Frequency and Spatial Characteristics of Droughts in the Conchos River Basin, Mexico

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Abstract: *The temporal and spatial characteristics of droughts are investigated to provide a framework for sustainable water resources management in a semi-arid region. Using the Palmer Drought Severity Index (PDSI) as an indicator of drought severity, the characteristics of droughts are examined in the Conchos River Basin in Mexico. This basin is important to both the United States and Mexico, because the Conchos River supplies approximately 80 percent of the flows of the Lower Bravo/Grande River above the binational reservoirs of Amistad and Falcon. The temporal and spatial characteristics of the PDSI are used to develop a drought intensity - areal extent - frequency curve that can assess the severity of a regional drought in the basin. The analysis of the PDSI suggests that the Conchos River Basin had a severe drought in the 1990s, which the basin has not experienced before. Based on this analysis, the recent drought that occurred in the 1990s has an associated return period of about 80 to 100 years over the basin.*

Keywords: *Droughts, semi-arid region, PDSI, frequency curve, return period.*

Introduction

Considerable research has been carried out in hydrology and water resources, but drought remains a serious concern in many regions of the world. Two major droughts, in terms of duration and spatial extent, occurred in North America in the 20th century. Both the drought of the 1930s, which lasted up to seven years in the Great Plains, and the drought of the 1950s, which lasted five years in the Southwestern United States, caused significant damages both in human lives and economic losses. These droughts also affected Mexico mainly in the northern and central regions of the country (Tinajero, 1986). In addition to these major droughts of the 20th century, there have been several other droughts in recent decades in the North American continent. For example, the 1987 to 1989 drought lasted three years and covered 36 percent of the United States, causing severe losses in energy, water, ecosystems, and agriculture, estimated at US$39 billion (NOAA Paleoclimatology Program, 2000). In Mexico, the droughts in the middle of the 1970s and the second half of the 1990s produced extended damages to crops and cattle in the northwestern states.

Droughts are generally associated with a sustained period of significantly lower soil moisture levels and water supply relative to the normal levels that the local environment and society have stabilized. There is not, however, a universal definition of drought due to conflicting concepts of drought magnitude and severity. Dracup et al. (1980) have defined the type of drought in order to consider a set of decisions. Based on the nature of the water deficit, they defined three types of droughts: meteorologic drought, hydrologic drought, and agricultural drought. The meteorologic drought is defined as a lack of rainfall so low as to severely affect the flora and fauna of a region. It leads to depleted water supplies both for domestic purposes and for the operation of power plants. The hydrologic drought is related to a period during which streamflows are inadequate to supply established uses under a given water resources management system. The agricultural drought is usually described in terms of crop failure from decline in soil moisture without any reference to streamflow (Dracup et al., 1980). Nowadays, the socioeconomic drought associated with the supply and demand of economic goods with elements of meteorologic, hydrologic, and agricultural drought is used. The socioeconomic drought occurs when the demand for an economic good exceeds supply as a result of a weather-related shortfall in water supply (National Drought Mitigation Center, 2000). In general, precipitation data has been used for meteorological drought analysis, and streamflow data has been applied for hydrologic drought analysis (Dracup et al., 1980; Henriques and Santos, 1999; Shin and Salas, 2000).

A large number of regional drought analyses may be found in the literature. Karl (1983) showed that droughts have longer persistence in the interior of the United States than in the coastal regions in the east and west. Clausen and Pearson (1995) presented a method for investigating the spatial and temporal variability of droughts by a regional frequency analysis of annual minimum streamflows. Best regional estimates of mean drought severity were found for lower truncation levels, and the severities and the durations of the annual maximum droughts at a site were almost linearly related. Shin and Salas (2000) proposed to analyze and quantify the spatial and temporal patterns of meteorological droughts based on annual precipitation data. By using a neural network algorithm, they determined the posterior probabilities of drought severity and assigned a Bayesian drought index for a site, which is useful for constructing drought severity maps that display the spatial variability of drought severity on a yearly basis.

Recently, several studies analyzed the relationship between droughts and climatic indicators. Piechota and Dracup (1996) investigated the hydroclimatic response in the United States to the extreme phases of the Southern Oscillation. A strong relationship between El Niño and extreme drought years was found in the Pacific Northwest and in the southern United States where dry conditions occur consistently during La Niña events. Chiew et al. (1998) presented the relationship between ENSO and droughts in Australia and showed that dry conditions tend to be associated with El Niño. Acosta (1988) found a remarkable relationship between El Niño occurrences and storage scarcity in dams in northern Mexico. Liu et al. (1997) utilized a Kalman filter to forecast droughts in the Gulf region of Texas.

In this study, we initially considered the drought as a meteorological phenomenon characterized by a prolonged and abnormal moisture deficiency as defined by Palmer (1965), who developed the Palmer Drought Severity Index (PDSI) to measure the departure of the moisture supply taking into account the precipitation deficit at certain locations. It has been widely used to detect the meteorological drought and is well documented (Karl, 1983; Piechota and Dracup, 1996; Cook et al., 1999; Kothavala, 1999). The point estimates of the PDSI may then be regionalized using geostatistics techniques like kriging. In spatial analysis, kriging has been widely applied in a variety of fields such as mining engineering, hydrology, and soil science. A practical methodology for developing a drought intensity - areal extent - frequency curve is proposed in this paper. This method would allow decision makers to characterize a regional drought and to provide useful information for water supply and management plans in a semi-arid basin. The methodology is applied to the Conchos River Basin in Mexico.

