# Water resources management under drought conditions

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## Abstract

The semi-arid/arid US Southwest and Northwestern Mexico are experiencing severe droughts while at the same time having significant increases in their water demands. This paper evaluates the demand and the efforts to manage water resources under drought conditions. Innovative water resources management techniques need to be implemented to address this scarcity which is aggravated under drought conditions. This paper also presents an application of a new drought index (Gonzalez and Valdes, 2006ab) in characterizing the spatial and temporal variability of droughts and its use in water resources management, particularly multi-reservoirs.
*Keywords: droughts, semi-arid regions, water resources management, US Southwest, Northern Mexico.*

## 1 Introduction

Water managers in the Southwestern U.S. face a number of daunting problems. On the water demand side, population growth in Southwest states is the fastest in the nation. Arizona and Nevada, the two most arid states, have been experiencing annual growth rates of 4% and 5.5%, respectively. Changing socio-

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demographics, such as decreasing household size, exurbs, and second homes, are increasing per-capita consumptive demand and exacerbating peak seasonal demand.

Weather and climate trends pose another set of challenges. Urban heat island effects in large Southwestern cities mean warmer nights and longer growing seasons for landscape plants. This extends the irrigation season. Climate fluctuations, such as the eight-year drought impacting parts of the Southwest, have directly killed large areas of forests, and created ideal conditions for beetle infestations and wild fires, eradicating additional forested areas. These abrupt, large-scale land cover changes fundamentally alter the partitioning of precipitation between infiltration and runoff. While the long-term impacts of climate change are still uncertain, there is a growing consensus that earlier snow melt will effectively reduce the amount of water that can be stored in the spring in reservoirs for use in summer and fall.

Other economic, legal, and political realities are creating pressures to shift over-allocated supplies among existing and new water demands. These include greater interest in water-based recreation, endangered species protection, settling American Indian water rights claims, and meeting the needs of a resurgent copper mining industry.

The US Southwest and Northern Mexico are populated semi-arid regions that suffer the effects of long droughts with the consequent stress over their water resources. The significant temporal and spatial variability of water resources and related droughts have also a significant impact on water resources availability and management. Integrating this uncertainty into planning and decision-making is a key issue, both for operation optimization and risk management strategies. In this paper a new indicator of drought exceptionality, the Drought Frequency Index (DFI, González and Valdés, [4]) is used in the management of a complex system of reservoirs in the semi-arid Lower Rio Grande/Rio Bravo basin. The approach is compared to alternative operating policies developed, as part of a Decision Support System (DSS) by Gastelum et al. [1].

# 2 The Conchos River Basin System

## 2.1 The Conchos River Basin (Mexico)

The Conchos basin is one of six Mexican tributaries to the international Lower Rio Grande/Rio Bravo (LRGRB) basin. It has an area of 64,000 km$^2$, which represents 14% of the surface area of the LRGRB. The entire basin is shown in Figure 1.

Agriculture in the Conchos Basin accounts for 72% (2,536 Hm$^3$/yr) of the total water demand. The water demands come from three Irrigation Districts (IDs), (ID005 Delicias, ID090 Rio Florido and ID103 Bajo Conchos), and several Irrigation Units (IUs) located along the river with a potential irrigated area of 108,562 and 14,509 Ha, respectively.

Low water distribution efficiencies are one or the more significant problems of the IDs (~40%) and the IUs (~48%). Commercial, energy and mining water requirements are 22% and domestic consumption is approximately 6%. The cities of Hidalgo del Parral and Delicias account for 87% of the total population. Runoff from the Conchos is controlled through a series of seven reservoirs (Table 1), with a combined storage capacity of 3,943 $Hm^3$, most of which is provided by the 2,903 $Hm^3$ capacity of La Boquilla reservoir. The reservoirs are conjunctively managed to provide irrigation, hydropower and flood control.


Figure 1: Lower Rio Grande/Rio Bravo [12].

