl (1983) showed that the Upper Missouri River Basin is favored for longer droughts than most other areas in the United States. In addition, Karl concluded that wet and dry periods tend to last longer in the Great Plains than in other areas of the country. Changes in these regimes can be abrupt and may last for periods of several years or more. One such change occurred in the early 1990's, when drought conditions were rapidly replaced by a wet period that has lasted for much of the 1990 decade. The closed basin of Devils Lake, North Dakota illustrates this transition. Baldwin and Lall (2000) described the recent record of water levels for Devils Lake. An abrupt shift from decreasing lake level to a rapid rise was shown to have begun in 1993, with a rise continuing through the end of the decade. The rate of rise and fall of the lake can be used to determine the intensity of a wet or dry cycle.

Karl and Quayle (1981) put the 1980 summer heat wave and drought into historical perspective. Their research showed that this drought was intense, but was much weaker in magnitude to the conditions during the 1930's across the Northern and Central Plains and across the Southern and Central Plains during the 1950's. This drought was also of shorter duration than either of these dry spells.

Changnon (1989) showed that the intensity of drought within a particular region can be highly dependent on conditions elsewhere. Below-average snowpack during several consecutive winters in the Northern Rocky Mountains produced very low spring runoff, which limited both surface and ground water across the basin. Very warm conditions during 1987 also reduced available surface and ground water for the region. These factors intensified the drought conditions experienced across the Northern Plains.

Drought Feedback Mechanisms

Droughts are perpetuated by feedback mechanisms in the surface/atmosphere system. Karl and Riebsame (1984) showed that a short period of very hot and dry conditions may dry soils enough to cause drought conditions to develop. On the other hand, they also showed that a brief, heavy rain event can increase soil moisture enough to fuel the development of additional rainfall, which may be a mechanism to end some droughts. Chang and Wallace (1987) concluded that above-average temperatures during the summer are significantly correlated with dry conditions. They showed that upper-level ridging creates sinking motion, which dries the mid- and upper-levels of the atmosphere. In turn cloud development is suppressed, which allows more solar energy to make it to the surface and dry soils further. Dry conditions allow the surface temperatures to heat more intensely as incoming energy is not used for evaporation, while hot temperatures feed back to re-enforce dry conditions at the surface.

Changnon (1989) showed that dry soil and ground water conditions leftover from late in the warm season of 1987 created a positive feedback in late spring of 1988 which allowed drought conditions to develop quicker and become more intense than would have otherwise been the case.

In order to illustrate the importance of the soil moisture feedback in drought, Oglesby and Erickson (1989) simulated conditions across North America with varying decreases in soil moisture. They found that several strong feedbacks were produced when soil moisture was decreased across a region. Diminishing soil moisture resulted in an increase in surface temperature, lower surface pressure, increased ridging aloft, and a northward shift of the jet stream (indicating that surface conditions, even over land masses, can play an essential role in the circulation patterns of the upper atmosphere). Another important conclusion is that the maintenance of drought conditions is highly dependent on the limitations of low-level moisture advection from the Gulf of Mexico.

Recurrence Intervals

Previous research has shown that droughts tend to occur at varying time intervals across much of the country. The irregularity of these time intervals makes prediction of specific drought periods difficult, but does indicate the recurrence of drought conditions are associated with larger scale global atmospheric and ocean conditions. This variability in recurrence intervals is especially true of droughts in the Northern Plains region. Karl and Riebsame (1984) found that 10- and 20-year precipitation fluctuations occur across the Great Plains, with strong climatic fluctuations being favored to occur during the summer months. The authors did not include a discussion of what the underlying factors may be in creating these particular intervals.

Yu and Ito (1999) have discovered a 400-year wet/dry cycle for the Northern Plains region. They attribute this cycle to solar minima, which occur on the same time scale. Wet/dry cycles of 200, 130, and 100 years were also shown to be statistically significant, although no physical explanation was given for these intervals. Ware and Thomson (2000) showed that the climate of the northeastern Pacific oscillates at 3 dominant time scales; these include the 2-8 year El-Niño Southern Oscillation (ENSO) cycle, a 20-40 year inter-decadal time scale, and a 60-80 year multi-decadal time scale referred to as the Pacific Decadal Oscillation (PDO). The PDO dominates climate change across Western North America. This investigation also showed that the last major shift in this pattern ushered in a warm period for the region beginning in 1976. The average length of a warm period is 32 years, implying that a change to a cooler regime with a less intense Aleutian Low is possible over the next decade. Biondi et al. (2001) studied the long-term record of the PDO back to 1661. They showed that the amplitude of this oscillation weakened from the late 1700's to the mid 1800's. The strongest oscillations occurred in 1750, 1905, and 1947. An important conclusion from this research was that the PDO is critical to understanding the effects of ENSO and other Pacific-based teleconnections on changes in climate across North America.

Diaz (1983) showed a strong, 20-year periodic interval for droughts in the north-central United States, although significant variability exists, yet Diaz did not speculate on possible causes of this interval. Mass and Schneider (1977) correlated both the sunspot and volcanic dust records to see whether either factor appeared in the climate record. The sunspot correlation is important to this study because its cycle has a period of around 22 years, which is similar to one of the major wet/dry cycles found in the Great Plains. Their results showed that there is no significant correlation between the sunspot cycle and temperatures, while there is some weak correlation at some sites when volcanic dust is considered. This study is limited because an analysis of precipitation data was not conducted. The authors did call into question any correlation between sunspots and climate trends due to the lack of a solid physical explanation provided by research up to this point.

Synopsis

Droughts can be characterized by their intensity, duration, magnitude and variability. These features provide information regarding the atmospheric conditions that promote drought occurrence through a measurement of soil moisture and hydrologic impact. Using various indices developed for measuring drought, comparisons can be made between droughts in spatially and temporally diverse settings. While no drought index is ideal, the PDSI is a widely used index within government and research applications. The intense droughts often promote a positive feedback mechanism that prolongs and strengthens an existing drought. This results from the depletion of soil and surface water that inhibits precipitation production that is necessary to mitigate the impact of drought conditions.

Characterization of an Extreme Drought

As described earlier the nature of droughts can be characterized by their magnitude, duration, and intensity resulting in a hierarchy of drought occurrence. Preparation for future droughts requires the identification of a 'reference' drought by which comparisons can be made and characterization of impacts be projected. In this study a reference drought is of such magnitude and duration that it will depict the most extreme drought event anticipated until the year 2050.

Severity of 1930's and 1980's droughts

Over a span of centuries droughts can be seen as a regularly occurring phenomenon resulting in major events multiple times each century. Due to the limited atmospheric observational data, which extends little more than one hundred years in many parts of North America, much of the study of droughts prior to the late nineteenth century have relied upon "paleoclimate proxies" to identify drought conditions. These paleoclimate proxies permit the reconstruction of precipitation and temperature patterns and inferences on past climate structures using such elements as tree rings, coral reefs, ice cores and sediments. Combination of these elements permits both regional and global drought patterns to be discerned. Using tree ring data, Cook et al. (1999) were able to reconstruct information on widespread drought for the continental United States for period from 1700 – 1978. When combined with instrumental data for the period from 1900 – 2002 (Fig. 3), the resulting information depicts drought, based upon the Palmer Hydrologic Drought Index (PHDI), as a common occurrence over the past three hundred years. Due to tree ring data underestimating severity, a PHDI of –2 was chosen to depict a strong drought from tree ring data (green bars) while a PHDI of –3 was chosen to depict a similar strong drought from instrumented data (blue bars).

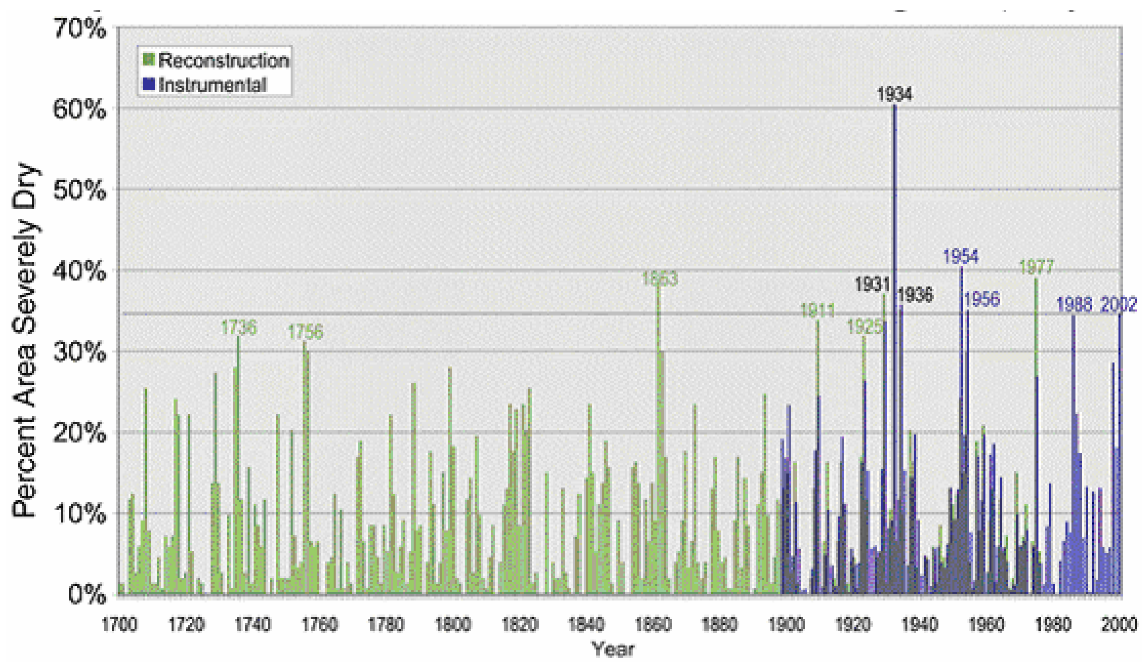

Figure 3: Percent area of contiguous U.S. severely dry (Jun-Aug). Green is 1700-1978 PDSI reconstructed from tree ring data, Dry ≤-2. Blue is 1900-2002 instrumental PHDI, Dry ≤ -3. ***Source: NOAA/NESDIS/National Climatic Data Center/Paleoclimatology Branch***

Within Figure 3 are important features that can be used to qualify the concept of drought severity. For droughts of interest across a broad region, the percent area coverage of the continental United States is a strong candidate for defining the most severe droughts. The drought of 1934 ranks as the most severe drought in the past three centuries based upon the percent area coverage as the sole qualifier. Using the 1988 drought area coverage (30% area coverage) as a threshold for an extreme drought, this would identify fifteen strong droughts in the past three centuries of similar to greater magnitude of the 1988 drought. However, the droughts identified represent the entire continental United States and do not always include the Red River Basin such as was the case with the 1928 – 1929 drought, thereby making the 1988 drought one of the ten most severe droughts to affect the Red River Basin in the past three hundred years. Using a combination of tree ring and instrumental PHDI values for the Red River Basin within the United States, Figure 4 shows that the 1988 drought was close to the severity of the 1934 drought.

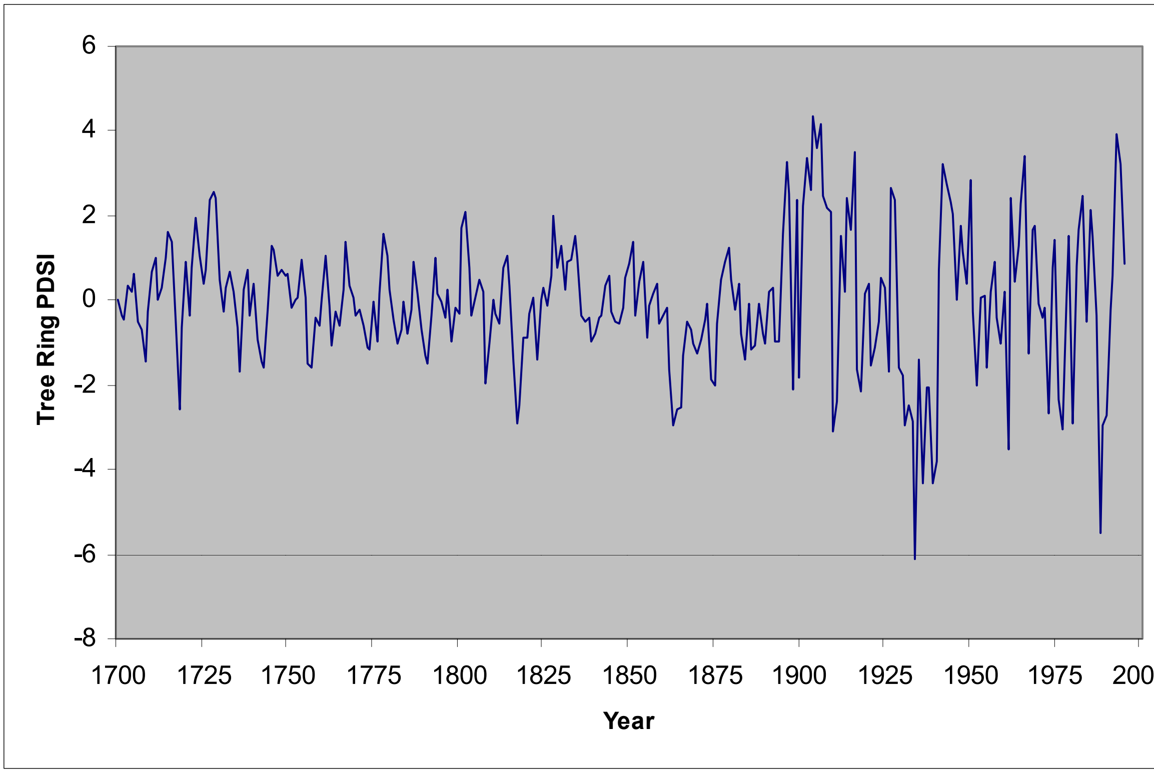

Figure 4: Reconstructed PDSI from tree ring data for Red River of the North Basin within the United States. ***Source: NOAA/NESDIS/National Climatic Data Center/Paleoclimatology Branch***

While severity based upon the PHDI provides a monthly indication of the drought conditions, it does not provide significant information relative to the magnitude of the drought. In an effort to identify the return interval of drought conditions, Dracup et al. (1980) considered the magnitude of drought as the ratio of the severity divided by the duration. Using this formulation, it is possible to identify longer-term debilitating drought conditions that will have a greater impact on a hydrologic system. Ponce et al. (2000) developed a conceptual model of estimating recurrence of drought given the climatic regime for a given region. Using the above concept for drought magnitude, the drought of the late 1980's across the Red River Basin can be compared to previous drought episodes by normalizing the severity by selecting a representative duration commensurate with the climate division for the Red River Basin. Following Ponce et al. (2000), definitions for climate divisions in the Red River Basin are characterized as being between semiarid and sub humid with mean annual precipitation between 400 mm and 600 mm. Using a mean duration between a semiarid and sub humid climate division and calculating the magnitude following Dracup et al. (1980), the data presented in Figure 5 reveal three droughts in the past one-hundred and fifty years that fall in the severe to extreme category, the late 1980's, the mid-1930's, and the early 1860's.

