Historical land-use changes and hydrological behavior of important watersheds in Mexico

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Abstract

Management of water resources requires understanding components of the hydrological cycle and the historical influence of natural and human-induced variability. Analysis of the hydrological behavior of watersheds in Mexico has been carried out using instrumental records, GIS of land-use change and paleoclimatic data. In the Nazas River basin, El Niño events result in great interannual variability of precipitation over the last 800 years. Changing land uses in the upper Nazas watershed have increased runoff and erosion problems. The Santiago-Lerma basin is the most populated in Mexico and instrumental and reconstructed records indicate decreasing water levels. Increased water demand is extracting groundwater over 9,000 years old. Water demand in these and other basins will continue to rise whilst simulation models indicate declines in water availability. The integration of knowledge of climate variability, hydrological impact of land use changes and water demand will be essential for water managers to address these issues.

Keywords: Paleoclimate, ENSO, Ancient water

Introduction

Water quality and availability is an important issue in central and northern Mexico where a growing population demands increasing water volumes for different uses but climate prediction models indicate an increase in aridity in the southwestern United Sates and northern Mexico with a direct reduction in precipitation (Seager et al., 2007, 2009). The natural availability of water in Mexico fluctuates across a latitudinal gradient. In the northern region (23.5° to 32.5°N) annual precipitation ranges from 200 to 800 mm/yr and restricts the practice of rainfed agriculture particularly in areas with precipitation below 500 mm where crop production has to rely on irrigation from surface or groundwater sources. The building of reservoirs to store runoff has produced important ecological impacts downstream of the dams and the use of groundwater exceeds recharge and also affects water quality, increasing the presence of heavy metals, particularly arsenic, that have negative effects on human health (Armienta and Segovia, 2008). At the present time several wells in the lower Nazas watershed have elevated arsenic concentrations that surpass the safety values for human consumption. In the central region (19° to 23.5° N) annual precipitation ranges from 500 to 1000 mm and both rainfed and irrigated agriculture are common. Over 50% of the Mexican population (>55 millions) live in this region and water demand for agriculture, industrial and human consumption is increasing year by year, impacting the aquifers and polluting most water sources such as Rio Lerma-Santigo and other important streams (Comisión Nacional del Agua, 2006). The southern region (15^o to 19^oN) is the wettest of the three with annual precipitation between 1000 to 3000 mm and a greater portion of the agriculture is rainfed. However, land use change from deciduous or tropical forest to grassland or agriculture land has diminished biodiversity, increased soil erosion in areas of higher relief and generally affected the hydrological cycle (Instituto Nacional de Ecología, 2003).

The main objective of this study was to analyze the impact of land-use changes on watersheds located in northern, central and southern Mexico, to determine the influence of land use change on the hydrological balance and to define the different uses of surface runoff and groundwater sources. A second objective was to determine historical hydroclimatic variability and the impacts of atmospheric circulation patterns, in particular the El Niño Southern Oscillation (ENSO) on hydrologic variability.

Methods

Representative watersheds in northern, central, and southern Mexico were selected (Figure 1) and land use data digitized using geographical information systems for 1970 and 2007 to determine the impact of land-use changes on surface runoff, aquifer recharge, the hydrological balance between recharge and withdrawls, and use of each water source for different productive activities. The age of the groundwater was determined by isotopic techniques with carbon 13 (δ^{13}C) for each aquifer to determine whether the water had been recently

recharged or was ancient (fossil). The age of the water constitutes a good indicator of the management processes employed on a particular aquifer. Thus, the presence of young water in the aquifer indicates recent recharge and probably good management of the aquifer with a positive balance between recharge and withdrawl. On the other hand, the presence of ancient water indicates overexploitation of the aquifer, decreases in the ground water table and potential problems of water quality for human consumption and agricultural uses due increased concentrations of heavy metals, saline intrusion and soil subsidence.
To analyze hydroclimate variability and the influence of atmospheric circulatory patterns, a network of climate sensitive tree-ring chronologies was developed for each selected watershed. Principal Component Analysis was used to produce regional chronologies with a common tree-ring signal in order to analyze historical hydroclimatic variability and to compare with instrumental climatic and streamflow variables.
Seasonal precipitation, streamflow and annual recovery of the Chapala Lake level (20.1^{o} to 20.35^{o}N, 102.7 to 103.43^{o} WG) were reconstructed and compared to the ENSO indices for region 3.4. The relationship between these variables was determined by correlation analysis and the frequency and intensity by power spectral procedures (Wavelet analysis).