Table 1: Reservoir characteristics Conchos Basin.

| River | Reservoir | Storage Capacity $Hm^3$ (MAF) | Uses |
|---|---|---|---|
| Florido | San Gabriel | 255 (0.21) | Irrigation District 103 flood control |
| Florido | Pico de Águila | 50 (0.045) | |
| Conchos | La Boquilla | 2903 (2.34) | Irrigation District 005 and Hydropower |
| Conchos | La Colina | 24 (0.195) | |
| San Pedro | F. Madero | 348 (0.28) | |
| Chuviscar | Chihuahua | 26 (0.021) | Municipal, Irrigation, flood control |
| Conchos | Luis L. Leon | 337 (0.29) | Irrigation District 090, flood control |

## 2.2 The 1944 International Water Treaty

In response to the rapid development of the RGRB region in Mexico and the U.S. State of Texas during the early part of the 20th century; to the differing institutional structures in the two nations and to the frequent conflicts over water due to variability of runoff, an international water treaty was negotiated in 1944 between Mexico and the United States which divided the waters of the RGRB system flowing between Fort Quitman, Texas and the Gulf of Mexico based on shares of runoff of the rivers.

The Treaty was designed to ensure that each nation had access to adequate water in drought years. The Treaty divides the waters of the RGRB equally while simultaneously requires Mexico to deliver an average of 431 $Hm^3$ per year over a 5-year period (TCPS [10]). One provision of the treaty allows Mexico to deliver less than 431 $Hm^3$ per year in cases of "extraordinary drought" as long as the deficit is made up in the following 5-year cycle. What constitutes "extraordinary," however, is not explicitly defined in the treaty. Interests on the U.S. side have interpreted it to mean that flow from Mexican tributaries must cease entirely for an extraordinary drought to have occurred (TCPS [10]).

Based on the absence of an accurate definition of "extraordinary drought," the DFI index was used to develop an operating policy for the reservoirs that takes into account the spatial and temporal characteristics of drought in the LRGRB.

# 3 Methodology

## 3.1 Drought areal-intensity-frequency characterization

Although the estimation of drought severity at a point gives generally useful information for water management, a more regional indicator usually is required 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, [9]) and it is important to address the "extraordinary drought" concept of the 1944 treaty.

One approach to assessing the regional status of a drought is the drought severity-area-frequency curve, which was originally proposed by Henriques and Santos [5] and expanded by Kim et al [6]. This approach regionalized the Palmer Drought Severity Index (PDSI), using geostatistical techniques and applying extreme value analysis to the regional values. The drought intensity (DI) is calculated multiplying the cumulative PDSI in a dry spell by the probability of drought occurrence (Figure 2) for each year. In this way, each drought event is allotted evenly for a particular year (Figure 3).

The drought intensity-areal extent-frequency curve provides useful information which contains drought intensity and area subjected to drought for a given drought return period (Figure 4).

The study by Kim et al. [6], suggests that the Conchos River basin has experienced severe droughts in the last 60 years. Particularly it suffered an extreme drought in the 1990s based on the PDSI indicator. Using the drought intensity-areal extent-frequency curve, shown in Figure 3, the drought in the basin based on the intensity of the return period may be examined. Note that the drought intensity means time average of drought severity in dry spell and represent the drought severity classified by Palmer, which is indicated by a gray scale between 0 and -6. Finally, in Figure 4, the historical droughts are compared with the drought intensity-areal extent-frequency curve, which was constructed using the recorded data.

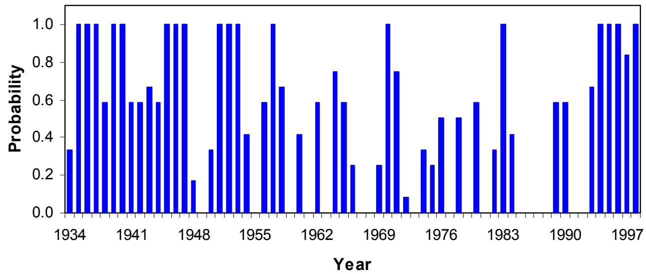
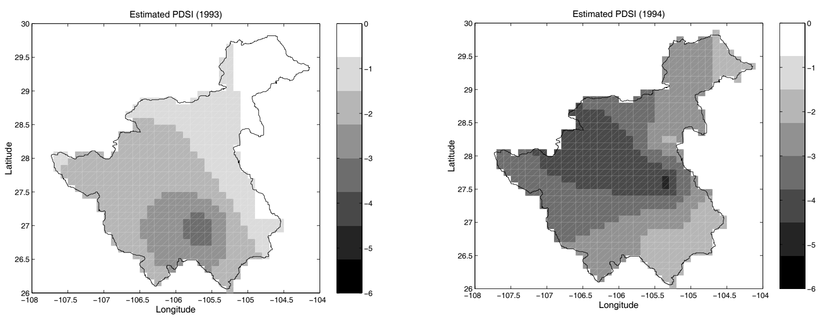



Figure 2: Annual probability of drought occurrence in the Conchos Basin (1934-1998) (from Kim et al, [6]).