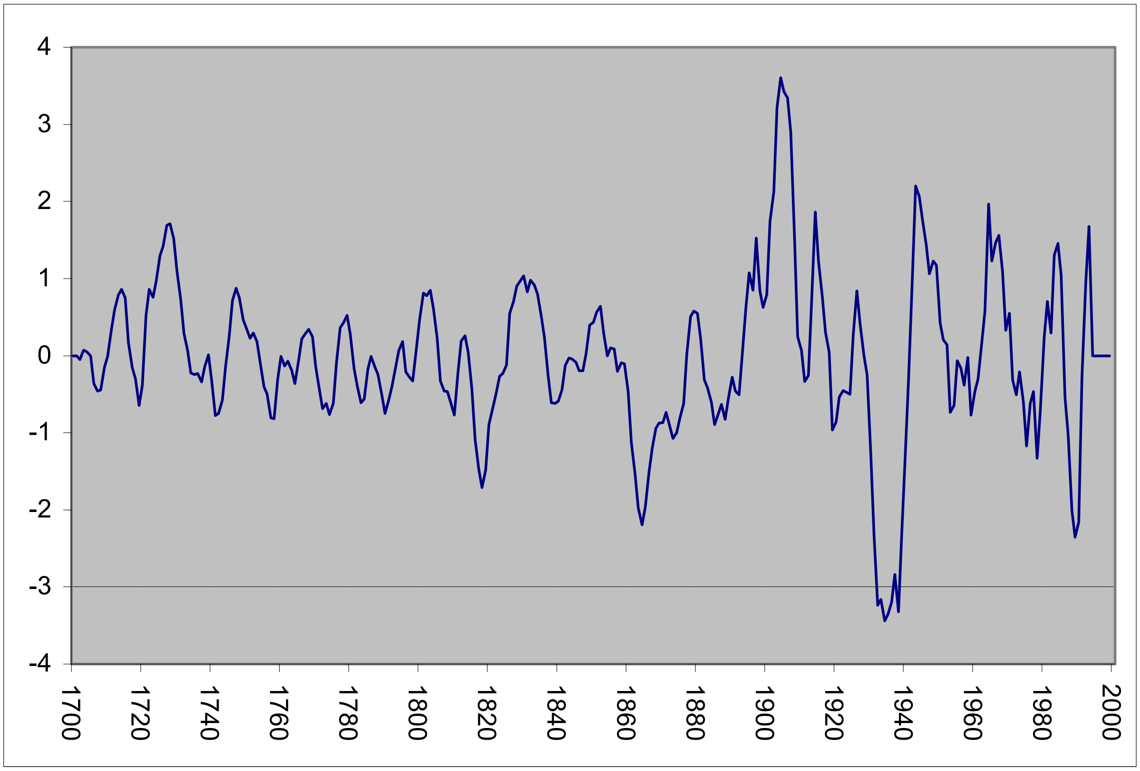

Figure 5: PDSI values from tree ring data filtered to remove drought conditions less than six years in duration following Ponce for semiarid to semi-humid climates.

The tree-ring reconstructed megadrought of the mid- to late-16th century over much of North America eclipses the above values as being the most significant drought in the past 2000 years. This drought, which spanned over a decade, is believed to have resulted in desertification of portions of the Great Plains.

Characterization of 25-, 50-, and 100-year droughts

Droughts are complex phenomena, which can be defined according to intensity and duration. The relationship between intensity and duration defines many different types of events, all of which may be considered droughts. It is difficult to compare a growing season with almost no rain to a multi-year period with below average precipitation. Even if these two types of events coincide, their recurrence intervals may be very different. Further, the intensity of precipitation that does occur during drought conditions can be an important element as intense rainfall may cause runoff without adding soil moisture and hence not alleviate agricultural drought conditions. Further, accumulated precipitation during extended periods of light rain can aid in alleviating agricultural drought, but have little effect on a hydrological drought. Unfortunately, the availability of precipitation intensity data is more lacking that precipitation accumulation. Only now over limited areas of the global does there exist technological capabilities to document both the precipitation and intensity by which it falls.

One way to indicate the relative severity of a hydrologic event e.g. high or low flow, is by calculating its frequency or recurrence interval. The recurrence interval is the average length of time between two events of a given magnitude and duration. It tells how likely an event is to occur, but says nothing about when it will happen. Recurrence intervals can be calculated for selected time scales and durations. As presented in the previous section using PHDI values, since 1700 the occurrence of drought conditions has occurred frequently with less frequent strong and extreme drought conditions. The focus of this study is to identify the less frequent yet more serious droughts and to understand the nature of their occurrence and recurrence.

Often the likelihood of extraordinary events is characterized through the representation of droughts relative to a recurrence interval of a specific period of interest. For the purpose of drought mitigation consideration in this study the intervals of interest are 25, 50 and 100 years representing a 4%, 2% and 1% non-exceedance probability.

In a report highlighting the annual impact of floods and droughts across North Dakota during 1988-89, Ryan (1991) presented recurrence intervals for previous droughts across North Dakota using streamflow records (Table 2).

Date	Area Affected	Recurrence Interval (years)	
1885-86	Western part of State	Unknown	Especially severe in 1886; crops poor
1929-42	Statewide	>25	Regional drought
1952-62	Statewide	10 to >25	Less than normal runoff for several consecutive years
1972-77	James River and Beaver Creek	>10	Localized drought in south-central part of State
1980-81	Parts of the Red River of the North and Missouri and James River Basins	>10	Less than normal runoff for 2 years
1988	Statewide	Unknown	Less than normal streamflow across the State

Table 2: Summary of drought occurrences in the Northern Plains since 1885 *(Ryan, 1991)*

Of note in Table 2 is the geographical variation in the location of drought. Of the six drought episodes referenced, three were statewide with the other three split between eastern and western North Dakota. This geographical distribution of drought is indicative of the localization of drought that is dependent upon the factors and influences responsible for the drought conditions. The three statewide periods of drought represent the more intense droughts during the period of record and are representative of droughts having sustained global forcing resulting in longer duration and more regional impacts. The areal extent of these droughts is seen in plots of national PDSI for the periods encompassing the droughts across North Dakota listed in Table 2 (Fig. 6). The periods where less than statewide drought is present show a more isolated impact within the state although other regions within the United States were experiencing wider coverage of drought conditions during these periods. While a distinction is made in the figures between the drought conditions in the mid-1970's and early 1980's, the short interval between the droughts suggest that the episode from the mid-1970's into the early 1980's are one drought episode with a brief respite between that is not indicative of a break in long-term drought conditions. This lengthening of the drought period is not inconsistent with the typical duration of drought for the semi-arid to semi-humid climate of the region (Ponce et al., 2000).

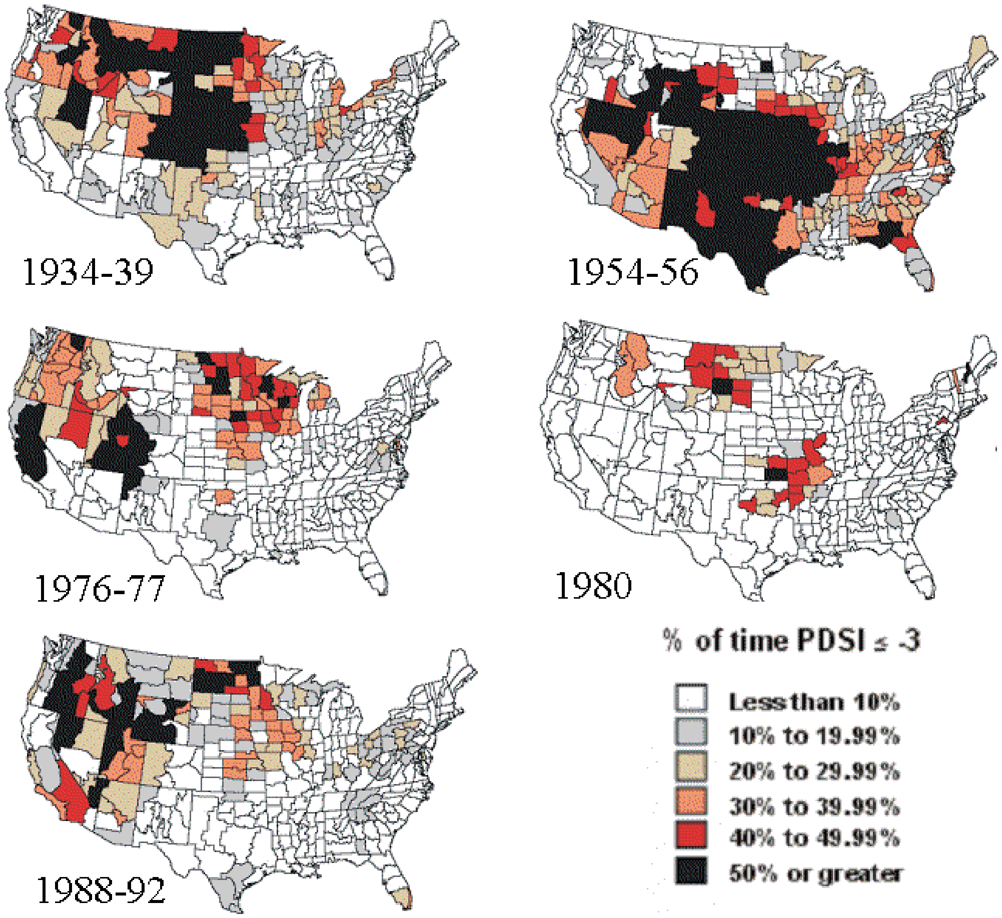

Figure 6: Distribution of severe droughts of the twentieth century across climate zones. Color coding denotes percentage of individual climate zone coverage at PDSI less than or equal to -3. ***Source: NOAA National Climatic Data Center.***

Except for the 1954-56 drought period, each of the drought periods in figure 6 have a clear coverage across North Dakota and the Red River of the North Basin south of the U.S.-Canada border and spanning east-to-west from eastern North Dakota into northwestern Minnesota. It is significant to note that the droughts of 1976-77 and 1980, while extending across almost all of North Dakota, did not include the Rocky Mountains of Montana, which are the primary source for Missouri River water supply. The U.S. portion of the Red River Basin spans all or parts of nine climate zones (Figure 7).

Comparing the PDSI percentage time of occurrence values of Figure 6 indicates that droughts of the1930's, middle to late1970's and the late 1980's to early 1990's were the greatest temporal and spatial coverage of drought in recorded observational period of record. Comparison of these three periods of greatest drought with the ten driest years since 1895 provides an interesting comparison. Table 3 lists the ten driest years for each of the climate zones across North Dakota and the Red River Basin (Figure 8). The extreme drought decade of the 1930's clearly dominates the top ten driest years, followed by the drought years from 1987 through 1992.

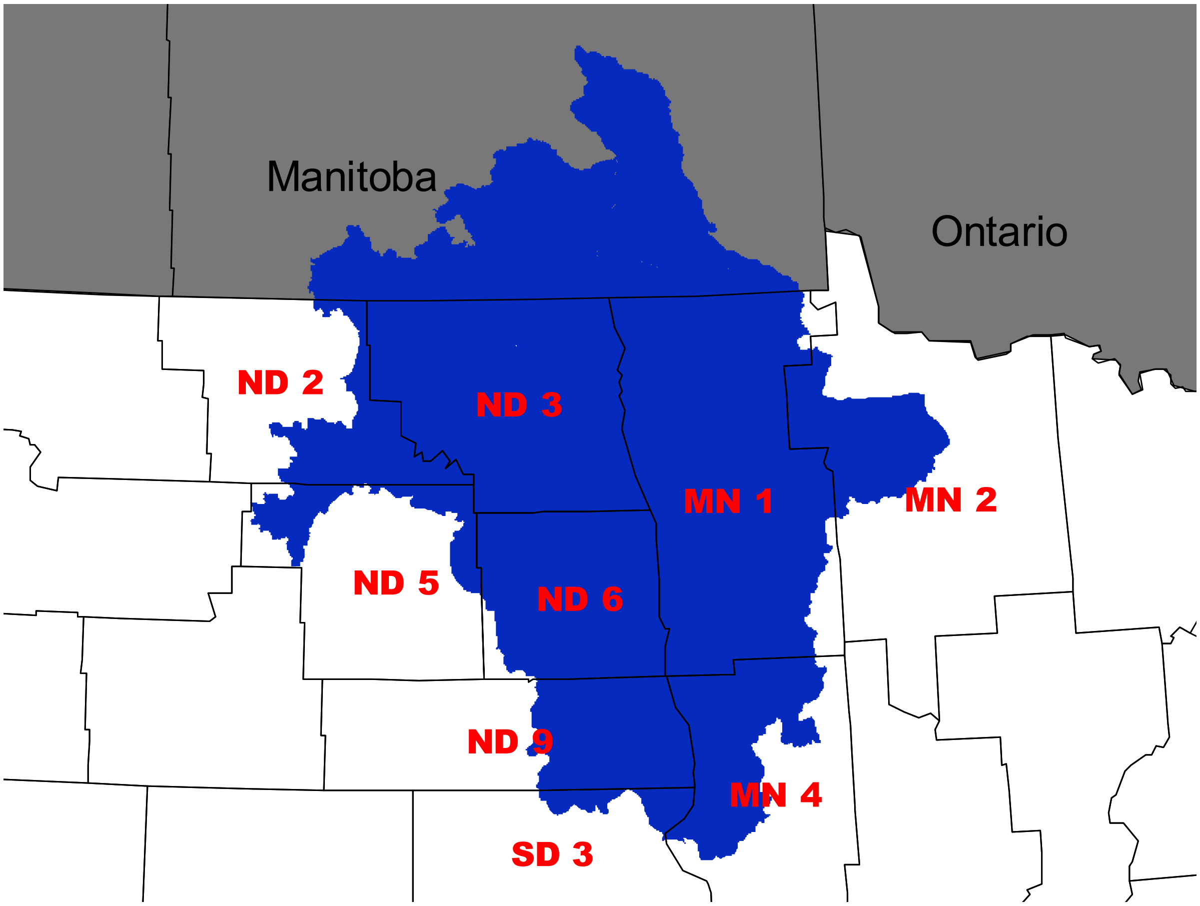

Figure 7: Location of the Red River of the North Basin with respect to NCDC climate zones. Climate zones listed are those included in the present study for the Red River Basin.

