Impacts of Droughts on the Rio Conchos Watershed over the International Water Treaty Between Mexico and the United States of America

manejo internacional del agua entre México y Estados Unidos

Luis E. Cervera Gómez[1]

[1] Investigador de El Colegio de la Frontera Norte (mexicano), Dirección Regional Noroeste. Candidato a doctor por la Universidad de Arizona. Tels. (656) 617-65-93 y 617-89-58. Fax: (656) 618-40-55. Correo: lcervera@colef.mx.

Fecha de recepción: 21 de abril de 2007
Fecha de aceptación: 07 de agosto de 2007

Introduction

The Conchos river basin, which drainage area entirely lies in Mexican territory is the most important tributary of the Rio Grande/Rio Bravo downstream of Fort Quitman, Texas. Since 1944 its flows together with other five tributaries are part of a binational treaty on water allocation between the United States and Mexico. Due principally to a prolonged drought Mexico had failed to deliver the water granted to the United States according to the Article 4 of the Water Treaty. As a consequence Mexico has an accumulated deficit that looks hard to pay. As part of this treaty, the concept of "extraordinary drought" is considered, but not measured. Thus, there is not a specific drought index to define different levels of drought including *extreme conditions*. Other relevant aspect of this treaty is the maximum time established as a maximum time with drought conditions, a five-year cycle. To understand the current international problems originated for drought, this work analyze hydrological conditions throughout a statistical analysis of the flows of the Conchos at the entrance of the two main dams (La Boquilla and P. Madero) to test the following:

1. Changes in the mean and variability of the inflows during historical records.
2. Analysis of indicators of drought, *i.e.* Palmer Drought Severity Index (PDSI) for the closest climatic region in Texas (Near Ojinaga).
3. Comparison of the 1950's drought and the 1990's drought. Similarities, differences?

The final purposes of this research in terms to clarify basic concepts of the 1944 International Water Treaty are twofold. First, the understanding of what can be considered as extreme drought conditions. Second, the understanding of duration of drought over time compared with the five-year periods politically pre-established as a maximum period of drought.

Rio Conchos

The study area is represented by the Rio Conchos Watershed (see Figure 1). This river is not only the Chihuahua's most important river, but it is also recognized as one of the most important river systems in all of northern Mexico (Kelly, 2001). Because its waters give life to an extensive territory in Mexico and it is also one of the principal tributaries of the Rio Grande, this watershed has a crucial importance as an international resource shared between Mexico and the United States of America.

Figure 1. Rio Conchos Watershed. Map used under permission of Israel Velasco, IMTA.

Climate and watershed characteristics

Using the Köeppen climatic system modified by Enriqueta Garcia for the *Republica Mexicana*, the Rio Conchos has four climatic divisions: (1) Very arid (BW) in the Chihuahua desert area; (2) Arid; (3) Semiarid (BS1); and (4) Sub-Humid (AC) in the forests areas of the Sierra Madre Occidental (SMO) (CNA, 1997). Rainfall in the Rio Conchos watershed averages 377 mm (14.8 inches), but it ranges from 300 (11.8 inches) to 1 000 mm (39 inches) at the upper basin to about 200 (8 inches) to 400 mm (16 inches) in the lower basin (CNA, 1997; CONABIO, 2000). The annual average temperature range is from 8-18°C in the upper basin to about 16-22°C in the lower basin (CONABIO, 2000).

In Mexico, the Rio Conchos Watershed has nine major populated municipalities (See Table 1) with about 1 068 901 inhabitants, of which 63% are concentrated in the municipality of Chihuahua (mainly in the city of Chihuahua). There are 273 658 housing units with an average of about 3.91 inhabitants per house.

In this basin, rapid rates of population and economic growth have led to the widespread conversion of natural ecosystems to farmland, industrial areas, and more urbanized areas. Urbanization, agricultural intensification, resource extraction, and water resources development are examples of human-induced phenomena that have had significant impact on the people, the economy and the natural resources of the Rio Conchos basin. Thus, higher rates of deforestation in the upper basin, intensive agriculture, and urbanization in the middle and lower basin areas are the principal factors undermining the natural conditions of this basin. Consequently, the natural hydrological conditions of this basin have been strongly affected in terms of hydrologic characteristics, water quantity and water quality.

Table 1. Municipalities Inside the Rio Conchos Watershed, Chihuahua, Mexico.

Municipality	# of inhabitants	# of housing units	Avg. inhab./ house
Ojinaga	24,313	6 568	3.68
Hidalgo del Parral	100,881	24 509	4.11
Jimenez	38,259	9 260	4.13
San Fco. De Conchos	2,837	748	3.78
Delicias	116,132	29 466	3.93
Chihuahua	670,208	173 582	3.85
Camargo	45,830	11 574	3.95
Meoqui	39,848	10 228	3.89
Saucillo	30,593	7 723	3.91

Source: INEGI, 2000. XII Censo General de Población y Vivienda: preliminary results.