(a) (b)

Figure 3: Areal distribution of drought intensity for historical droughts in the Conchos Basin (a) 1993 (b) 1994 (from Kim et al, [6]).

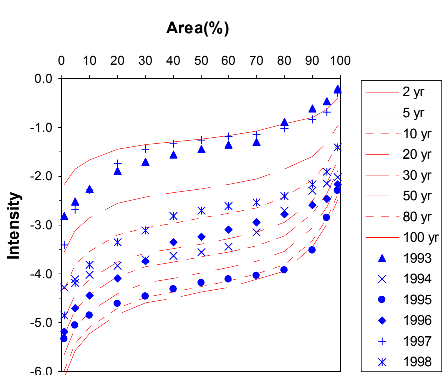



Figure 4: Drought Intensity-Areal Extent-Frequency Curve for the Conchos River basin for the historical droughts occurring in the 1990s (from Kim et al, [6]).

From this analysis, the droughts that occurred in 1993 and 1997 have an associated return period of 2-5 years; however, the droughts that occurred in 1994, 1996, and 1998 have an associated return period of 10-30 years. The drought that occurred in 1995 is the most severe drought the basin has ever experienced in the period of record. The data from after 1990 were not used to construct the drought intensity-areal extent-frequency curve, and the 1990's drought has a higher return period of more than 80 years. The drought intensity is close to a return period of 100 years with an increase in areal extent. In addition to the high return period, considering the lack of the data period, it is the most extreme drought in that more than 70% of the basin experienced a PDSI below –4 (extreme drought condition). Exploding water demands in the basin, as in most of the northern Mexico has contributed to 1990s droughts having severe impacts.

### 3.2 The Drought Frequency Index (DFI)

The PDSI and the Standardized Precipitation Index (McKee et al., [8]) are frequently used drought indicators, but they have some limitations. González and Valdés [3,4] presented an approach for the stochastic characterization of extreme hydrologic droughts according to their random nature. The approach is based on the characterization of random variable extreme persistent deviations, referred to as the variable's normal variation regime. The characterization is quantified in terms of the mean frequency of recurrence, providing the basis of a new drought index: the Drought Frequency Index (DFI).

The DFI index allows analyzing and evaluating droughts over any random hydro-climatic variable affected by droughts. To complement the approach, a methodology is proposed to analyze the spatial-temporal progress of a drought over a region by generating DFI maps and characterizing droughts from a stochastic point of view, based on their extraordinary persistence and areal extent. In the computation, the DFI algorithm searches and analyzes, for every time step, the period at this step which is the most extreme from the point of view of persistent lower deviation of the random variable. Each of these periods is characterized in term of its mean frequency of recurrence and this value is associated to the corresponding time step. The scale provided by the DFI is general, universal, and attend to the random nature of the phenomenon. Each application may use the DFI scale to define drought state, setting the threshold frequency according to its vulnerability, which will allow homogenizing drought definitions on a single scale.

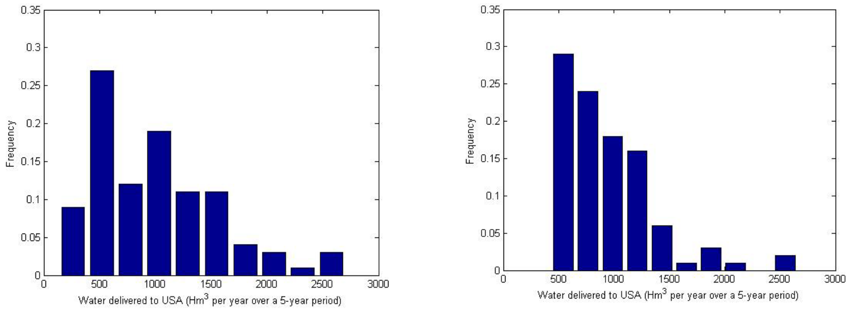
### 3.3 Operation of multi-reservoir system under drought conditions

A comprehensive review of the most recent application on the use of optimization techniques for reservoir operation is presented in Labadie [7]. Labadie acknowledges that a wide gap exists between operations research in academic or scientific communities and its real-world implementation in existing reservoir systems operations, where more simple and intuitive rules are preferred.

