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Historical and recent changes in Lake Texcoco, a saline lake in Mexico

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Abstract. Historical and recent changes in the nature of Lake Texcoco, a saline lake in Mexico, are described. These changes are particularly important since they significantly affect water supply, drainage and other urban issues in Mexico City, Mexico's largest city and capital located within the general boundaries of the lake basin and gradually sinking (mean annual sinking rate is 30 cm). After brief reviews of the present status of the lake and background geological, palaeolimnological and climatic features, human activities during historical and recent times are considered. Of particular note have been drainage basin activities, diversion of inflows, pollution and over-exploitation of groundwater and biological resources (especially fish and waterfowl). The major effects of these activities are water shortages, soil erosion, salinization, dust storms, sinking ground, poor water quality and decreased biological resources. Conservation measures are discussed.

Key words: conservation, human impacts, Lake Texcoco, Mexico, saline lake

Introduction

The Valley of Mexico is an endorheic basin in the highest part of the Mexican Plateau (2,240–2,390 m.a.s.l.) between 19°01′18″–20°09′12″ N and 98°31′58″–99°30′52″ W. It is oval in shape with axes of 125 km (N–S) and 90 km (E–W) and a mean area of 9,600 km^2 (Alvarez and Navarro, 1957; DDF, 1975).

Originally, the basin was almost totally occupied (80%, approximately 7,868 km^2) by ancient Lake Texcoco. Later, it split into a smaller freshwater lake in the south (Xochimilco), and a larger saline lake, Texcoco Lake, in the north. When the Aztecs arrived in 1245, a lacustrine complex of four interconnected water-bodies was present in the Valley: Zumpango, Xaltocan, Texcoco, and Xochimilco. Through damming, Xaltocan was separated into Xaltocan and San Cristobal lakes, Texcoco into Texcoco and Mexico lakes, and Xochimilco into Xochimilco and Chalco lakes. Climatic change, drainage, and the growth of Mexico City has led to the now almost complete demise of this once huge lake complex. There remain just sparse remnants, namely fragments of Zumpango, Texcoco and Xochimilco (Alcocer and Escobar, 1990; DDF, 1975).

Control of fluctuating water-levels by the inhabitants of the Mexico basin through hydraulic works acquired great importance in Aztec times. An example of this work was the building of the Albarradón de Nezahualcóyotl dyke in the fifteenth century. This was 16 km long and 20 m wide and was constructed of stones and clay (García and Romero, 1978). It divided the saline waters of Lake Texcoco from the less saline waters of Lake Mexico, and avoided floods in Tenochtitlán from overflows of Lake Texcoco as in 1449 during the Moctezuma Ilhuicamina reign (Bribiesca, 1958a, Gurría, 1978).

With the arrival of the Spanish in 1519, many dykes were destroyed. Subsequently, not only the growth of the city but also the Spanish way of life (e.g. horse and carriage transportation instead of canoes) changed the nature of the lakes; they became less a benefit and more a problem, mainly due to floods lasting several years, the worst being in 1555, 1579–80, 1604, 1629–35, and later. Although several hydraulic works were constructed in the Colonial epoch (Bibriesca, 1958b), in the seventeenth century it was decided to eliminate the lake complex altogether.

According to Alcocer-Durand and Escobar-Briones (1992), it took four centuries and a considerable amount of hydraulic work to complete the drainage of the lakes through north-western canals. The first of five drainage canals was the Tajo de Nochistongo (the Nochistongo Cut), the construction of which began in 1609 and lasted for 25 years (Gurría, 1978). This canal was not fully effective and in 1884 the Tunel de Tequixquiac (the Tequixquiac Tunnel) was constructed (Gurría, 1978). In 1900, yet another canal, the Gran Canal del Desagüe (the Great Drainage Channel) was constructed (Lemoine 1978). It was, however, not until 1976 that drainage was completed with the construction of a second Tunel de Tequixquiac and, finally, the Sistema de Drenaje Profundo (the Deep Drainage System).

The annual rainfall on the Mexico basin is high (~700 mm); most falls in a short period and causes floods. Since colonial times therefore drainage off the basin has been a national priority. Following drainage of surface aquatic resources, groundwater became the main water supply to the city (70%). The city now requires ~60 cm^2/sec (Carabias, 1988) and groundwater extraction exceeds natural inputs. Over-explotation of groundwater has led to the compression of the clay and thus to the sinking of buildings. The sinking rate of the city now averages 30 cm per year and creates great maintenance problems (e.g. in water supply and drainage systems and building repairs).