The Rio Conchos basin in its entirety contains one-half the entire Rio Grande drainage in Mexico. Historically, this river has supplied water mainly for agricultural activities (agriculture and livestock). Furthermore, adequate streamflow is necessary to support riparian habitats, and finally to satisfy downstream demands by the U.S. and Mexico according to international agreements (USDOI, 1998). In the Rio Conchos watershed, upstream from the subarea (Rio Grande-Rio Conchos to Amistad Reservoir), expanding agricultural, mining, and timber harvesting activities as well as urban and industrial development affect both the quantity and quality of Rio Grande flows and its aquatic-biological characteristics within the subarea (USDOI, 1998; Davis, 1980).

At the confluence of the Conchos with the Rio Grande (Presidio/Ojinaga), the inflow of the Conchos increase significantly the Rio Grande's streamflow. Thus, the Rio Conchos supplies the largest percentage of Rio Grande flows allocated by Mexico in accordance with the international water treaty (USDOI, 1998). During the 1980's the total annual flow of the Rio Conchos averaged 737 000 acre-feet (908.7 Mm^3), representing this flow approximately five times the flow of the Rio Grande measured upstream (IBWC, 1989 in USDOI, 1998).

The 1944 International Water Treaty

In 1944, the U.S and Mexico signed a treaty to allocate the water resources from the international watersheds shared by these two countries. In general, this treaty includes the Colorado River, the Tijuana River and the Rio Bravo/Rio Grande. The Rio Grande/Rio Bravo waters between Fort Quitman, Texas and the Gulf of Mexico are "hereby allotted to the two countries in several manners, but in this research I will only focused to the waters granted to the United Sates under Article 4 of the Water Treaty.

In accordance with the 1944 Water Treaty, the United States has right to a portion of water coming from six tributaries. This granted water is described in the Subparagraph (c) of Article 4 as follows:

One-third of the flow reaching the main channel of the Rio Grande from the Conchos, San Diego, San Rodrigo, Escondido and Salado Rivers and the Las Vacas Arroyo, provided that this third shall not be less, as an average amount in cycles of five consecutive years, than 350,000 acre-feet annually (IBWC, 2002).

However, same Article 4 considers in its last part, what to do in case that Mexico fail to pay the aforesaid water allocation. Thus, the Water Treaty literally states:

In the event of extraordinary drought or serious accident to the hydraulic systems on the measured Mexican tributaries, making it difficult for Mexico to make available the run-off of 350,000 acre-feet (431,271,000 m3) annually, allotted in subparagraph (c) of paragraph B as the minimum contribution from he aforesaid tributaries, any deficiencies existing at the end of the aforesaid five-year cycle shall be made up in the following five-year cycle from the said measured tributaries.

Persistence of drought in Chihuahua for a ten years period from 1990 to 2000 had seriously impacted water quantity generated from the Rio Conchos and as a consequence less water was reaching the Rio Bravo. This situation put a Mexico in a deficit situation, which affects the 1944 U.S./Mexico water treaty. Kelly (2001) reports that in the five-years cycle ending on October 2, 1997, Mexico owed about 1,240 Mm^3 (1.024 million acre-feet). In the current five year cycle corresponding to the period from October 3, 1997 to April 6, 2002, Mexico has an accumulated deficit of 1 476 181 acre-feet (1,820.13 Mm^3) (IBWC, 2002).

Drought

1) Changes in the mean and variability of the inflows during the period of record

For this part, I did a statistical analysis of the Rio Conchos flows at the entrance of the two main dams; these are La Boquilla, and P. Madero. A 63 years spanning period of inflows from 1935 to 1998 were considered from La Boquilla. Also, a 49 years spanning period from 1949 to 1998 were analyzed for the Madero reservoir. Statistical analysis comprises descriptive parameters to study patterns and changes in flows regime. These stats are mean, coefficient of variation, maximum, minimum, standard deviation, skew and Kurtosis. All descriptive data were analyzed using EXCEL spreadsheets and results are displayed in Appendixes I and II. Additionally to test statistical differences between drought conditions during 50's and 90's the SPSS was used.

The annual flows of the Rio Conchos before to reach La Boquilla dam and the Madero reservoir are highly variable, this because the most important climatic factor affecting Chihuahua's rivers is the spatial and temporal variable pattern of its rainfall. Figures 2a and 2b show the inflows of the two studied reservoirs. As we can observe river flows of the Rio Conchos varies greatly from year to year representing a pattern of possible droughts, floods and what can be considered normal conditions. In La Boquilla, the mean annual flow was estimated in 1 229 39 millions of cubic meters (Mm^3). The maximum registered annual flow was about 3 529 20 Mm^3 (almost three times the average flow) during 1991. The minimum annual flow was estimated in 137 Mm^3, corresponding this figure to the year of 1951 when the region was having extreme drought conditions. According to Fierro (1999) during 1951 the average annual precipitation was about 129.8 mm for the State of Chihuahua.

