

Analysis of the short term geo-environmental evolution of an endorreic basin using satellite images: the case of Tecocomulco Lagoon, Mexico

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Abstract. The Great Basin of the Valley of Mexico was composed of several lagoons that have disappeared due to their geologic evolution and anthropogenic activities. The Tecocomulco lagoon, Hidalgo, is a relict of that basin and has undergone extreme changes in its size and water composition during geologic periods; however, climatic changes, the deforestation of the sub-basin and the agricultural activities have modified its morphology, area and depth, leading to a great accumulation of sediments that fill up the lagoon. The estimate of changes in the lagoon's surface through five decades (1975, 1985, 1990, 2001, 2002) was the objective of the present work using satellite images, jointly with an environmental interpretative analysis. The factors that have modified the Tecocomulco lagoon are: climate, the contribution of a high load of sediments to the sub-basin, agricultural activities and their interaction, to such a degree that its disappearance is very likely, following the same trend as other lagoons of the Great Basin of Mexico.

Key words: Tecocomulco lagoon, satellite images.

Análisis de la evolución geoambiental de corto término de la cuenca endorreica usando imágenes de satélite: el caso del Lago de Tecocomulco, México

Resumen. La Gran Cuenca del Valle de México estuvo formada por diferentes lagunas que han desaparecido en su evolución geológica y por actividades antropogénicas. La laguna de Tecocomulco, Hidalgo, es un relicto de aquella cuenca, que ha experimentado cambios extremos en sus dimensiones y composición hídrica durante periodos geológicos; sin embargo, cambios climáticos, la deforestación de la subcuenca y la agricultura han modificado ampliamente su morfología, superficie y profundidad, consecuencia del gran aporte de sedimentos y el azolvamiento lacustre resultante. La estimación de los cambios en la superficie del lago en cinco años de diferentes décadas (1975, 1985, 1990, 2001, 2002) fueron el objetivo de este trabajo, para ello se utilizaron imágenes de satélite, conjuntamente con un análisis ambiental interpretativo. Los factores que han modificado a la laguna de Tecoco-mulco son: clima, aporte de sedimentos de la subcuenca y agricultura que se sinergizan, al grado de su posible desaparición, como ha sucedido en los otros lagos de la Cuenca del Valle de México.

Palabras clave: Lago de Tecocomulco, imágenes de satélite.

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INTRODUCTION

The Great Basin of the Valley of Mexico was constituted by several lagoons and lagoons; being some of the most important: Texcoco, Xaltocan, Zumpango, Chalco, Xochimilco, Apan, Tochac, Tecocomulco, among other smaller ones which have already disappeared due to many natural and human related causes.

Tecocomulco Lagoon is a relict of that great basin with dynamic geological and hydrological characteristics that have caused many important changes since > 42 000 years before present times (BP) (Caballero *et al.* unpublished): there have been cold, wet and dry periods, the forest composition has suffered many changes as has quite conspicuously, the level of the lagoon.

According to Caballero *et al.* (unpublished), the lagoon originated after a devastating eruption approximately 50 000 BP, and until around 42 000 years BP it was moderately deep, with fresh slightly acidic water, abundant aquatic vegetation and surrounded by large conifer forests (*Pinus*, *Alnus* and *Abies*) in a damp and cold climate. Between this last date and 25 000 years BP, there were periods with opposite characteristics: the lagoon became shallower, the water became slightly alkaline, the weather turned warm and even dry, and the forest with a dominance of herbaceous species reduced in area. Based on palynologic records, these authors indicate that there is no information for some periods due to the absence or scarcity of pollen in the stratigraphic column. They also mention the tendency to a reduced tree coverage during the time when the level of the lagoon was high, indicating there was human influence in the area during the Early Medium Formative Period (1 500 – 500 BP).

According to Ruiz-González (2000), the exogenous processes that give shape to the actual landscape are:

1. Water erosion:

- a) laminar, in flat areas and slopes with vegetation
- b) lineal, in furrows and abundant gullies.

2. Wind erosion, which affects the whole sub-basin.

3. Anthropogenic erosion, which is the most active.

According to this author, erosion is heterogeneous depending on the region. Areas with vegetation and a slope less than 2%, can lose 0.2 cm/year of soil, on the other hand, those with no vegetation and slope above 2% can reach linear erosion values of 3.6 cm/year. A model of the average value of soil loss in the entire sub-basin would reach 40 000 tons that could be transported by different erosive agents to the flood plain of which the lagoon is part. Considering the current depth of the lagoon (60 cm) and a rate of 3.6 cm/year, it could become completely silted in around 18 years. The author also indicates that this period of time could vary because the erosive process varies depending on the precipitation and evapo-transpiration intensity which can be different every year. Moreover, the agricultural management of the lagoon must be included, because water extracted for crop irrigation, reduces the area of the lagoon that could eventually recuperate, both in surface or depth.

The wide variations in water table and in the reservoir expansion are the result not only of the lagoon's own evolution, but of climatic changes on a small (inter-annual) and large (geological periods) scale; today, human activities have also accelerated the sedimentation rate and, consequently, the rapid disappearance of the lagoon. Nevertheless, this sedimentation enlarges the areas predisposed to be covered by water during the rainy season, flooding surfaces that go beyond the lagoon's littoral, just as Ayala-Castañares *et al.* (1969) have stated occurs in other aquatic systems, a fact that is more notorious during climatic events that include very high precipitation rates or during extreme droughts by erosion and wind transportation (Ruiz-González, 2000).