Subsequent to the 1988-1992 drought, Williams-Sether et al. (1994) computed recurrence intervals for each major hydrological drought identified by Ryan (1991) using streamflow data from six gauging stations distributed across North Dakota. Due to differences in recurrence interval calculation methods and the additional data available due to a later date of calculation, the Williams-Sether team proposed a different set of recurrence intervals (Table 4) that provided more distinct values as opposed to the generalized estimates by Ryan.

The results of Williams-Sether et al. (1994) provided a range of recurrence intervals and with four of the six gauging stations in the Red River Basin the information provides more clarity than Ryan on possible recurrence intervals associated with the observed hydrological droughts since the 1930's. The grouping of Red River Basin drought recurrence intervals versus those further west into the Upper Missouri River Basin reflects the spatial variability of drought forcing. That the severity of drought was similar in western North Dakota (i.e. Upper Missouri River Basin), to those in the Red River Basin during the 1930's but the recurrence interval is significantly less, supports the assertion of Ponce et al. (2000) that more arid regions than the Red River Basin should have a lower anticipated recurrence interval for similar drought conditions. The factor of two to three differences between the Red River Basin and the Upper Missouri River Basin in western North Dakota is consistent with the conceptual model they proposed.

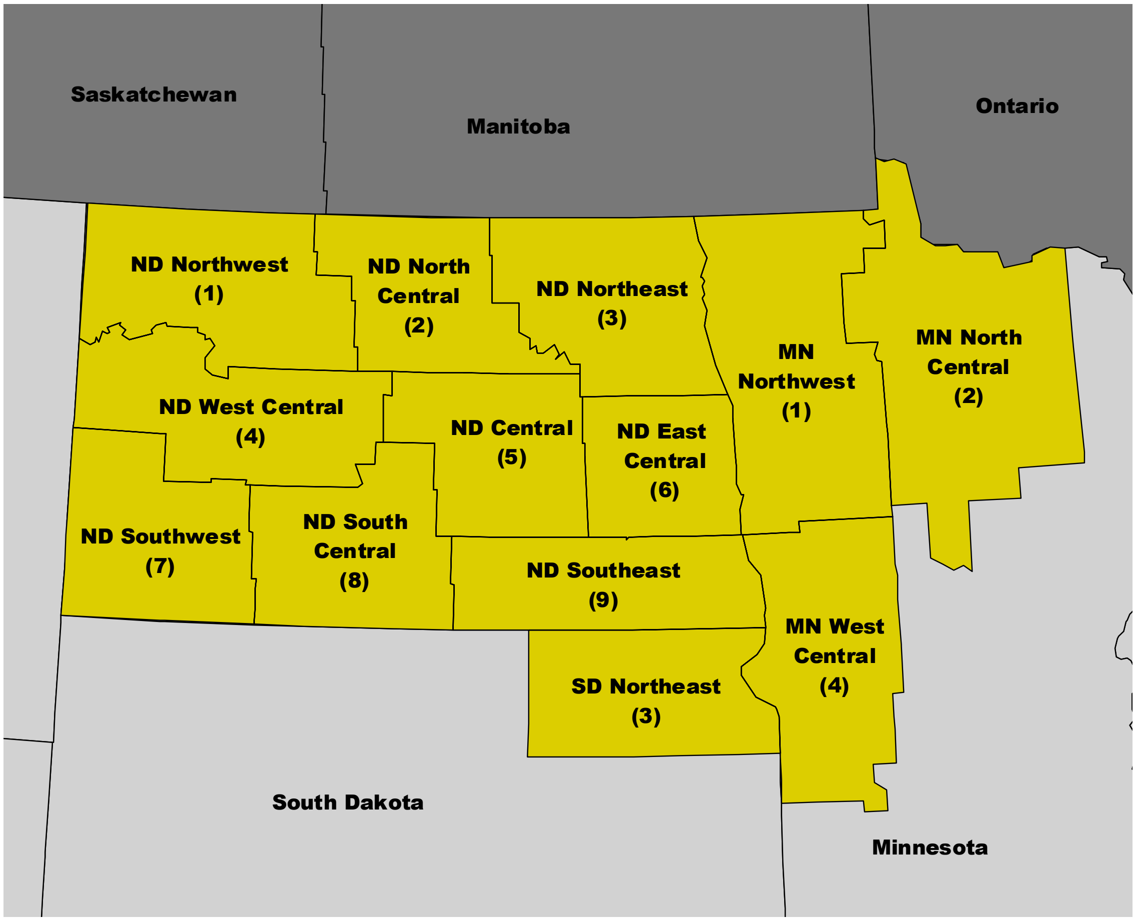

Figure 8: Depiction of all climate zones used in the present study. Zones outside of the Red River Basin are included to characterize conditions in the Upper Missouri Basin.

The preceding work of Ryan (1991) and Williams-Sether et al. (1994) relied upon the use of streamflow gauging station data to determine recurrence intervals. However, the low recurrence interval values for the severe drought of the 1988-92 hydrological drought reflected in the Red River streamflow values at Grand Forks are inconsistent with the trend with the previous drought recurrence intervals at Grand Forks and other locations in the Red River Basin. Williams-Sether et al. (1994) suggests this discrepancy is due in part to measures to regulate streamflows on the Red River after the early 1980's drought conditions. If correct, this makes the use of mainstem streamflow gauging of the Red River less representative of appropriate recurrence intervals and underscores the potential anthropogenic impacts on streamflow data used to identify natural hydrologic drought conditions.

Ranking	ND Northeast	ND East Central	ND Southeast	MN Northwest	ND Southwest	ND South Central	MN West Central
1	1917	1936	1936	1936	1936	1936	1976
2	1952	1976	1976	1910	1934	1934	1910
3	1936	1910	1910	1976	1988	1917	1934
4	1988	1917	1952	1917	1917	1988	1936
5	1934	1934	1917	1934	1952	1952	1933
6	1933	1938	1934	1952	1990	1933	1987
7	1910	1939	1933	1990	1949	1913	1958
8	1976	1963	1988	1967	1980	1974	1932
9	1989	1967	1907	1980	1979	2002	1931
10	1939	1907	1987	1961	2002	1990	1980

19030's Period	Middle to late 1970's Period	Late 1980's to early 1990's Period

Ranking	ND North Central	ND Central	MN North Central	SD Northeast	ND Northwest	ND West Central
1			1910			
2				1898		
3	1917				1961	
4		1917			1917	1917
5	1961			1910		1961
6		1910	1967	1958	1958	
7		1907	1923	1952		
8			1956		1960	1910
9	1958	1961	1958		1952	1952
10		1967	1917	1987	1967	1958

Table 3: The ten driest years on observed record identified relative to individual climate zones. Rank of value "1" indicates driest calendar year observed. Color coding denotes respective drought periods of 1930's (red), late 1980's to early 1990's (gold), and middle to late 1970's (light yellow). Representation by color also indicates respective intensity of drought with red the most intense and light yellow least intense. *Source: NOAA National Climatic Data Center*.

Streamflow gauging station	Recurrence Intervals			
	1930's to early 1940's	1950's to early 1960's	Mid- to late 1970's and early 1980's	1988-92
Wild Rice River, near Abercrombie, North Dakota	52	26	14	19
Sheyenne River, near Cooperstown, North Dakota		37	5	45
Red River of the North, at Grand Forks, North Dakota	66	27	30	28
Pembina River, at Neche, North Dakota	74	27	16	42
Little Missouri River, near Watford City, North Dakota	27	50	29	54
Cannonball River, at Briene, North Dakota	25	49	58	27

Table 4: Recurrence intervals identified by *Williams-Sether et al. (1994)* from streamflow gauge measures.

To alleviate problems with solely using streamflow measurements, the use of precipitation can be considered albeit with an understanding that a direct mathematical relationship between streamflow measurements and accumulated precipitation is difficult to establish and only that they are positively correlated. Unfortunately, as with streamflow gauging, in most situations the lack of a sufficiently long observational record hinders the estimation process, particularly for investigating the most extreme drought recurrence. Therefore much of the analysis on drought recurrence is predicated on meteorological drought conditions, which are highly correlated to accumulated precipitation and evaporation. A method proposed by Hosking and Wallis (1993) using L-moments as part of a regional frequency analysis provides an opportunity to build more robust statistics from a limited single-site through the use of clustering with other regionally representative locations. As part of the work in developing the National Drought Atlas, this L-moment analysis approach can provide from a specially developed Historical Climatology Network (HCN) (Karl et al., 1990) estimates of non-exceedance frequencies based upon precipitation data. Using values derived from the National Drought Atlas (Werick et al., 1994) for a location within hydrologic region nine that is most representative of the Red River Basin, estimates of drought non-exceedance frequencies can be obtained that are synonymous to the recurrence intervals obtained from streamflow calculations.

The National Drought Atlas provides analysis datasets for 111 precipitation station clusters distributed across the eighteen hydrologic regions in the 48 contiguous states. From the L-moment analysis worksheets non-exceedance frequencies can be computed for drought durations extending from one month to sixty continuous months. To properly characterize the relative precipitation variations both spatially and temporally across the climate regions of the study, mean precipitation levels were associated with the base period normals spanning the 30-years prior to the year(s) of drought conditions. The variability in the base period precipitation normals (Table 5) indicate a slight variation in expected annual precipitation over the past decade. The table also reveals variation in precipitation from western North Dakota eastward into western Minnesota (i.e. from the Upper Missouri River Basin to the Red River Basin). The large standard deviations found within Table 5 (Table 6) are indicative of the transition from an arid climate in western North Dakota to a semi-humid climate in northwestern Minnesota.

For the purpose of assessing the impact of sustained drought that would provide greatest hydrologic limits, a range of drought durations of one-, two-, three- and five-years was chosen to identify precipitation levels that correspond to 25-, 50- and 100-year drought events (Table 7). It should be noted that, as the 2% frequency (50-year return interval) was the upper limit explicitly computed in the National Drought Atlas, the 100-year value required extrapolation of information and is subject to possible greater root mean square error relative to the rest of the data. Using the base period precipitation normals corresponding to the 1930's and late 1980's to 1990's droughts, the threshold precipitation levels for 25-, 50- and 100- year droughts were computed from the National Drought Atlas (Tables 8 and 9). Applying these thresholds to the actual mean precipitation for each climate zone in North Dakota and non-North Dakota climate zones in the Red River Basin, the years of drought and intensity of drought relative to the above non-exceedance frequencies can be highlighted (Tables 10 thru 17).

From Table 10 through Table 17, it is clear that the drought years of 1934 and 1936 were the more extreme of the two drought periods compared where 50+ year drought conditions existed both within the Red River Basin and across a large portion of North Dakota. The western edge of the Red River Basin into central and northern North Dakota had more extreme drought conditions with 100+ year drought conditions. In contrast, the 1988-1992 drought was more limited in duration and intensity with only sporadic climate divisions, demonstrating beyond a 25-year drought based upon deviations from base period expected precipitation. While noteworthy relative to other droughts during the past century, the limited duration and areal extent of the drought relative to the 1930's drought underscores the significance of the 1930's drought as the major drought of the twentieth century across the Northern Plains.

Base Precipitation Periods	ND Northeast				MN West Central	Red River Basin Mean
1901-1930	18.70	19.21	18.95	21.72	22.32	20.18
1911-1940	17.68	18.16	18.03	20.23	21.06	19.03
1921-1950	18.11	18.70	18.57	20.75	21.69	19.56
1931-1960	17.94	18.69	18.85	20.98	23.11	19.91
1941-1970	18.77	19.88	20.00	22.41	24.70	21.15
1951-1980	18.02	19.29	19.46	21.60	24.10	20.50
1961-1990	18.05	19.57	19.39	21.92	24.14	20.61
1971-2000	18.98	20.57	20.37	22.88	24.70	21.50
Mean	18.28	19.26	19.20	21.56	23.23	20.31
Std Dev	0.47	0.76	0.76	0.88	1.40	0.81

Base Precipitation Periods	ND Northwest	ND West Central	ND Southwest	ND South Central	ND North Central	ND Central	MN North Central	SD Northeast
1901-1930	16.42	17.12	16.31	16.31	17.73	18.09	24.72	18.57
1911-1940	15.21	15.99	15.39	15.20	16.48	16.97	23.50	18.42
1921-1950	15.31	16.32	15.70	15.94	16.64	17.37	23.83	19.51
1931-1960	14.64	15.85	15.13	15.77	16.14	17.35	24.50	19.83
1941-1970	15.64	16.91	16.13	16.86	16.98	18.12	25.64	20.68
1951-1980	15.63	16.47	15.92	16.21	16.82	17.49	25.14	19.60
1961-1990	15.80	16.42	16.00	16.16	16.87	17.34	25.69	20.11
1971-2000	16.29	16.62	15.83	16.91	17.80	18.33	26.18	21.29
Mean	15.62	16.46	15.80	16.17	16.93	17.63	24.90	19.75
Std Dev	0.58	0.43	0.39	0.56	0.58	0.48	0.94	0.97

Table 5: Base periodic precipitation normals (inches annually by calendar year) for the climate zones across North Dakota and the Red River of the North Basin. ***Source: NOAA National Climatic Data Center.***

Stand Deviations Across Climate Zones		
Across all study climate zones	Across Red River Basin	Outside of Red River Basin
2.56	1.70	2.79
2.49	1.51	2.79
2.56	1.57	2.85
3.07	2.11	3.29
3.21	2.38	3.32
3.08	2.39	3.18
3.21	2.41	3.38
3.30	2.27	3.49

Table 6: Standard deviations found within the Table 5 for each base period. Values are in inches.