In this section the operation of the multi-reservoir system in the Conchos basin is operated under two alternative operating policies. One uses a linear optimization procedure that tries to minimize long-term deficits without using an explicit definition of drought. The second, an extension of the approach proposed by Gonzalez [2], utilizes the DFI as a criterion for determining releases in a given period. Both models were also compared with the preliminary results of the DSS developed by Gastelum et al. [1] that are described in Stewart et al. (2004). In both optimization models there was a priority in meeting the international treaty obligations during a 5-year cycle. However, the DFI-based operating policy considered the case of an "extraordinary drought" to postpone deliveries in a 5-year cycle to be met in the next 5-year cycle.

The DFI-based operation model has a two-step optimization. First a linear optimization is used to determine an approximate operating policy, which is then used to derive the operating policy utilizing the DFI indicator. For the particular case of the Conchos basin the definition of "extraordinary drought" was for a DFI value of 70 years return period. Below a DFI value of 70 years the deficits are significantly lower. As discussed in Gonzalez [2] using the DFI to define operating policies for multiple reservoirs is more attractive when the demand is more resilient to deficits, i.e., irrigation vs. municipal water supply.

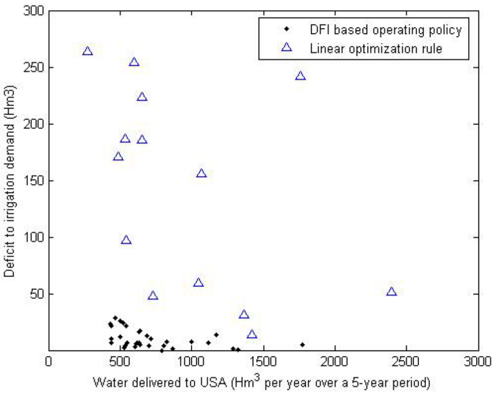
The results were computed at the main irrigation districts (Rio Florido, Delicias and Bajo Conchos). Figure 5 shows the histograms of water deliveries to the US from both optimization models. Although similar, the DFI optimization performs better than the linear optimization rule in terms of the minimum requirements for deliveries to the US. Figure 5b shows that the DFI-based model is able to deliver the US requirements every 5-year period as required in the treaty while at the same time decreasing the number of uncontrolled releases in the system.




(a) linear optimization (b) DFI-based optimization

Figure 5: Histogram of water deliveries to US for both optimization models.

Figure 6 compares the cumulative deficits in the irrigation districts demands for 5-year periods with the releases to the US for the same periods. This figure shows that the DFI-based operating policy is able to significantly reduce the magnitude of irrigation demand deficits for all districts, e.g., no irrigation deficit in the DFI-based operating policy is above 50 $Hm^3$/yr, significantly less than the deficits in the linear optimization policy. In contrast, the number of 5-year periods that experience some deficit with the DFI-based operating policy doubles that of the linear optimization.




| | Optimization model | |
|---|---|---|
| | DFI | Linear |
| 5-year periods with deficit (%) | 34 | 14 |
| Mean deficit ($Hm^3$) | 1.05 | 142 |
| Std dev deficit. ($Hm^3$) | 0.8 | 89 |

Figure 6: Comparison of deficits to irrigation demands vs. supplies to the US.

## 4 Final comments

This paper describes a criterion to characterize droughts and its potential use in the management of complex water resource systems. The characterization acknowledges the multiple dimensions that define the severity of a drought (intensity, duration, and areal extent) while at the same time expressing them in a concept easier for water resources managers to understand, i.e., the return period. The temporal and spatial characteristics of a drought are represented by several criteria, e.g. areal-intensity-frequency curves and spatial DFIs. The non-parametric evaluation of the bivariate characteristics of droughts offers more flexibility than the more frequently used extreme value distributions. The use of the DFI as a criterion for the operation policy of reservoirs in the Conchos Basin proves to be advantageous over conventional optimization rules, promising reliable applications to similar single-purpose reservoir systems.

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