Drying out? Water, society and climate in central Mexico

A report for the Royal Geographical Society (with IBG) Research Programmes Group

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Introduction

The overall aims for this project are as follows:

- To test whether recent declines in lake levels in central Mexico can be attributed to a drier climate
- Assess how changes in economic structures and patterns of resource exploitation may have affected, and been affected by, water availability
- Attempt to identify whether the impacts and/or perception of reduced surface water availability are socially or culturally specific
- Refine definitions of meteorological, hydrological and agricultural drought
- Identify who the key actors are in determining water use and developing management strategies

Approach

Our approach has been to combine the methods drawn from the physical and social sciences to:

- Reconstruct climate change and the response of the hydrological system using both the available instrumental record and a variety of proxy records
- Explore patterns of economic change and social response to changing water availability, using the colonial archives and documents in the Archivo Histórico del Agua (AHA) as a starting point

Programme of work

The project began with a review of existing data and a project field meeting in Mexico in July 2006. The group met in CentroGeo, Mexico D.F. and then went on a field trip to the study area, visiting the craters around the Valle de Santiago and La Piscina de Yuriria, talking to local people, the offices of the Modulo de Riego 4 and identifying suitable documentary collections held in the local archives in the town of Valle de Santiago. Presentations were made on the different strands of the work and areas for further work identified. Dr. Fernández Tejedo was employed on a part time basis to carry out further work in the Archivo Historico del Agua and the Archivo General de la Nación. A poster on the project was presented at the RGS-IBG conference in August 2006. In February 2007 Dr. Tapia visited Nottingham and met with Drs. Metcalfe, Endfield and Davies to discuss progress. A paper will be presented at the RGS-IBG conference in August 2007 as part of the RGS's Climate Change Research Group session

In addition to work carried out directly for the project there has been other related research activity at CentroGeo with an MSc dissertation on vegetation in the Valle de

Santiago area and a new PhD student who will be working on community attitudes to water. The latter project is seen as a very important development.

Study area

Our proposed study area includes Cuitzeo (the second largest lake in Mexico by area) and the crater lakes of the Valle de Santiago (Figure 1). The levels of these lakes have been falling, in some cases dramatically, over at least the last 20 years. Cuitzeo periodically dries out completely. The lakes of the Valle de Santiago have been particularly adversely affected. La Alberca and the Hoya Rincon de Parangueo, both originally about 50 m deep, are now dry. The water levels of many other lakes in the region, such as Pátzcuaro, Chapala and Zirahuen, have also fallen. The reasons for this trend have been disputed and one of our goals is to resolve this question.

The chosen study area lies on the northern margin of the central volcanic highlands of Mexico, in the modern states of Michoacán and Guanajuato (Figure 1a). The area lies on a climatic gradient, from semi-arid in the north, to sub-humid in the south. Lake basins have provided the focus for human settlement in this region since pre-Hispanic times. At its simplest, the lakes and springs that fed them, provided a continuous supply of water in an area where rainfall is highly seasonal (>70% in the summer (June – September) rainy season), but communities capitalised on a whole range of lacustrine resources. Whilst the indigenous peoples of central Mexico are known to have manipulated surface hydrological systems (e.g. irrigation systems and dykes), large scale hydrological modifications came with the arrival of the Spanish in 1521.

The area is within the Lerma-Chapala-Santiago drainage basin (see end note), formed by the Rio Lerma, rising near the Nevado de Toluca (Estado de Mexico), passing through the Lago de Chapala and finally draining into the Pacific Ocean (Figure 1a). The Lerma basin covers an area of 125,500 km^2, including parts of nine states (Rodriquez Langone, 1999). The basin is traditionally divided into the Upper (Alta) and Lower (Baja) Lerma, the former being upstream of Lago de Chapala. Alta Lerma comprises 31% of the total area and within this, more than 70% lies within the states of Michoacán and Guanajuato (Figure 2).

Our initial focus has been the Valle de Santiago, Guanajuato (Figure 1b) which was the location for one of the first areas of planned irrigation with the development of the Lago de Yuriria by Fray Diego de Chavez in 1550. Today, the area lies within irrigation district No. 11, 'Upper Lerma', and the wider hydrological basin (see end note) includes Lago de Cuitzeo, the crater lakes of the Valle de Santiago, the Lago de Yuriria and the nearby crater lake La Piscina de Yuriria. Valle de Santiago itself lies within irrigation module (Modulo de riego) 4 of district 11. The area forms part of the *Bajio*, long regarded as the 'breadbasket' of Mexico, being the country's major producer of wheat since the Colonial period. Commercial agriculture has expanded recently and the area is now Latin Americas's largest producer of broccoli. The two largest settlements in the area are the town of Valle de Santiago (population > 56,000) and Jaral de Progreso (> 16,000) (INEGI).

Instrumental records of climate and lake level

Meteorological records are currently the responsibility of the Servicio Meteorologico Nacional (SMN) which is part of the Comisión Nacional del Agua (CNA). Some of these data are available on a CD ERIC2, but do not cover the full period of record and only extend to about 1990. Additional data have been obtained directly from the CNA. The primary records for this study are described in Table 1

Station	Period	Mean precipitation (mm)	Lowest precipitation (mm)	Year	Highest precipitation (mm)	Year
Morelia	1917-2003	767	466	1982	1159	1958
Valle de Santiago	1945 – 2005	687	360	1945	1193	1958
Cuitzeo	1933 – 1996	675	395	1945	1116	1958
Pátzcuaro	1969 – 2004	892	704	1982	1209	2004
Guadalajara	1881-2005	934	552	1949	1567	2004

Table 1. Meteorological stations in the study area with climatologically useful records

Unfortunately, the record for Valle de Santiago has very significant gaps, particularly in the early and late 1980s and the early 1990s. The longest continuous record in this area is for Guadalajara (capital of the Estado de Jalisco and Mexico's second largest city). This is reproduced in Figure 3.

The climate of Mexico is dominated by the NH summer North American Monsoon (NAM) (Douglas et al., 1993; Ropelewski et al., 2005) which draws in moisture from both the Gulf of Mexico and from the eastern tropical Pacific/Gulf of California. Many studies of the NAM have focused on the Gulf of California as this is the main source of precipitation reaching the Arizona and New Mexico. For most of Mexico, however, the Gulf of Mexico is the more important source region. Tropical storms also make an important contribution to total annual precipitation in many areas of Mexico (Englehart and Douglas, 2001). Only limited amounts of winter precipitation reach our study region from mid-latitude storm tracks and *nortes* (outbreaks of cold, polar air that pick up moisture crossing the Gulf of Mexico). The mechanisms which control inter-annual variability in Mexican rainfall include ENSO and the PDO (e.g. Magaña et al., 2003; Engelhart and Douglas, 2006). The impacts of ENSO are complex, but in La Niña events the NAM is enhanced, whereas in El Niños it is reduced (although winter precipitation increases in NW Mexico). The direct effects of ENSO on Mexico are, however, quite limited. The effects of the PDO are similar to those of ENSO, with reduced monsoonal rainfall in El Niño and high index PDO conditions (Castro et al., 2001). The relationships between ENSO and the PDO are complex and it appears that ENSO teleconnections are more pronounced with positive phase PDO (Englehart and Douglas, 2002). The mechanisms responsible for drought are clearly highly variable across the different areas of Mexico. This complexity is enhanced by the major role played by topography in dictating the distribution of precipitation across Mexico (Mosiño Aleman and Garcia, 1974).