This research analyzes changes that have taken place, at a small time scale, on the surface or cover of Tecocomulco Lagoon, using satellite images from the years 1973, 1985, 1990, 2000 and 2002.

STUDY SITE

Tecocomulco Lagoon is located on the north eastern region of the Great Basin of the Valley of Mexico and represents 5.59% of its total area, as part of a sub-basin measuring 564 km² (Comisión Nacional del Agua, CNA, for its initials in Spanish, 2002; Figure 1, 2), located between 19° 53' N and 98° 21' W (central parallel and meridian), within a basin found at 19° 03' - 21° 11' N and 98° 11' - 99° 30' W, in the central-eastern part of the Trans Mexican Volcanic Belt (Alatríste-Vilchis *et al.*, unpublished). This basin has a tectonic volcanic origin, bordered by several faults that run in a NNE – SSW direction (García Palomo and Macías, unpublished). The bathymetry of the lagoon is flat, with high plasticity clays and dispersed hard clays, with surrounding

volcanic structures which are the source of volcanic sediments: lava, breccias and ashes of lithologic composition that vary from basaltic to rhyolitic, with ages that range from the Late to the Recent Pliocene Period. Intemperism has taken place on the superficial rocks possibly facilitated by regional fractures moving on an E-W direction (CNA, 2002).

The Tecocomulco sub-basin is endorreic, with a dendritic drains pattern, and four main fluvial contributions (rivers: Cuatlahco, Sarabia, Toronjil and Tepozan; Figure 3) which do not carry much water due to a low precipitation rate, high evaporation and soil permeability. There are several natural springs in the basin, located mainly in at the south-eastern part (Ruiz-González, 2000). Most of the runoffs are intermittent, with heavy

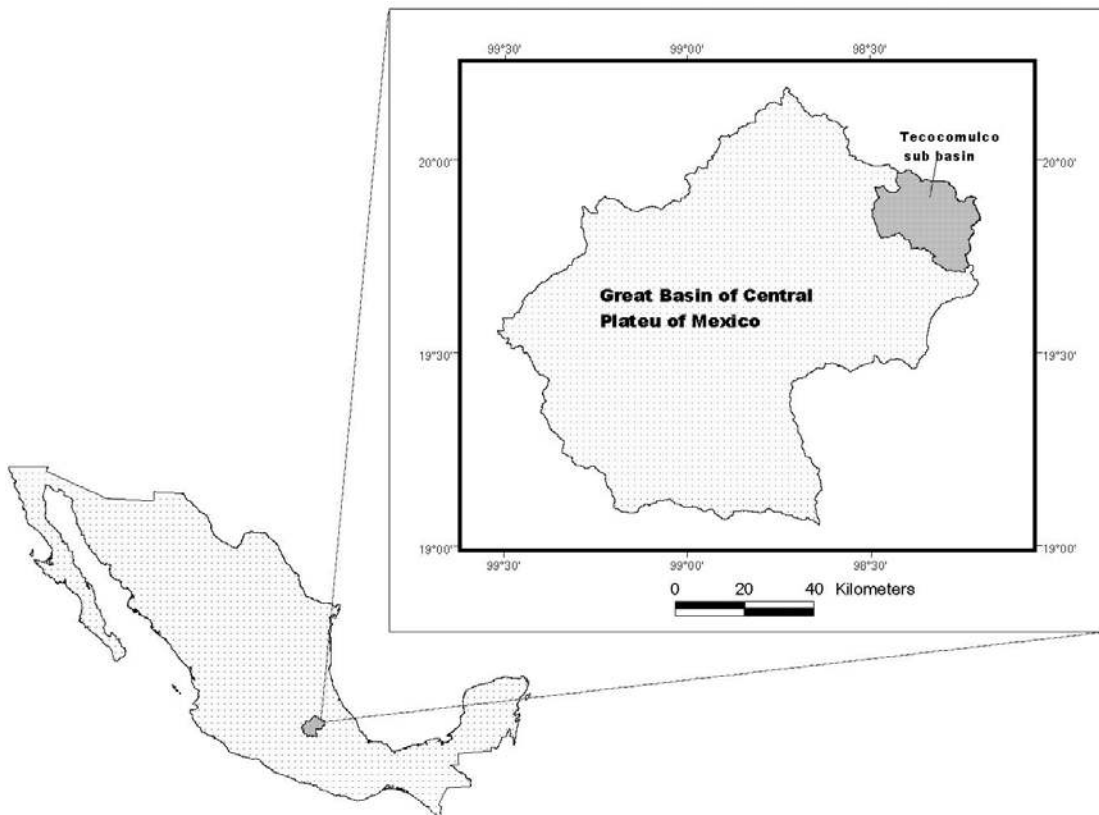


Figure 1. Location of Tecocomulco Lagoon, Mexico.