Red River Basin			
Months	1%	2%	4%
12	0.504	0.579	0.6315
24	0.621	0.682	0.7247
36	0.717	0.76	0.7901
60	0.752	0.793	0.8217

Central North Dakota			
Months	1%	2%	4%
12	0.473	0.55	0.6039
24	0.65	0.697	0.7299
36	0.746	0.767	0.7817
60	0.73	0.773	0.8031

Western ND			
Months	1%	2%	4%
12	0.417	0.505	0.5666
24	0.537	0.616	0.6713
36	0.601	0.671	0.72
60	0.644	0.715	0.7647

Table 7: Fraction of base period precipitation normal required to threshold non-exceedance frequencies associated with 1% (100-year), 2% (50-year) and 4% (25-year) droughts. Values are dimensionless fractions of annual precipitation. Monthly accumulations are provided from each non-exceedance level.

25-Year Drought	ND Northeast	ND East Central	ND Southeast	MN Northwest	MN West Central	Red River Basin Mean	ND Northwest	ND West Central	ND Southwest	ND South Central	ND North Central	ND Central	MN North Central	SD Northeast
1 year	11.81	12.13	11.97	13.72	14.10	12.75	9.30	9.70	9.24	9.24	10.71	10.93	15.61	11.73
2 year	27.11	27.85	27.47	31.48	32.35	29.25	22.04	22.98	21.90	21.89	25.88	26.41	35.83	26.91
3 year	44.33	45.54	44.93	51.49	52.91	47.84	35.46	36.97	35.23	35.22	41.57	42.43	58.59	44.01
5 year	76.84	78.94	77.88	89.24	91.70	82.92	62.76	65.45	62.37	62.35	71.18	72.65	101.55	76.28

50-Year Drought	ND Northeast	ND East Central	ND Southeast	MN Northwest	MN West Central	Red River Basin Mean	ND Northwest	ND West Central	ND Southwest	ND South Central	ND North Central	ND Central	MN North Central	SD Northeast
1 year	10.83	11.12	10.97	12.58	12.92	11.69	8.29	8.64	8.24	8.24	9.75	9.95	14.31	10.75
2 year	25.51	26.21	25.85	29.63	30.44	27.53	20.22	21.09	20.10	20.09	24.71	25.22	33.72	25.33
3 year	42.64	43.81	43.22	49.52	50.89	46.02	33.04	34.46	32.84	32.83	40.79	41.63	56.36	42.33
5 year	74.15	76.18	75.16	86.12	88.50	80.02	58.68	61.19	58.32	58.30	68.52	69.92	98.01	73.62

100-Year Drought	ND Northeast	ND East Central	ND Southeast	MN Northwest	MN West Central	Red River Basin Mean	ND Northwest	ND West Central	ND Southwest	ND South Central	ND North Central	ND Central	MN North Central	SD Northeast
1 year	9.43	9.68	9.55	10.95	11.25	10.17	6.85	7.14	6.80	6.80	8.39	8.56	12.46	9.36
2 year	23.23	23.86	23.54	26.98	27.72	25.07	17.63	18.38	17.52	17.51	23.05	23.52	30.70	23.06
3 year	40.23	41.33	40.77	46.72	48.01	43.41	29.60	30.86	29.41	29.40	39.67	40.49	53.17	39.94
5 year	70.32	72.24	71.27	81.67	83.92	75.89	52.86	55.12	52.52	52.51	64.70	66.03	92.94	69.81

Table 8: Threshold (minimum) precipitation required to trigger 25-, 50-, and 100-year drought designation for the 1901-1930 base period precipitation normals. Precipitation amounts are accumulated over the length given in the first column. Values are in inches annually by calendar year.

25-Year Drought	ND Northeast	ND East Central	ND Southeast	MN Northwest	MN West Central	Red River Basin Mean	ND Northwest	ND West Central	ND Southwest	ND South Central	ND North Central	ND Central	MN North Central	SD Northeast
1 year	11.38	12.18	12.29	13.64	15.22	12.94	8.86	9.33	9.02	9.18	10.16	10.56	15.88	12.38
2 year	26.12	27.96	28.20	31.31	34.93	29.71	20.99	22.11	21.38	21.76	12.28	25.54	36.44	28.40
3 year	42.72	45.72	46.12	51.21	57.13	48.58	33.77	35.58	34.40	35.01	39.44	41.02	59.60	46.45
5 year	74.05	79.25	79.94	88.76	99.02	84.21	59.78	62.98	60.89	61.98	67.54	70.24	103.31	80.51

50-Year Drought	ND Northeast	ND East Central	ND Southeast	MN Northwest	MN West Central	Red River Basin Mean	ND Northwest	ND West Central	ND Southwest	ND South Central	ND North Central	ND Central	MN North Central	SD Northeast
1 year	10.44	11.17	11.27	12.51	13.95	11.87	7.90	8.32	8.04	8.19	9.25	9.62	14.56	11.35
2 year	24.58	26.31	26.54	29.47	32.87	27.96	19.26	20.29	19.62	19.97	11.72	24.38	34.30	26.73
3 year	41.09	43.98	44.36	49.26	54.95	46.73	31.47	33.16	32.06	32.63	38.70	40.25	57.33	44.68
5 year	71.46	76.49	77.15	85.66	95.56	81.26	55.89	58.89	56.93	57.95	65.01	67.61	99.70	77.70

100-Year Drought	ND Northeast	ND East Central	ND Southeast	MN Northwest	MN West Central	Red River Basin Mean	ND Northwest	ND West Central	ND Southwest	ND South Central	ND North Central	ND Central	MN North Central	SD Northeast
1 year	9.08	9.72	9.81	10.89	12.15	10.33	6.52	6.87	6.64	6.76	7.96	8.27	12.67	9.88
2 year	22.39	23.96	24.17	26.83	29.93	25.46	16.79	17.69	17.10	17.41	21.87	22.74	31.23	24.34
3 year	38.77	41.49	41.85	46.47	51.84	44.09	28.19	29.70	28.71	29.23	37.64	39.15	54.09	42.15
5 year	67.77	72.53	73.16	81.23	90.62	77.06	50.34	53.04	51.28	52.20	54.66	63.85	94.54	73.68

Table 9: Threshold (minimum) precipitation required to trigger 25-, 50-, and 100-year drought designation for the 1951-1980 base period precipitation normals. Precipitation amounts are accumulated over the length given in the first column. Values are in inches annually by calendar year.

Year	ND Northeast	ND East Central	ND Southeast	MN Northwest	MN West Central	Red River Basin Mean	ND Northwest	ND West Central	ND Southwest	ND South Central	ND North Central	ND Central	MN North Central	SD Northeast
1929	14.85	16.28	16.38	17.3	18.99	16.76	12.7	14.34	14.01	14.03	13.79	14.68	19.27	18.39
1930	15.01	15.35	16.23	19.4	20.1	17.22	13.84	14.85	13.1	15.82	15.37	16.88	23.11	17.16
1931	17.79	19.8	19.98	19.33	18.11	19.00	9.48	13.16	15.33	16.76	11.43	18.19	21.07	18.39
1932	18.66	17.47	19.08	17.87	17.68	18.15	16.93	15.66	17.67	15.18	16.13	17.62	23.17	19.6
1933	12.67	17.35	13.52	18.04	16.08	15.53	13.66	13.54	13.43	10.79	13.11	14.85	21.37	14.37
1934	12.5	13.86	13.15	16.66	14.85	14.20	6.26	8.37	8.09	8.29	8.26	11.12	19.15	14.48
1935	19.43	19.94	21.28	20.38	22.5	20.71	14.97	18.16	15.06	16.27	19.48	19.97	26.15	21.54
1936	12.22	8.89	8.93	13.01	15.41	11.69	10.05	7.59	6.55	6.34	9.46	7.45	16.19	12.77
1937	21.63	21.97	18.91	22.76	25.63	22.18	14.85	15.44	14.54	16.28	19.83	17.02	29.04	24.46
1938	13.7	14.23	16.61	18.57	23.15	17.25	16.23	17.53	15.9	13.36	14.18	14.58	23.61	19.49
1939	13.69	14.29	18.88	17.3	20.32	16.90	12.56	13.25	14.38	15.25	12.55	13.89	21.68	20.7
1940	18.99	18.15	18.78	20.22	23.84	20.00	15.63	16.42	17.06	15.56	18.27	18.03	23.32	20.14
1941	25.64	25.58	24.61	27.56	26.49	25.98	22.27	21.74	22.97	19.99	24.53	23.35	28.06	24.71
1942	18.95	21.18	26.03	23.46	29.02	23.73	13.54	18.6	17.9	19.62	14.58	20.77	26.96	27.27

Orange denotes 25-year drought	Red denotes 50-year drought	Magenta denotes 100-year drought

Table 10: Application of National Drought Atlas to 1-year accumulated precipitation for 1930's drought. Values are in inches by calendar year.

Year	ND Northeast	ND East Central	ND Southeast	MN Northwest	MN West Central	Red River Basin Mean	ND Northwest	ND West Central	ND Southwest	ND South Central	ND North Central	ND Central	MN North Central	SD Northeast
1929	34.84	38.08	35.73	38.73	40.09	37.49	28.64	31.9	29.79	29.69	32.59	33.69	43.23	35.6
1930	29.86	31.63	32.61	36.7	39.09	33.98	26.54	29.19	27.11	29.85	29.16	31.56	42.38	35.55
1931	32.8	35.15	36.21	38.73	38.21	36.22	23.32	28.01	28.43	32.58	26.8	35.07	44.18	35.55
1932	36.45	37.27	39.06	37.2	35.79	37.15	26.41	28.82	33	31.94	27.56	35.81	44.24	37.99
1933	31.33	34.82	32.6	35.91	33.76	33.68	30.59	29.2	31.1	25.97	29.24	32.47	44.54	33.97
1934	25.17	31.21	26.67	34.7	30.93	29.74	19.92	21.91	21.52	19.08	21.37	25.97	40.52	28.85
1935	31.93	33.8	34.43	37.04	37.35	34.91	21.23	26.53	23.15	24.56	27.74	31.09	45.3	36.02
1936	31.65	28.83	30.21	33.39	37.91	32.40	25.02	25.75	21.61	22.61	28.94	27.42	42.34	34.31
1937	33.85	30.86	27.84	35.77	41.04	33.87	24.9	23.03	21.09	22.62	29.29	24.47	45.23	37.23
1938	35.33	36.2	35.52	41.33	48.78	39.43	31.08	32.97	30.44	29.64	34.01	31.6	52.65	43.95
1939	27.39	28.52	35.49	35.87	43.47	34.15	28.79	30.78	30.28	28.61	26.73	28.47	45.29	40.19
1940	32.68	32.44	37.66	37.52	44.16	36.89	28.19	29.67	31.44	30.81	30.82	31.92	45	40.84
1941	44.63	43.73	43.39	47.78	50.33	45.97	37.9	38.16	40.03	35.55	42.8	41.38	51.38	44.85
1942	44.59	46.76	50.64	51.02	55.51	49.70	35.81	40.34	40.87	39.61	39.11	44.12	55.02	51.98

Orange denotes 25-year drought — Red denotes 50-year drought — Magenta denotes 100-year drought

Table 11: Application of National Drought Atlas to 2-year accumulated precipitation for 1930's drought. Values are in inches by calendar year.

Year	ND Northeast	ND East Central	ND Southeast	MN Northwest	MN West Central	Red River Basin Mean	ND Northwest	ND West Central	ND Southwest	ND South Central	ND North Central	ND Central	MN North Central	SD Northeast
1929	57.45	58.54	55.86	61.81	63.16	59.36	50.82	54.47	51.79	49.95	55.7	55.12	68	55.13
1930	49.85	53.43	51.96	58.13	60.19	54.71	42.48	46.75	42.89	45.51	47.96	50.57	66.34	52.76
1931	47.65	51.43	52.59	56.03	57.2	52.98	36.02	42.35	42.44	46.61	40.59	49.75	63.45	53.94
1932	51.46	52.62	55.29	56.6	55.89	54.37	40.25	43.67	46.1	47.76	42.93	52.69	67.35	55.15
1933	49.12	54.62	52.58	55.24	51.87	52.69	40.07	42.36	46.43	42.73	40.67	50.66	65.61	52.36
1934	43.83	48.68	45.75	52.57	48.61	47.89	36.85	37.57	39.19	34.26	37.5	43.59	63.69	48.45
1935	44.6	51.15	47.95	55.08	53.43	50.44	34.89	40.07	36.58	35.35	40.85	45.94	66.67	50.39
1936	44.15	42.69	43.36	50.05	52.76	46.60	31.28	34.12	29.7	30.9	37.2	38.54	61.49	48.79
1937	53.28	50.8	49.12	56.15	63.54	54.58	39.87	41.19	36.15	38.89	48.77	44.44	71.38	58.77
1938	47.55	45.09	44.45	54.34	64.19	51.12	41.13	40.56	36.99	35.98	43.47	39.05	68.84	56.72
1939	49.02	50.49	54.4	58.63	69.1	56.33	43.64	46.22	44.82	44.89	46.56	45.49	74.33	64.65
1940	46.38	46.67	54.27	56.09	67.31	54.14	44.42	47.2	47.34	44.17	45	46.5	68.61	60.33
1941	58.32	58.02	62.27	65.08	70.65	62.87	50.46	51.41	54.41	50.8	55.35	55.27	73.06	65.55
1942	63.58	64.91	69.42	71.24	79.35	69.70	51.44	56.76	57.93	55.17	57.38	62.15	78.34	72.12

Orange denotes 25-year drought | Red denotes 50-year drought | Magenta denotes 100-year drought

Table 12: Application of National Drought Atlas to 3-year accumulated precipitation for 1930's drought. Values are in inches by calendar year.