The meteorological records from our primary sites since 1933 are brought together in Figure 4. These plots highlight the discontinuous nature of many of these records. Meteorological data were apparently collected at Pátzcuaro from 1921, but so far, we have not been able to obtain these. Broadly, the data show below average precipitation in the late 1930s and much of the 1940s, 1956 and 1957, the early 1960s, the late 1970s and late 1980s. A compilation of drought records by Castorena (1980) confirms the widespread occurrence of drought in the 1930s and into the early 1940s. The severity of drought in 1957 is also emphasised, particularly in September when Guanajuato experienced increased unemployment amongst farm workers and about 50% of crops were lost. The drought apparently persisted into early 1958, although the data show that ultimately 1958 was a wet year. Castorena also illustrates the impact of drought in 1977, although it was apparently more severe in northern Mexico.

Measurements of the levels of natural lakes in Mexico are very scarce. Lake level data have been obtained for Lago de Chapala (1900 – 2006), Lago de Pátzcuaro (1950 – 2004) and Lago de Cuitzeo (1930 – 1996). Minimum lake levels usually occur in May/June and maximum levels in October. The interannual range is between 0.5 and 3 m. The levels of Chapala and Cuitzeo are artificially controlled. The level of Chapala is constrained by the Presa de Poncitlán (constructed between 1893 and 1905) which limits the lake's level to a maximum of 97.8 (equivalent to 1524.6m a.s.l., maximum depth 13 m) (Rodríquez Langone, 1999). Using Poncitlán, the level of Chapala has usually been maintained between 95 and 97, 95 being the level of the outflow into the Rio Santiago. The systematic collection of lake level data from Cuitzeo seems to have been started in response to flooding from 1926 (Aprov. Superficiales Caja 646, Exp. 9359). In 1927 saline water flooded out of Cuitzeo and in to the Lago de Yuriria breaching a dyke constructed at La Cinta. A letter dated 1928 complained that closing the natural outlet of Cuitzeo 'se convierte Michoacán en presa de Guanajuato' (turned Michoacán into the reservoir for Guanajuato). A document from 1955 (Consultivo Tecnico, Caja 427, Exp. 3815) reports that the level of Cuitzeo started to fall once the Presa Cointzio (on the Rio Grande de Morelia) was completed in 1939. The level of Pátzcuaro is not controlled.

It is important in this study to establish how far lake levels are controlled by climate. Lake level data from the three basins are compared with precipitation in Figure 5. The correlation between annual precipitation and lake level is generally low, being highest (0.5) for Cuitzeo and only 0.2 for Chapala and Pátzcuaro. The most notable features of the Chapala record are the dramatic falls in lake level through the 1940s, in the late 1980s and 1990s. The fall in level in the late 1940s was attributed to lack of rain, increased abstraction upstream and the need to keep pumping water from the lake to maintain the power supply for Guadalajara (Rodriquez Langone, 1999). Minimum levels were attained in 1954/55. It was noted, however, that equally low levels had been noted in the late 19th century (e.g. 1897). The lowest maximum lake level was recorded in 2001 (91.96), although the record minimum is still 1955 (90.08). The Cuitzeo record shows low levels through much of the 1940s and into the 1950s, the early 1960s and late 1980s. The much more limited record from Pátzcuaro shows a gradual decline in 1969 to a minimum level in 2001. There are some similarities between this and the Chapala record over this period.

There are no direct measurements of water levels in the crater lakes of the Valle de Santiago, or La Piscina de Yuriria. These lakes have no surface inflows or outflows being fed largely by groundwater. In the past, a number of them had springs around their margins. The lakes and springs were used for small scale irrigation, the collection of *moscos* (flies) to use as fertiliser, to feed poultry and for fishing. Information about these basins has been obtained from intermittent observations and material in the AHA. The main dimensions of the craters (hoyas) are set out in Table 2.

	Location	Elevation (m)	Diameter (m)
Rincon de Parangueo	20°25'N, 101°15'W	1950	1550
Alvarez		1950	1650
Blanca		1950	1000
La Cintora	20°21'N, 101°12'W	1900	1500
Estrada		1810	1050
La Alberca	20°23'N, 101°12'W	1800	500
San Nicolas	20°23'N, 101°15'W	1760	1250

Table 2. Dimensions of the crater lakes of the Valle de Santiago (Ortuño Ramirez, 1993)

The Hoya San Nicolas and La Cintora dried out in the late 1970s, while the Rincon de Parangueo and La Alberca were dry by 2003. Changes in La Alberca are the best documented, as it lies close to the town of Valle de Santiago and was an important recreational centre for the local population. It was originally about 50 m deep, was recorded by J. Platt Bradbury as being 32 m deep in 1973, was 10 m deep by 1997 and was dry by 2002. This sequence of events is illustrated in Figure 6. There is less information about the Rincon de Parangueo possibly because it has probably always been too saline to use for irrigation or recreation. In the 1930s a tunnel was excavated through the crater wall apparently to access the water, but it was never used as the water was unsuitable. The lake was more than 50 m deep in 1982, but had shrunk to 7.5 m by 1995. At La Piscina de Yuriria, the lake was recorded as being 2 m deep in 1981 and was dry by 1985. In 1997, the lake was 30 cm deep and this had increased to 1.8 m by 2003. The restoration of the lake was due to the deliberate pumping of groundwater into the basin, apparently in response to concerns over the health effects of wind blown alkaline dust following desiccation of the lake. There are periodic measurements of lake chemistry which are summarised in Table 3.

Lake	Year	pH	EC µS cm^{-1}	Salinity ‰	Dominant anions
La Alberca	1982				HCO_3 > CO_3 = Cl
	1997	9.4	6,030		CO_3>HCO_3>Cl
Rincon de Parangueo	1982	8.8 – 9.3	22,000 – 23,500	13 - 15	Cl > CO_3 > HCO_3
Rincon (well outside crater)	1982	6.9	2650	0.8	HCO_3

La Piscina de Yuriria	1982	10 -11	24,500 – 29,000	14.8 – 16.2	CO_3 > Cl > HCO_3
	1985	10	> 20,000		
	1997	10	8,000		CO_3 > Cl > HCO_3
	2003	9.5	1,900		CO_3 > HCO_3 > Cl
La Piscina (spring)	1982	7	500 – 1,100	0.2	HCO_3 > CO_3

Table 3. Selected water chemistry parameters for the Guanajuato crater lakes

Further information on changes in the area can be obtained from the use of remote sensing imagery. LANDSAT images for 1989, 1999 and 2002 have been obtained and can be used to track changes in the lakes, as well as changes in land use.

A number of data sets have been entered into the GIS system at CentroGeo (ArcView 3.2) using information from the Comision Nacional del Agua (CNA), the Instituto Nacional de Estadistica y Geografia (INEGI) and the Instituto Meteorológico Nacional

Changes in structures of water management

Four separate periods can be identified:

- Colonial period: 1538-1821
- Post-Independence period: 1821- 1877
- Industrial revolution: 1877-1917
- Post Mexican revolution period: 1917-2007

Colonial period. The Crown basically kept the *costumbre antigua* (the pre-Hispanic system of land tenure and resource management) and awarded grants of land (*mercedes reales*) for agricultural land use or livestock and also to encourage the establishment of settlements. In addition to land grants (which didn't necessarily include water resources) there were water grants awarded for: irrigation, grain and fuelling mills, sugar cane plantations, livestock grazing lands and mining enterprises. The Colonial administration gave the rights to water use and management to communities, corporations (towns, cities, *ayuntamientos*, the clergy, irrigation communities) and individual holders of grants (e.g. *hacendados*) within their respective properties and regions. Agricultural production increased across the Bajio region throughout the late 17th and 18th centuries, with a concomitant increase in the demand for water. Monopolies emerged and landed estates which accumulated Mercedes and rights of access to water. This was a time when the water management infrastructure including dams, channels and reservoir reached its zenith (Murphy, 1986) and when. disputes of water increased dramatically.