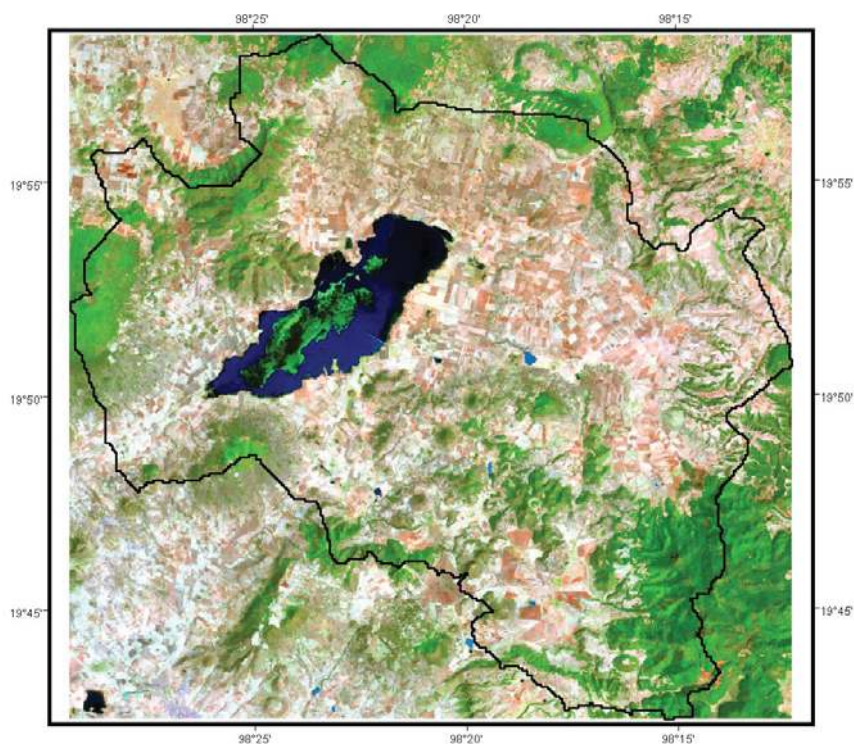


Figure 2. Landsat ETM +image of Tecocomulco Lagoon and its sub-basin (March, 2002).

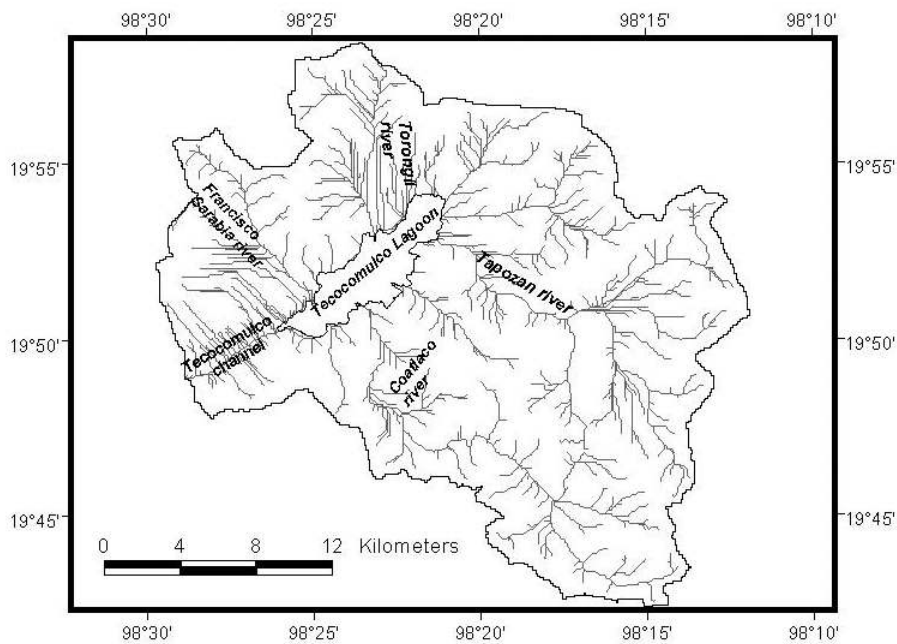


Figure 3. Lagoon of Tecocomulco with its drainage network calculated from digital elevation model.

avenues carrying large amounts of sediments from the deforested mountain slopes. Tecocomulco Lagoon receives, in average, a mean volume of water from runoffs of 1.4 million cubic meters from June to September, concentrating 88% of the drains. A decrease of 3.0 m, equivalent to a yearly average of 0.30 per year, was observed in the static level (CNA, 2002), from 1987 to 1999.

According to CNA calculations of 2002, with a precipitation of 669 mm and an infiltration rate of 2.8%, an aquifer area measuring 365.12 km² would have an infiltrated volume of 6.83 Mm³/year, plus the infiltration of superficial water which is 1.59 Mm³/year, resulting in a total volume of natural water recharge of 8.42 Mm³/year. In storage rate of the aquifer, the total input of water to the lagoon considers the 8.42 Mm³/year, and the horizontal flow of 19,35 Mm³/year, which results in a volume of 27.770 Mm³/year with the following losses or outputs: water pumped out, 13.109 Mm³; natural discharges 0.50 Mm³, = 13.929 Mm³/year.

Inputs - outputs = storage rate of the aquifer

$$27.770 - 13.629 = 14.141 \text{ Mm}^3 \text{ per year.}$$

The lagoon has an elongated and irregular shape, and a variable surface; Ruiz-González (2002) calculates a surface of approximately 27 km². Sediments have a volcanic, fluvial and windswept origin, a mixture that depends on the main activity (volcanic or weather related). The basin is surrounded by volcanoes, calderas, cineritic conus and the Tepozan and Chichicauautla Mountains (Figure 4).

There are four weather subtypes:

- a) to the south, temperate sub-humid with rain in summer.
- b) to the northeast, temperate sub-humid with rain in summer and a "canícula" (two rain periods separated by two dry periods).
- c) to the southeast, temperate sub-humid with rain in summer, and a slightly cold summer.
- d) to the west, temperate sub-humid with rain in summer, with a "canícula", slightly cold summer, isothermal (Ruiz-González, 2000).