Year	ND Northeast	ND East Central	ND Southeast	MN Northwest	MN West Central	Red River Basin Mean	ND Northwest	ND West Central	ND Southwest	ND South Central	ND North Central	ND Central	MN North Central	SD Northeast
1929	92.7	93.18	89.99	103.93	102.42	96.44	81.95	85.89	81.48	79.59	88.75	87.94	115.72	87.76
1930	89.86	91.47	88.8	101.8	103.18	95.02	78.87	84.38	78.63	79.79	86.74	87.92	114.41	88.82
1931	90.25	93.69	92.07	100.54	101.37	95.58	74.14	82.48	80.22	82.53	82.5	90.19	112.18	90.68
1932	86.3	90.7	91.02	95.33	95.98	91.87	68.89	75.57	75.89	77.45	75.52	86.38	110.58	90.75
1933	78.98	86.25	85.19	91.94	90.96	86.66	66.61	71.55	73.54	72.58	69.83	82.22	107.99	87.91
1934	76.63	83.83	81.96	91.3	86.82	84.11	60.17	65.58	67.62	66.84	64.3	78.66	107.87	84
1935	81.05	88.42	87.01	92.28	89.22	87.60	61.3	68.89	69.58	67.29	68.41	81.75	110.91	88.38
1936	75.48	77.51	75.96	85.96	86.52	80.29	61.87	63.32	60.8	56.87	66.44	71.01	106.03	82.76
1937	78.45	82.01	75.79	90.85	94.47	84.31	59.79	63.1	57.67	57.97	70.14	70.41	111.9	87.62
1938	79.48	78.89	78.88	91.38	101.54	86.03	62.36	67.09	60.14	60.54	71.21	70.14	114.14	92.74
1939	80.67	79.32	84.61	92.02	107.01	88.73	68.66	71.97	66.43	67.5	75.5	72.91	116.67	98.96
1940	80.23	77.53	82.11	91.86	108.35	88.02	69.32	70.23	68.43	66.79	74.29	70.97	113.84	97.56
1941	93.65	94.22	97.79	106.41	119.43	102.30	81.54	84.38	84.85	80.44	89.36	86.87	125.71	109.5
1942	90.97	93.43	104.91	107.11	122.82	103.85	80.23	87.54	88.21	83.78	84.11	90.62	123.63	112.31

Orange denotes 25-year drought | Red denotes 50-year drought | Magenta denotes 100-year drought

Table 13: Application of National Drought Atlas to 5-year accumulated precipitation for 1930's drought. Values are in inches by calendar year.

Year	ND Northeast	ND East Central	ND Southeast	MN Northwest	MN West Central	Red River Basin Mean	ND Northwest	ND West Central	ND Southwest	ND South Central	ND North Central	ND Central	MN North Central	SD Northeast
1987	18.98	20.48	15.37	18.72	17.59	18.23	13.39	15.67	15.44	15.72	16.52	17.74	23.25	14.62
1988	12.46	14.9	14.44	17.99	19.23	15.80	11.99	9.17	9.15	10.69	11.39	10.56	24.8	17.85
1989	13.62	15.73	18.38	19.17	22.29	17.84	11.8	13.25	14.41	13.03	13.67	15.1	24.95	20.43
1990	15.77	17.74	16.89	17.04	23.05	18.10	14.31	15.2	10.61	11.84	16.48	18.13	20.53	20.92
1991	25.27	20.68	22.81	26.56	31.21	25.31	18.96	17.82	15.48	16.03	21.28	18.19	27.17	27.28
1992	15.47	21.12	19.96	22.2	22.26	20.20	12.92	12.55	13.25	14.07	10.87	13.65	23	19.76
1993	23.59	23.72	26.5	23.19	29.89	25.38	21.65	20.72	17.52	24.17	21.04	27.13	26.88	28.75
1994	23.32	26.62	22.56	25.7	24.39	24.52	17.16	19.04	16.66	19.61	22.12	23.06	28.04	23.39

Table 14: Application of National Drought Atlas to 1-year accumulated precipitation for late 1980's - early 1990's drought. The orange shading denotes a 25-year drought. Values are in inches.

Year	ND Northeast	ND East Central	ND Southeast	MN Northwest	MN West Central	Red River Basin Mean	ND Northwest	ND West Central	ND Southwest	ND South Central	ND North Central	ND Central	MN North Central	SD Northeast
1987	39.46	45.06	44.53	40.62	49.62	43.86	31.82	36.01	35.69	39.45	34.29	40.17	49.21	43.91
1988	31.44	35.38	29.81	36.71	36.82	34.03	25.38	24.84	24.59	26.41	27.91	28.3	48.05	32.47
1989	26.08	30.63	32.82	37.16	41.52	33.64	23.79	22.42	23.56	23.72	25.06	25.66	49.75	38.28
1990	29.39	33.47	35.27	36.21	45.34	35.94	26.11	28.45	25.02	24.87	30.15	33.23	45.48	41.35
1991	41.04	38.42	39.7	43.6	54.26	43.40	33.27	33.02	26.09	27.87	37.76	36.32	47.7	48.2
1992	40.74	41.8	42.77	48.76	53.47	45.51	31.88	30.37	28.73	30.1	32.15	31.84	50.17	47.04
1993	39.06	44.84	46.46	45.39	52.15	45.58	34.57	33.27	30.77	38.24	31.91	40.78	49.88	48.51
1994	46.91	50.34	49.06	48.89	54.28	49.90	38.81	39.76	34.18	43.78	43.16	50.19	54.92	52.14

Table 15: Application of National Drought Atlas to 2-year accumulated precipitation for late 1980's - early 1990's drought. The orange shading denotes a 25-year drought. Values are in inches by calendar year.

Year	ND Northeast	ND East Central	ND Southeast	MN Northwest	MN West Central	Red River Basin Mean	ND Northwest	ND West Central	ND Southwest	ND South Central	ND North Central	ND Central	MN North Central	SD Northeast
1987	60.41	64.97	61.99	68.03	77.11	66.50	48.44	53.1	50.75	55.76	52.32	57.67	80.33	64.28
1988	51.92	59.96	58.97	58.61	68.85	59.66	43.81	45.18	44.84	50.14	45.68	50.73	74.01	61.76
1989	45.06	51.11	48.19	55.88	59.11	51.87	37.18	38.09	39	39.44	41.58	43.4	73	52.9
1990	41.85	48.37	49.71	54.2	64.57	51.74	38.1	37.62	34.17	35.56	41.54	43.79	70.28	59.2
1991	54.66	54.15	58.08	62.77	76.55	61.24	45.07	46.27	40.5	40.9	51.43	51.42	72.65	68.63
1992	56.51	59.54	59.66	65.8	76.52	63.61	46.19	45.57	39.34	41.94	48.63	49.97	70.7	67.96
1993	64.33	65.52	69.27	71.95	83.36	70.89	53.53	51.09	46.25	54.27	53.19	58.97	77.05	75.79
1994	62.38	71.46	69.02	71.09	76.54	70.10	51.73	52.31	47.43	57.85	54.03	63.84	77.92	71.9

Table 16: Application of National Drought Atlas to 3-year accumulated precipitation for late 1980's - early 1990's drought. The orange shading denotes a 25-year drought. Values are in inches.

Year	ND Northeast	ND East Central	ND Southeast	MN Northwest	MN West Central	Red River Basin Mean	ND Northwest	ND West Central	ND Southwest	ND South Central	ND North Central	ND Central	MN North Central	SD Northeast
1987	94.37	102.89	100.47	114.59	130.32	108.53	76.03	81.33	77.17	85.95	83.89	91.08	132.9	108.68
1988	89.31	97.04	97.56	106.93	125.74	103.32	74.31	77.11	73.28	81.98	79.73	83.99	130.13	105.93
1989	86.49	95.6	94.81	105.19	118.63	100.14	72.23	75.52	74.31	79.48	77.38	83.33	130.08	102.56
1990	81.31	93.43	94.24	94.82	114.19	95.60	69.92	73.63	69.86	75.01	75.83	83.96	119.49	103.11
1991	86.1	89.53	87.89	99.48	113.37	95.27	70.45	71.11	65.09	67.31	79.34	79.72	120.7	101.1
1992	82.59	90.17	92.48	102.96	118.04	97.25	69.98	67.99	62.9	65.66	73.69	75.63	120.45	106.24
1993	93.72	98.99	104.54	108.16	128.7	106.82	79.64	79.54	71.27	79.14	83.34	92.2	122.53	117.14
1994	103.42	109.88	108.72	114.69	130.8	113.50	85	85.33	73.52	85.72	91.79	100.16	125.62	120.1

Table 17: Application of National Drought Atlas to 5-year accumulated precipitation for late 1980's - early 1990's drought. Values are in inches by calendar year.

In an effort to identify long-term drought recurrence, investigations have been required to utilize non-observed data. The use of these paleoclimatic proxies have been focused on tree ring and lake sediment records in investigating early climate variations including drought. Research by Laird et al. (1996b, 2003), Cole and Cook (1998), Cumming et al. (2002), Ashworth (1983) have focused efforts on interpreting proxies to determine the nature of climate variability in North America and create a better understanding of causes and prospects for future conditions. All researchers are in agreement that, prior to 1200 AD, extended drought conditions were more commonplace in North America than the present time and that an abrupt change in global conditions around the thirteenth century occurred resulting in a wetter climate that is still dominant to date. Only during periods of infrequent extreme droughts such as experienced across North America in the decade of the 1930's do conditions become anywhere similar to these paleodroughts. A major source of information on ancient and recent droughts has been limnological analysis of diatoms extracted from lake bottom sediment. The use of closed basin lakes across the continent interior has produced data records exceeding 5,000 years and resulted in considerable knowledge of climate variability. Through transfer functions based upon modern distributions of diatom assemblages (Fritz et al. 1999) the variations in lake salinity have been inferred. As salinity has a direct correlation to lake depth, the use of salinity as a surrogate for wet and dry climate periods is possible. Where salinity values increase due to a drop in lake level, the presence of dry periods is inferred. Cumming et al. (2002) found a coherent structure between millennial-scale dynamics and large changes in closed basin lake (Big Lake) depth in British Columbia suggesting these large variations are a common feature across North America. Investigations of a varved lake in northern Minnesota, Elk Lake, (Bradbury & Dieterich-Rurup, 1993; Dean and Schwalb, 2000) has produced a less clear sample than Big Lake, but one that does reveal an abrupt change within the past 1,000 years. Their investigations have shown multidecadal periodicities of approximately 10, 29, 32, 42 and 96 years throughout the record and a strong multicentennial periodicity of about 400 years. Performing a comparison

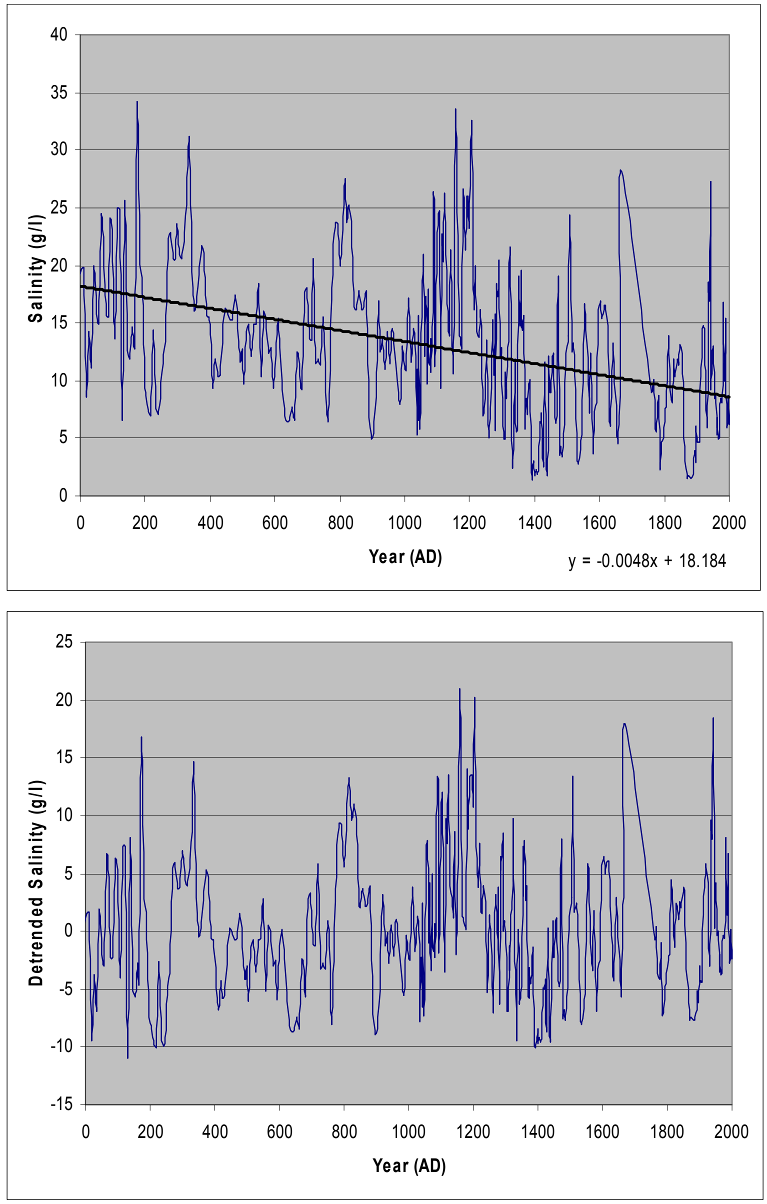

Figure 9: Diatom salinity-drought record from Moon Lake, North Dakota depicting a 2000 year record. Top figure is a plot of data with trend line. Bottom figure has been de-trended to remove non-climate related salinity variation *(based upon methods of Leavitt, 2001).*

with climate induced signals, they concluded that the 10-year cycle was well correlated with the 11-year solar sunspot cycle.

Most of the closed basin investigations have sought to draw comparisons of limnological data to climate variations without significant emphasis on identifying recurrence intervals of drought. Innovative work by the Prairie Drought Project located at the University of Regina (Leavitt, 2001) has conducted investigations specifically desired to measure the risk of future severe drought on the Canadian Prairie. Part of their work included a detailed study of Moon Lake, North Dakota, having a small effective drainage basin that has been extensively studied for its response to climate variability (Laird et al., 1996a). Using diatom salinity-drought data constructed from the lake bottom sediment of Moon Lake (Laird et al., 1998) (Fig. 9), Leavitt and his team of investigators constructed a de-trended analysis that was censured to present only drought information representative of those droughts more significant that the 1988-1992 drought. This analysis revealed the presence of twenty-nine droughts equal or greater in

Inter-arrival Time (Years)	
Mean	63.4
Standard deviation	95.9
Mode	10
Maximum	442
Minimum	5

Drought Duration (Years)	
Average drought duration	5.5
Standard deviation	7.9
Mode	1
Maximum duration	31
Minimum duration	1

Other Statistics	
Number of droughts	29
Major Periods (years)	63
	158
Minor Periods (years)	45
	26
	15
Periodicity Confidence	$P < 0.05$

Table 18: Summary statistics from Moon Lake drought analysis for late 1980's or greater droughts.

magnitude to the 1988-1992 drought. Using the distributions of time periods between drought episodes, which they referred to as inter-arrival time, they constructed statistical characteristics of the drought record and evaluated the behavior of the drought frequencies. The average inter-arrival time was determined to be 63.4 years with average drought duration of 5.5 years with a range from one year to thirty-one years. Probabilities of future droughts were estimated by describing the past drought behavior using a Weibull model and then calculating the conditional probabilities of future droughts.