Post-Independence period. With the rise of the national state, local and private management of water was reinforced. The invigoration of local political oligarchies favoured greater access of private interests to water resources and rights. The further expansion of privately owned estates undermined towns and communities' water rights. Changes in water use and water rights in indigenous settlements and irrigation communities dramatically transformed traditional colonial water policies.

Industrial revolution (the Porfiriato). The nation state is reinforced and the development of centrally planned irrigation projects becomes a priority. Irrigation schemes, hydroelectric dams and urban water supply systems are constructed and there is expansion of industries with high potential water demand such as electricity generation, steel and cement production.
A number of schemes to drain lakes and marshes were instigated, many of which failed:
a) Upper-Lerma project (1915)
b) Ciénega de Chapala (1910) 50,000 ha. irrigated
c) Ciénega de Zacapú (1903)

Post-(Mexican)Revolution period. The development of centralised policies of management continued. Agrarian reform changed rights of access to water and land, based on the principles of *dotacion y restitucion*.
Article 27 of the 1917 Constitution gave the nation rights to all surface water, groundwater and inshore waters. Only the federal government could grant concessions of water and land use to:

1) Individuals.
2) Ejidos, agrarian communities and cooperatives.

In 1929, the agrarian reforms "dotación y restitución" were enforced in Guanajuato and by 1939 54 % of the best land (agricultural) in the Bajío was in ejidos.

The institutions for water management in the post-Revolution period are listed below:

- 1921-1924 Secretaría de Fomento **SF** (Secretariat for Enterprise Development)
- 1926-1946 Comisión Nacional de Irrigación. **CNI** (National Irrigation Commission)
- 1946-1976 Secretaria de Recursos Hidráulicos. **SRH** (Secretariat of Water Resources).
- 1976 Secretaría de Agricultura y Recursos Hidraúlicos. **SARH** (Secretariat of Agriculture and Water Resources)
- 1989 Comisión Nacional del Agua. **CNA** (National Water Commission)
- 2000 Secretaría de Ecología, Medio Ambiente y Recursos Naturales. **SEMARNAT** (Secretariat of Ecology, Environment and Natural Resources)

Between 1926 and 1976, the general principal of water management was i) to increase central control and ii) develop large scale projects. The expansion of irrigation was seen as key means to resolve the problems of the agricultural sector. In Irrigation District 11, two reservoirs were constructed: Tepuxtepec (1928) and Solis (1949), the later requiring the relocation of 22 settlements (Garcia Huerta, 2003). The idea that the drainage of lakes and marshes could reduce 'unnecessary' losses of water to evaporation, was continued by SARH. The Lago de Cuitzeo was a frequent target of such drainage plans. A document of 1922 (when Cuitzeo was apparently very low) suggests that 500,000 m^3 of water was being evaporated each year and this could irrigate 75,000 ha (Consultivo Tecnico, caja 502, exp. 4478), a further assessment of possible drainage was carried out in 1955 (CT, caja 427, exp. 3815). After 1976, there was a move towards decentralisation and private management of water resources received increasing support. This trend was continued by the CNAwho created a decentralised operating system. The responsibility for the construction and operation of infrastructure and the management of water distribution (urban and rural) was passed to local and regional authorities. Regional authorities became directly involved in the allocation of water.

The CNI were responsible for the creation of 32 large scale irrigation districts, including the Lerma-Chapala district. It is estimated that there were 10,000 ha under some form of irrigation in the Lerma basin in the Colonial period, this increased to 69,000 ha by 1926 and 275,000 ha by 1946. The expansion of population and irrigation in the Lerma basin is illustrated in Figure 7. The area under irrigation continued to expand until 1997, since when it has undergone a slight decline (Winkell and Le Page, undated).

The importance of groundwater abstraction as a driver of lake level changes in central Mexico has been emphasised by a number of authors. Alcocer et al. (2000) specifically identify overexploitation of groundwater as a cause of desiccation of the crater lakes. There are two important aquifers in the Valle de Santiago area: a shallow aquifer (acuífero granular) in alluvial, lacustrine and pyroclastic sediments extending from 20 to 30 m down to about 50 m and a deep aquifer of fractured basaltic rock. The shallow aquifer is the primary source of groundwater extracted using legal and illegal wells. Ortuño Ramirez (1993) reports that 79 million m^3 were being abstracted from the shallow aquifer, by 235 registered wells and a similar number of illegal wells. Until 1992 there was basically free access to groundwater and groundwater levels were falling by about 1 m per year. A Federal Decree of 1992 issued regulations for the use, exploitation and abstraction of groundwater in the Lerma-Chapala basin. In this document, the area of Valle de Santiago was designated as a groundwater reserve area allowing the operation of only approved wells and new abstraction for public water supply. The efficacy of this legislation has been questioned. Escolero and Alcocer (2004) report that groundwater levels in the valley fell 3 m between 1996 and 1998. The equipotential height of the shallow aquifer in the lower part of the valley lies at about 1690 m a.s.l. The volcanic zone of the crater lakes is an important control on groundwater, although here may be other inputs from the Celaya Valley. Groundwater levels apparently continue to fall at between 0.5 and 2.5 m per year as a result of both increased abstraction and reduced recharge due to the extraction of sands and gravels for construction and deforestation. The measured change in groundwater levels (1976 – 1983) and the number of wells in the region in the late 1990s are illustrated in Figures 8a and b. Documents in the AHA provide insights into the demand from wells from individual communities. Between 1980 and 1986 there are many papers (in the category Infraestructura hidraulica) relating to requests to drill wells, disputes over access to water, misuse of water and unauthorised well construction.

Information for irrigation module 4 (Valle) provides a more detailed picture. The module, created in 1995, covers 13, 480 ha, but specifically excludes the crater lakes. The land within the module is 47% ejido and 53% private, but the users are dominated by the ejidos (80%). In 2006, there were 262 wells in the module area, of which 241 were private (ejidos and private) and 21 official. Each well can irrigate about 25 ha and farmers usually use all their groundwater allocation. The water table is usually at 35 to 40 m depth, stabilising at 55 to 60 m; the strongest groundwater flow is at > 100 m. Users pay $300 for irrigation and the water is mainly used to grow maize, sorghum, wheat, barley and vegetables (Roberto Romero Garcia, pers. comm.). The module is trying to improve the condition of the infrastructure and make water use more efficient (e.g. through the use of low pressure irrigation systems). The offices for the irrigation district are in Salamanca and will be a source of additional information, including information about requests for wells. Although the focus of this study is water shortage (drought), the module staff emphasised the damage caused by flooding, with an insurance scheme paying out about $930,000 following floods in 2003.

Archival sources
Pertinent documents held in the central archives of both the AHA and the AGN have been consulted. At the AGN the emphasis has been on the archives of the Colonial period.