Figure 4. Landsat ETM +image with digital model overlaid.

The highest precipitation occurs from June to September (70%), with a yearly average precipitation of 550 mm (in the plains) to 1 117 mm (in the mountains). Due to the climatic inter-annual variability and to the different methodologies used to calculate the evapotranspiration (which take into consideration: precipitation, humidity, temperature and winds, and vegetation), results in general differ widely. Nevertheless, the CNA (2002) has calculated an annual potential evaporation of 1 413 mm and a precipitation of 669 mm. Temperature varies according to topography: high in the plains and low in the mountains, with a mean yearly average of 13.5° C. The highest evapo-transpiration takes place in spring and summer, with a mean annual rate of 550 mm and a maximum in the lower region.

In 1950, the Secretaría de Recursos Hidráulicos built a canal which nowadays is silted (allowing the lagoon to maintain its volume), originally designed to allow the flow of water only when there was an excess of rain. Nevertheless, a study done by a company (Ariel Consulters, 2003) indicates that this canal still drains practically all year round, except in February and March when there is no water flow. In July and August (rainy season) it reaches up to 240-260 l/s. Agricultural workers have also built canals both for irrigation and for draining the water out of their plots, as a consequence sedimentation was promoted and a water table decreased.

The mean flow at the San Jerónimo station (SW of the study area) has been calculated in 4 098 Mm³/year (0.130 m³/s), with a run off tendency to increase, not because there is more precipitation but because there has been an increase in deforested areas that retain less water, causing the infiltration to diminish and evaporation to increase (Huizar-Álvarez *et al.*, unpublished). ROMACO (1999), indicates that the mean annual runoff is 37 336.35 Mm³, minus the 2 718.24 Mm³ mean yearly that are drained out, which leaves 34 618.11 Mm³ in the lagoon; if we subtract the amount that evaporates, which is 28,404.75 Mm³, the result is 6 213.36 Mm³ per year.

However, according to the Comisión Nacional del Agua (2002), the lagoon has a tendency to recharge naturally from water of the Tepozan Mountain; it is also estimated that the rate of recharge is higher than the rate of extraction by agricultural activities and evaporation rates. The water table is located less than five meters deep and the static depth is shallow.

MATERIAL AND METHODS

Five satellite images corresponding to the dry and rainy seasons were used to analyze and quantify the changes in the surface of the Tecocomulco lagoon. The Instituto de Geografía at the Universidad Nacional Autónoma de México (IGG-UNAM) provided three Landsat MSS images (November 23, 1973, October 30, 1985 and November 21, 1990), a fourth image –Landsat ETM+ of March 21, 2001 (all images of dry seasons)– was also provided by IGG-UNAM, and the most recent one, of the Landsat ETM+ type, was acquired by the U.S. Department of the Interior, the U.S. Geological Survey (USGS; August 2002). This last one was co-registered to the 2001 image by means of the PCI 8.0 program.

The outline of the lagoon was drawn on screen with the 73, 85, 90 and 2001 images using Arcview GIS 3.2, then the surface of the water body in different years was calculated (Figure 5).

The 2002 image was first worked with an algorithm of principal components, and, subsequently, with a non-supervised classification, to obtain not only the lagoon's outline but also for to identifying and mapping aquatic vegetation and sediments. All this was done with the ENVI 6.0 program.

INEGI's digital elevation model (DEM), with spatial resolution of 100 m, was also used to delimit the sub-basin. The flow's direction and accumulation were identified using the Arc/Info 7.2 program.

Land use and vegetation map from INEGI (1976) and the National Forestry Inventory 2000-2001 map were used to assess land use change.

The results were integrated using GIS Arcview 3.2.