Overview of the Conchos River Basin

The Conchos River Basin lies within 26°N-30°N and 104°W-108°W and has an area of 71,964km^2 at its mouth to the Bravo/Grande River near Ojinaga, Mexico. The Conchos River originates in the arid/semi-arid Tarahumara range in the Mexican state of Chihuahua. Before reaching the Bravo/Grande River at Ojinaga, Mexico, the river flows almost 560 km through Lake La Boquilla, which was formed by La Boquilla dam, and receives flow from three major tributaries (e.g., Florido, San Pedro, and Chuvíscar rivers) as shown in Figure 1. Topographically,

Figure 1. Stem diagram of the Conchos River (1935 to 1998).

the Conchos River can be divided into three main zones: a relatively small mountainous region in the Chihuahuan Sierra with massive plateaus, which have a mean altitude of 2,500 m and an annual precipitation of around 1,000mm; a transition zone formed by series of valleys surrounded by mountainous zones, with an annual precipitation of about 450 mm; and the Chihuahuan desert at an altitude of about 1,200 m and an annual precipitation of nearly 300 mm. Mean annual precipitation in the whole basin is about 390 mm, although it is not evenly distributed in time or space.

The waters of the Conchos River are used primarily for irrigation of nearly 80,000 ha in three major irrigation districts and for use in hydroelectric power plants located at La Boquilla and other minor dams. Surface water irrigation is fed by water stored in La Boquilla, Francisco I. Madero and Luis L. León dams, among others. Additionally, about 70,000 ha are irrigated by groundwater. Important Mexican cities such as Chihuahua, Hidalgo del Parral, and Delicias are in the basin and growing rapidly due to increasing industrialization. The Conchos River is also the most important tributary of the Bravo/Grande River. The flow of the Conchos River supplies approximately 70 to 80 percent of the flow of the Bravo/Grande River above the mainstream binational reservoirs of Amistad and Falcon. A binational treaty between the United States and Mexico signed in 1944 specifies the minimum flows to be delivered by Mexico at the confluence of the Conchos River with the Bravo/Grande River. Details of this treaty may be found in Houston Advanced Research Center (2000) and Texas Center for Policy Studies (2001). This treaty allows the flows to be below the minimum (in a five-year average) under conditions of "extraordinary drought." However, this concept is not explicitly defined in the treaty (Texas Center for Policy Studies, 2001). The sustainability of the expanding water uses for agriculture and urban purposes, as well as the water rights for this region, are the main issues between the United States and Mexico.

The flows of the Conchos River to the Bravo/Grande River, shown in Figure 2, have declined substantially since 1994 due to an extended drought in Mexico (Texas Center for Policy Studies, 2001). Liverman et al. (2001) pointed out that northern Mexico and the southwest United States experienced the worst droughts on record in the 1950s, which suggests that the enhanced impact of a large-scale forcing mechanism over the climate of subtropical North America. The basin was also under extreme drought conditions from the mid 1940s to early 1960s, and wetter conditions began in the late 1970s and ended at the beginning of the 1990s.

Failure of the summer rains has a dramatic impact over the basin. Dry soil and high surface temperatures increase the evapotranspiration, which affects grassland and agriculture. The drought in the Conchos River Basin, with respect to lower than normal rainfalls, resulted in irrigation cutbacks and severe agricultural losses on both sides
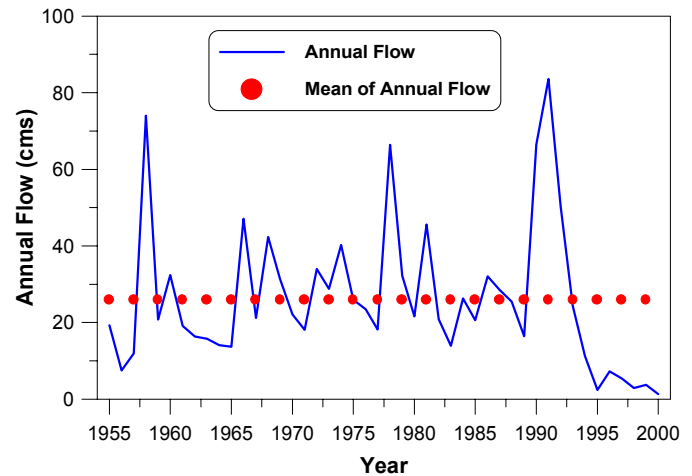

Figure 2. Annual flows of the Conchos River at Ojinaga, Mexico, 1955 to 2000.

of the border. Despite the enormous water management challenge in the Conchos River Basin and the deep interdependence between the availability of water in the Lower Bravo/Grande River and flows from the Conchos River, there has been little investigation and public discussion of water use and trends in the Conchos River Basin (Texas Center for Policy Studies, 2001; Liverman et al., 2001).