The very rich archival collections of Mexico provide a unique window through which to view regional environmental change at a range of time scales. Unpublished colonial archival sources, including fiscal and judicial documentation, historical census data, surveys, maps as well as a range of published travelogues and accounts can be used to explore social responses to climate changes in different parts of the country and to reconstruct regional drought and flood histories. In this project the archives are being used to investigate changes in water availability in the Valle de Santiago and how communities in the area conceptualised and responded to these changes. More generally, the archives are also being used to investigate long-term changes in land and water use and tenure in the region from the immediate post-conquest period up to the present day.

It is clear that there was a certain amount of theoretical protection afforded the existing *Indio* communities and their territories in the early post-Conquest period. This extended into water management (see the section on Changes in structures of water management above). A *Real Cédula* (royal decree) issued in November 1536 illustrates the crown's commitment to maintaining the traditional indigenous systems of resource exploitation:

> "*the distribution of waters should be according to Indio custom*"

Water management and access also featured among the fifty-four articles of the New Laws of the Indies issued in 1542:

> *"the use of water was to be communal....we order that the use of all the pastures, woodlands, waters of the provinces of the Indies are to be common to all the present residents, and to those of the future so that they can enjoy them freely"* (cited in Musset, 1992).

The right of common use of water, however, was understood to apply only to the use of streams and rivers for drinking, fishing and domestic purposes. It did not permit the free diversion of water for irrigation and forbade unauthorized private appropriations (Muphy, 1986). Communities, institutions or individual landowners could, however, petition for a *merced* or viceregal grant of land or water. Early grants were for water were, for the most part, awarded relatively straight forwardly, cash payments of variable amounts being one of the only criteria for an award to be made (Lipsett-Rivera, 1999: 27). Generally, however, awards of *mercedes* for water rights were rare (Murphy, 1986; Prem, 1974). However, land grants could be awarded with specific mention of rights to access to water. Murphy (1986) for example, highlights three different forms of water "concession." These included awards made of caballerías de riego, or irrigable land, which in effect were construed to confer water rights. Land might be awarded "con el agua necessario…" for a specified use. As long as the conditions that accompanied for a *merced* grant had been met, such a grant also provided a right to any water within the land. Water that was not subject to any form of *merced* remained the property of the Crown according to previous Royal decrees.

Preliminary work in Guanajuato has established that there were significant modifications to the management and distribution of water in the region following Spanish conquest. There was a general expansion in land under irrigation to facilitate the growth of Mediterranean wheat and this led to dramatic changes in the way water was administered and managed. Permanent and ephemeral watercourses, rivers and arroyos all began to be exploited and it is clear that groundwater was also tapped in many locations, though perhaps more so in the later colonial period. (AGN Historia 72, exp. 9; AGN Civil, vol. 73, exp. 3; AGN Tierras vol. 514, exp. 1, cuad. 2, f. 47; vol. 618, exp. 1, cuad. 3, fa. 61; vol. 1353, exp. 1, f. 69). There was extensive use of water storage, diversion and water management systems. Storage of water, for example, for use during the dry season, a strategy referred to in the documentation as *medio riego*, is thought to have been an early practice (AGN Tierras 2705, exp.3, fa.1; AGN Mercedes, vol. 10, fa. 3). The scale and complexity of water management in the region expanded significantly in the eighteenth century (Murphy, 1986). Many earthen and brick built dams, canals and reservoirs were constructed and water was diverted from key rivers in the region to irrigate wheat fields or to provide water for livestock, or for the growing population in the region.

The level of water management had a number of implications in the region. Indigenous communities, for example, had to petition for fishing rights on water bodies to which they had previously had free access (AGN Indios vol 6, exp. 44; vol. 17 exp. 11). Moreover, illegal abstraction and private appropriation of water for irrigation and use of waters that had not been subject to formal granting processes caused considerable unrest. Competition for water frequently led to legal conflict and, in some rare instances, physical clashes and all cross-sections of society appear to have been involved in water disputes at some stage throughout the colonial period. For example, 1712, a *pleito* (legal dispute) over water rights was recorded between the convent of San Nicolás Yuririapúndaro and local landowner Joseph de Guzmán. The document details a survey of the lands known as Las Carretas in the vicinity of the town of Yuririapúndaro and refers to dried up water sources at this time (AGN Tierras 2987, exp. 3).

The archives reveal interesting arrangements regarding water-sharing agreements between different land users in the region. Where there were many different users of water in a single irrigation system, water rights were allocated by shifts, or *tandas* (see, for example, AGN Tierras, vol. 2959, exp. 141), though such arrangements appear to have regularly contributed to- rather than resolving disputes. There were also water -haring agreements. *Mercedes* were awarded for use of *remanientes* or "left over water" in the region, though this concept was unavoidably vague and sometimes resulted in disputes. One such case involves water sharing and use of *remanientes* and concerned the indigenous residents of the town of Acambaro and one Francisco de Villadiego Senderos. According to Senderos, the community had attempted to drain all the waters of the river of Tarandaquaro for which he had legally secured water rights. In this case, an agreement was drawn up between the two parties to share the use of the water. The water was to first go to run Senderos' mill and the used water would then be used to irrigate the community's fields. (AGN Tierras, vol. 2680, exp. 29). Other similar water recycling arrangements in the region, however, were regularly breached, once again leading to the filing of lawsuits (AGN Tierras, vol. 2963, exp. 116, fs. 246-308).

In addition to disputes over water, the archives also chart some interesting concerns over environmental health in the region. In a letter dated 29th June 1780, local priests Antonio Moreda and Sebastian Flores reported how local farmers in the Valley of Santiago regarded the "emanations" from the reservoir of Yuririapundaro as being particularly damaging to the health of the local communities (AGN Ayuntamientos vol. 97, exp. 2). Moreover, a drought in the Valle de Santiago in the summer of 1780, appears to have stimulated some degree of co-operation between local water users and the Augustinians in the area. In this case, it involved investment in a new canal to drain the water from Lake Yuriria for use by the local communities in the valley as well as the Augustinians who invested heavily in the construction work (Murphy, 1986).

There is a vast amount of documentary material available for the Valle de Santiago region, charting land use and tenure changes, legal disputes and providing information on periods of water scarcity, some of which may relate to drought. Preliminary research has established a need to investigate materials covering the nineteenth century systematically.

Proxy sources of palaeoclimatic information

The study of high resolution lake sediment cores and tree rings have been identified as the most promising source of climatic information for the period beyond that covered by instrumental records and historical archives. Few lake sediment records have either the inherent resolution or dating control required for meaningful correlation with written records. Cores collected from the Hoya Rincon de Parangueo and La Alberca have revealed that the sediments are laminated and may have sub-annual resolution. The presence of tephras of known age and provenance (Colima, 1913 and Paricutin, 1943) has provided a means of dating cores from these two crater lakes and correlating between them. The laminae show a strong response to the seasonality of precipitation with carbonate (Ca and Sr) deposition during the dry winter months and detrital (clastic and organic) deposition in the wet summer. The cores document frequent droughts, many of which correspond to El Nino events. Initial analyses indicate drought episodes in the late 1850s, around 1870, the late 1880s and 1890s, the first decade of the 20th century and from around 1920 to the 1950s. Interestingly, sediments from both lakes continue to indicate dry conditions through the late 1960s, the wettest period in the Mexican instrumental record. It appears, therefore, that by the 1960s the hydrological response of these lake systems was already being affected by human activity in the region. Preliminary results from the lake sediment studies are being presented at the Limnogeology conference in Barcelona in July 2007 (Kienel et al.).