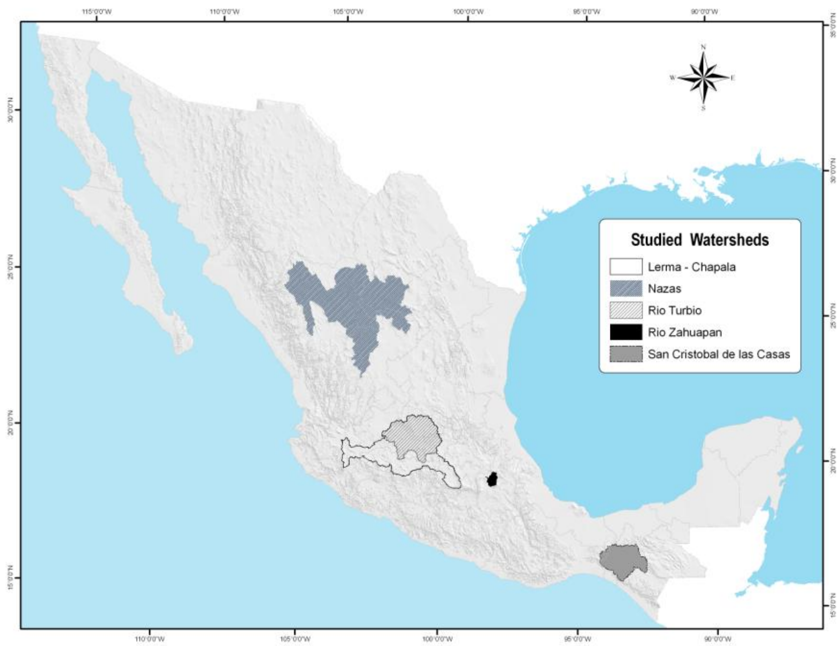

Figure 1. Geographical location of the watersheds studied in northern, central and southern Mexico.

Findings and discussion

The Rio Nazas watershed in the Sierra Madre Occidental of Northern Mexico is located at 24^{o} to 26.6^{o}N and 101.6^{o} to 106.3^{o} W. The area of this watershed is over 57,000 km^2. Most of the runoff is produced by the upper watershed in the Sierra Madre Occidental which has 600 to 800 mm precipitation per year (Estrada et al., 1993). All of the runoff from the upper watershed drains toward the Chihuahua desert highlands and is stored in two main reservoirs, the “Lazaro Cardenas” dam (capacity 4,000 Mm^3 (millions of cubic meters) and the “Francisco Zarco” dam (capacity 400 Mm^3) From the total volume an average of 850 Mm^3 are used to grow forage and other crops in an irrigated area of ca.70000 ha. Authorized ground water withdrawls from the main aquifer in the lower portion of the Nazas watershed are 577.8 Mm^3 per year. Of this water 424.1 Mm^3 (73.5%) is for agricultural use, 117.9 Mm^3 (20.4%) for urban use, 9.92 Mm^3 (1.7%) for industrial use, 6.58 Mm^3 (1.1%) for livestock use, and 19.3 Mm^3 (3.3%) for other uses. In practice, the authorized volume has been exceeded in the last 50 years and the estimated withdrawl volumes are at least 900 Mm^3, producing a deficit of 400 Mm^3 between withdrawl and recharge causing a drop in the water table of 1.5 to 3.0 m year^{-1} (Loyer et al., 1993). The current depth of the water table is 100 to 300 m affecting water quality and increasing arsenic concentrations from the bedrock in the area (Armienta and Segovia, 2008). The age of the groundwater ranges from 1,500 to 22,000 years indicating that ancient water is being used for agricultural activities. The problems affecting this region include hydrological modification of the main stream due to dam construction, deforestation of the upper Nazas watershed by logging and land use change (25% of the forest was lost between 1970 to 2002), overuse of water resources and forecasts of future reduction in precipitation attributed to climate change (Seager et al., 2009). Therefore, better planning of water resources has to be implemented to support a growing population which currently is over 1.6 million people in this region.