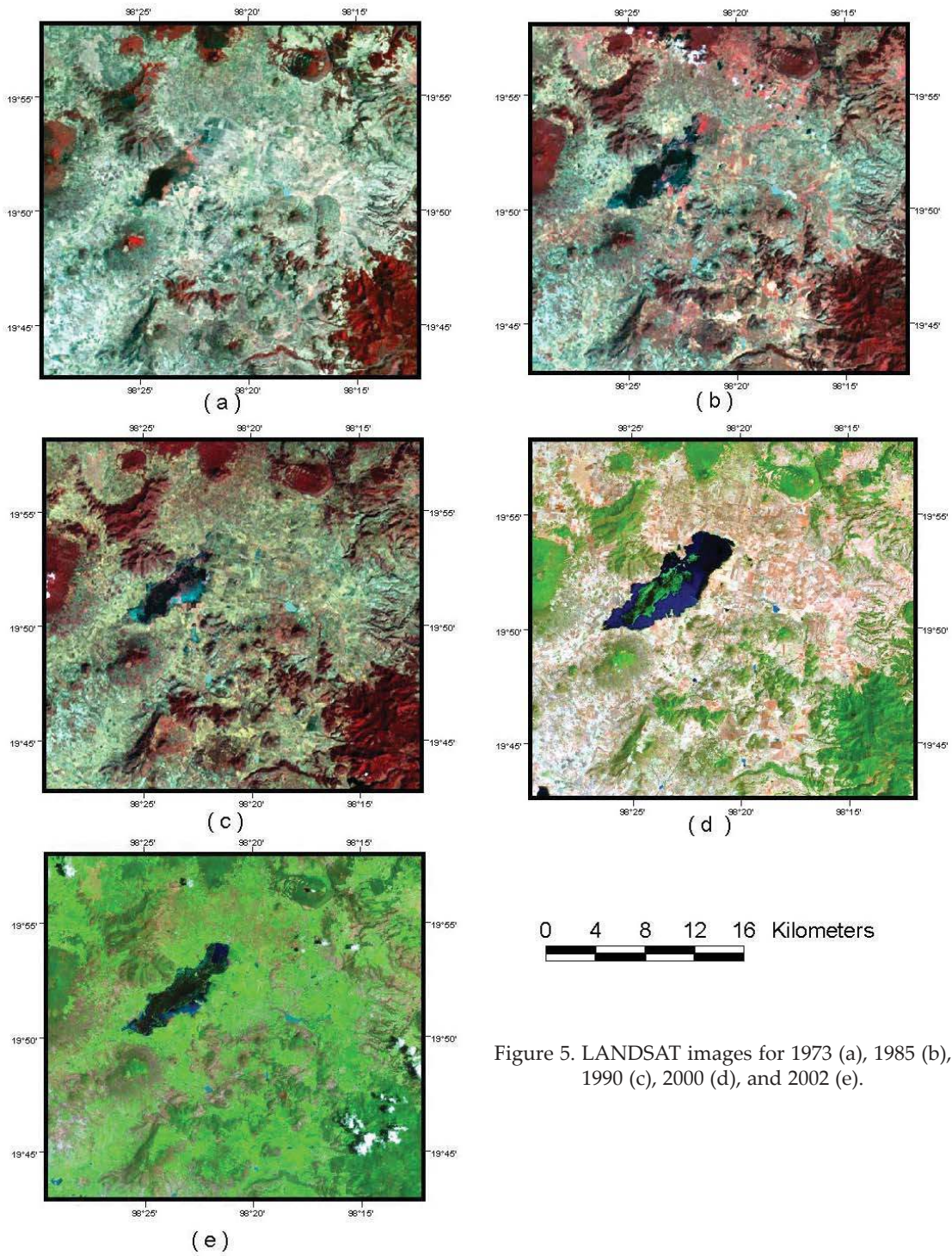


Figure 5. LANDSAT images for 1973 (a), 1985 (b), 1990 (c), 2000 (d), and 2002 (e).

- a) Landsat Image MSS, November 23, 1973
- b) Landsat Image MSS, October 30, 1985
- c) Landsat Image MSS, November 21, 1990
- d) Landsat Image ETM+, March 21, 2000
- e) Landsat Image ETM+ August 2002
- f) Landsat Image ETM+ 2002 classified
- g) Map of change land use and vegetation, INEGI 1976, 2000-2001 for the sub-basin.

RESULTS AND DISCUSSION

Changes in coverage and water volume in Mexican lagoons and lagoons have been caused by their own geological origin and evolution, as well as to the world's climate change between Eras, and, at a different time scale due to inter-annual climatic variations. In some cases, the study of the Tecocomulco Lagoon has been based on the stratigraphic analysis of the geological, structural and mineral composition, as well as on the palynological composition, all of which have provided information about long periods of time (e.g., García-Palomo and Macías unpublished; Alatríste-Vilchis *et al.*, unpublished; Caballero *et al.*, 2002; Huízar-Álvarez *et al.*, unpublished), which allow to infer that Tecocomulco originated as a paleo-lagoon during the Pleistocene Period (1.6 million years B.P.). Since 42 000 years B.P. it has experimented a series of great changes in its dimensions and the water's physical and chemical characteristics as a result of tectonics and weather.

Nevertheless, information acquired over short time periods (inter-annual) can indicate important changes in the geomorphology and dimensions of Tecocomulco lagoon, especially those related to weather and accelerated by human activities, as can be seen in four decades (Table 1).

It is remarkable that in 1973 the area was six times smaller (4.5 km²) that the surface reported by Ruiz-González (2000) in 1999

(27 km²), with the lagoon presenting a very irregular configuration. Based on the morphology presented by this author, the 1973 image (Figure 5) indicates that the area which lost the highest volume of water and was most silted was the NW area, which corresponds to the foot of the mountain, between the "La Paila" and "Del Viejo" hills (both of which belong to the Chicicuatla Mountain), the most eroded section and the source of sediments (> 12 ton/km²/year, Huízar-Álvarez *et al.* unpublished), and the place where the lagoon receives more direct tributaries. It must be said that in 1972-73 there was a strong draught associated with the "El Niño" phenomenon, (maximum) according to the NOAA scales (2004) that affected the entire country; thus, it is possible to consider that this climatic phenomenon had to do with the significant decrease in the lagoon's water. In support of this, Ruiz-González (2000) indicates that during 1996 and 1997 there was almost no rain and that in 1998 the lagoon dried completely, El Niño occurred during these years and was considered one of the most severe events in the 20th century.

The loss of water from evaporation and evapo-transpiration in anomalous years, as El Niño, must be significant not only for the lack of rain but also for high temperatures, with increases of 1 to 3° Celsius in summer, depending on the site.

According to Ruiz-González (2000), from 1981 to 1994 there was a tendency of the drain to increase, although oscillations due to draughts and severe rainfall can be associated with phenomenon El Niño that have a certain periodicity, as can be seen in Figure 6.

According to NOAA (2004) the most important climatic events are:

- 1973 El Niño (strong), high evaporation rate with a decrease in precipitation and runoff (Figure 5a)
- 1982-83 El Niño (strong), high evaporation with a decrease in precipitation and runoff.