The 1990s rainfall was significantly below normal. For example, as shown in Figure 3, in 1998 not only the magnitude of precipitation was affected but also the timing. Less than 13 percent of the mean annual precipitation in the region fell in the winter-half year (November to May), and more than 85 percent of the rainfall occured during the summer (May to October). The drought during the 1990s drove many small farmers off the land and pro-
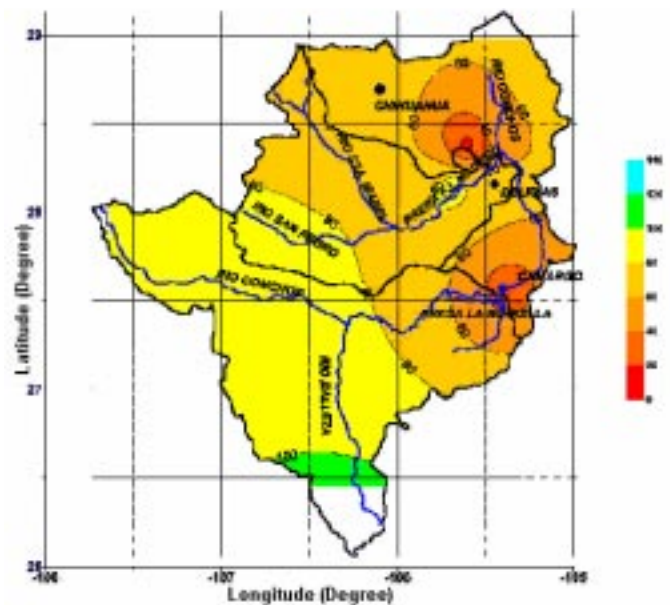

Figure 3a. The spatial distribution of precipitation in 1998 in the Conchos River Basin (Velasco, 2000).
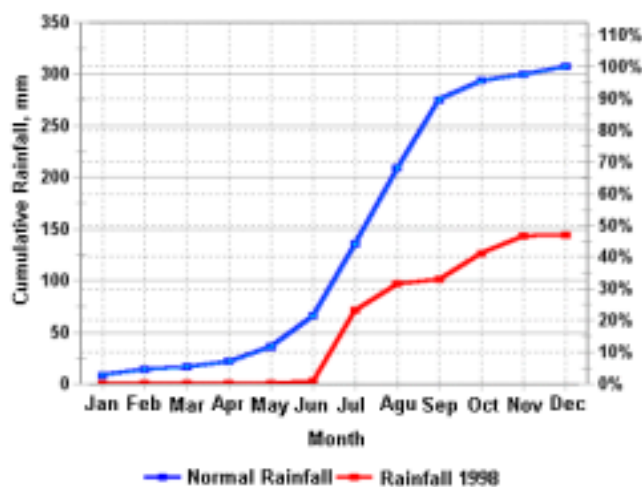
Figure 3b. The cumulative precipitation in 1998 in the Conchos River Basin (Velasco, 2000).

duced a 30 percent reduction in the cattle inventory (Comisión Nacional del Agua, 1997). In addition, in the five-year cycle of the treaty ending on October 2, 1997, due to severe reduction of the Conchos River inflow to the Bravo/Grande River in the 1990s (Figure 2), Mexico owed the United States about 1,240 Mm^3 (1.024 million ac-ft) with respect to water delivery under the 1944 U.S./Mexico Treaty on the use of the Bravo/Grande River (Texas Center for Policy Studies, 2001).

The Palmer Drought Severity Index (PDSI)

Palmer (1965) proposed the Palmer Drought Severity Index (PDSI) based on a balance between moisture supply and demand. The index uses a monthly time series of precipitation (P) and temperature (T) to produce a single numerical value that represents the severity of wetness or aridity for a particular month. In dry spells, a PDSI of -0.5 to 0 is considered near normal, -1.0 to -0.5 incipient drought, -2.0 to -1.0 mild drought, -3.0 to -2.0 moderate drought, -4.0 to -3.0 severe drought, and -4.0 or less extreme drought.

The following procedure to calculate the PDSI is originally described in the report by Palmer (1965) and related papers (Karl, 1983; 1986; Alley, 1984; 1985). The computation of the PDSI begins with a climatic water balance using historic records of monthly precipitation and temperature. Soil moisture storage is considered by dividing the soil into two layers. The upper layer, called surface soil layer, is assumed to contain one inch of available moisture at field capacity, which Palmer originally used and the National Climatic Data Center (NCDC, http://www.ncdc.noaa.gov/) recommends. The underlying layer has an available capacity that depends on the soil characteristics of the site being considered. Palmer used an available water capacity (AWC) of nine inches for central Iowa and five inches for western Kansas. The AWC varies soil to soil and can be taken as a value, which is more or less

representative of the area in general. Moisture cannot be removed from the underlying layer until all of the available moisture has been removed from the surface layer. Run-off (RO) is assumed to occur if both layers reach their combined moisture capacity (AWC).

Four potential values are computed for climate coeficients. Potential evapotranspiration (PE) was computed in our study using the Hargreaves method, which is commonly used because of its broad empiricism (Shuttleworth, 1992). The Hargreaves equation has shown to provide more reasonable estimates of evapotranspiration, because it contains an explicit link to solar radiation through the water equivalent of extraterrestrial radiation, and the difference between maximum and minimum temperature (Jensen et al., 1990; Shuttleworth, 1992) instead of the Thornthwaite method originally used by Palmer. Potential recharge (PR) is the amount of moisture required to bring the soil to field capacity. Potential loss (PL) is the amount of moisture that could be lost from the soil to evapotranspiration provided precipitation during the period was zero. Potential runoff (PRO) is the difference between the potential precipitation and the potential recharge.