Though water supply is already insufficient in many areas, the city continues to grow thus increasing the cost of obtaining and distributing water. Without sufficient water, industry has declined. The drainage of the lake complex has also left much derelict land. During the dry season, this erodes, creating dust storms. The problem seems insoluble given that city growth is still high and groundwater extraction increasing. The clay soil keeps compressing and the city continues to sink.

This paper provides a review of both historical and recent human activities which have led to change in the lake, and thus aims to provide a limnological perspective on the present situation. It provides brief background accounts of the present status of the lake and of major geological, palaeolimnological and climatic features, and then considers in more detail, first, the nature of human impacts upon the largely physical and chemical attributes of the lake itself, and, second, the effects of human impact upon the nature of its biology. Finally, some conservation measures are discussed.

The present situation

The natural water-bodies of Lake Texcoco at present cover 70 km^2 and comprise permanent (15 km^2) and temporary ponds and wetlands (55 km^2; CONAGUA, 1991). Recently, several reservoirs have been constructed. 'Lake' Churubusco and 'Lake' Regulación Horaria were designed as storm water regulators. The role of 'Lake' Nabor Carrillo is to store and regulate the effluent of the Comisión del Lago de Texcoco wastewater treatment plant. Lagoon Xalapango retains wastewater drainage. 'Lake' Recreativo and 'Lake' Churubusco increase the water storage capacity of the Texcoco municipality. Finally, 'El Caracol' (the Snail), a solar evaporator, is another water-body.

At the centre of Lake Texcoco itself is a large area without vegetation. This is the lowest part of the basin and is usually inundated to shallow depth (<1m) during the wet season. In the dry season, the thin (few centimetres) water layer has a salinity of up to 80–90 g L^{-1} and a crust of salts (sodium carbonate mainly, but with some sodium chloride) covers large areas (Flores, 1918; Rzedowski, 1978; SHCP, 1969). Sparse *Distichlis spicata*, *Sesuvium portulacastrum* and *Suaeda nigra* occur marginally. Although generally flat (mean slope of 0.05%), some sand dunes up to 2 m high occur and also some small depressions. The soil has an extremely high salt content (conductivity up to 200 mS cm^{-1}). Sodium carbonate, bicarbonate and chloride are the dominant salts, with a high percentage of exchangeable sodium (up to 95%). pH values are high (9.5–11), salts are significantly hydrated, and groundwater is highly saline and near the surface. Surface soil drainage is poor. Irrigation with wastewater has partially modified the physical and chemical characteristics of the soil and led to an increasing density of saline grass (*Distichlis spicata*). This protects erosion, diminishing dust storms. Nonetheless, wastewater is polluted with heavy metals and other toxic substances, thus polluting the groundwater.

Several rivers and streams discharge into Lake Texcoco. San Juan Teotihuacán, Papalotla, Xalapango and Coxcacoaco in the north-east; Texcoco, Chapingo, San Bernardino, Santa Mónica and Coatepec to the east; La Compañía (Canal de Ayotla) and Churubusco in the south-southeast; and Los Remedios and Tlalnepantla (when joined, Desviación Combinada) in the west. The north-eastern and eastern tributaries come from the Sierra Nevada and are ephemeral (Cruz, 1986), but the southern and western rivers are permanent (SHCP, 1969).

Geological features

Texcoco and other lakes of the lacustrine complex of the Mexico basin were formed by the enclosure of a depression by volcanic mountain building (Hutchinson, 1957, type 18a). The origin of the Mexican basin is discussed by Bradbury (1971), Imaz (1989), Marsal and Graue (1969), Mooser (1963), and Tricart (1985).

In brief, the bottom of Lake Texcoco arose in the centre of an extensive tectonic depression (graben) formed in the Tertiary (Balsas formation) trans-Mexico volcanic belt, and bounded on the east and west by two fault zones and their associated volcanoes, Sierra de Las Cruces and the Sierra Nevada. The Cretaceous basin was covered by continuous Tertiary volcanic activity with massive acidic laval flows. During the Miocene and Pliocene, the graben floor sank, delineating a valley that drained to the south through the Balsas River. The northern border was formed by lower mountains produced by faulting and volcanism in the Pachuca region. The valley was finally closed from the Sierra del Chichinautzin and Sierra del Ajusco at the southern frontier in the late Pliocene (700,000 years B.P.) by damming following basaltic volcanic activity. Clastic and pyroclastic material rapidly sedimented (up to 800 m) in the basin so formed, directing the drainage to the lowest portion where Lake Texcoco remnants now exist.

Palaeolimnological features

According to Bradbury (1971) and Tricart (1985), Lake Texcoco has fluctuated from deep to shallow and from fresh to salt water over time. These changes undoubtedly reflect natural climatic and hydrological changes in the Mexico basin. Nonetheless, implicated in changes since about 6,000 years ago is an additional factor, namely the impact of human agriculture.