Table 1. Variation in the flooded area of Tecocomulco Lagoon (Mexico), in five years from three decades, determined by analysis of satellite images

| Year | Area (km ²) |
|------|-------------------------|
| 1973 | 4.5 |
| 1985 | 11.3 |
| 1990 | 11.9 |
| 2001 | 35.0 |
| 2002 | 22.0 |

- 1984-85 La Niña (strong), increase in precipitation and runoff (Figure 5b).
- 1986-87 El Niño (from moderate to strong), evaporation > runoff.
- 1988-89 La Niña (strong), increase in runoff.
- 1990-93 El Niño (from moderate to strong), high evaporation rates with a decrease in precipitation and runoff (Figure 5c).
- 1995-96 La Niña (weak), increase in runoff (Figure 5d).
- 1997-98 El Niño (strong), high evaporation rates with a decrease in precipitation and runoff (Figure 5e).
- 1999-2001 La Niña (from moderate to strong), increase in runoff.

- 2002 El Niño (weak), increase in evaporation.

All this data can be compared to degree of desiccation and water cover in Tecocomulco lagoon.

The images for 1973, 1985 and 1990 (Figure 5) show that the desiccated areas which had a high degree of silting are associated with the two most important permanent rivers: the Tepozan to the east, with its water held by the Tezoyo Dam, and the Cuatlaco river to the southwest, which feeds the Benito Juárez dam. The Sarabia river, which passes through the El Viejo hill, is seasonal and feeds the lagoon only during the rainy season, as it infiltrates during the dry periods. It should be mentioned that there is a natural underground exit to the southwest, through faults and fractures.

It has been considered that the piezometric level has been variable, with zero depth at the level of the lagoon, becoming deeper as it moves away from it; this is, when the elevation increases. The Comisión Estatal del Agua del Estado de Hidalgo (2003) mentions piezometric depressions of the order of 14 cm/year indicating that there was some slight water exploitation, or less rain, between 1990 and 1997 coinciding with Ruiz-González

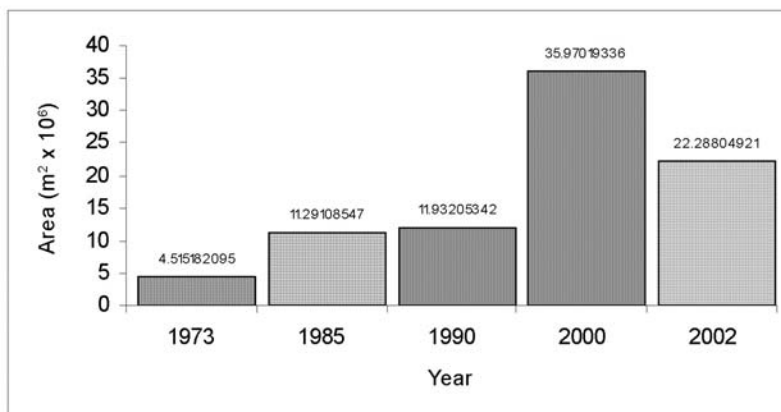


Figure 6. Coverage fluctuations calculated from LANDSAT images. Coverage fluctuations calculated from LANDSAT images.

(2000) in the lack of rain, also as a consequence of the El Niño. Present CNA's calculations (2003) regarding the balance of underground water indicate a slight over exploitation, as is shown in Table 2, and is corroborated by the piezometric depressions.

In spite of Ruiz-González (2000,) who indicates that the Cuatlaco river is the only one feeding the lagoon throughout the year, the images for 1973, 1985 and 1990 show that the place where the river discharges is also where more surface has been lost; this can be the result of water management through the dam for agricultural purposes. In 1973, the advance of agriculture in terms of land was not evident as a cause for the reduction in the lagoon's surface for irrigation purposes or for gaining land from the lagoon's own body through the construction of small dams for future agricultural areas. Nevertheless, this study –based on INEGI's cartographies of 1976, and from the Instituto de Geografía de 2000 (Figure 7)– calculates an agricultural increase of 9.3%, as is shown in Figure 8 and, precisely the region where Ruiz-González (2000) indicates, is found the highest concentration of canals built to improve the drainage from agricultural areas and to stop the water from becoming stagnant. Agricultural workers have also built small dams to hold water for irrigation, and which, once dried, will provide extra land from the lagoon, as has happened in the northeastern area. This can be seen in the 1990 and 2000 images (Figures 5).

In the lagoon's southwestern area, there is another desiccated surface that can be associated to the canal built by the Secretaria de Recursos Hidráulicos in 1953 so the lagoon could drain out when the water level rose; this place is very close to the area that remains flooded even during dry years like 1973. It can clearly be seen in Figure 9, and it demonstrates the effect of building the canal and removing sediments on the bottom. The tendency of the surface to grow (expansion from flooding but with a smaller water table and transformed into marshland) has taken place towards the northeastern area, which has a higher alluvial surface used for irrigation and seasonal agriculture.