The climate coefficients are computed as a proportion between averages of actual versus potential values for each of 12 months at each location. These climate coefficients are used to compute the amount of precipitation required for the Climatically Appropriate For Existing Conditions (CAFEC). The difference, *d*, between the actual (*P*) and CAFEC precipitations ($\hat{P}$) is an indicator of water deficiency for each month.

$$d = P - \hat{P} = P - (\alpha PE + \beta PR + \gamma PRO + \delta PL) \qquad (1)$$

where $\alpha = \overline{ET}/\overline{PE}$, $\beta = \overline{R}/\overline{PR}$, $\gamma = \overline{RO}/\overline{PRO}$, and $\delta = \overline{L}/\overline{PL}$ for 12 months. The value of *d* is regarded as a moisture departure from normal because the CAFEC precipitation is an adjusted normal precipitation.

A Palmer Moisture Anomaly Index (PMAI), *Z*, is defined as

$$Z = Kd \qquad (2)$$

where *K* is a weighting factor. The value of *K* is determined from the climate record before the actual model calculation. After considerable experiments, Palmer suggested empirical relationships for *K* such that

$$K_i = \left(\frac{17.6}{\sum_{i=1}^{12} \overline{D}_i K_i'} \right) K_i' \qquad (3)$$

where $\overline{D}_i$ is the average of the absolute values of *d*, and K_i' is dependent on the average water supply and demand, given by

$$K_i^{'} = 1.5\,log_{10}\left[\left(\frac{\overline{PE} + \overline{R} + \overline{RO}}{\overline{P} + \overline{L}} + 2.8\right)\overline{D}^{-1}\right] + 0.5 \tag{4}$$

where PE is the potential evapotranspiration, R is the recharge, RO is the runoff, P is the precipitation, and L is the loss.

Having established the value of K, the PDSI is given by

$$PDSI_i = 0.897\,PDSI_{i-1} + \frac{1}{3}Z_i \tag{5}$$

where the PDSI of the initial month in a dry or wet spell is equal to $\frac{1}{3}Z_i$.

Although the PDSI is considered as a meteorological drought index, the procedures mentioned above contain the concepts of hydrological drought. The term hydrologic drought index is used as it pertains to systematic accounting of the terms associated with moisture inflow, outflow, and change of storage (Karl, 1986).

According to Alley (1984), the PDSI has positive characteristics useful for drought monitoring. For example, it provides a measurement of the abnormality of weather for a region and an opportunity to place current conditions in historical perspective. In addition, the PDSI is a standardized value available to compare and assess regional drought (National Drought Mitigation Center, 2000). It has also been applied as an index to forecast droughts in the Gulf region of Texas by Liu et al. (1997) using climatic precursors.

Temporal Characteristics of Droughts in the Conchos River Basin

The PDSI was used to provide an indicator of drought severity in this study. There are some limitations to consider when using the PDSI. The PDSI is sensitive to the AWC of a soil type, and only two soil layers for soil moisture storage is a simplification so that these assumptions may not be accurate for a location. Due to the lack of soil type information in the basin, it was assumed that the surface soil layer water capacity is one inch and the underlying soil layer water capacity is six inches. These values, which were adopted from the NCDC, are values of the AWC used in the Texas Climatologic Region 5, located in the immediate vicinity of the Conchos River Basin. Another limitation is that the PDSI may be inaccurate in winter when snow occurs or in regions where the ground is frozen, because all precipitation is treated as rain (Alley, 1984; Karl and Knight, 1985). However, in this case, because the basin lies in a semiarid region, the annual precipitation falls during the warm season, so that a large part

of the interannual variations are strongly associated with the summer precipitation variability.

The precipitation and temperature data in the Conchos River Basin were provided by the Mexican Institute of Water Technology (IMTA, http://www.imta.mx). Each station has a different data period (Table 1) and is irregularly distributed in the Conchos River Basin (Figure 4). The regional representative of PDSI was calculated using the areal mean of precipitation and temperature to reconstruct across the basin (Figure 5a). The basin has experienced droughts in terms of severity and duration in the late of the 1930s, at the beginning of the 1950s, and in the 1990s. During the period of 1934 to 1998, the basin also had 234 months of moderate drought (PDSI < -2.0), 127 months of severe drought (PDSI < -3.0), and 76 months of extreme drought (PDSI < -4.0). Severe droughts continued in the 1990s with respect to severity and duration. The drought in the 1990s resulted in the lack of available water in northern Mexico, which brought several problems to the society and in the lack of available water in the Lower Bravo/Grande River (Texas Center for Policy Studies, 2001).

The Standardized Precipitation Index (SPI) is another indicator of drought severity widely used. The SPI was designed to facilitate the detection and monitoring of droughts by McKee et al. (1993), and it is easier to calculate than the PDSI. The SPI is mainly based on the probability of precipitation for a given time period. A key feature of the SPI is the flexibility to measure drought at different time scales. Values range from 2.00 and above (extremely wet) to –2.00 and less (extremely dry) with near normal conditions ranging from 0.99 to –0.99. A drought is defined whenever the SPI reaches a value of –1.00 and continues until the SPI becomes positive again. Figure 5b shows the SPI in the Conchos River Basin. Velasco (2000) also indicated a significant drought during the 1990s from the analysis of SPI for the Conchos River Basin. In this study, the PDSI was mainly used for regional drought analysis because it takes into account the moisture stored in the upper soil layers and therefore considers, even if in a rela-