Figure 2a. The annual inflows to La Boquilla Reservoir, Rio Conchos (1935-1998)

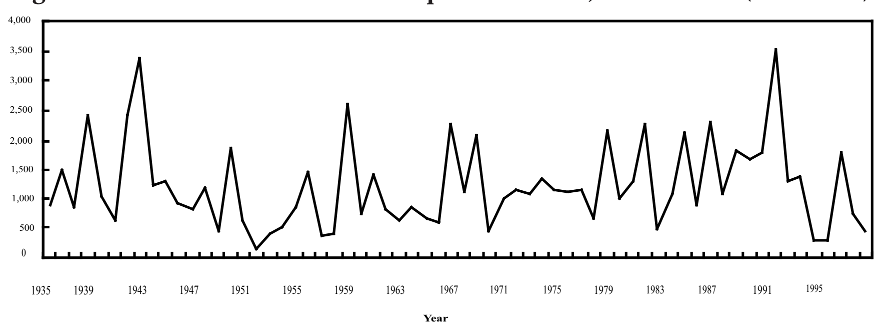
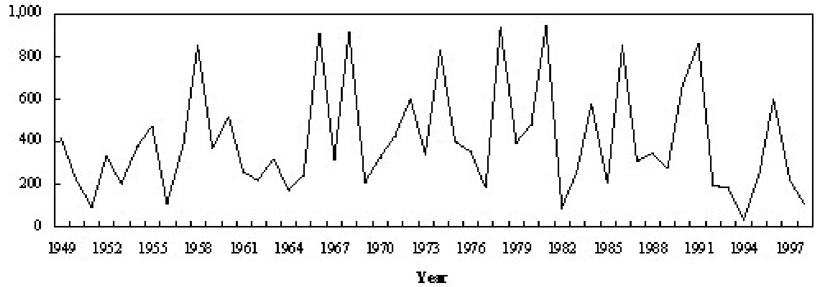


Figure 2b. The annual inflows to Madero Reservoir, Rio Conchos (1949-1998)



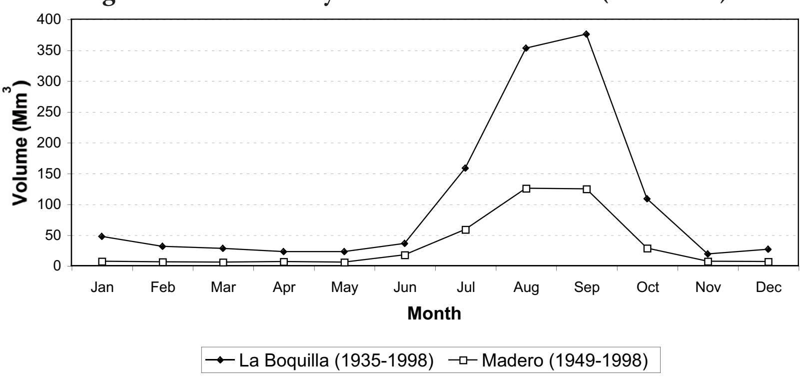
Considering the mean streamflow value of about 1229.39 Mm^3 as normal conditions of flow and from a hydrologic perspective we can detect a kind of hydrological drought or extreme hydrological drought conditions during 1940, 1948, 1950-1951, 1956-1957, 1959, 1969, 1982, 1985, 1994-1995, and 1997-1998. Also, we can emphasize wet or extreme wet conditions during 1938, 1941-1942, 1958, 1966, 1968, 1978, 1981, 1984, 1986, and 1991 (three times the mean value). Finally, the annual flow variability presents a coefficient of variation of about 60%.

In the Madero reservoir, the mean annual flow was estimated in 400.81 millions of cubic meters (Mm^3). The maximum registered annual flow of about 941.30 Mm^3 (more than two times the average flow) was presented during 1981. The minimum annual flow was estimated in 36.70 Mm^3, corresponding this figure to the year of 1994 when the region was having extreme drought conditions (this is also analyzed in the next task). The impacts of drought during 1994 were very drastic for the region, in such a way that the 50% of the livestock inventory (1 000 000 heads) was lost. Also, great problems were reported for the temporal and irrigated agriculture.

Considering the mean value of about 400.81 Mm^3 normal conditions of flow we can detect drought or extreme hydrologic drought conditions during 1950-1951, 1952-1954, 1956, 1961-1962, 1964-1965, 1967-1969, 1977, 1982-1983, 1985, 1992-1995, 1997-1998. In addition, we can emphasize wet or extreme wet conditions during 1949, 1955, 1958, 1960, 1966, 1968, 1971-1972, 1974, 1978, 1980, 1981, 1984, 1986, 1990-1991, and 1996. Finally, the annual flow variability presents a coefficient of variation of about 63%.

In La Boquilla dam, the greater mean monthly inflows start in July to end in October. From the summer season, the maximum values are during August and September (352.91 and 376.01 Mm^3 respectively). In the Madero reservoir, we found that the maximum flow values are during July to September, reaching a maximum during August (125.2 Mm^3), see figure 3.