In central Mexico two watersheds belonging to the Rio Lerma-Santiago basin were analyzed. The "Rio Turbio" watershed (21^{o}N) contains the Leon, Guanajuato city with a population close to two million people. The volume of surface runoff yield from the upper watershed is not sufficient to fulfill the demand for agriculture and industrial use (INEGI, 1998). Urban demand is around 50 Mm^3 per year but the runoff satisfies only 10% of this volume, the remaining 90% is provided by groundwater. In addition, deep groundwater is used for irrigation and the depletion of the aquifer is a serious problem. In this watershed the deficit between recharge and withdraw was 129 Mm^3 in 1992 and had increased to 147 Mm^3 in 2009. The age of the mined water is nearly 9,000 years old indicating the use of fossil water. Based on this information water management planners from local governments are considering building a new reservoir in the State of Jalisco with a storage capacity of 500 Mm^3 to satisfy the current and future water demands of settlements in Guadalajara and other cities in the State of Jalisco and Leon in the state of Guanajuato.

The second site is the Lerma-Chapala basin draining toward the Chapala Lake.This basin has suffered serious hydrological alteration due to land-use changes affecting the annual recovery of the lake. Examination of the historical fluctuations of lake levels was derived from a network of cypress (*Taxodium mucronatum* Ten.) tree-ring chronologies from thriving trees growing along the main tributaries draining to the lake. The tree-ring series were analyzed by Principal Component Analysis and a 547 year long (1462-2008) regional ring-width chronology was developed. Correlation analysis indicated that this regional chronology and lake levels (lagged one year) were significantly related and a regression model was developed for reconstruction purposes. The reconstructed levels showed high inter-annual and multiannual variability associated with intensive ENSO events- however, aggressive land-use changes may have masked the influence of this phenomenon on lake levels in the last decades. Low levels of the lake were associated to intensive droughts reconstructed for the periods 1508-1560, 1581-1608, 1685-1725, 1770-1840, 1916-1924, and 1988-2000. On the other hand, pluvials took place in the periods 1561-1578, 1610-1616, 1760-1769, 1842-1850, 1863-1893, and 1926-1963. From 1960 to the present the annual variability of lake level fluctuations has decreased due to increased human pressure on available water resources (Figure 2). The historical understanding of the recovery of the lake levels is important to promote actions toward a better use of water resources and for conservation of riparian ecosystems that depend on the water yielded in the Lerma-Chapala basin.