Table 1. Precipitation and Temperature Stations in the Conchos River Basin

Station #	Station Name	Period
1	Chihuahua	1960–1998
2	Balleza	1943–1993
3	Camargo	1942–1998
4	Ciudad Jimenez	1944–1998
5	Ojinaga	1941–1998
6	Ciudad Delicias	1934–1998
7	Hidalgo Del Parral	1941–1998
8	La Boquilla	1949–1998
9	Las Burras	1949–1998
10	Meoqui	1941–1993
11	Ojo Caliente	1937–1984
12	Villa De Aldama	1960–1993
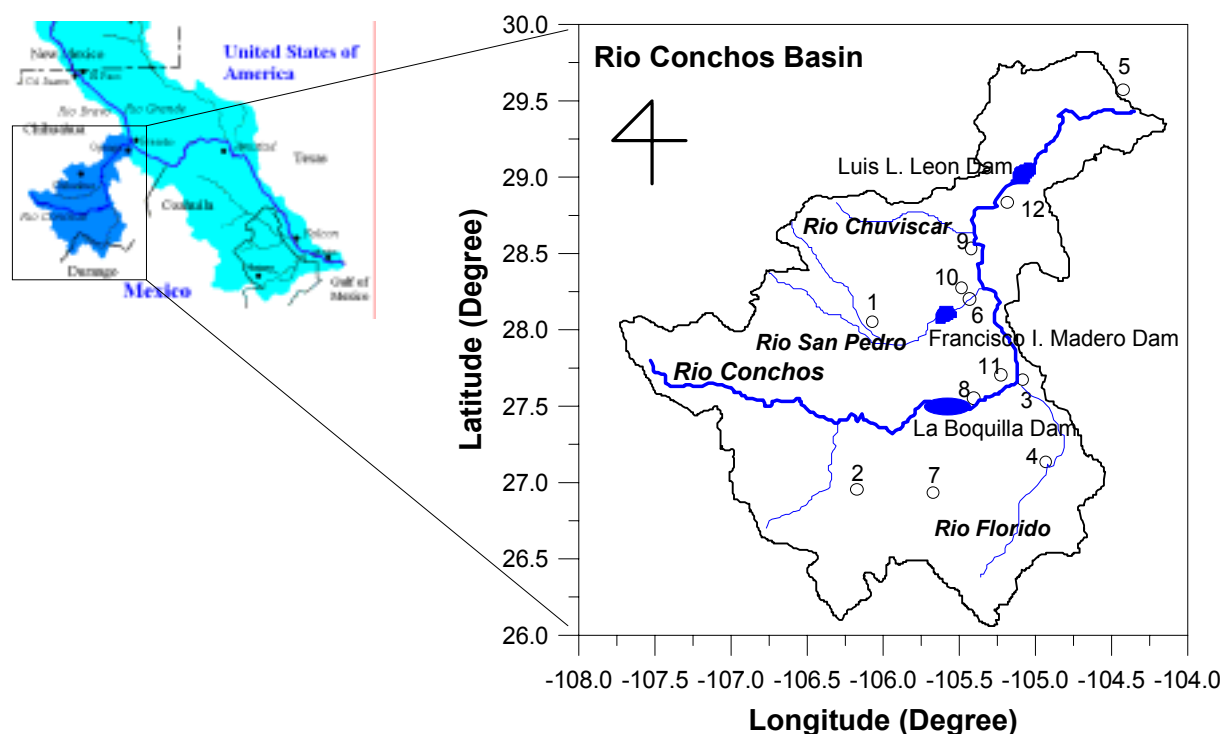
Figure 4. Location of precipitation and temperature stations in the Conchos River Basin (Adapted from Houston Advanced Research Center, 2000).

tively elementary fashion, the drought persistence. However, a more profound research on the matter of persistence will be made in future researches.

Regional Drought Analysis

Although the estimation of drought severity at a point or as a regional representative generally gives useful information for water management, it may be interesting to assess the drought for the entire basin. This regional drought analysis is useful for declaring the drought condition or determining the drought intensity during a particular year (Shin and Salas, 2000). One of most useful methods to assess drought in a region is the drought severity – area – frequency curve, which was proposed by Henriques and Santos (1999). They obtained the area of influence of each station using the Thiessen method and constructed the severity – area – frequency curves using the drought severity from the synthetic precipitation series. The Thiessen method, however, does not consider the stochastic characteristics of the data. In this study, the regional drought is analyzed based on a drought intensity – areal extent – frequency curve developed using a geostatistic technique to estimate "regional variables" (Matheron, 1963) for each return period. Geostatistics is a collection of generalized linear regression techniques, which is used to estimate the areal extent of the droughts in the Conchos River Basin. This spatial display will provide valuable information for the preparation of drought preparedness plans for the ba-

sin. Details of the kriging technique are provided in the Appendix of this paper.

In order to make a regional variable for describing a phenomenon spatially distributed over a region, drought intensity was introduced at each station. Drought intensity can be calculated by multiplying the annual sum of PDSI in dry spells by the probability of drought occurrence for each year. The probability of drought occurrence is determined by dividing the number of months that have a PDSI lower than –1.0 by 12 months. In this way, each drought event can be allotted evenly for the particular year, and we can examine the drought for the year avoiding the intermittence. The drought intensity – areal extent – frequency curve provides useful information that contain drought intensity and area subjected to drought for a given drought return period. A summary of the procedure for the drought intensity – areal extent – frequency curve proposed in this study follows:

- For every year, evaluate drought intensity at each station.
- Estimate the spatial distribution of the drought intensity using a kriging estimator.
- Obtain the drought intensity associated with the areal extent percent using the distribution map produced in the previous step.
- Perform the frequency analysis for each drought areal extent to associate drought intensity with return periods.
- Construct the drought intensity – areal extent – fre-

quency curve for the region by considering the adequate probability distribution.