An increasing number of tree-ring records are being published from the central highlands of Mexico, although there are none for the immediate area of the Valle de Santiago. Composite reconstructions of the Palmer Drought Severity Index (PDSI) have been made for Mexico and the results for the two grid cells closest to our study area are presented in Figure 9. These reconstructions confirm the spatial variability in drought occurrence and intensity referred to above. The detailed reconstructions from the Valle de Santiago area can be compared with these more generalised data. PDSI is not widely applied in Mexico, but has been used by Mendoza et al. (2006) in a study of the Lago de Cuitzeo.

Outstanding issues

- Ensure that all meteorological and lake level data sets are as complete as possible and continue exploration of these data
- Add attribute data to GIS
- Obtain more information on groundwater hydrogeology and yields and relate groundwater basins to surface basins
- Extend archival work into 19th century, focus on relevant haciendas and ejidos
- Interviews with community leaders, officials and individuals to explore attitudes to water
- Access census data in relation to population change and land use change
- Develop lake sediment work

Future developments

Our preliminary studies have confirmed the potential of both our approach and our study area to provide new perspectives on the relationship between water, society and climate. We intend to submit an application for further funding to the Leverhulme Trust who we feel are likely to be sympathetic to this cross-disciplinary approach. We shall also consider submitting an application to AHRC who have previously funded work in Mexico encompassing the physical sciences and humanities. There may also be opportunities through the ESRC's Environment and Human Behaviour strand and through the new NERC strategy theme Living with Environmental Change.

Budget

	Initial budget (£)	**Actual spend (£)**
Staff costs	3000	3182
Consumables	100	
Travel and subsistence	3800	3718*
Total	6900	6900

***** includes 4 air fares (£2920), balance = subsistence and consumables

End note

In Mexico the concept of a hydrological basin is used to identify a group of hydrographical basins when this is useful for public information. In the case of the Lerm-Chapala system, the hydrological basin includes the closed lakes Cuitzeo and Pátzcuaro, while the hydrographical basin (i.e. the watershed of the Río Lerma) does not as these closed basins have no surface links to the Lerma river.

Acknowledgements

We would like to thank the following for their contributions to this study: Claudia Coronel and Franz Mora (CentroGeo) and Ulrike Kienel (GFZ Potsdam)

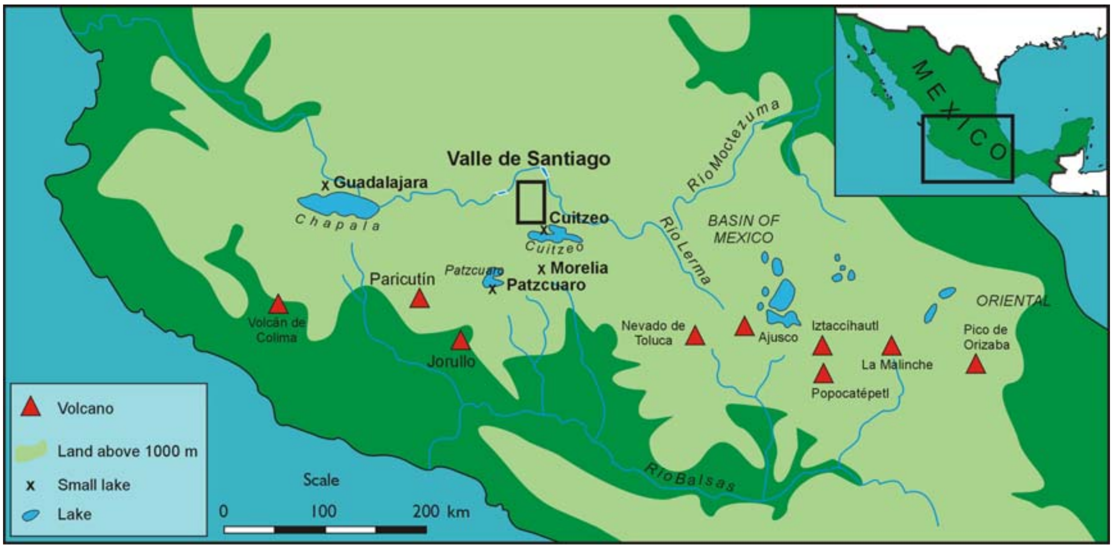

Figure 1a. Central volcanic highlands of Mexico, showing the course of the Rio Lerma and the location of the Valle de Santiago