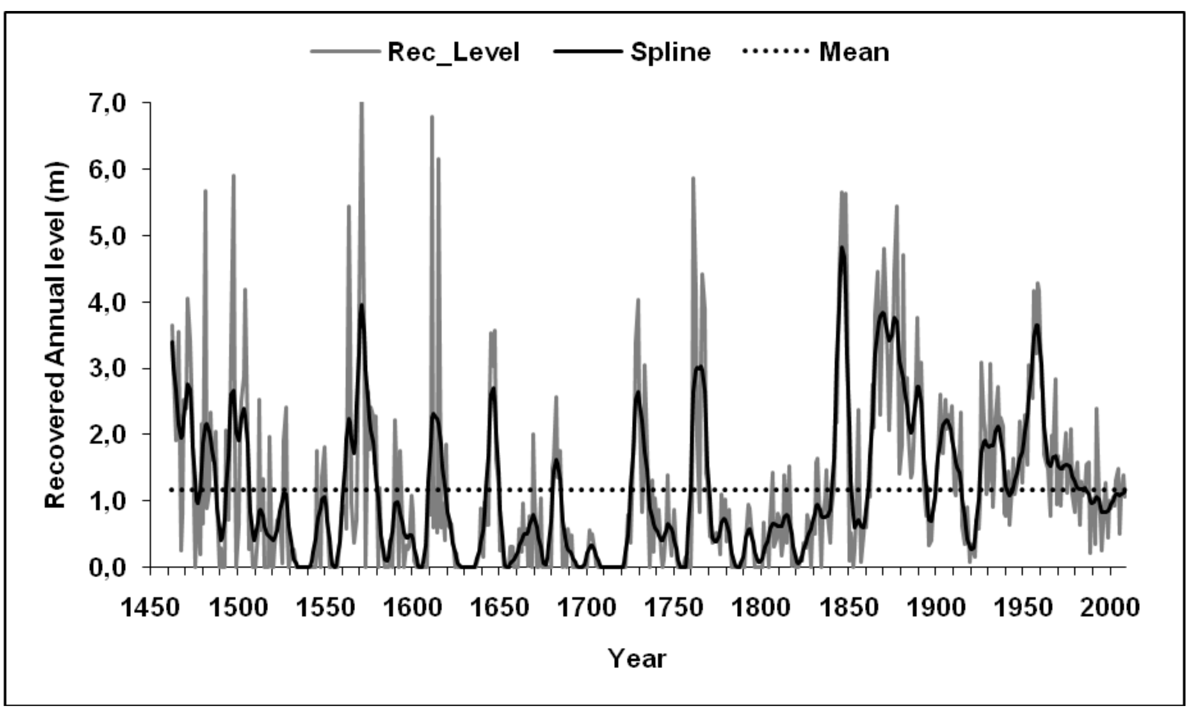

Figure 2. Reconstructed levels of the Chapala Lake for the last 550 years. Note the decrease in the lake level variability for the last 30 to 40 years attributed to overuse of water resources.

The "Rio Zahuapan" watershed (19.2^{o} to 19.7^{o}N) in the State of Tlaxcala has a population of 1.1 million. Most of the agriculture for growing barley and corn is rainfed and irrigation water is focused to vegetable production and some water is used for industrial purposes. This watershed does not have a water deficit, as the age of the groundwater is dominantly young (< 50 years) though there is some ancient water (5,800 years old) from specific wells. However the main problem in this watershed is land-use change due to deforestation to expand agricultural land. The soils are of volcanic origin and easily eroded (INEGI, 1986). The rate of soil erosion is greatest in the upper watershed, decreasing water quality of the tributaries and other water sources. An additional problem is the pollution of the streams due to the lack of treatment of industrial and urban water. Much of this polluted water is reused for growing maize, beans, and vegetables that are later sold at the local markets producing health problems in the population.

In southern Mexico the San Cristobal de las Casas watershed (16.7^o to 16.8^o N) is located in the state of Chiapas. Precipitation in this watershed ranges from 1,200 to 3,000 mm per year and surface runoff considerably exceeds the water demand of a growing population of 250,000 inhabitants. However, the major problem here is the distribution of drinking water and drainage services to a sparse population living in small settlements spread over broken terrain all over the watershed. The lack of treatment of residual water increases mortality, mostly of the infant population. Deforestation and a traditional agriculture that plants crops on steep slopes increases soil erosion, depletes fertility and decreases water quality of downstream water bodies.

Atmospheric Circulatory Patterns

The hydroclimatic variability in northern and central Mexico is highly influenced by the El Niño Southern Oscillation. The relationship between ENSO and cool season precipitation in northern Mexico has been well documented (Ropelewski and Harper, 1989; Stahle et al., 1998; Cleaveland et al., 2003; Villanueva et al., 2009). For the upper Nazas watershed a precipitation reconstruction indicated a strong association between the ENSO indices for region 3.4 and the winter-spring precipitation (January-June) for the period 1895-2008 (Villanueva et al., 2005). Dry events were associated to the cool phase (La Niña) of ENSO, whereas wet periods are associated with the warm phase (El Niño). Some of the most intensive droughts took place in the periods 1954-1956, 1974-1975, 1988-1999 and wet events related to El Niño took place in 1968, 1973, 1977, 1981, 1987, 1992, and 1997 (Figure 3).