In drought studies, the frequency analysis is a traditional and practical method. Using the annual values in the frequency analysis, only the magnitude of a drought is of interest. In our study, the drought intensity has definitely negative values. To be applied before fitting to an available distribution, the drought intensity should be converted to positive values in order to represent the extreme condition and to analyze the associated risks of the droughts using the exceedance probability. The Kolmogorov-Smirnov (K-S) test and the Chi-Square (χ^2) tests, which are standard tests for probability distributions, were used. As shown in Table 2, most of the distributions passed the test. The Extreme Value Type I (EV I) distribution was selected in this study. This distribution is a special case of the Generalized Extreme Value (GEV) distribution with two parameters. It has been conventional to use the EV I distribution to represent precipitation extremes, and also has been used for drought analysis, e.g., Henriques and Santos (1999).

The time series of PDSI (Figure 5a) and SPI (Figure 5b) suggest that the Conchos River Basin has experienced severe droughts in the last 60 years. It also shows that the Conchos River Basin had an extreme drought in the 1990s based on the PDSI (Figure 5a). Using the drought intensity – areal extent – frequency curve we proposed, we examined the drought in the basin based on the intensity of the return period. For examining the drought in the 1990s, the spatial distribution of droughts that occurred in the 1990s was estimated by a kriging estimator using the drought intensity, as shown in Figure 6. The kriging estimated the areal extent subjected to drought using 12 sites (Table 1 and Figure 4). The drought intensity means time average of drought severity in dry spells and represents the drought severity classified by Palmer, which is indicated by a gray scale between 0 and -6. Kriging exhibited a good approach
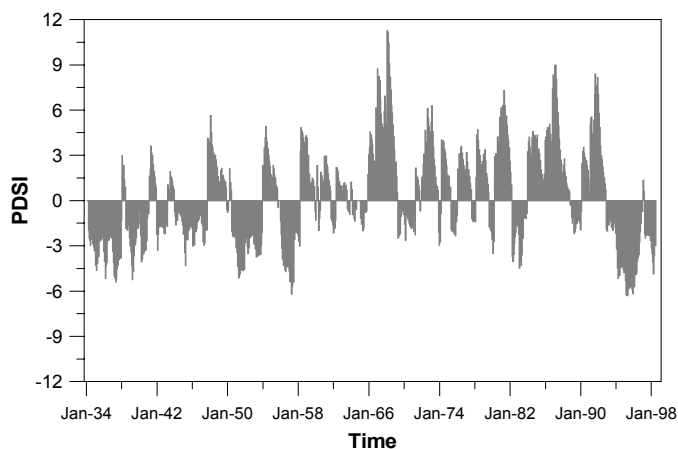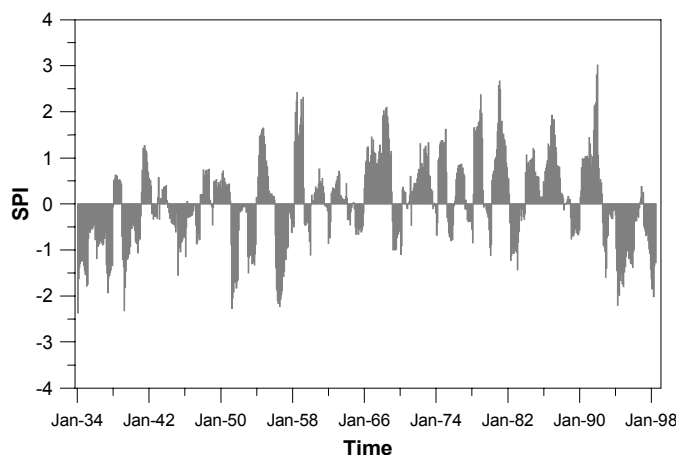
Figure 5b. The Standard Precipitation Index (SPI) in the Conchos River Basin.

in estimating the distribution of drought intensity, even though data stations are irregularly distributed. Because kriging considers an implicit covariance structure within the data, it is able to produce unbiased estimates. In fact, when we use a deterministic method in estimating regional variables, it is troublesome to deal with the sparse and irregularly distributed data points. Finally, in Figure 7, the historical droughts are compared with the drought intensity – areal extent – frequency curve, which was constructed using data before 1990.

Under this analysis, the droughts that occurred in 1994, 1996, and 1998 have an associated return period of 10 to 30 years. Especially the drought that occurred in 1995 is the most severe drought ever experienced in the basin. As shown in Figure 5a, the basin has never experienced droughts like that before 1990. Data after 1990 was not used to construct the drought intensity – areal extent – frequency curve, which has a higher return period of more than 80 years. The 1990s drought intensity has a return period of approximately 100 years with an increase in areal extent. In addition to the high return period, it is a very extreme drought of the basin since more than 70 percent of the basin was below –4 (Extreme drought condition). The 1990s droughts caused exploding water demands and subsequent impacts in the basin and in northern Mexico. A survey of some of these severe impacts affecting several binational rivers may be found in Liverman et al. (2001).