Figure 3. Mean monthly flow at the Rio Conchos (1949-1998)



2) Analysis of indicators of drought, i.e. PDSI for the closest climatic region in Texas

2.1 Definition of drought.— It is widely accepted that drought is a normal, recurrent feature of climate, and it can be present in most of the different climatic zones. Furthermore, it is also generally accepted that there is not a general definition of drought. Thus, we can find more than 150 different concepts, which can be based on meteorological, agricultural, hydrological, and socioeconomic disciplinary perspectives. Basically we can find two main types of drought definitions, the first one is conceptual and the second one is operational. The first kind of definitions is formulated in general terms, and its utility relies in that it helps people to understand the meaning of drought. According to the National Drought Mitigation Center (NDMC), the operational concepts are useful to detect the beginning, end, and degree of severity of a drought. Furthermore, the operational definition can be used to analyze drought frequency, severity, and duration for a given period.

In this research to analyze drought conditions I am using the Palmer Drought Severity Index (PDSI). The PDSI in an important climatological tool to evaluate the scope, severity, and frequency of prolonged periods of abnormally dry or wet weather (Climatic Prediction Center, 2000). This PDSI was designed to characterize drought solely in terms of meteorological phenomena. Thus, monthly precipitation and monthly temperature are used to estimate it. According to Steila (1972), Palmer defines a drought period as:

> *An interval of time, generally of the order of months or years in duration, during which the actual moisture supply at a given place rather consistently falls short of the climatically expected or climatically appropriate moisture supply. Further, the severity of drought may be considered as being a function of both the duration and magnitude of the moisture deficiency.*

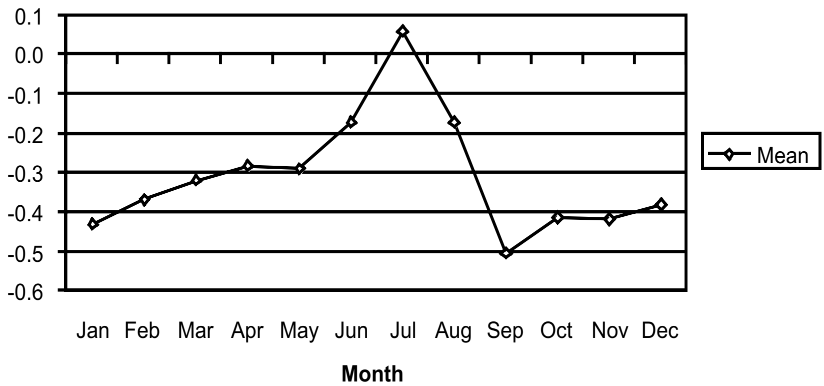
After this definition, it is necessary to analyze PDSI in terms of both duration and magnitude of dry or wet conditions. For the PDSI, 11 categories of wet and dry conditions are defined (Table 2).

Table 2. PDSI Values for the 11 Drought (or wet) Categories

Category	Dryness or Wetness conditions
4.0 and above	Extreme moist spell
3.0 to 3.99	Very moist spell
2.0 to 2.99	Unusual moist spell
1.0 to 1.99	Moist spell
0.5 to .99	Incipient moist spell
0.49 to –0.49	Near normal
-0.50 to –0.99	Incipient drought
-1.0 to –1.99	Mild drought
-2.0 to –2.99	Moderate drought
-3.0 to –3.99	Severe drought
-4.0 and below	Extreme drought

The mean monthly variation of PDSI estimated for the period 1895 to 2000 is presented in Figure 4. This chart may represent the general drought conditions of the arid and semiarid areas of the Rio Conchos basin over time. Considering the average PDSI values from 1895 to 2000, the Plamer's Index places January to June and August and October to December in the same drought category (0.49 to -0.49); this category represent a "near normal" condition. The wetter PDSI category occur during the summer months (June, July and August), here it is observed an increase in moisture conditions. During the rainy season the peak value is reached during July, which is considered as incipient moist spell. In general the near normal condition of drought may represent the average drought conditions for the State of Chihuahua, Mexico. Furthermore, PDSI recorded a maximum of "incipient drought" intensity, which reached its peak in September.

Figure 4. Mean Palmer Indices of Drought (1895-2000): Texas 05



To give us some ideas in practical terms about what the different stage conditions of drought can represent, we can see what was reported by Steila (1972) for the state of Arizona.

Table 3. Descriptive References of Main Drought Categories for the State of Arizona Reported by Steila (1972)

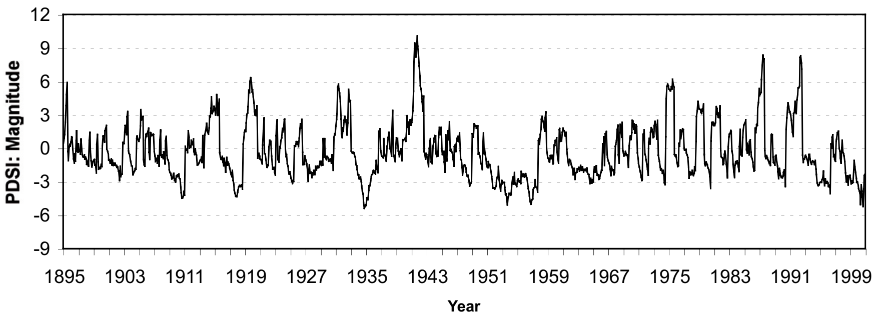
Drought category	Description*
Mild drought	"In the early part of the year, ranges are fair and soil moisture generally adequate. In late spring and summer, stock tanks are drying, ranges are dry, and fire hazards in grass and forest grazing land becomes apparent."
Moderate drought	"Ranges are very dry and beginning to deteriorate, stock water is short, and rains are needed. Fire hazards increase."
Severe drought	"Ranges are extremely dry, water supply scarce, and the hauling of stock water and supplemental feed is common. The threat of fire is very high."
Extreme drought	"Parched vegetation, hauling of water and extensive pumping needed, and range animals are loosing weight and suffering death losses."