Based upon a Monte Carlo simulation, the conditional probability analysis of their data suggests that the probability of a drought as or more severe than that of 1988 is 23.3% by 2015 AD rising to 39.7% by 2030 AD. There was a 95% confidence that the true probability for such a drought lies between 29.5 and 54.0% by 2030 AD (Table 18). Construction of power spectra of the drought frequencies showed the presence of significant cycles within the drought time series. The major drought periods were 63 and 158 years with smaller peaks at 45, 26, 23, 18 and 15 years. Within the time series analysis it was shown that drought occurrence, but not intensity, has been greater since 1900 than the previous two centuries. However, due to a gap in the Moon Lake data record for the 17th century, some conclusions on frequency are left uncertain.

A spectral analysis of patterns with differing drought intensity revealed that the mid-point of the 1988-92 drought, 1988-89, was not exceptional in the long-term record falling in the 70th percentile of drought severity. The probability of occurrence of the 1988-89 drought conditions had a similar probability of occurrence (39.7%) as milder events (50th percentile; 46.9%). Possibly more significant was their statistical conclusion that a very extreme drought event falling within the 95th percentile or greater had an 11.1% chance of occurring by 2030 AD.

Synopsis

The results of the above analyses indicate the presence of a greater likelihood of occurrence of an extreme drought the longer the period of time that lapses since the previous extreme drought. While the mean period of time (inter-arrival times) between droughts similar to the late 1980's drought is approximately 65 years, the probability of occurrence of a recurring extreme drought of this type increases over time. Similarly, the likelihood of occurrence of a 1930's type drought increases over time such that time to occurrence decreases over time. Further, the detrended salinity-drought record shows the 1930's drought to be the most dramatic event in over 200-years. With the magnitude of the 1930's drought typical of historical extreme droughts, the 1930's drought should be considered a representative drought for future comparisons of extreme drought conditions.

Scenarios Relating Extreme Drought to Hydrologic Streamflows

Scenario Considerations

Relating future drought conditions to impacts on potential hydrologic streamflows provides decision makers the opportunity to consider issues that might exist when preparing for the water needs within the urban and rural settings within the Red River of the North Basin. *Unfortunately, methods do not presently exist to relate projected annual precipitation to expected streamflow values.* Hence, drawing specific conclusions as to streamflow values using only historical annual precipitation averaged for a particular geographical region is not possible at this time. However, making informed decisions in water resource management involves understanding risks associated with the imprecise processes of anticipating future climatic conditions. As has been presented in early sections of this report, the variability of drought conditions exist in space and time and are not considered highly ordered and regular. Although drought conditions may exist in one locale, precipitation processes dictate that spatial inconsistencies will always exist, especially at short time intervals. Only in major drought events are coherent patterns present in the geographical distribution of drought, yet even then spatial variability limits the uniformity of drought conditions. Therefore, providing scenarios that can be uniformly applied to the entire Red River of the North watershed and the adjacent Upper Missouri River watershed is not possible and should be avoided.

Hence, in constructing relevant scenarios for extreme drought, it is best to consider factors that provide plausible conditions and are within the limits of climate realities. This can best be accomplished by identifying a known severe sustained drought and constructing a template that is scalable to the level of extreme drought considered most relevant for water resources planning purposes.

The history of drought on the northern Great Plains as described in this document can be categorized into two distinct modes of significant drought. The first is associated with the droughts indicated in paleoclimate data where significant desertification and sustained decadal drought occurred. These droughts were associated with dramatic global climate events that resulted in dramatic alteration of human, animal and vegetation reordering. While droughts of this magnitude have not been experienced in North America for over 400 years, oceanographic data indicates that alteration of ocean currents can result in an abrupt climate change leading to major climate upheaval lasting for over a century with the potential for multi-decadal drought conditions. Although these conditions are expected to occur again in the future, no basis for predicting when they will occur presently exists that would be of benefit to water resources planners. Furthermore, should these conditions come to exist, the magnitude of the impact will be of such extreme change that no recourse may exist except complete out migration from extreme drought affected areas. This scenario will be considered as the most extreme scenario where no appreciable precipitation exists and water resources planning is not practical.

The other category of drought to be considered is associated with a severe sustained drought that can be expected to occur without the presence of a major abrupt global climate shift. This drought can be considered to be a scaleable version of the most significant drought of this past century, the drought of the 1930's. As presented earlier in this report, this drought exceeded in parts of North Dakota the 1% non-exceedance frequency or a 100-year drought. However, even within the midst of the mid-1930's when the drought conditions were at their greatest, a respite providing increased precipitation existed in time and the locus of maximum drought conditions migrated across the region. Using these criteria as the basis for scenario development, it is possible to generate a scenario depicting the precipitation characterizing extreme hydrologic drought conditions.

Defining a Characteristic Extreme Drought

From inspection of the 1-year mean Red River Basin precipitation for the driest year of the 1930's, 1936, it is seen that the difference between the actual mean precipitation and the precipitation threshold for a 100-year drought is 1.52 inches of precipitation. For a basin-wide 100-year drought to exist for this year, the precipitation would have to be reduced by approximately 13%. Using this as a guide and rounding to a 15% decrease and using this as the foundation for a drought scenario, it is possible to apply the reduction in precipitation across the climate zones to generate a scenario that preserves spatial and annual variability in precipitation across the basin. Further, applying this to the annual precipitation for the period from 1929 through 1942 and then computing multi-year precipitation accumulation, permits an assessment of the multi-year drought impact. Since the Moon Lake analysis projected the mean duration of drought to be approximately 5 years, the full reduction in precipitation above is only applied for the five-year period centered on 1936 with a half reduction applied to an additional one year on either side of this five-year period. The resulting seven-year reduction in precipitation gives a realistic drop in precipitation that might be expected to be associated with a persistent global forcing feature. Should a broader drought period be desired, this envelope of precipitation decrease can be extended just as the magnitude of the overall precipitation decrease can also be reduced. Decreasing the overall precipitation by 1.52 inches at drought maximum approximates an extreme drought approaching a 200-year drought. Tables 19 thru 22 give the results of the precipitation decrease and the associated level of drought severity by year and climate division. It can be seen that the accumulated impact of extending the precipitation deficit over the span of seven years results in a far greater impact both in space and time across the basin. Preserving this form of spatial variability is realistic and can be used to perform multiple permutations of the precipitation deficits at differing locations across the watershed. It also provides a method of estimating potential water supplies outside the Red River Basin available for importation, and this will be important for future water resource planning. As has been observed with previous droughts over the past century, drought conditions in the Red River Basin generally indicate some form of drought-like conditions adjacent to the basin.

The summary tables (Tables 23 thru 30) provide a percentage deficit relative to the 1930 base period normals that are reflected in the 1930 drought and the scenario of a more severe drought than the 1930s, one approaching a 200-year event. The percentages for precipitation reduction vary from 0% to approximately 50% depending upon the year in the drought and location within the basin. The nature of the environment resulting in drought-related hydrologic streamflows can be estimated from the percentage reduction in the precipitation within the tables for a given year and given climate zone. Through this approximation method it is possible to replicate the drought of the 1930's and to extend this to a more extreme drought that represents a 200-year event. Further, since Tables 23-30 provide a percentage of annual precipitation for all climate zones in North Dakota, it is possible to estimate the hydrologic impacts of these events beyond the Red River of the North Basin and into the Upper Missouri River Basin. Following the methodologies outlined to generate the above tables, it is possible to extend the method outside of North Dakota into other portions of the Upper Missouri River Basin.

Synopsis

The development of hydrologic projections of future extreme droughts requires knowledge of anticipated drought extents. The use of a characteristic extreme drought as a reference provides this needed baseline. Unfortunately, the limitations in streamflow data as it relates to meteorological drought information make the direct application of such drought information difficult as methods do not presently exist to correlate annual and/or seasonal precipitation to hydrologic streamflows. However, using the 1930's drought as a characteristic extreme drought and applying L-moment analysis to climate zone precipitation values, percentages of normal annual precipitation were computed to represent the best estimate of what a 1930's-type drought would be projected into the future. Further, more extreme drought conditions were estimated through a reduction in climate zone precipitation to project a 200-year drought.

Year	ND Northeast	ND East Central	ND Southeast	MN Northwest	MN West Central	Red River Basin Mean	ND Northwest	ND West Central	ND Southwest	ND South Central	ND North Central	ND East Central	MN North Central	SD Northeast
1929	14.85	16.28	16.38	17.30	18.99	16.76	12.70	14.34	14.01	14.03	13.79	14.68	19.27	18.39
1930	15.01	15.35	16.23	19.40	20.10	17.22	13.84	14.85	13.10	15.82	15.37	16.88	23.11	17.16
1931	17.79	19.80	19.98	19.33	18.11	19.00	9.48	13.16	15.33	16.76	11.43	18.19	21.07	18.39
1932	18.66	17.47	19.08	17.87	17.68	18.15	16.93	15.66	17.67	15.18	16.13	17.62	23.17	19.60
1933	11.72	16.05	12.51	16.69	14.87	14.37	12.64	12.52	12.42	9.98	12.13	13.74	19.77	13.29
1934	10.63	11.78	11.18	14.16	12.62	12.07	5.32	7.11	6.88	7.05	7.02	9.45	16.28	12.31
1935	16.52	16.95	18.09	17.32	19.13	17.60	12.72	15.44	12.80	13.83	16.56	16.97	22.23	18.31
1936	10.39	7.56	7.59	11.06	13.10	9.94	8.54	6.45	5.57	5.39	8.04	6.33	13.76	10.85
1937	18.39	18.67	16.07	19.35	21.79	18.85	12.62	13.12	12.36	13.84	16.86	14.47	24.68	20.79
1938	11.65	12.10	14.12	15.78	19.68	14.66	13.80	14.90	13.52	11.36	12.05	12.39	20.07	16.57
1939	12.66	13.22	17.46	16.00	18.80	15.63	11.62	12.26	13.30	14.11	11.61	12.85	20.05	19.15
1940	18.99	18.15	18.78	20.22	23.84	20.00	15.63	16.42	17.06	15.56	18.27	18.03	23.32	20.14
1941	25.64	25.58	24.61	27.56	26.49	25.98	22.27	21.74	22.97	19.99	24.53	23.35	28.06	24.71
1942	18.95	21.18	26.03	23.46	29.02	23.73	13.54	18.60	17.90	19.62	14.58	20.77	26.96	27.27
Orange denotes a 25-year drought					Red denotes 50-year drought					Magenta denotes 100-year drought				

Table 19: Drought scenario based on 1930's characteristic extreme drought. Center of drought is 1936. Values are 1-year annual precipitation (inches).

Year	ND Northeast	ND East Central	ND Southeast	MN Northwest	MN West Central	Red River Basin Mean	ND Northwest	ND West Central	ND Southwest	ND South Central	ND North Central	ND East Central	MN North Central	SD Northeast
1929	34.84	38.08	35.73	38.73	40.09	37.49	28.64	31.9	29.79	29.69	32.59	33.69	43.23	35.6
1930	29.86	31.63	32.61	36.7	39.09	33.98	26.54	29.19	27.11	29.85	29.16	31.56	42.38	35.55
1931	32.8	35.15	36.21	38.73	38.21	36.22	23.32	28.01	28.43	32.58	26.8	35.07	44.18	35.55
1932	36.45	37.27	39.06	37.2	35.79	37.15	26.41	28.82	33	31.94	27.56	35.81	44.24	37.99
1933	30.38	33.52	31.59	34.56	32.55	32.52	29.57	28.18	30.09	25.16	28.26	31.36	42.94	32.89
1934	22.34	27.83	23.68	30.85	27.50	26.44	17.96	19.64	19.30	17.03	19.15	23.19	36.04	25.60
1935	27.14	28.73	29.27	31.48	31.75	29.67	18.05	22.55	19.68	20.88	23.58	26.43	38.51	30.62
1936	26.90	24.51	25.68	28.38	32.22	27.54	21.27	21.89	18.37	19.22	24.60	23.31	35.99	29.16
1937	28.77	26.23	23.66	30.40	34.88	28.79	21.17	19.58	17.93	19.23	24.90	20.80	38.45	31.65
1938	30.03	30.77	30.19	35.13	41.46	33.52	26.42	28.02	25.87	25.19	28.91	26.86	44.75	37.36
1939	24.31	25.31	31.58	31.79	38.47	30.29	25.41	27.16	26.82	25.46	23.66	25.24	40.12	35.71
1940	31.65	31.37	36.24	36.22	42.64	35.62	27.25	28.68	30.36	29.67	29.88	30.88	43.37	39.29
1941	44.63	43.73	43.39	47.78	50.33	45.97	37.90	38.16	40.03	35.55	42.80	41.38	51.38	44.85
1942	44.59	46.76	50.64	51.02	55.51	49.70	35.81	40.34	40.87	39.61	39.11	44.12	55.02	51.98

Orange denotes a 25-year drought — Red denotes 50-year drought — Magenta denotes 100-year drought

Table 20: Drought scenario based on 1930's characteristic extreme drought. Center of drought is 1936. Values are 2-year annual precipitation (inches).