Concluding Remarks

This study was focused on analyzing temporal and spatial extents of droughts in the Conchos River Basin using the PDSI as an indicator of drought severity. The PDSI is one of the drought indices that have been more widely used for a variety of applications. It provides decision makers with a measurement of the abnormality of recent weather for a region and an opportunity to place

Figure 5a. The Palmer Drought Severity Index (PDSI) in the Conchos River Basin.

Table 2. The Results of Goodness Fit Test for Candidate Distributions for Areal Extent 50 Percent

Distribution	K-S	Remark 1%	Remark 5%	χ^2	# of D.F.	Remark 1%	Remark 5%	S.L. 1%	S.L. 5%
Normal	0.11	OK	OK	4.21	8	OK	OK	20.1	15.5
Log-Normal	0.10	OK	OK	5.44	8	OK	OK	20.1	15.5
Gamma	0.12	OK	OK	9.17	8	OK	OK	20.1	15.5
Pearson Type-3	0.10	OK	OK	5.45	7	OK	OK	18.5	14.1
Log-Pearson Type-3	0.14	OK	OK	7.31	7	OK	OK	18.5	14.1
Extreme Type I	0.09	OK	OK	7.93	8	OK	OK	20.1	15.1
Generalized Extreme	0.10	OK	OK	6.69	7	OK	OK	18.5	14.1
Wakeby	0.09	OK	OK	8.55	5	OK	OK	15.1	11.1

Significant Level (S.L.) of K-S Test 1% = 0.27 and 5% = 0.23
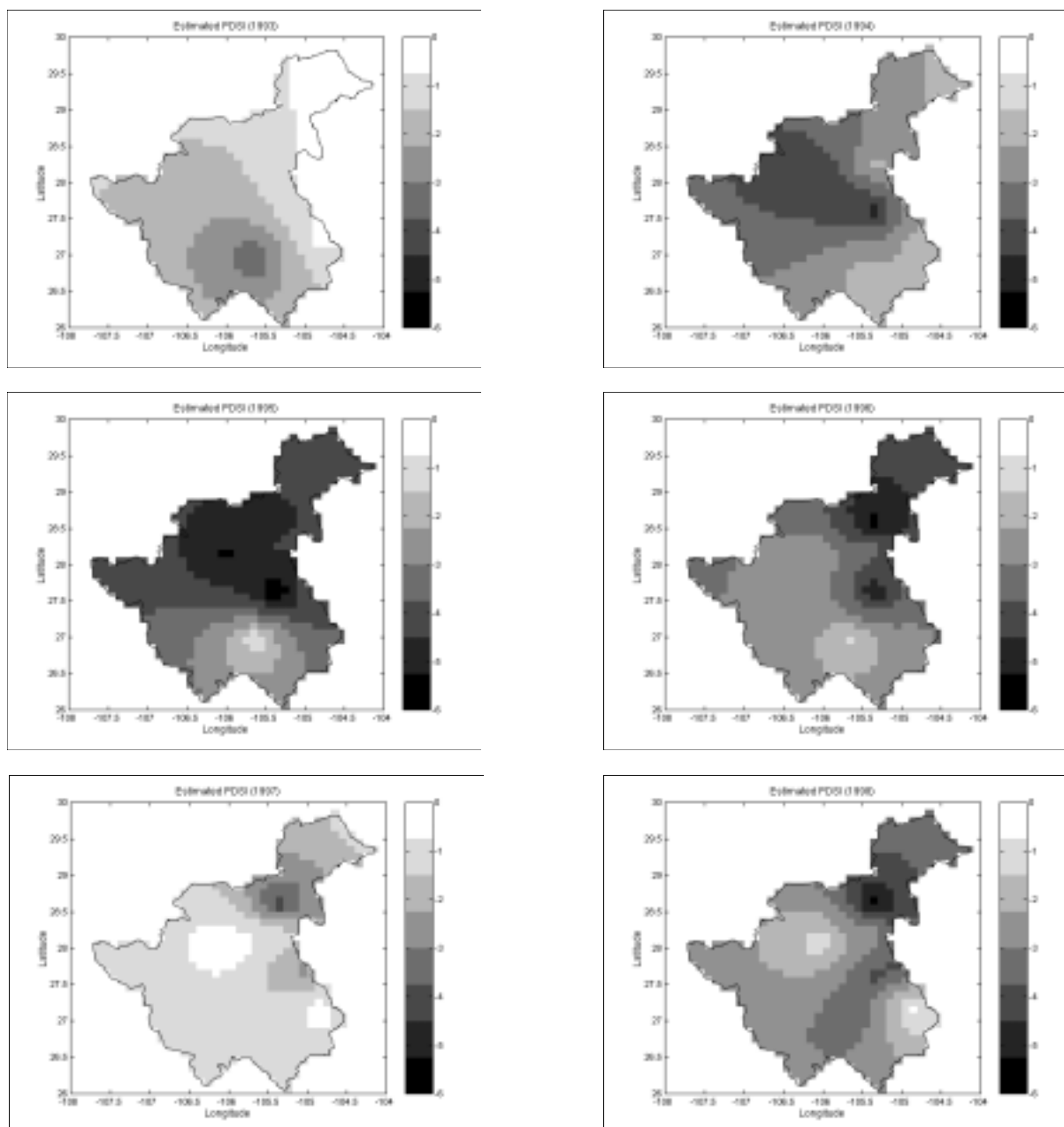
Figure 6. Areal distribution of drought intensity for historical droughts that occurred in the 1990s for the Conchos River Basin.
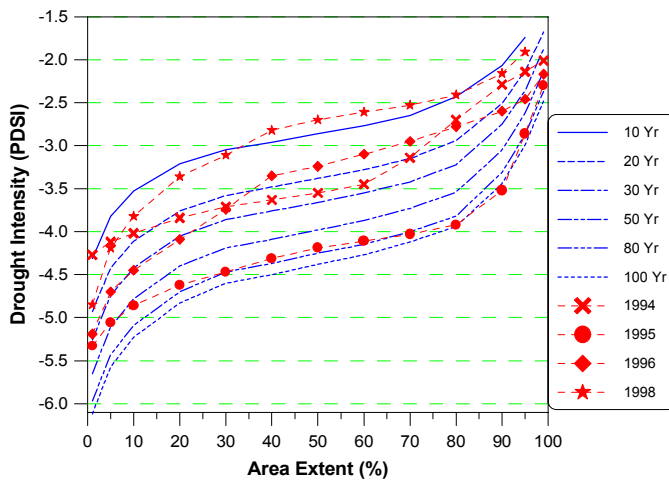
Figure 7. Drought intensity - areal extent - frequency curve for the Conchos River Basin with the historical droughts that occurred in the 1990s.