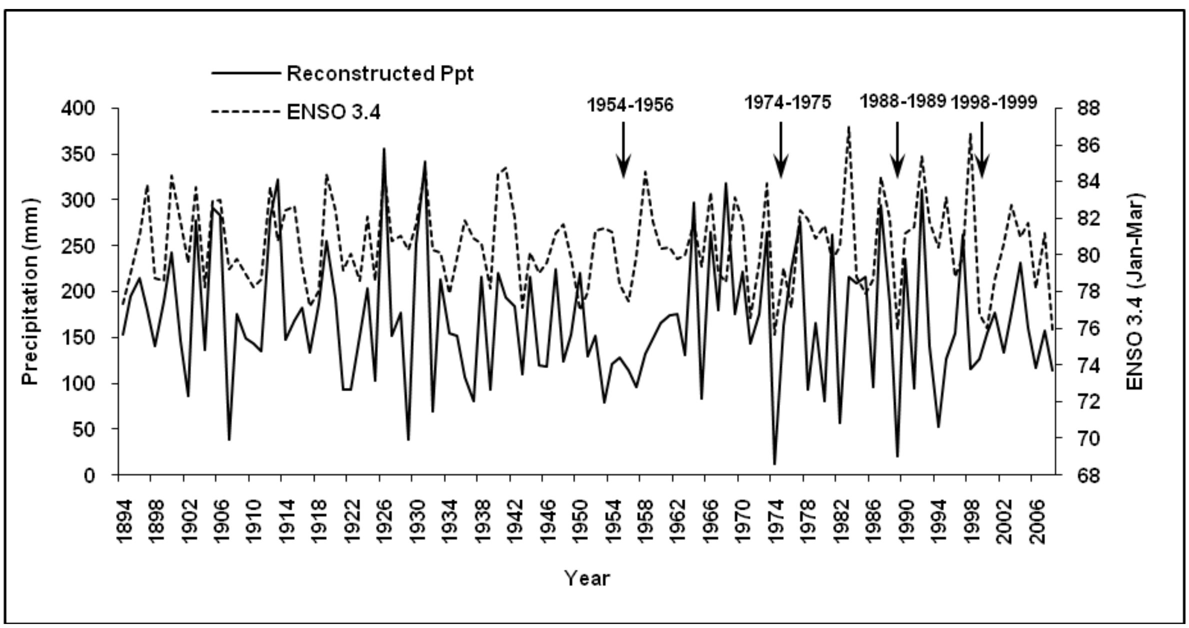

Figure 3. Reconstructed periods of low precipitation for the upper part of the Nazas watershed and its association to La Niña years.

A wavelet analysis between the reconstructed precipitation (available for the last 800 years) and the ENSO indices for region 3.4 indicated significant coherences between both variables in a range of 1 to 14 years for the period 1900-1950, and 1 to 8 years from 1986 to 2000 (Figure 4). The results suggest that ENSO has a strong signal and determines a high proportion of the interannual hydroclimatic variability observed in this region. The impact of hydroclimate variability in the Nazas watershed has a direct effect on the irrigated area that can be used which depends on the water stored in the dams from flow in the year prior to the growing season (Villanueva et al., 2005). Thus, the drought years 1993-94 and 1995-96 produced a drop in the stored water in reservoirs and area irrigated was reduced by more than 50%.