*These drought descriptions were based on 40-year period, for each of the drought category.

Magnitude and duration of dry and wet conditions—. The PDSI values are highly variable over time. As we already know, these drought indexes are computed using precipitation and temperature; these are highly variable climatic factors, very characteristic of arid and semiarid regions. Figure 5, is showing the PDSI values for the 1895-2000 period. PDSI values represent the magnitude of a dry or wet condition. From this figure and just analyzing data that match with the hydrologic data (river flows) we found the following dry or wet conditions.

Having an extreme drought class we can identify the years of 1935, 1953, 1957, 1997, and 2000. The years of 1951-1954, 1965, 1971, 1975, 1991, 1995-1996 are considered with severe drought. With mild to moderate drought we can detect the following years: 1937, 1938-1940, 1945-1948, 1951, 1963-1964, 1973, 1978, 1985, 1990, 1993-1995, and 1998. Conversely, with extreme wet conditions we can see the years of 1941, 1975, 1979, 1981, 1987, and 1993. As very moist spell conditions are considered the years of 1959, 1979, and 1981.

Figure 5. Palmer Drought Severity Index (1895-2000): Texas 05

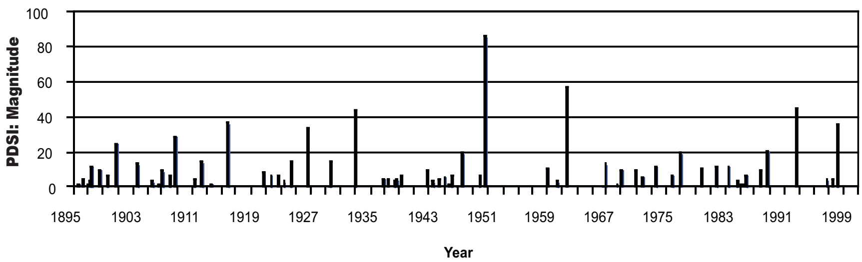


Maybe the most important aspect of a drought condition is its persistency over time. In this analysis, we are considering the consecutive months with dry conditions. Figure 6 is showing duration of drought in months for the studied region. From this figure, it is easy to detect years as 1915, 1927, 1933, 1950-1951, 1961, 1992, and 1997 that have longer duration periods of drought.

Extreme drought.—

> *It is a very serious situation which results from many months, or even years, of abnormally dry weather. During extreme drought, agricultural crops are complete failure; industries and municipalities may face the need for rationing water; and the local and regional economy begins to become disrupted. Thus extreme drought is essentially a disaster.*

Figure 6. Duration of Drought (PDSI: 1895-2000): Texas 05



3) Compare the 1950's drought and the 1990's drought. Similarities, differences?

To compare 1950's versus 1990's drought conditions, in this section I am only considering data corresponding to these two decades. Figure 7 is showing the PDSI values for two periods, from 1950 to 1960 and from 1990 to 2000. First, data indicates that 1950's drought was more persistent than the 1990's, but the severity index of both decades was similar. In the year of 1950, initiate the longest period of drought during a total of 86 months of consecutive dry months. In the year of 1990, initiate another extensive period of drought having 45 consecutive dry months (Figure 8). From Figure 8, we found a similar condition regarding to total duration of drought between the 1950's and 1990's drought periods. Thus, between 1950 and 1950 we have a total of 87 consecutive months and from the 1992 to 1998 period we have a total of 89 consecutive months of dry conditions. The last comparison between 1950's and 1990's drought conditions was made using two histograms of frequency of drought for every decade period. These histograms are represented by figures 9a and 9b. In general, apparently there were more extreme drought and moderate drought during the 1950's. Conversely, there were more wet conditions during the 1990's, having this period very moist and extreme moist spell conditions. Finally, considering the total inflow volume for one of the reservoirs (La Boquilla), we found that the total volume received during the 1950's was about 9 617 5 Mm^3 compared to the 11 602 1 Mm^3 received in the 1990's.