current conditions in historical perspective. In addition, it provides spatial and temporal representations of historical droughts. The main objective of this study is to develop methodologies to analyze and quantify regional droughts in semi-arid regions. The proposed drought analysis approaches were applied to the Conchos River Basin, which is one of the most important river basins of the United States/Mexico border region. The basin has experienced droughts in terms of severity and durations in the 1930s, 1950s, and 1990s. In particular, the persistent droughts in the 1990s seriously affected urban water supply and agricultural irrigation, as well as reduction of inflows into the Bravo/Grande River.

A regional frequency analysis was presented as a method for investigating the spatial and temporal variability of droughts based on the drought intensity using the PDSI. The spatial drought distributions were examined using a kriging estimator. The drought intensity – areal extent – frequency curve constructed in this study contains drought severity and drought area with respect to drought return period so as to describe and characterize the spatial and recurrence patterns of droughts. It is shown that the drought that occurred in the 1990s is associated with a return period of 80 to 100 years with a large areal extent.

The droughts in the Conchos River Basin and the related significant decrease in the flows of the Conchos River reaching the Bravo/Grande River have created strong controversy in both the United States and Mexico. Characterization of the droughts in the Conchos River Basin will be useful not only for the development of a drought preparedness plan in the basin but also for the provisions of the international treaty that regulates the flows of the Bravo/Grande River tributaries between the United States and Mexico.

The next step in our research will be to evaluate the forecasting potential using climatic precursors to predict

drought indices like Liu et al. (1997; 1998). Preliminary analyses performed by the authors indicate small correlations between ENSO and the summer precipitation in the Conchos River Basin. Liverman et al. (2001) also analyzed possible teleconnections in the basin. Also, an analysis including persistence will be done in a future work.

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Discussions open until March 1, 2003.

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Appendix: Brief Description of Kriging Technique

The kriging estimator $z^*(x_0)$ in Equation 6 is a best linear unbiased estimator (BLUE) because the weights l_i are chosen to satisfy the conditions of unbiasedness and minimum variance (Borga and Vizaccaro, 1997; Olea, 1999).

$$z^*(x_0) = \sum_{i=1}^{N} \lambda_i z(x_i) \qquad (6)$$

A kriging system of $n+1$ linear equations with $n+1$ unknowns, i.e., $\lambda_1, \cdots, \lambda_n, m$ is

$$\sum_{j=1}^{N} \lambda_j \gamma_{ij} + \mu = \gamma_{i0}, \quad i=1, \cdots, N \qquad (7)$$

$$\sum_{j=1}^{N} \lambda_j = 1 \qquad (8)$$

where μ is a Lagrange multiplier arising from the unbiasedness condition (Borga and Vizaccaro, 1997), and γ is the semivariogram function, which represents the spatial correlation structure of the regionalized variables.

Let $z(x)$ is the observed value at point x. The experimental semivariogram can be estimated by

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [z(x_i) - z(x_i + h)]^2 \qquad (9)$$

where $N(h)$ is the number of pairs of observations separated by a distance, h.

Using matrix, the kriging system can be expressed in more compact form.

$$\mathbf{AX} = \mathbf{b} \qquad (10)$$

where $\mathbf{X}$ is the vector of the unknowns, $\mathbf{b}$ is the right-hand-side in Equation 7, and $\mathbf{A}$ is the coefficient matrix.

$$\mathbf{X} = [\lambda_1 \quad \lambda_2 \quad \cdots \quad \lambda_N \quad \mu]' \qquad (11)$$

$$\mathbf{A} = \begin{bmatrix} \gamma_{11} & \gamma_{21} & \cdots & \gamma_{N1} & 1 \\ \gamma_{12} & \gamma_{22} & \cdots & \gamma_{N2} & 1 \\ \vdots & \vdots & \cdots & \vdots & 1 \\ \gamma_{1N} & \gamma_{2N} & \cdots & \gamma_{NN} & 1 \\ 1 & 1 & \cdots & 1 & 0 \end{bmatrix} \qquad (12)$$

$$\mathbf{b} = [\gamma_{10} \quad \gamma_{20} \quad \cdots \quad \gamma_{N0} \quad 1]' \qquad (13)$$