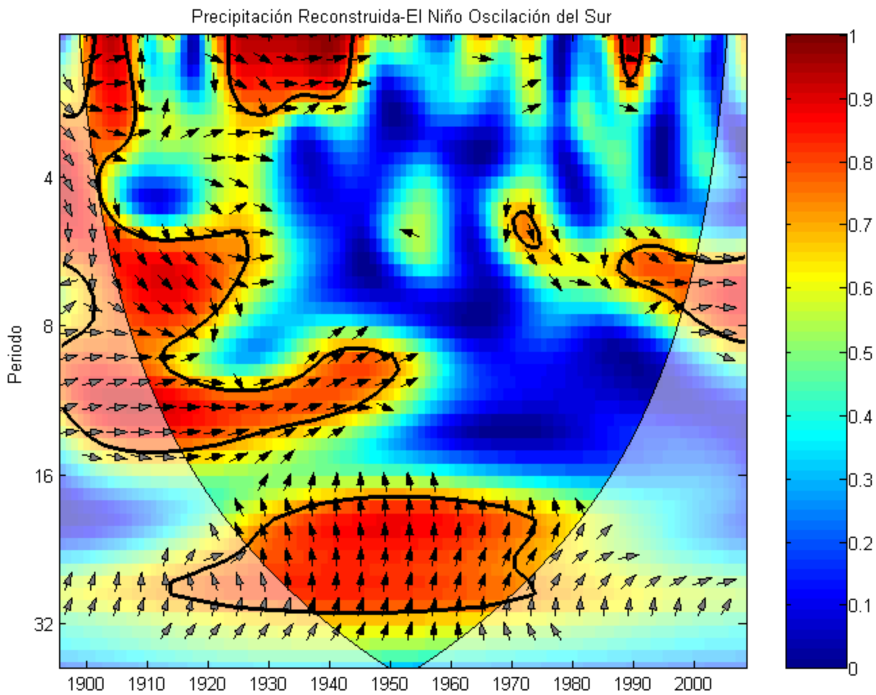

Figure 4. Wavelet analysis between the reconstructed precipitation for the upper Nazas watershed and the cold season winter ENSO indices from region 3.4. The red area represents significant periods ($p<0.05$) and the black color line of the oval figure refers to the confidence limit.

In the central Mexican watersheds a regional cypress tree-ring chronology for the central-southern part of Guanajuato state was compared with the seasonal October-April Tropical Rainfall Index (TRI) which is an estimate for ENSO (Wright, 1979), A wavelet analysis produced significant frequencies at 4 to 8 years (ENSO signal) for the periods 1905-1922 and 1942-1965 (Figure 5). The relationship is supported by an increase in winter-spring precipitation during la Niña years (Magaña et al., 1999), However, the relationship between TRI and high cool season precipitation is not significant for other time periods. This information is confirmed by comparison between the years with reduced crop yields from rainfed crops and ENSO years (El Niño, La Niña) for the period 1980-2005. In the El Niño years such as 1982, 1987, 1992, and 2005 the reduction in crop yield was almost 50%, but in La Niña years (1989, 1996, 1999, and 2000) that usually show normal or higher precipitation in central Mexico, the reduction in crop yield was similar or greater than those from the El Niño years. Crop failure occurred even in those years which would be considered normal (Secretaria de Desarrollo Agropecuario, 2006). This information confirms the poor relationship existing between ENSO and crop yield in central Mexico suggesting that other climatic phenomena such as the North America Monsoon System, tropical storms, and hurricanes may have a greater impact in determining the hydroclimatic variability of this region (Therrell et al., 2002).

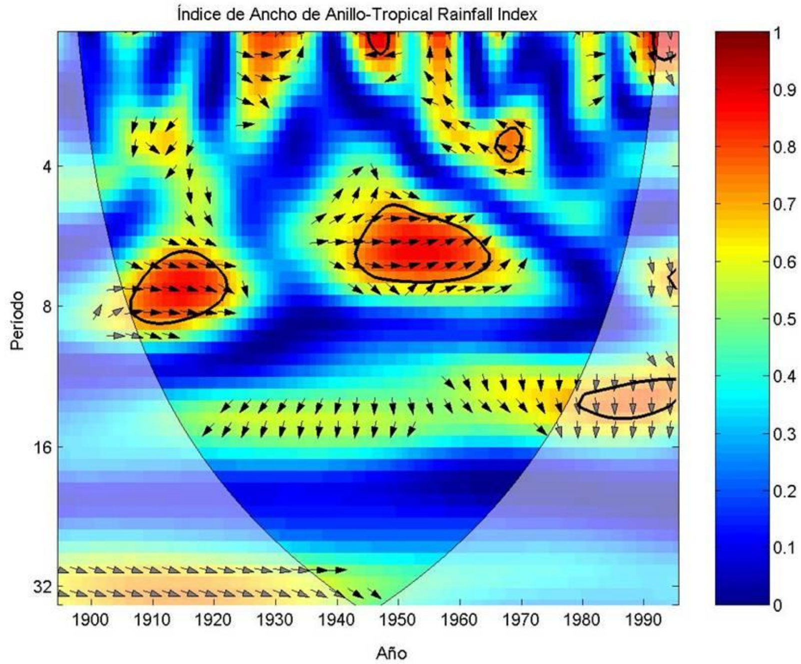

Figure 5. Wavelet analysis between a regional cypress ring width chronology for central-southern Guanajuato region and the TRI. Significant episodes (red areas) were only found at frequencies of 4 to 8 years for the periods 1905-1922 and 1942-1965.