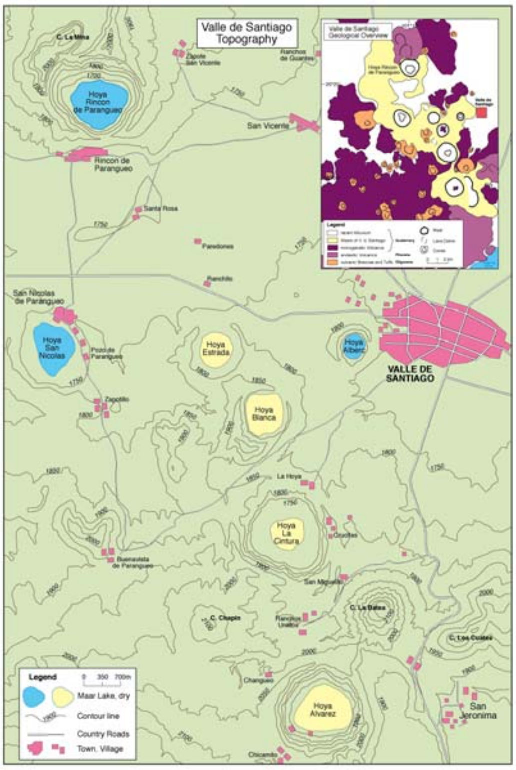

Figure 1b. Valle de Santiago

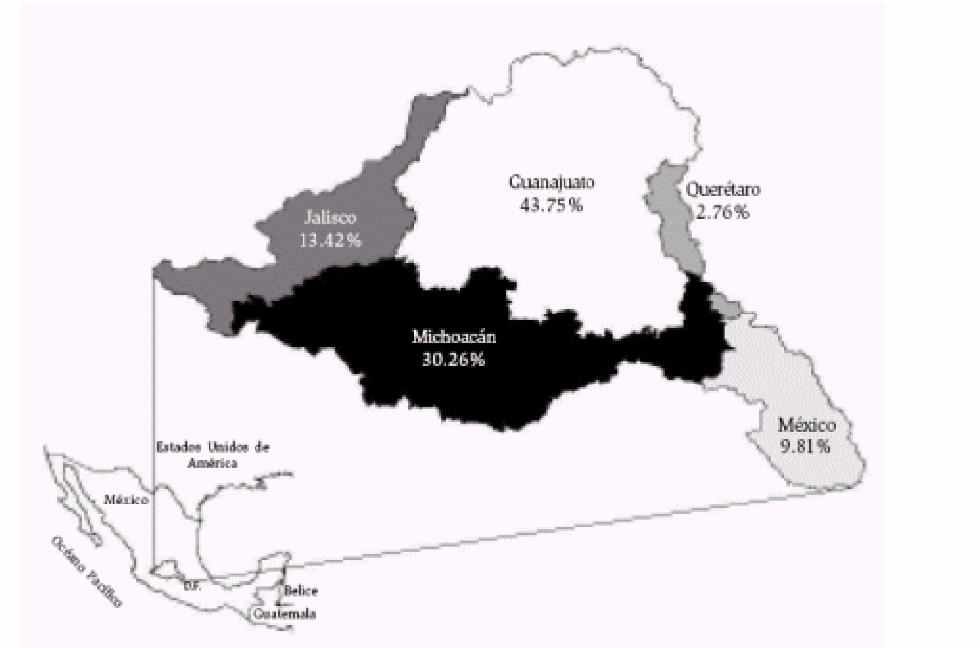

Figure 2. Upper (Alta) Lerma basin, showing the distribution by state

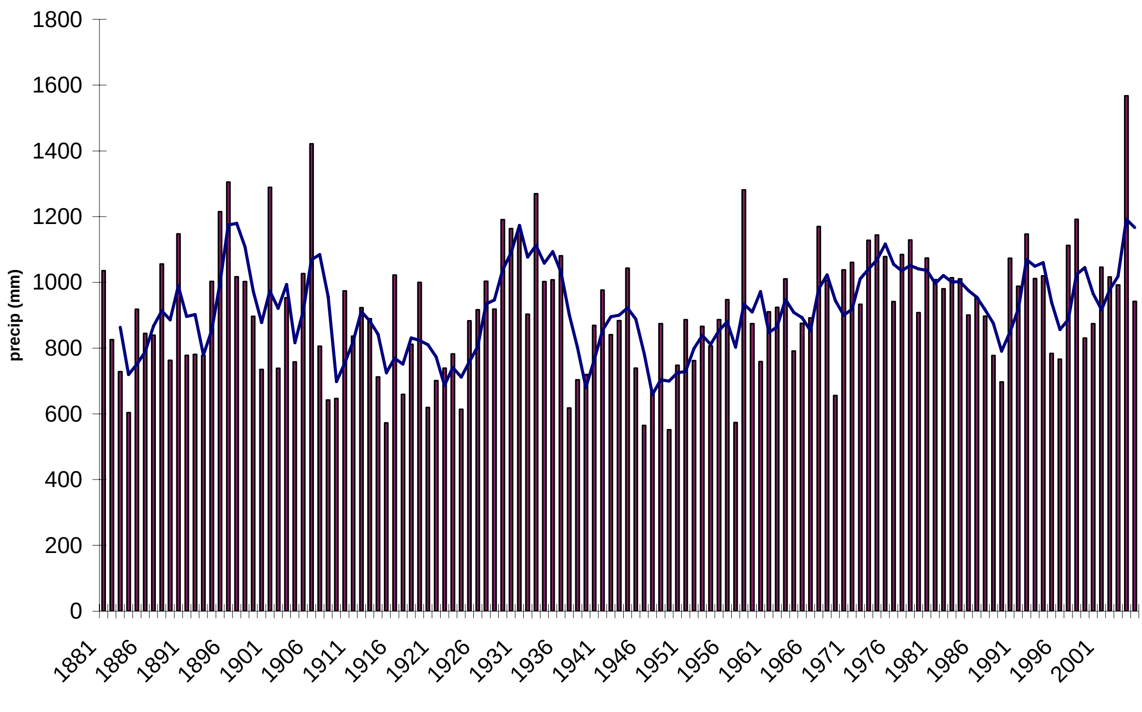

Figure 3. Full precipitation record from Guadalajara showing the 5-year running mean

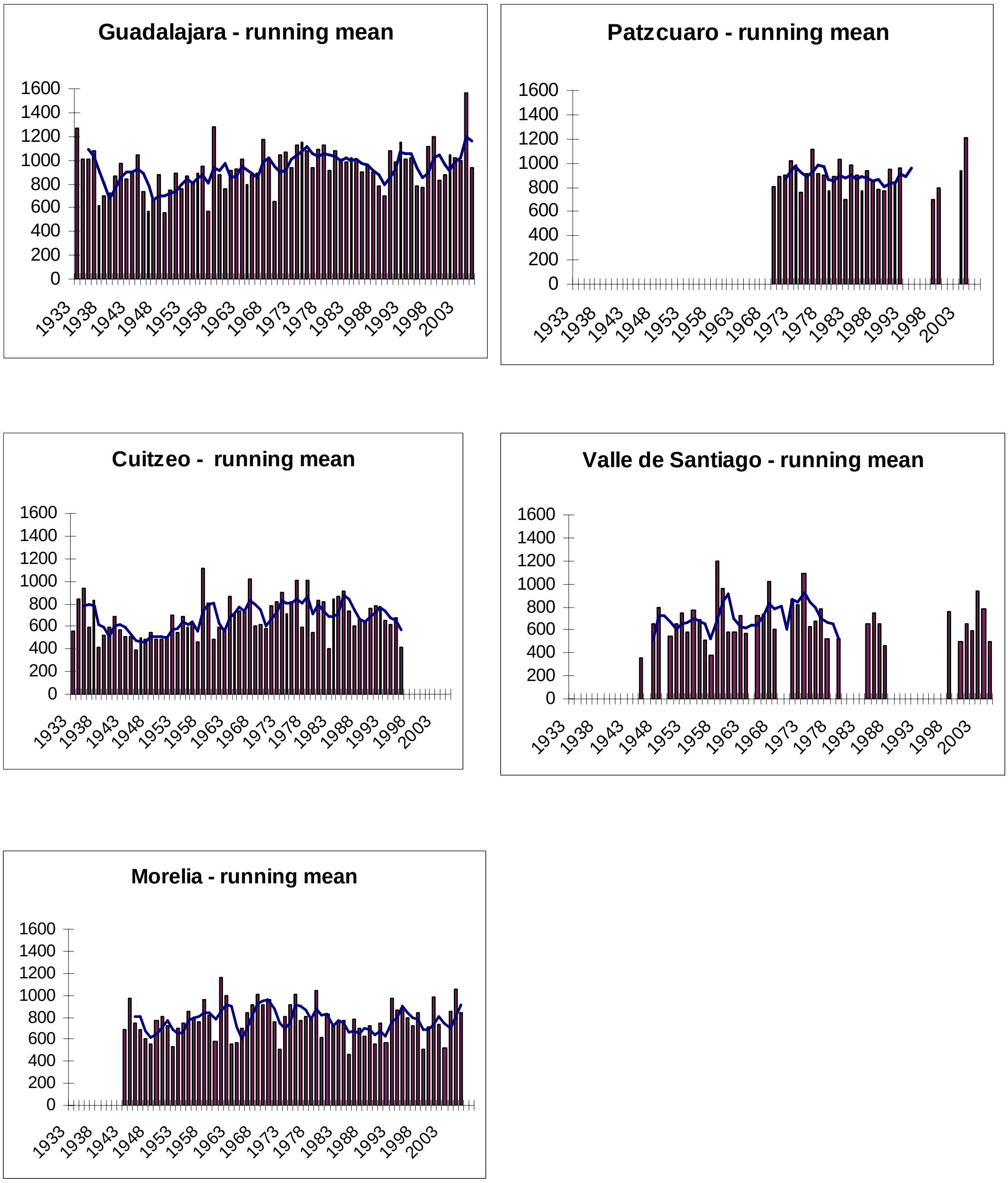

Figure 4. Precipitation since 1933 for key meteorological sites in the study area. 5-yr running means also shown.