Year	ND Northeast	ND East Central	ND Southeast	MN Northwest	MN West Central	Red River Basin Mean	ND Northwest	ND West Central	ND Southwest	ND South Central	ND North Central	ND East Central	MN North Central	SD Northeast
1929	57.45	58.54	55.86	61.81	63.16	59.36	50.82	54.47	51.79	49.95	55.7	55.12	68	55.13
1930	49.85	53.43	51.96	58.13	60.19	54.71	42.48	46.75	42.89	45.51	47.96	50.57	66.34	52.76
1931	47.65	51.43	52.59	56.03	57.2	52.98	36.02	42.35	42.44	46.61	40.59	49.75	63.45	53.94
1932	51.46	52.62	55.29	56.6	55.89	54.37	40.25	43.67	46.1	47.76	42.93	52.69	67.35	55.15
1933	48.17	53.32	51.57	53.89	50.66	51.52	39.05	41.34	45.42	41.92	39.69	49.55	64.01	51.28
1934	41.00	45.30	42.76	48.72	45.18	44.59	34.89	35.30	36.97	32.21	35.28	40.81	59.21	45.20
1935	38.86	44.78	41.77	48.17	46.62	44.04	30.68	35.08	32.10	30.86	35.71	40.16	58.27	43.91
1936	37.53	36.29	36.86	42.54	44.85	39.61	26.59	29.00	25.25	26.27	31.62	32.76	52.27	41.47
1937	45.29	43.18	41.75	47.73	54.01	46.39	33.89	35.01	30.73	33.06	41.45	37.77	60.67	49.95
1938	40.42	38.33	37.78	46.19	54.56	43.46	34.96	34.48	31.44	30.58	36.95	33.19	58.51	48.21
1939	42.69	43.99	47.66	51.13	60.26	49.15	38.04	40.28	39.18	39.30	40.52	39.71	64.81	56.51
1940	43.30	43.46	50.36	52.01	62.31	50.29	41.04	43.58	43.88	41.02	41.93	43.27	63.44	55.85
1941	57.29	56.95	60.85	63.78	69.13	61.60	49.52	50.42	53.33	49.66	54.41	54.23	71.43	64.00
1942	63.58	64.91	69.42	71.24	79.35	69.70	51.44	56.76	57.93	55.17	57.38	62.15	78.34	72.12

Orange denotes a 25-year drought | Red denotes 50-year drought | Magenta denotes 100-year drought

Table 21: Drought scenario based on 1930's characteristic extreme drought. Center of drought is 1936. Values are 3-year annual precipitation (inches).

Year	ND Northeast	ND East Central	ND Southeast	MN Northwest	MN West Central	Red River Basin Mean	ND Northwest	ND West Central	ND Southwest	ND South Central	ND North Central	ND East Central	MN North Central	SD Northeast
1929	92.7	93.18	89.99	103.93	102.42	96.44	81.95	85.89	81.48	79.59	88.75	87.94	115.72	87.76
1930	89.86	91.47	88.8	101.8	103.18	95.02	78.87	84.38	78.63	79.79	86.74	87.92	114.41	88.82
1931	90.25	93.69	92.07	100.54	101.37	95.58	74.14	82.48	80.22	82.53	82.5	90.19	112.18	90.68
1932	86.3	90.7	91.02	95.33	95.98	91.87	68.89	75.57	75.89	77.45	75.52	86.38	110.58	90.75
1933	78.03	84.95	84.18	90.59	89.75	85.50	65.59	70.53	72.53	71.77	68.85	81.11	106.39	86.83
1934	73.80	80.45	78.97	87.45	83.39	80.81	58.21	63.31	65.40	64.79	62.08	75.88	103.39	80.75
1935	75.31	82.05	80.83	85.37	82.41	81.19	57.09	63.90	65.10	62.80	63.27	75.97	102.51	81.90
1936	67.91	69.81	68.44	77.10	77.40	72.13	56.15	57.19	55.34	51.43	59.88	64.12	95.20	74.36
1937	67.63	71.01	65.44	78.58	81.51	72.83	51.85	54.65	50.03	50.08	60.60	60.96	96.72	75.55
1938	67.56	67.06	67.05	77.67	86.31	73.13	53.01	57.03	51.12	51.46	60.53	59.62	97.02	78.83
1939	69.60	68.49	73.33	79.51	92.48	76.68	59.30	62.17	57.54	58.52	65.12	63.02	100.80	85.67
1940	72.07	69.69	74.03	82.41	97.20	79.08	62.21	63.15	61.80	60.25	66.83	64.07	101.89	87.50
1941	87.32	87.72	91.05	98.91	110.59	95.12	75.94	78.44	79.21	74.85	83.32	81.09	116.19	101.36
1942	87.89	90.22	101.00	103.03	117.82	99.99	76.85	83.92	84.75	80.63	81.04	87.39	118.46	107.83

Orange denotes a 25-year drought | Red denotes 50-year drought | Magenta denotes 100-year drought

Table 22: Drought scenario based on 1930's characteristic extreme drought. Center of drought is 1936. Values are 5-year annual precipitation (inches).

Drought Year	ND Northeast	ND East Central	ND Southeast	MN Northwest	MN West Central	Red River Basin Mean	ND Northwest							
1	-5%	6%	7%	3%	-3%	2%	-49%	-30%	-18%	-10%	-39%	-3%	13%	-2%
2	0%	-7%	2%	-4%	-5%	-3%	-9%	-16%	-6%	-19%	-14%	-6%	24%	5%
3	-32%	-7%	-28%	-4%	-14%	-17%	-27%	-28%	-28%	-42%	-30%	-21%	14%	-23%
4	-33%	-26%	-30%	-11%	-21%	-24%	-67%	-55%	-57%	-56%	-56%	-41%	2%	-23%
5	4%	7%	14%	9%	20%	11%	-20%	-3%	-19%	-13%	4%	7%	40%	15%
6	-35%	-52%	-52%	-30%	-18%	-37%	-46%	-59%	-65%	-66%	-49%	-60%	-13%	-32%
7	16%	17%	1%	22%	37%	19%	-21%	-17%	-22%	-13%	6%	-9%	55%	31%
8	-27%	-24%	-11%	-1%	24%	-8%	-13%	-6%	-15%	-29%	-24%	-22%	26%	4%
9	-27%	-24%	1%	-7%	9%	-10%	-33%	-29%	-23%	-18%	-33%	-26%	16%	11%
10	2%	-3%	0%	8%	27%	7%	-16%	-12%	-9%	-17%	-2%	-4%	25%	8%

Table 23: Characteristic extreme drought for point-source profiles of annual precipitation for given climate zones. Percentages based upon 1930's drought relative to base period precipitation normals. Values for 1-year accumulation.

1	-5%	6%	7%	3%	-3%	2%	-49%	-30%	-18%	-10%	-39%	-3%	13%	-2%
2	0%	-7%	2%	-4%	-5%	-3%	-9%	-16%	-6%	-19%	-14%	-6%	24%	5%
3	-37%	-14%	-33%	-11%	-20%	-23%	-32%	-33%	-34%	-47%	-35%	-27%	6%	-29%
4	-43%	-37%	-40%	-24%	-33%	-35%	-72%	-62%	-63%	-62%	-62%	-49%	-13%	-34%
5	-12%	-9%	-3%	-7%	2%	-6%	-32%	-17%	-32%	-26%	-11%	-9%	19%	-2%
6	-44%	-60%	-59%	-41%	-30%	-47%	-54%	-66%	-70%	-71%	-57%	-66%	-26%	-42%
7	-2%	0%	-14%	3%	16%	1%	-33%	-30%	-34%	-26%	-10%	-23%	32%	11%
8	-38%	-35%	-25%	-16%	5%	-22%	-26%	-20%	-28%	-39%	-36%	-34%	7%	-11%
9	-32%	-29%	-7%	-14%	1%	-16%	-38%	-34%	-29%	-25%	-38%	-31%	7%	2%
10	2%	-3%	0%	8%	27%	7%	-16%	-12%	-9%	-17%	-2%	-4%	25%	8%

Table 24: Characteristic extreme drought for point-source profiles of annual precipitation for given climate zones. Percentages based upon 1930's drought relative to base period precipitation normals. Values for 1-year accumulation, modified for greater drought severity depicting a 200-year event.

Drought Year	ND Northeast	ND East Central	ND Southeast	MN Northwest	MN West Central	Red River Basin Mean	ND Northwest							
1	-12%	-6%	-3%	4%	2%	-3%	-38%	-25%	-24%	-13%	-28%	-6%	18%	-5%
2	-3%	0%	4%	-1%	-4%	-1%	-29%	-23%	-12%	-15%	-26%	-4%	18%	2%
3	-16%	-7%	-13%	-4%	-10%	-10%	-18%	-22%	-17%	-31%	-22%	-13%	19%	-9%
4	-33%	-17%	-29%	-7%	-17%	-21%	-47%	-41%	-42%	-49%	-43%	-31%	8%	-23%
5	-15%	-10%	-8%	-1%	0%	-7%	-43%	-29%	-38%	-34%	-26%	-17%	21%	-4%
6	-15%	-23%	-19%	-11%	1%	-13%	-33%	-31%	-42%	-40%	-23%	-27%	13%	-8%
7	-10%	-17%	-26%	-4%	10%	-9%	-33%	-38%	-44%	-40%	-22%	-35%	21%	0%
8	-6%	-3%	-5%	10%	30%	5%	-17%	-12%	-19%	-21%	-9%	-16%	41%	17%
9	-27%	-24%	-5%	-4%	16%	-9%	-23%	-18%	-19%	-24%	-29%	-24%	21%	7%
10	-13%	-13%	1%	0%	18%	-1%	-25%	-21%	-16%	-18%	-18%	-15%	20%	9%

Table 25: Characteristic extreme drought for point-source profiles of annual precipitation for given climate zones. Percentages based upon 1930's drought relative to base period precipitation normals. Values are for 2-year accumulations.

1	-12%	-6%	-3%	4%	2%	-3%	-38%	-25%	-24%	-13%	-28%	-6%	18%	-5%
2	-3%	0%	4%	-1%	-4%	-1%	-29%	-23%	-12%	-15%	-26%	-4%	18%	2%
3	-19%	-10%	-16%	-8%	-13%	-13%	-21%	-25%	-20%	-33%	-24%	-16%	15%	-12%
4	-40%	-26%	-37%	-18%	-26%	-29%	-52%	-47%	-48%	-54%	-49%	-38%	-4%	-32%
5	-27%	-23%	-22%	-16%	-15%	-21%	-52%	-40%	-47%	-44%	-37%	-29%	3%	-18%
6	-28%	-34%	-31%	-24%	-14%	-26%	-43%	-41%	-51%	-49%	-34%	-38%	-4%	-22%
7	-23%	-30%	-37%	-19%	-7%	-23%	-43%	-48%	-52%	-49%	-33%	-44%	3%	-15%
8	-20%	-18%	-19%	-6%	11%	-10%	-29%	-25%	-31%	-33%	-23%	-28%	20%	0%
9	-35%	-32%	-16%	-15%	3%	-19%	-32%	-27%	-28%	-32%	-37%	-33%	7%	-5%
10	-15%	-16%	-3%	-3%	14%	-5%	-27%	-23%	-19%	-21%	-20%	-17%	16%	5%

Table 26: Characteristic extreme drought for point-source profiles of annual precipitation for given climate zones. Percentages based upon 1930's drought relative to base period precipitation normals. Values are for 2-year accumulations, modified for greater drought severity depicting a 200-year event.

Drought Year	ND Northeast	ND East Central	ND Southeast	MN Northwest	MN West Central	Red River Basin Mean	ND Northwest							
1	-15%	-8%	-6%	0%	2%	-6%	-36%	-25%	-24%	-17%	-28%	-11%	13%	-4%
2	-8%	-6%	-1%	1%	0%	-3%	-28%	-22%	-18%	-15%	-23%	-6%	20%	-2%
3	-12%	-3%	-6%	-2%	-8%	-6%	-29%	-25%	-17%	-24%	-28%	-10%	17%	-7%
4	-22%	-13%	-18%	-6%	-13%	-15%	-34%	-33%	-30%	-39%	-33%	-22%	14%	-14%
5	-21%	-9%	-15%	-2%	-5%	-10%	-38%	-29%	-35%	-37%	-27%	-18%	19%	-10%
6	-21%	-24%	-23%	-11%	-6%	-17%	-44%	-39%	-47%	-45%	-34%	-31%	10%	-13%
7	-5%	-9%	-12%	0%	13%	-3%	-29%	-27%	-36%	-31%	-13%	-21%	27%	5%
8	-15%	-20%	-21%	-3%	14%	-9%	-27%	-28%	-34%	-36%	-23%	-30%	23%	1%
9	-13%	-10%	-3%	4%	23%	0%	-22%	-18%	-20%	-20%	-17%	-19%	32%	15%
10	-17%	-17%	-3%	0%	20%	-3%	-21%	-16%	-16%	-21%	-20%	-17%	22%	8%

Table 27: Characteristic extreme drought for point-source profiles of annual precipitation for given climate zones. Percentages based upon 1930's drought relative to base period precipitation normals. Values are for 3-year accumulations.

1	-15%	-8%	-6%	0%	2%	-6%	-36%	-25%	-24%	-17%	-28%	-11%	13%	-4%
2	-8%	-6%	-1%	1%	0%	-3%	-28%	-22%	-18%	-15%	-23%	-6%	20%	-2%
3	-14%	-5%	-8%	-4%	-10%	-8%	-30%	-26%	-19%	-25%	-29%	-12%	14%	-9%
4	-27%	-19%	-24%	-13%	-19%	-21%	-38%	-37%	-34%	-43%	-37%	-27%	6%	-19%
5	-31%	-20%	-26%	-14%	-17%	-22%	-45%	-37%	-43%	-45%	-36%	-28%	4%	-22%
6	-33%	-35%	-34%	-24%	-20%	-29%	-53%	-48%	-55%	-53%	-44%	-42%	-7%	-26%
7	-19%	-23%	-26%	-15%	-4%	-17%	-40%	-38%	-45%	-41%	-26%	-33%	8%	-11%
8	-28%	-32%	-33%	-18%	-3%	-23%	-38%	-39%	-44%	-45%	-34%	-41%	4%	-14%
9	-24%	-22%	-15%	-9%	7%	-12%	-32%	-28%	-30%	-30%	-28%	-29%	16%	1%
10	-23%	-23%	-10%	-7%	11%	-10%	-27%	-22%	-22%	-27%	-25%	-23%	13%	0%

Table 28: Characteristic extreme drought for point-source profiles of annual precipitation for given climate zones. Percentages based upon 1930's drought relative to base period precipitation normals. Values are for 3-year accumulations, modified for greater drought severity depicting a 200-year event.