The effect of ENSO on the hydroclimatic variability of the Zahuapan watershed in the state of Tlaxcala was analyzed by comparing a regional precipitation reconstruction and TRI. The influence of ENSO in this part of the country was not as intense as that observed for the northern region, however intensive El Niño events recorded in the periods 1970-74, 1988-89 and 1998-1999 produced below normal precipitation, similarly, La Niña events recorded in 1958, 1968, 1976, 1982, 1986, 1997, and 2000 increased precipitation (Figure 6).

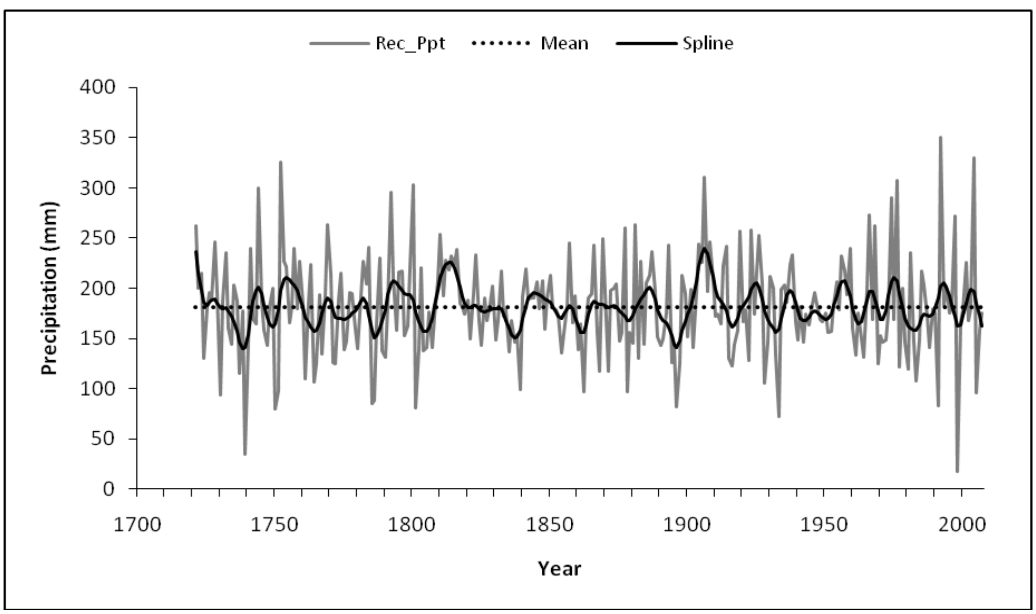

Figure 6. Reconstructed January-June precipitation for northeastern Tlaxcala. Note the severe drought recorded in year 1998-99 related to an intensive ENSO event.

The impact on ENSO in the southern region watershed (San Cristobal de las Casas, Chiapas) was significant, particularly for the most intense El Niño events. Power Spectral Analysis between a ring width chronology of cypress for Tuxtla Gutierrez, Chiapas, detected significant frequencies ($p < 0.05$) at 1 to 4 (1790 – 1800), 1 to 9 (1705 – 1730), and 30 to 50 years (1730 – 1890) (Figure 7). The 1 to 9 year frequency corresponds to the ENSO signal and 30 to 50 year frequency is more related to the Pacific Decadal Oscillation (PDO) signal. Given the great hydroclimatic variability that characterizes the southern region of Mexico and the importance of water to produce electricity, irrigation, and other uses a more complete network of tree-ring chronologies is urgently needed in order to analyze in more detail the ENSO signal and other circulatory patterns.