Based on diatom palaeolimnology, Bradbury (1971) hypothesized four distinct lacustrine environments for Lake Texcoco. First, there was a large, possibly deep, cool lake with low and constant salinity as shown by the dominance of freshwater planktonic diatoms. Probably this lake had an outlet and may have overflowed. Then, through evaporation, the water-level decreased, thus increasing salinity. Texcoco became a saline lake as demonstrated by the nature of its planktonic diatoms. As water-level continued to drop, saline benthic diatoms flourished. At the lowest water-level, small saline ponds remained inhabited by saline benthic diatoms. Spring-fed freshwater marshes extended basinward from the lake's margins and freshwater benthic diatoms were deposited in the central saline pools jointly with autochtonous saline benthic diatoms. This sequence represented a fluctuation from a moister to a drier climate but was not continuous. Diatom assemblages reveal alternate stages of fresh and salt water, deep and shallow, cool and warm, slightly or clearly alkaline conditions.

Climatic features

The climate of the Mexico basin has fluctuated from moist to dry, and from temperate to warm. In recent geological times, the climate has apparently become drier, threatening the permanence of Lake Texcoco.

Today, the local climate is semi-arid, with most rain in summer, and less (5%) in winter. Temperature fluctuates widely (−11 °C to 36 °C) but averages 15.3°C. Annual mean evaporation is three times mean annual precipitation (1,801 and 600 mm, respectively), but can reach 2,454 mm. When totally filled, the evaporation rate of Lake Texcoco reaches 7 m^3/s (SARH, 1971).

The dry and rainy seasons last about six months each (from November to April, and May to October, respectively). During the rainy season, 88% of the total rainfall falls. Mean maximum temperatures are associated with the wet period, and mean minimum temperatures with the drier one.

Human impacts

In spite of natural fluctuations, Lake Texcoco continued without significant change until the arrival of human civilization in the Mexico basin. Since then, the population has greatly increased and is now almost 18 million distributed over 1,300 km^2 (INEGI, 1990a). Human activities have not only modified but almost eradicated Lake Texcoco. At the end of the century, the basin will be just a memory of a lacustrine past. Then, Mexico City will cover 2,500–2,700 km^2 (92% of the Mexico basin surface) and have 30 million inhabitants (Ezcurra, 1992).

The nature of human activities has been varied, extensive, comprehensive and invariably irreversible. Below we document the main types of activity which have impacted upon the largely physical and chemical attributes of the lake.

Drainage basin activities

The most important impact on the drainage basin has been its transformation from an endorheic basin into an exorheic one through construction of canals at the northern basin boundary which drained the once huge lacustrine complex. Natural climatic changes further modified the hydrological balance. Nonetheless, these impacts were preceded by other less extensive modifications before 1521.

The Aztecs started the desiccation of Lake Texcoco by constructing low banks, levees or large hydraulic structures such as the Albarradón de Nezahualcóyotl. The main purposes were (a) to avoid frequent Tenochtitlán floods, (b) to stop salt water from Texcoco from reaching the chinampas area located in the western and southern areas of the basin, and (c) to clean Lake Mexico by replacing its polluted water with clean freshwater from Chalco and Xochimilco lakes and discharging polluted water to Texcoco. Nevertheless, by constructing these levees, drainage was initiated (i.e. by increasing sedimentation and evaporation rates).

Together with the natural processes of desiccation (evaporation and filling), dyke construction divided the original lake into several smaller water-bodies at different altitudes. In the north, the saline lakes Zumpango (2,269 m.a.s.l.), Xaltocan (2,266 m.a.s.l.) and San Cristobal (2,266 m.a.s.l.); the freshwater Lakes Xochimilco (2,269.5 m.a.s.l.) and Chalco (2,269.5 m.a.s.l.) in the south; in the middle, the freshwater Mexico Lake (2,266.85 m.a.s.l.) on the west and the larger saline Texcoco (2,266 m.a.s.l.) in the east (Bonaparte et al., ca. 1900 in Bradbury, 1971; Flores, 1918).

Teotihuacans, in the north-eastern part of the Mexico basin near to Lake Texcoco, began the deforestation of the southern, western and eastern slopes (DDF, 1975). When the Spaniards arrived, Teotihuacán was already significantly deforested. To manufacture mortar and stucco for pyramid construction and decoration, tens of thousands tons of firewood were burned to calcine limestone. Domestic necessities (e.g. cooking) probably led to an additional loss of 30 thousand tons. Both activities led to the deforestation of large areas (Ezcurra, 1992).