Drought Year	ND Northeast	ND East Central	ND Southeast	MN Northwest	MN West Central	Red River Basin Mean	ND Northwest							
1	-3%	0%	-2%	8%	8%	2%	-21%	-12%	-14%	-12%	-12%	-4%	20%	-3%
2	-8%	-3%	-3%	2%	3%	-2%	-26%	-19%	-19%	-17%	-19%	-8%	18%	-3%
3	-16%	-8%	-9%	-2%	-3%	-7%	-29%	-23%	-21%	-22%	-25%	-12%	15%	-6%
4	-18%	-10%	-12%	-2%	-7%	-10%	-36%	-30%	-28%	-29%	-31%	-16%	15%	-10%
5	-13%	-5%	-7%	-1%	-5%	-6%	-34%	-26%	-26%	-28%	-27%	-13%	19%	-5%
6	-19%	-17%	-19%	-8%	-7%	-14%	-34%	-32%	-35%	-39%	-29%	-24%	13%	-11%
7	-16%	-12%	-19%	-3%	1%	-10%	-36%	-33%	-38%	-38%	-25%	-25%	20%	-6%
8	-15%	-16%	-16%	-2%	9%	-8%	-33%	-28%	-36%	-35%	-24%	-25%	22%	-1%
9	-14%	-15%	-10%	-2%	14%	-5%	-27%	-23%	-29%	-28%	-19%	-22%	25%	6%
10	-14%	-17%	-12%	-2%	16%	-6%	-26%	-25%	-27%	-29%	-21%	-24%	22%	4%

Table 29: Characteristic extreme drought for point-source profiles of annual precipitation for given climate zones. Percentages based upon 1930's drought relative to base period precipitation normals. Values are for 5-year accumulations.

1	-3%	0%	-2%	8%	8%	2%	-21%	-12%	-14%	-12%	-12%	-4%	20%	-3%
2	-8%	-3%	-3%	2%	3%	-2%	-26%	-19%	-19%	-17%	-19%	-8%	18%	-3%
3	-17%	-9%	-10%	-3%	-4%	-9%	-30%	-25%	-22%	-23%	-26%	-13%	14%	-7%
4	-21%	-14%	-16%	-6%	-11%	-14%	-38%	-32%	-30%	-31%	-34%	-19%	11%	-14%
5	-19%	-12%	-14%	-9%	-12%	-13%	-39%	-32%	-30%	-33%	-32%	-19%	10%	-12%
6	-27%	-25%	-27%	-18%	-17%	-23%	-40%	-39%	-41%	-45%	-36%	-31%	2%	-20%
7	-28%	-24%	-30%	-16%	-13%	-22%	-45%	-42%	-47%	-46%	-35%	-35%	3%	-19%
8	-28%	-28%	-28%	-17%	-8%	-22%	-43%	-39%	-45%	-45%	-35%	-36%	4%	-16%
9	-26%	-27%	-22%	-15%	-1%	-18%	-37%	-34%	-38%	-37%	-30%	-33%	8%	-8%
10	-23%	-25%	-21%	-12%	4%	-15%	-33%	-32%	-34%	-36%	-29%	-31%	9%	-6%

Table 30: Characteristic extreme drought for point-source profiles of annual precipitation for given climate zones. Percentages based upon 1930's drought relative to base period precipitation normals. Values are for 5-year accumulations, modified for greater drought severity depicting a 200-year event.

Summary

The purpose of this study was to evaluate the effects of climatic cycles on streamflow within the Red River of the North Basin through an assessment of drought occurrence. This work was performed as a result of a wide range of public perceptions regarding the nature of what constitutes an extreme drought. In particular this included an investigation as to whether the severe drought of the 1930's was an anomaly or sufficient in its likelihood of recurrence that it could effectively be used in designing future water projects to account for a recurrence of such a characteristic extreme drought. The work described in the report has attempted to provide insight into the nature of droughts in general, specific drought related issues found in North America and the northern Great Plains, and to provide insight as to the potential for severe drought conditions across the Red River of the North Basin within the next half-century.

The work accomplished and cited in this report was the result of a comprehensive literature search and review of previous studies relating to drought in the northern Great Plains. As exhibited in the report bibliography, much has been published on drought. The bibliography, while lengthy, does not begin to cover the entire list of literature on droughts. An attempt was made to address relevant literature and to gain as much insight into the state of knowledge. In the short time of this project a tremendous amount of material was reviewed; however, more exists and the vast wealth on climate and drought-related literature is worthy of continued review.

The review of scientific literature identified appropriate metrics for estimating severity of droughts and how to apply these metrics to the 1930's and late 1980's droughts in the Red River of the North and Upper Missouri River Basins. Although many differing metrics are better than the PDSI and the PHSI, the widespread historical use of these indices constrained this study to rely heavily upon their use. Using strong negative values of these indices as indicators of moderate, severe, and extreme drought enables a comparison of national and regional drought conditions since 1895 to present. Further, comparison of these values across individual climate zones permitted consideration of spatial and temporal variability in drought severity. The magnitude and duration of previous droughts were compared to drought conditions previously reported within the scientific literature to assess the relative severity of the 1930's and late 1980's droughts.

There have been five significant droughts during the past century with four of these droughts affecting the Upper Missouri River and Red River of the North Basins. The most severe of these droughts was clearly the 1930's drought based upon the duration (thirteen years) and the extensive area with PDSI at or below –3. And while the 1954-56 drought had a comparable national area of coverage to the 1930's drought, it lacked the duration and it was primarily centered over the central and southern Rocky Mountain states with little significant coverage across the northern Great Plains. Beyond the 1930's drought the next significant drought was the late 1980s to early 1990s drought that was centered across the northern Great Plains. This drought lacked the area of coverage of the previously two mentioned droughts, but the duration of the drought and the localized extent of coverage in the interest area of this project resulted in its ranking as the second most significant northern Great Plains drought of the past century. As precipitation is the signal carrier for all forms of drought, a comparison of the ten driest years on record across North Dakota and the Red River Basin proved useful in corroborating the identification of the 1930's and late 1980's meteorological droughts as the two most significant. This was accomplished through the use of mean precipitation for each climate zones as prepared by the National Climate Data Center. However, it is somewhat surprising that the late 1980's were not predominantly high in the rankings for driest years.

Using the data and results of previous research on drought recurrence intervals, it was possible to estimate recurrence intervals for the 1930's and late 1980's droughts. The length of observation data was an important factor in not only the identification of drought rankings, but also in the recurrence intervals of drought. As with all statistical estimation of recurrent activities, the length of the data record is critical in estimating event repeatability. Early work by Ryan (1991) to investigate hydrological droughts through streamflow analysis failed to identify a recurrence interval for the late 1980's drought due to the lack of data available at the time. A few years later, Williams-Sether et al. (1994) estimated the recurrence interval of the 1930's drought as being between 27 and 74 years while the 1980's drought has a recurrence interval varying between 19 and 54 years. The broad ranges in the estimates are a direct result of the distributed nature of drought variability even across limited geographical regions. Since these estimates were derived solely from streamflow values, the variability of land-use and streamflow regulation is to be considered a notable factor. As precipitation is a carrier of the drought signal, applications of climate zone mean precipitation values were applied to the worksheets of the National Drought Atlas. The results of the National Drought Atlas computations provided precipitation-based non-exceedance values relating to the frequency of drought conditions for the period of the observed record. The return intervals found through the National Drought Atlas provided a similar variability in results as noted from the streamflow computations. Recurrence intervals ranging from less than 25 years to greater than 100 years were computed for the 1930's drought. In particular, the North Dakota North Central climate zone exhibited precipitation deficits exceeding the threshold of a 100-year drought. A significant difference was noted in the National Drought Atlas worksheets between the 1930's and the late 1980's drought. In general across all climate zones in North Dakota and the Red River of the North Basin, the recurrence intervals were significantly shorter for the 1980's drought as opposed to the 1930's drought indicating lessening in drought severity for the 1980's drought relative to the 1930's.

A more definitive estimation of the 1980's drought recurrence interval is reported from the Prairie Drought Project at the University of Regina. This project's main goal was to identify sustainability of agricultural practices by identification of likely drought conditions using limnological techniques. The advantage of this method was that lake sediment extends the data record to millennial lengths and thus creates a more statistically robust sample for analysis. Their method, which uses the 2,000 year diatom salinity-drought data from Moon Lake, North Dakota, provides a conditional probability of a return of droughts greater than the intensity of the 1988-89 drought conditions. This method, based upon a Weibull model of the inter-annual return distribution to 29 major droughts identified in the Moon Lake data, provided an estimate of a 63-year recurrence interval of a drought equal or greater than the late 1980's drought. A significant statistic from their analysis was the high probability (between 29% and 54%) that a late 1980's-like drought or stronger will occur before 2030. Further, most significantly was their finding that the 1980's drought ranked only in the 70th percentile of droughts in the Moon Lake data and that there was better than an 11% chance or risk for a drought in the 95th percentile before 2030.

A major effort of the study was the identification of the severity for 25-, 50-, and 100-year droughts. Again, the National Drought Atlas was used to construct the appropriate non-exceedance values necessary to identify precipitation thresholds associated with these drought levels. A table was prepared that can be used to identify the precipitation accumulation needed on a 1-, 2-, 3-, and 5-year formulation to identify the appropriate recurrence interval for a particular drought. Using these values, non-exceedance frequencies were assigned to precipitation occurring in geographically specific regions across the northern Great Plains.

The final activity of the study was preparation of a drought scenario relating to precipitation for the purpose of future hydrologic consideration. Efforts were made to define a drought scenario that would provide precipitation estimations based both upon multiple years and geographical distributions across the Red River of the North Basin and the Upper Missouri River Basin, i.e., the remainder of North Dakota. The scenario chosen was based upon a severe sustained drought constructed as a permutation of the 1930's drought. As reviewed research indicated the strong likelihood of an eventual recurrence of a drought having at least the magnitude of the 1930's, this drought seemed appropriate for conceptual design development. In the design, the spatial and temporal variability of the 1930's drought were retained as a baseline for precipitation estimation relative to the 1901-1930 base period normal precipitation. This included retaining the near average annual precipitation of 1935 rather than performing an average across all years. While the process of averaging would give a more severe drought scenario, it would mask the nature of multi-year drought and the natural variability that often occurs. A multiplier was applied to the resulting base period that brought the 1930's drought, averaged across the Red River Basin, to a 100-year drought level for one year of a multi-year drought. This multiplier was then applied evenly across a five-year period centered on the extreme drought year. An additional one-year tail of one-half the multiplier was added on either side of the five-year period to reflect a ramping of drought conditions. The precipitation deficits were then computed for the subsequent 2-, 3-, and 5-year periods. The resulting precipitation deficits (surpluses) were normalized and summarized for each climate zone. A range of precipitation deficits extending from the 1930's drought base to a drought more severe than the 1930's drought were generated for each climate zone over a ten year period. The extensibility of the method permits the selection of another drought, for example if a base is desired with the late 1980's drought, through substitution for the 1930's precipitation distributions. Unfortunately, methods do not presently exist to relate projected annual precipitation to expected streamflow values. Hence, drawing specific conclusions as to streamflow values using only historical annual precipitation averaged for a particular geographical region is not possible at this time. However, making informed decisions in water resource management involves understanding risks associated with the imprecise processes of anticipating future climatic conditions.

Conclusions

Droughts are an expected by-product of variations in the global atmosphere-ocean-solar radiation exchange process. Evidence is compelling that the past several hundred years has been generally wetter across the Northern Great Plains than the period prior to 1600. It is only a matter of time before an extreme drought reoccurs across the Red River of the North Basin. Planning and preparation for this drought is appropriate and prudent given the major impact it will have upon all facets of human existence in the region. And although the current above normal precipitation across the Red River Valley since the early 1990's is anticipated to continue through this decade, the possibility clearly exists for a sudden change to sustained significantly drier conditions for the majority of the twenty-first century.

Due to the short duration of this study, the majority of the investigation was built upon prior research performed by other scientists or by the authors. The complex nature of droughts does not permit reliable forecasting of their occurrence, duration or intensity. The information provided in this study should be but a beginning to a much more comprehensive research initiative to identify the nature of drought and the indicators of drought onset across the Northern Great Plains.

Further, due to the possible wide variability in precipitation across a given climate zone, it is difficult to precisely adapt values from climate zone summaries for the climate zones that only partially intersect the Red River Basin. However, time did not permit, nor does the long-term station density support, computing basin-wide statistics independent of the climate zones. As the period of record grows and the availability of more dense precipitation reporting expands through either *in-situ* observations platforms or the use of remotely sensed data such as weather radar, it is recommended that a more detailed basin-specific precipitation climatology be developed and incorporated into both drought and flood non-exceedance frequency analyses.

Of particular importance in the projection of future drought conditions for the Upper Missouri River Basin is the estimation of mountain snowpack across the Montana Rocky Mountains. As data presented in this report indicates, the occurrence of both drought conditions and areal coverage of drought are highly variable. Hence, the presence of drought conditions simultaneously across both the Red River Basin and the Upper Missouri River Basin cannot be concluded to always occur during even an extreme drought event. However, the presence of extreme drought conditions across the Montana Rocky Mountain region will dramatically reduce snowpack levels. Since snowmelt is the primary water source for the Missouri River and since any future availability of Missouri River water for the Red River will depend upon having adequate mountain snowpack, understanding the relationship of large-scale drought to mountain snow amounts will be important in future planning for water resources management within both the Upper Missouri River Basin and the Red River Basin.

The result of this study provides an understanding of the nature of drought conditions in the Northern Plains, a ranking of droughts over the past century, identifies the minimum threshold precipitation to define 25-, 50-, and 100-year droughts, and establishes a drought scenario that can be used to consider future hydrologic streamflow situations of a severe sustained drought. Results of the study indicate that a drought of the magnitude and intensity of the 1930's drought is a realistic and statistically significant representation of an extreme drought in that it typifies the most extreme event anticipated until at least 2050. Utilization of the 1930's drought as a baseline for drought potential will provide necessary precipitation statistics to characterize a future drought over an extended drought period and of sufficient spatial extent to consider the impact on adjacent basins.

Finally, the analyses of drought recurrence intervals indicate that the lack of a drought of the intensity of the 1930's drought suggests that there is a greater likelihood of such an extreme drought with time. Recent research indicates a strong probability of an extreme drought event occurring before 2050 AD.

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