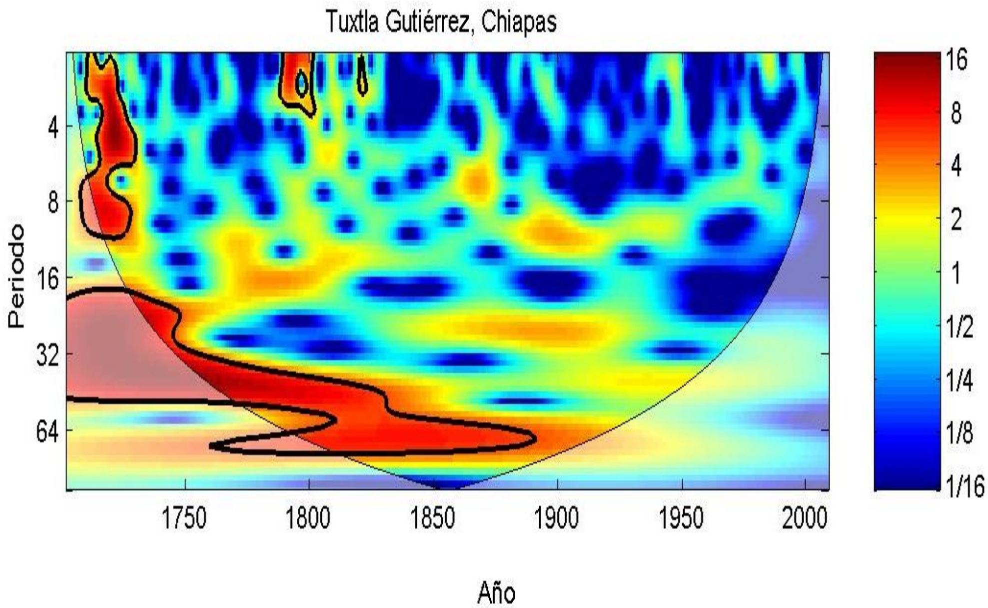

Figure 7. Wavelet analysis between a cypress ring-width chronology for Tuxtla Gutierrez, Chiapas and ENSO indices. Significant episodes (red areas) were found at frequencies of 1 to 4 years (1790-1800), 1 to 9 years (1705-1730) and 30 to 50 years (1730-1890).

Conclusion

Water availability in Mexico is related to a north-south latitudinal gradient. Land-use changes have impacted the hydrological cycle by decreasing available water volumes and decreasing water quality. The aquifer of the Nazas watershed has been overexploited in the last 50 years and fossil water is now being used that is 1,500 to 22,000 years old. This situation has produced a water deficit and changes in water quality with increases in heavy metal concentration, particularly arsenic and consequent effects on human health. Most of the streamflow of this watershed is derived from the upper watershed and is collected behind two dams. The volume of water available for release to agriculture activities during the growing season is highly dependent on natural variability and is strongly influenced by ENSO. Human activities have also had a significant effect on water availability and, given that climate change models predict an increase in aridity, future water shortages may become serious. Central Mexican watersheds have been significantly impacted by deforestation and other human uses. ENSO influence is less significant in this part of the country but intense ENSO events have been recognized in dendroclimatic reconstructions of precipitation and streamflow. The Rio Turbio watershed has severe problems of aquifer overuse, confirmed by the age of fossil water (>9,000 years old) now being used. On the other hand, the Zahuapan watershed in the state of Tlaxcala has a positive hydrological balance but pollution of main water sources is one of the main problems. The Lerma-Chapala basin draining toward the Chapala Lake is one of the most disturbed hydrological regions in the country. The high hydroclimatic variability and lake level fluctuations prior to the 1970´s was influenced by extreme ENSO events. However this variability has diminished in the last 30 to 40 years as consequence the withdrawl of streamflows for agriculture, industrial and human use. Pollution of water bodies and streams constitute also a big problem.

In southern Mexico water availability in the San Cristobal de las Casas watershed considerably exceeds human demands. However, much of the population lack drinking water due to topographic obstacles to delivering water to scattered settlements in the watershed. Extreme ENSO events also affect water availability in this watershed but other climatic phenomena such as the PDO, tropical storms and hurricanes could explain in more detail water availability for this region.

The technical support to plan for sustainable water use in Mexico requires historical and modern knowledge of the behavior of atmospheric circulatory patterns, the determination of hydrological balances of regional representative watersheds, knowledge of water uses and volumes plus the development of future water scenarios. In this study several representative watersheds in Mexico were analyzed to examine these problems. Ongoing actions like payment for hydrological services, improving irrigation efficiencies and controlling withdrawl volumes have been undertaken to improve the management of water resources in some of these watersheds.

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