Figure 7. Palmer Drought Severity Index (1950's and1990's): Texas 05

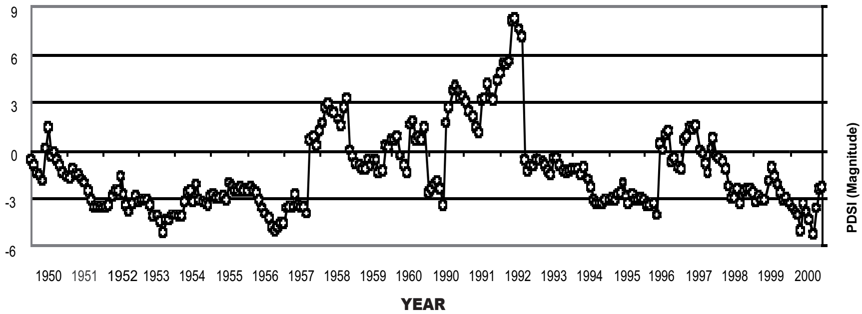
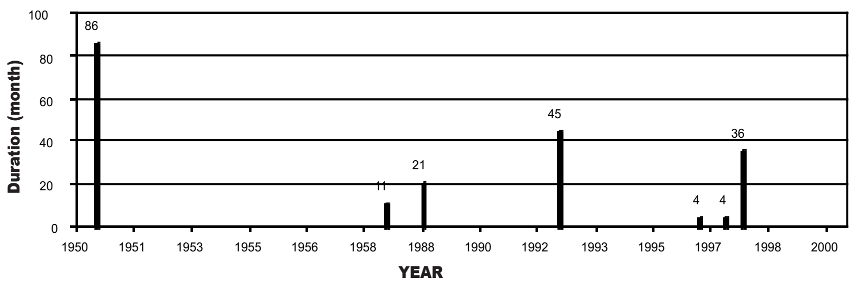


Figure 8. Duration of Drought (PDSI: 1950's and1990's): Texas 05

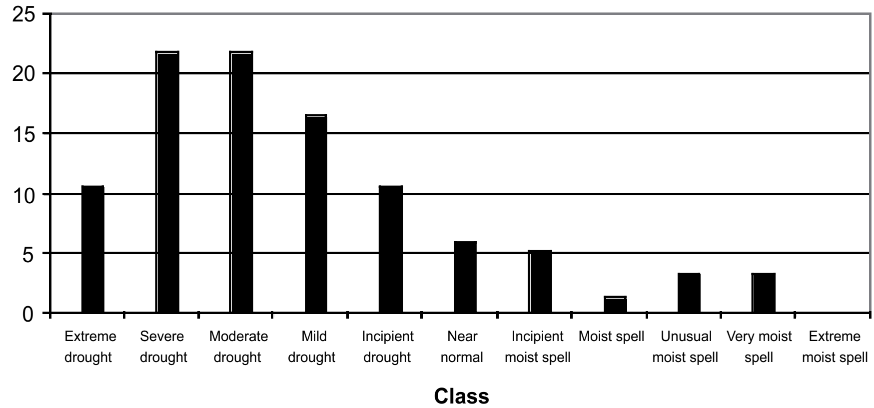


As a concluding remark I found a visible common aspect between the 1950's and the 1990's drought; both decadal periods have the most extensive consecutive dry condition.

Table 4. Initiation of Consecutive Dry Months: Texas 05, Near Ojinaga

Year	Months	Year	Months	Year	Months	Year	Months	Year	Months	Years	Months
1895	2	1908	29	1926	33	1945	8	1965	2	1981	3
1896	7	1911	4	1929	15	1946	8	1966	10	1982	4
1897	15	1912	14	1933	44	1947	19	1968	9	1983	7
1898	10	1913	2	1936	5	1949	7	1969	6	1985	10
1899	7	1915	37	1937	4	1950	86	1970	12	1986	21
1900	25	1920	8	1938	7	1956	11	1973	7	1990	45
1903	13	1921	7	1939	7	1957	3	1974	19	1994	8
1905	3	1922	7	1942	9	1958	57	1977	11	1995	36
1906	2	1923	3	1943	3	1963	2	1979	12	1996	4
1907	16	1924	14	1944	4	1964	13	1980	12	1997	4
										1998	36

Figure 9a. Frequency of Drought (1950-1960): Texas 05



Analytical comparisons between decadal periods of drought

To analyze if there are statistical differences between drought conditions during 1950's versus 1990's I did a simple comparison between the means values. Thus, considering that in the Rio Conchos watershed the rainy seasons correspond to the months of July, August and September, a mean three-monthly PDSI value was computed for every decadal period. After that I did a comparison between means using the one tail T-student probability function.