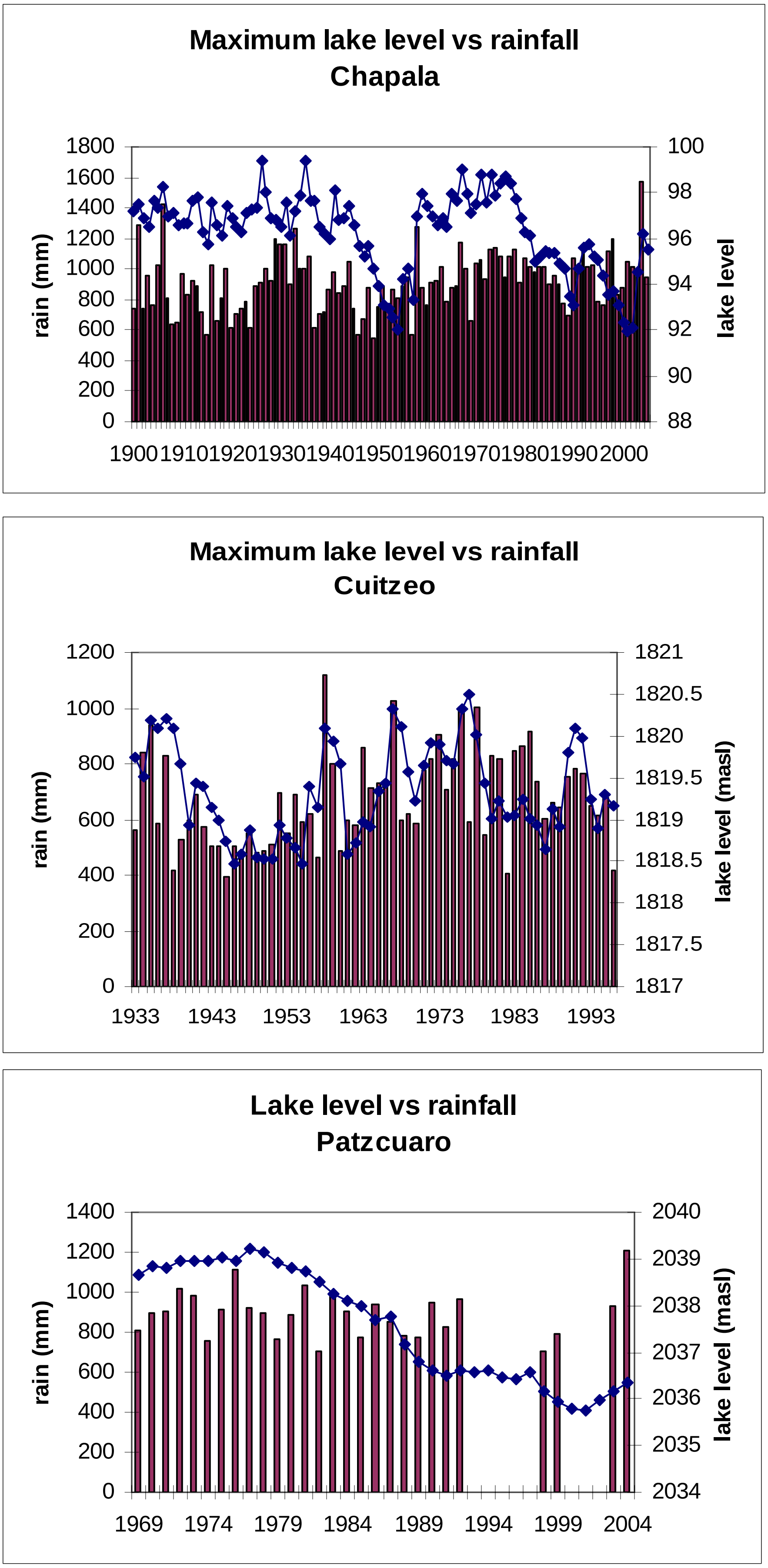

Figure 5. Lake level vs precipitation for Chapala/Guadalajara, Cuitzeo, Patzcuaro