The tendency of the drain to increase, registered by Ruiz-González (2000) in a 14 year time lapse (Figure 6), from 1980 to 1994, can be corroborated with the tendency of the flooded area to increase from 1973 to 2002 (Figure 5), as can also be seen in figure 9. In 2000, considered as a La Niña year, the surface of the lagoon was calculated on the image, as having 35 km², against the 27 km², quoted by the author. It should be said, nevertheless, that the northeastern side had a low water table, referred to as a muddy area (Figure 10) and which borders with the high density (irrigated) agricultural area as well as with the area located to northwest, in the foot of the mountain at the Chichicuautila mountain, which is smaller and has seasonal agriculture. This last area coincides with the highest input of sediments from erosion (between 3.1

Table 2. Underground water balance (mm³/year) of the Tecocomulco Lagoon (extracted from the CNA, 2003)

| Inputs | Volume mm ³ /year | Output | Volume mm ³ /year |
|---------------------|------------------------------|---------|------------------------------|
| Rain | 5.7 | Pumped | 0.5 |
| Urban Public use | 0.1 | Lateral | 2.0 |
| Agricultural Use | 0.1 | | |
| Lateral | 3.0 | | |
| Evapo-transpiration | | | 6.7 |
| Adds | 8.9 | | 9.2 |
| From storage | | | 0.3 |

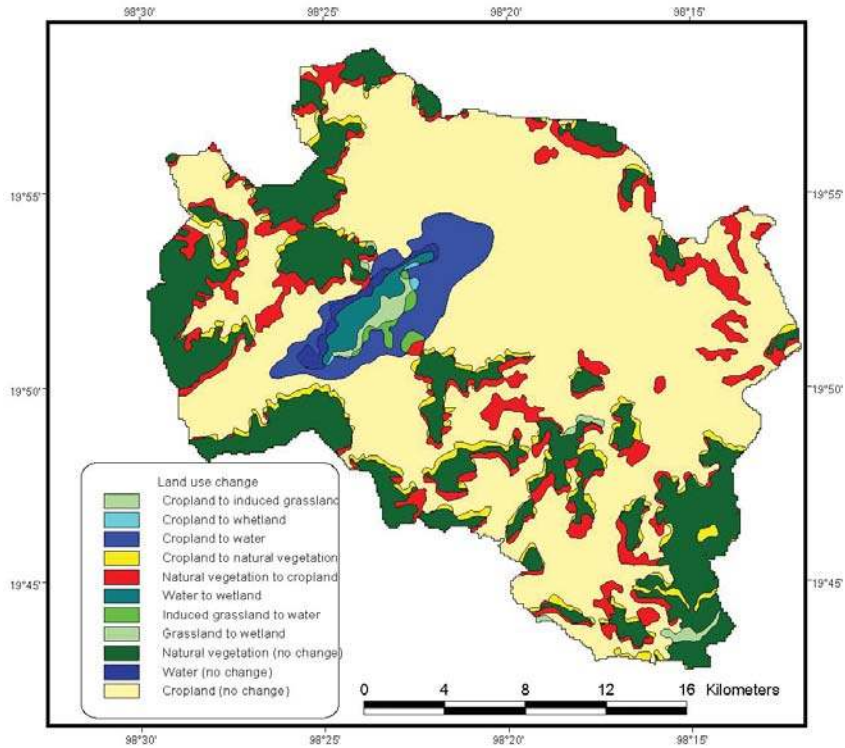


Figure 7. Land use changes in Tecocomulco sub basin from 1976-2000.

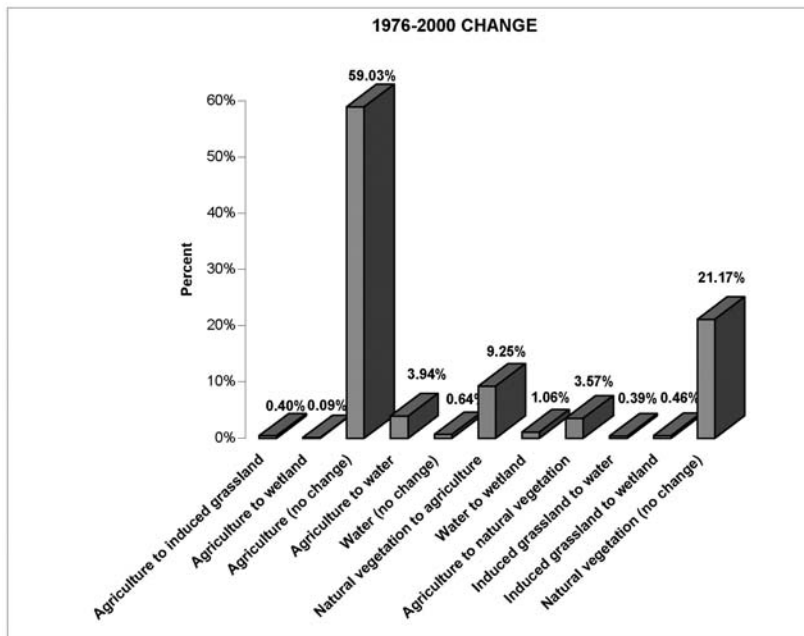


Figure 8. Land use change from 1976 to 2000.