Figure 9b. Frequency of Drought (1900-2000): Texas 05

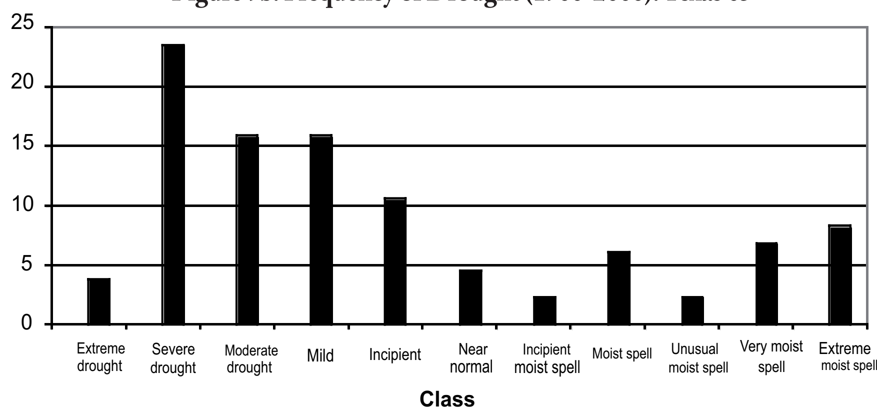


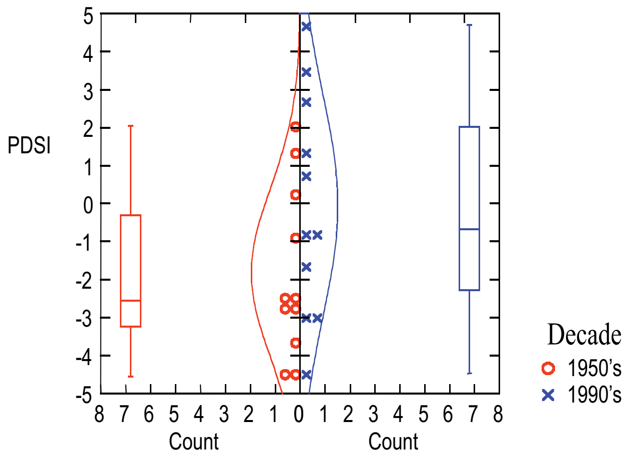
Table 5 exhibits the mean PDSI values computed with three summer months for the two decadal period. The mean PDSI values for the decadal period during fifties was computed in –1.824 versus the –0.055 mean PDSI value registered during 90's. Looking at the PDSI scale, the first value corresponds to Mild Drought conditions and the second corresponds to Near Normal conditions. Comparing these two decades throughout a paired test we have the following conclusions. Although the difference in means was equal to –1.769, we are unable to report a difference between means for the fifties and nineties periods (t=-1.411, p value= 0.189).

Table 5. Summer PDSI Values: Texas 05, Near Ojinaga

Year	July	August	September	Mean PDSI
1950	1.37	-0.48	-0.1	0.26
1951	-2.08	-2.52	-3.07	-2.55
1952	-1.65	-2.81	-3.41	-2.62
1953	-4.1	-4.5	-5.1	-4.56
1954	-3.23	-2.17	-3.09	-2.83
1955	-2.07	-2.3	-2.53	-2.30
1956	-3.94	-4.3	-4.78	-4.34
1957	-3.5	-3.49	-3.94	-3.64
1958	1.91	1.54	2.71	2.05
1959	-0.64	-0.62	-1.39	-0.88
1960	1.66	1.78	0.63	1.35
1990	1.69	2.72	3.7	2.70
1991	3.12	3.18	4.19	3.49
1992	7.63	7.09	-0.64	4.69
1993	-0.55	-0.55	-0.96	-0.68
1994	-2.35	-3.11	-3.31	-2.92
1995	-2.86	-3.35	-2.75	-2.98
1996	0.02	1	1.21	0.74
1997	-0.03	-0.26	-0.88	-0.39
1998	-3.03	-2.48	-3.31	-2.94
1999	-1.1	-1.63	-2.19	-1.64
2000	-3.83	-4.38	-5.22	-4.47

In a second analysis a Two-sample test was computed and as a result of the T test procedure we have two density plots as showed in Figure 10. On the far left and right sides of the density plot for each test variable. The middle portion of each graph shows the actual distribution of data points, with a normal curve for comparison. The standard deviation differs considerably (2.232 and 2.917). The box plot on the left is for the 1950's. In this case the peak of the curve are no very close from the median values (horizontal line). This indicates that this curve is asymmetrical. 1990's PDSI values show a higher standard deviation, but more symmetrical having higher variance than 1950's data.

Figure 10. PDSI density plots: Texas 05, near to Ojinaga



Testing decadal flow data against historical monthly averages

To know if the average monthly streamflow values are different from the average monthly historic means registered in every reservoir (Boquilla, Madero) and Ojinaga we made the following One-sample t test.

The mean monthly registered stream flow entering to La Boquilla reservoir is about 102.45m^3 considering the period from 1935 to 1998, with a maximum of 1,539 and a minimum of 0; the mean monthly stream flow registered in the streamflow entering into Madero dam was about 33.40m^3, with a maximum of 596 and a minimum of 0; finally, the mean monthly registered stream flow registered in the Ojinaga was about 70.38m^3, with a maximum of 1 285 5 and a minimum of 6.30m^3.

Testing data from the Boquilla dam during 50 and 90

During 50's we are able to say that the historical mean (102.45) does differ significantly from the mean value for this decadal period (72.857) ($t = -1.67$, p value= 0.126). Conversely during 90's there is not significant difference from the historical mean (102.45) against the mean value for this decadal period (114.554) ($t= 0.512$, p value= 0.620).

Testing data from the Madero dam during 50 and 90

During 50's we are able to say that the historical mean (33.40) does not differ significantly from the mean value for this decadal period (29.618) ($t = -0.706$, p value= 0.49). Same happen during 90's since there is not significant difference from the historical mean (33.41) against the mean value for this decadal period (28.125) ($t=-0.819$, p value= 0.432).