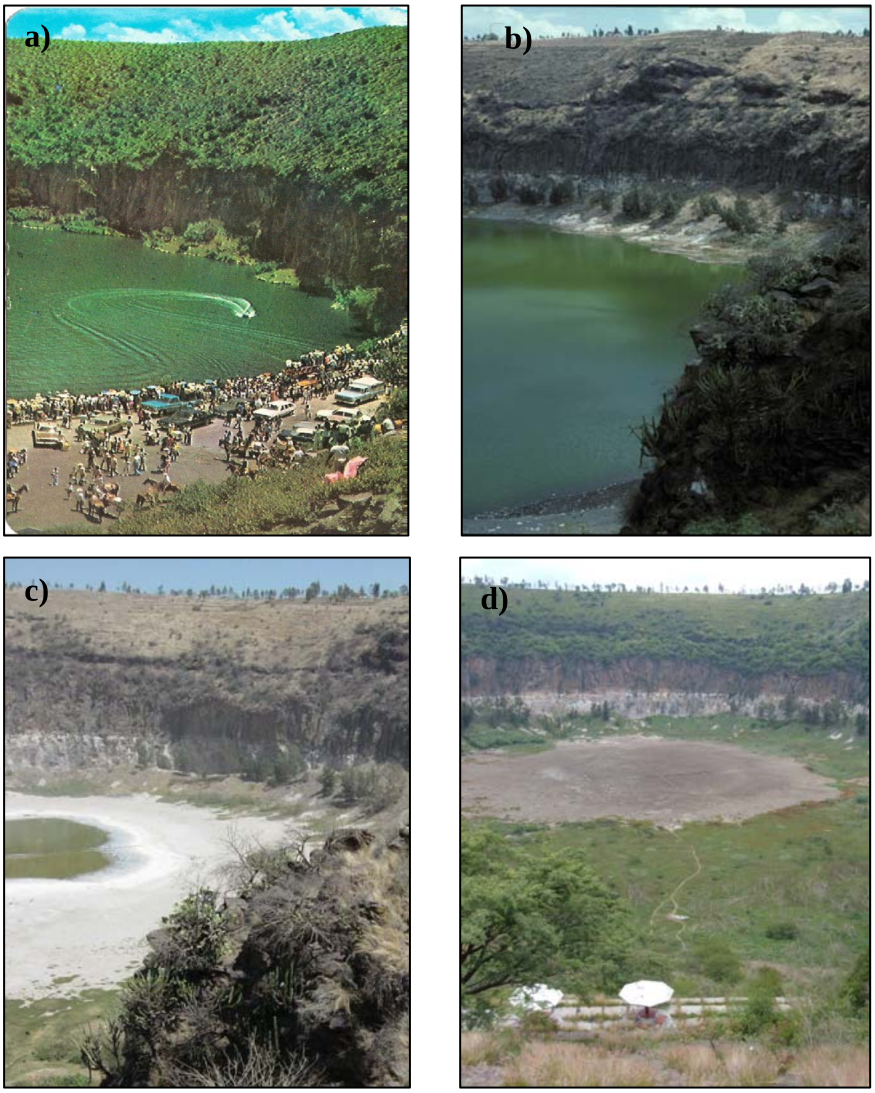

Figure 6. Hoya La Alberca in a) ca. 1972, b) 1997, c) 2003, d) 2006

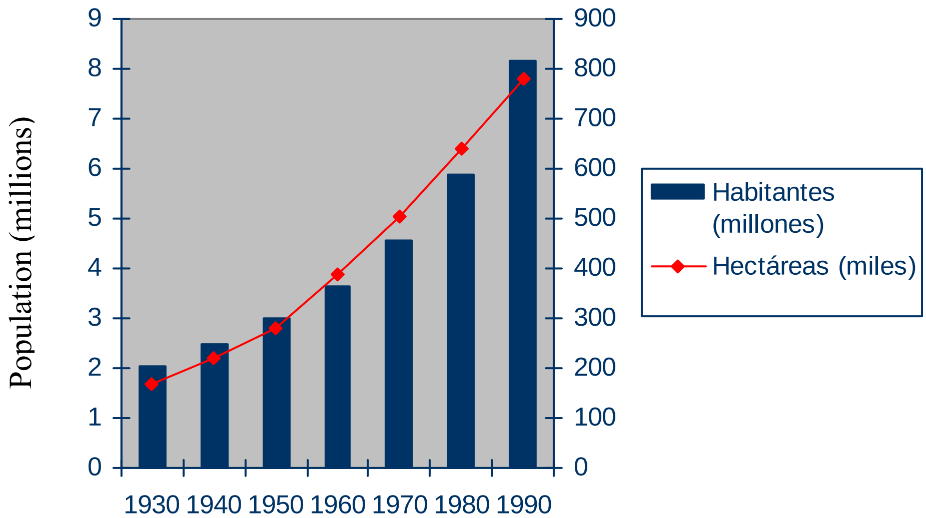

Figure 7. Population and irrigated area in the Lerma-Chapala Basin. AHA, Aprov. Sup. Caja 3060, Exp. 53331

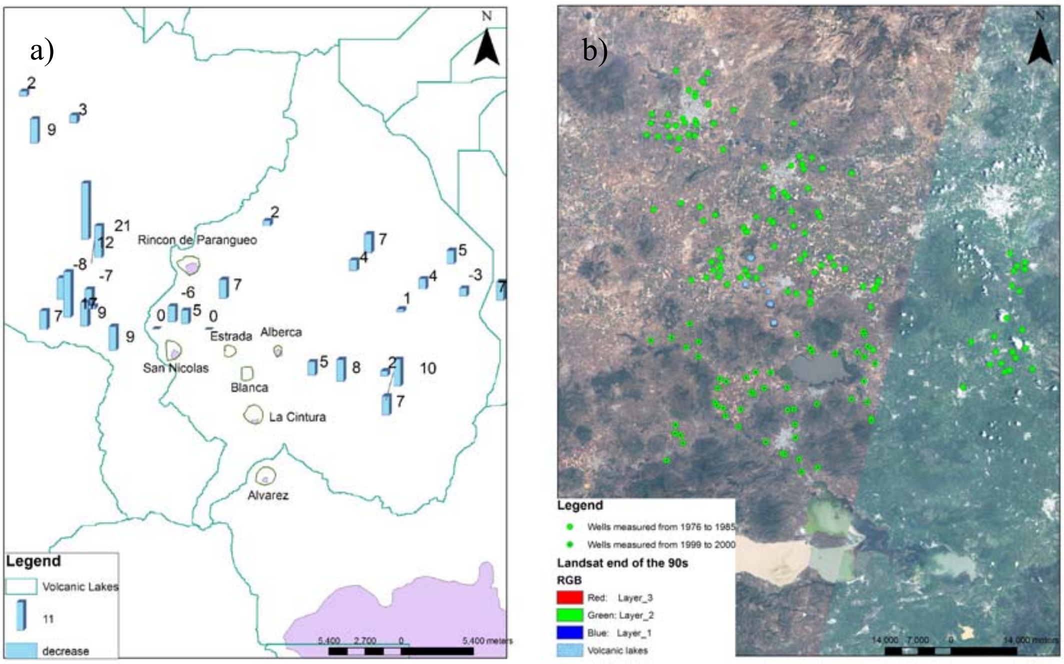

Figure 8 a) change in groundwater level (in m) 1976 – 1983. b) groundwater wells in the Valle de Santiago area late 1990s

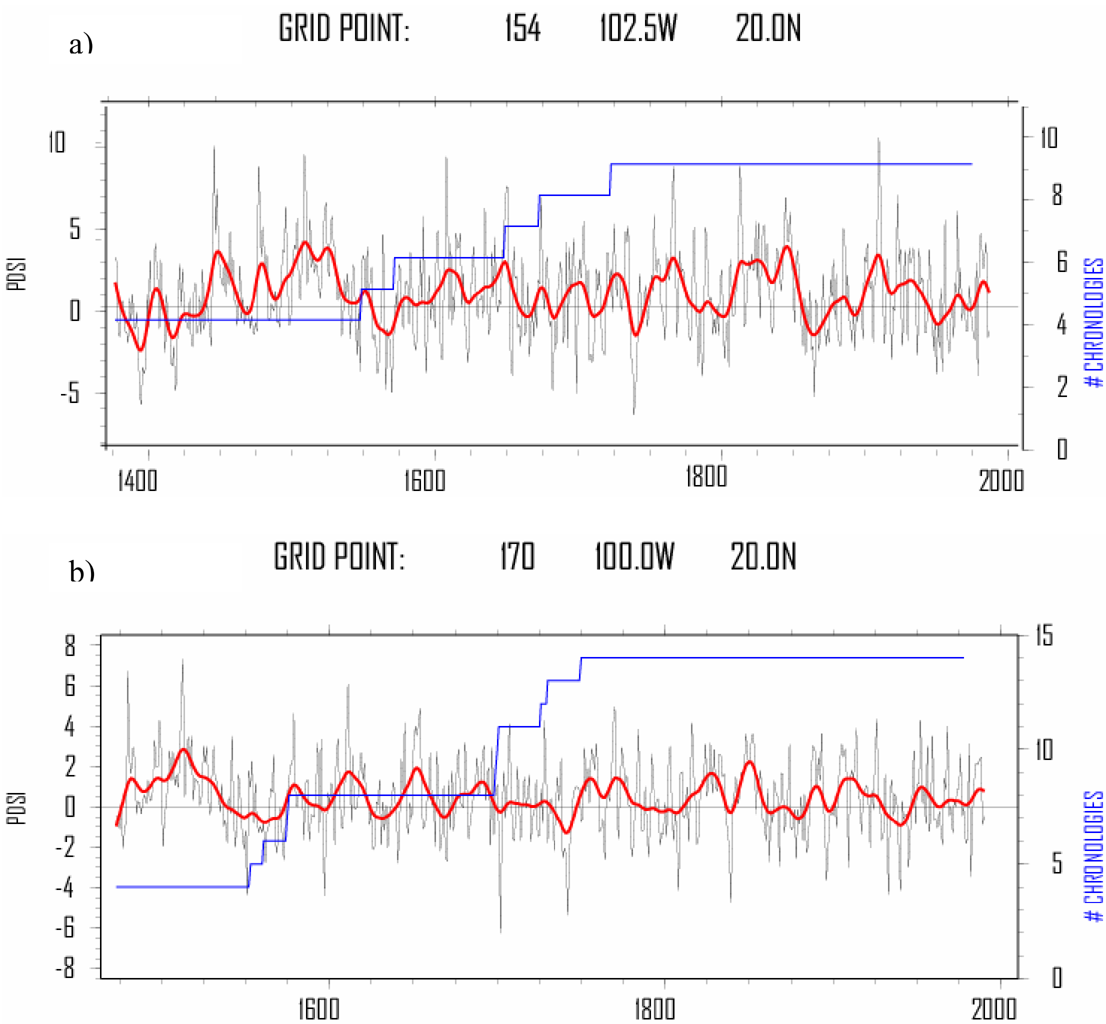

Figure 9. Tree ring reconstructed drought (PDSI) for two grid cells (a) 154, b) 170) closest to the study area