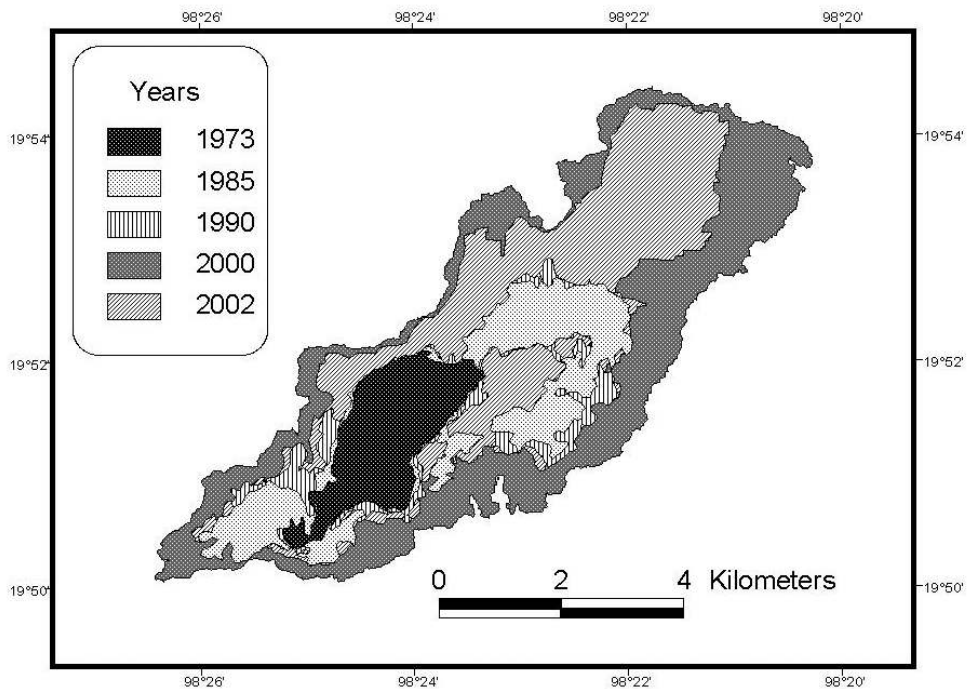


Figure 9. Coverage change of the Tecocomulco Lagoon between 1973-2002.

to 8.1-12.0 tons/km², according to Huízar-Álvarez *et al.*, 2003), seen desiccated in the 1973, 1985 and 1990 images, with high possibilities of flooding during periods of intense rainfall, and with shallow depths (muddy areas) as seen in the 2001 image (Figure 10). It is important to state that the heterogeneity in flooded and desiccated areas can be the result, among other things, of the sediments moving to form deltas at a sedimentation rate of 5.7 cm/year, as indicated by Ruiz-González (2000).

CONCLUSIONS

This study concludes that changes in morphology and surface of the Tecocomulco lagoon occur over short periods of time and are associated to weather variations and recurrent phenomena such as El Niño and La Niña; they are also a consequence of the origin of the sub-basin (volcanic), with faults and frac-

tures that have caused a significant infiltration even before deforestation took place, and to the development (in present times) of agriculture, which has increased 9.3% in three decades. By using satellite images we were able to obtain detailed descriptions of the wide variation in the lagoon coverage (which has shifted from desiccation to increase over than eight times the minimum flooded surface), the vegetation cover, the silted areas, and the encroaching of agriculture, showing a precise technique, useful not only to record all of these changes but also useful in the hydrological management of endorreic basins.

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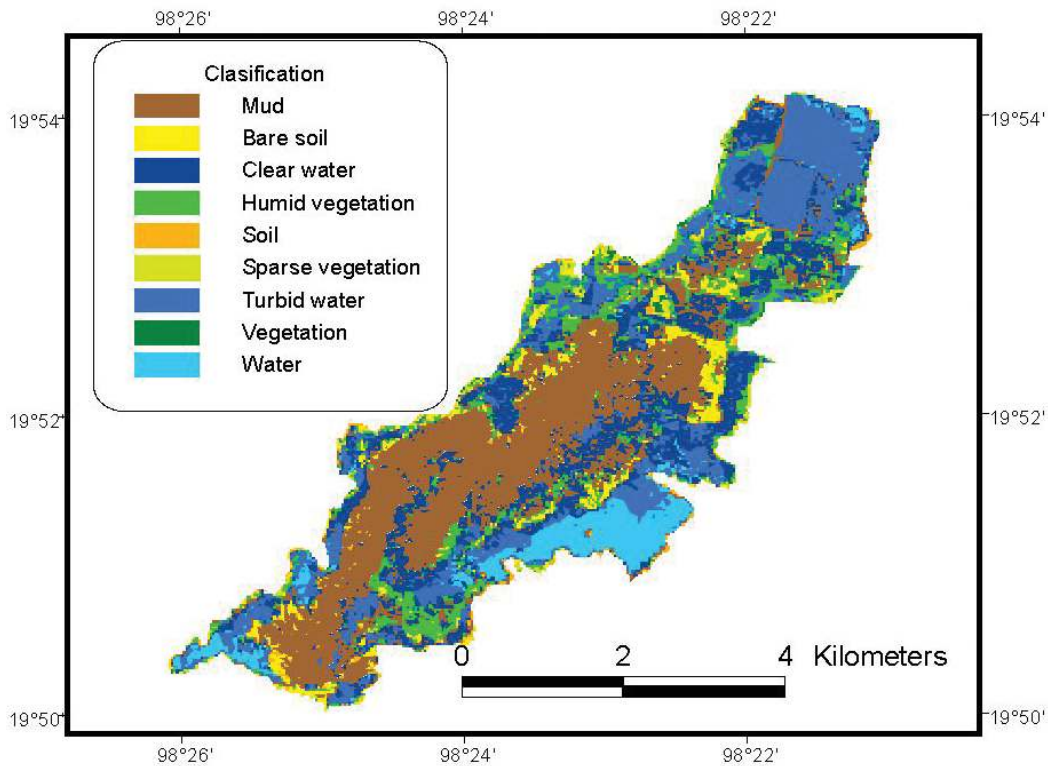


Figure 10. Classified Landsat ETM+ of 2000.

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