Testing data from the Ojinaga streamflow during 50 and 90

During 50's data were limited, so for this decade we are using data from 1955 to 1960. Assuming that this period represent the 50's we are able to say that the historical mean (70.38) does not differ significantly from the mean value for this five years period (72.648) ($t = 0.087$, p value= 0.934). Although in this case we have complete data same happen during 90's since there is not significant difference from the historical mean (70.38) against the mean value for this decadal period (70.653) ($t=0.012$, p value= 0.990).

Concluding remarks

Climatic drought is very characteristic of the middle and lower areas of the Rio Conchos Basin, which drainage area is inside the Chihuahuan desert region except for the upper basin located on the Sierra Madre Occidental. In this region, droughts had been historically reported since 1576 affecting seriously to the population and its economics activities —agriculture and livestock mainly. More recently severe and prolonged droughts had been registered in the Rio Conchos Basin especially during the 1930's, 1950's and 1990's. Evidence suggests that it is the last decade of drought that more had affected hydrological conditions lowering its surface runoff, and water stocks of main dams such as La Boquilla and Madero dams. As a consequence less water is reaching the Rio Grande near Ojinaga, causing problems to Mexico to provide unless the minimum flows allotted to the United States under the 1944 International Water Treaty between these two countries.

Now, Mexico has a significant water debt, which looks hard to pay if severe drought conditions persist.

In this work, drought was analyzed using two approaches. The first one includes the historical analyses of stream runoff measured before the entrances of the La Boquilla and Madero dams. The second analysis was focused in a statistical analysis of the Palmer Severity Drought Index (PDSI) measured in a Texas climatic station near to Ojinaga. Analysis indicates that one of the main characteristics of the stream runoff is its high variability, presenting the annual flow a coefficient of variation of about 60% for surface runoff entering the Boquilla and Madero dams. Thus, the high variability of the Rio Conchos flows are evident presenting great changes year to year revealing us periods with drought, floods and normal conditions. Special attention requires hydrological droughts during 50's and 90's.

Analyzing PDSI data we have that the most frequent condition of drought for Chihuahua near Ojinaga region is a state of incipient drought, followed by a mild drought condition. Results indicate that under extreme drought conditions we have the following years: 1935, 1953, 1957, 1997, and 2000. Severe drought conditions were present during 1951-1954, 1965, 1971, 1975, 1991, 1995-1996. The longer periods of drought were detected the following years: 1915, 1927, 1933, 1950-1951, 1961, 1992, and 1997.

In this research it was found that 1950's drought was more persistent than the 90's, although the severity index was similar. Thus, during 1950, initiate the longest period of drought totalizing 86 (7 years) dry months. Furthermore, 45 (≅ 4 years) consecutive dry months initiated in 1990. During the period from 1992 to 1998 we have a total of 89 (≅ 7.4 years) months having dry conditions. Significant differences were found between the 1950 and 1990's, having more extreme to moderate drought conditions during 50's. There is evidence that there are longer drought periods having more than five years with severe to extreme conditions. This is important to note because under these conditions it could be more difficult for Mexico to do one's duty regarding water agreements.

Testing data from the Boquilla dam, statistical analysis indicates that the average stream runoff values during 50's differ significantly from the historical mean. Conversely, during 90's there is not significant difference from the historical mean. For the Madero dam there were no significant differences between both decadal periods (50's and 90's) against the historical mean values.

References:

Climatic Prediction Center. "Weekly Palmer Drought and Crop Moisture Data Products Explanation". 2000 [Online] Available in http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/cdus/palmer_drougt.

Comisión Nacional del Agua (CNA). "Programa Hidráulico de Gran Visión del Estado de Chihuahua 1996-2020". Subdirección General de Programación, Gerencia Regional Norte, Gerencia Estatal de Chihuahua. 1997, Contrato: SGC-GRN-CHIH-96-82.

Fierro, L.C. "Relación de sequías en la antigua Nueva Vizcaya y en el actual estado de Chihuahua". 1999 [Online] Available in http://www.sequia.edu.mx/articulos/lcf-01.html.

IBWC. "Deliveries of Waters Allotted to the United States Under Article 4 of the United States-Mexico Water Treaty of 1944", Report of the United Sates Section, 2002.

IBWC. "Utilization of Waters Treaty of 1994. Treaty Between the United States of America and Mexico", 2002 Available in http://wwwibwc.state.gov [2/23/2002].

INEGI. "XII Censo General de Poblacion y Vivienda: Resultados Preliminares", 2000, [Online] Available: http://www.inegi.gob.mx/difusion/espanol/cpyv/indice.html.

Kelly, M.E. "The Rio Conchos: A preliminary Overview", Texas Center for Policy Studies, 2001.

Steila, D. "Drought in Arizona: A Drought Identification Methodology and Analysis", University of Arizona, Tucson, Arizona, 1972.

The National Commission for the Knowledge and Use of Biodiversity (CONABIO), "Cuenca Alta del Río Conchos y Río Florido". 2001, [Online] Available: http://www.conabio.gob.mx.

USDOI. "Water-Resources in the Rio Grande-Rio Conchos to Amistad Reservoir Subarea". Field Coordinating Committee, Fact Sheet 3, April 1988.