The Spaniards also altered the drainage basin in several ways. Further deforestation took place to increase the area of agricultural land; exotic animals (e.g. cattle, sheep, goats) were introduced; overgrazing led to erosion; and houses were constructed on drained marginal wetlands (Imaz, 1989).

More recently, urban and industrial development has taken place on marginal lowlands (Cervantes, 1990). The urban areas were developed to provide housing for the economically disadvantaged. In the rainy season, however, these areas (e.g. Ciudad Nezahualcóyotl) are flooded. The expansion of urban areas has also displaced agriculture to the basin slopes and led to further deforestation. The chaotic construction of municipal areas to the north, east and south-east of Lake Texcoco causes urban problems. Deforestation in Mexico has grown by 1.3% a year, more than twice the world mean (0.6%) (Anon., 1992).

To avoid frequent floods in Mexico City, Lake Texcoco was progressively drained. In 1521, its area was almost 700 km^2, by 1608, it was only 410 km^2, by 1856, 350 km^2, by 1904, 267 km^2, and by 1966, only 140 km^2. The mean depth during the wet season was 5.0 m in 1800, 2.0 in 1850, and 0.5 m in 1918. Drainage of surface water has apparently led to a hotter and a drier local climate, water scarcity, dust storms and soil salinization (Bassols, 1977). With regard to dust storms, Lake Texcoco displays three wind patterns: high-altitude, low-level (2.3–4.1 m/s), and convection winds. The second and the third patterns generate dust storms. These storms are the result of two factors: the availability of great quantities of loose, fine sediments (silt and clay), and considerable wind strength. Fine sediments result from the desiccation of large areas of Lake Texcoco. Sediments are further loosened by agriculture. Low-level winds have always occurred but deforestation has increased fetch, thus velocity. Dust storms are most frequent during the second half of the dry season (February through April) when the soil is totally dry and temperatures are high. The trajectory of the dust storms is from the NE and ENE (where Lake Texcoco is located) to the SW or WSW. At least forty percent of the dust storms are generated in Texcoco itself (Mooser, 1963; SARH, 1983).

Another activity on the drainage basin of note is the development of refuse dumps. Huge quantities of domestic refuse (15,000 tons) are generated daily by Mexico city. Most is deposited in open spaces without further treatment (Carabias, 1988). Some 1,200 tons are dumped in the area surrounding 'Lake' Nabor Carrillo in sanitary landfills. This refuse comes not only from municipalities bordering Estado de México but also from the Distrito Federal.

Finally, mention should be made of the fact that Lake Texcoco was used as a source of construction material during the development of part of the Mexican railway system.

Diversion of inflows

The prehispanic inhabitants of the Mexico basin began the diversion of Lake Texcoco influents for agricultural purposes. Some dykes were also constructed for river inflow control. Around 300 AD, the Teotihuacans began crop irrigation and the construction of chinampas by the canalization of north-eastern rivers (e.g. San Juan River), streams and springs (McClung, 1979; Vaillant, 1947). This action had a small impact when compared to the deviation of the Cuautitlán River from the basin through the Tajo de Nochistongo in the 17th century by Enrico Martín. The Cuautitlán River was the most important inflow not only to Texcoco Lake but also to the Mexico basin (it contributed more than 25% of the total annual river inflow). By this deviation, lake drainage was accelerated even though more than 20 streams – most temporary – still drained into Lake Texcoco (Flores, 1918).

Until 1969, the most important inflows to Texcoco were San Juan Teotihuacán (0.192 m^3s^{-1}), Papalotla (0.387 m^3s^{-1}), Xalapanco (0.127 m^3s^{-1}) to the north-east; Coxcacoaco (0.158 m^3s^{-1}), Texcoco (0.088 m^3s^{-1}), Chapingo (0.063 m^3s^{-1}), San Bernardino (0.052 m^3s^{-1}), Santa Mónica (0.103 m^3s^{-1}), and Coatepec (0.075 m^3s^{-1}) to the east; De la Compañía (0.125 m^3s^{-1}), and Churubusco (4.399 m^3s^{-1}, mostly wastewater) to the south-southeast; and Desviación Combinada (1.538 m^3s^{-1}) to the west. Today, nine of the eastern tributaries have been illegally dammed upstream for agricultural activities or diverged to irrigate fields, and most are highly polluted with domestic and industrial wastewater (Avila, 1992; SHCP, 1969). There is a negative deficit of $57 \times 10^6 m^3yr^{-1}$; river restraint, evaporation and groundwater extraction cause this deficiency (Orozco, 1963; SARH, 1971).

Pollution

Aztec culture was a sustainable one. Small huts were built along roads where human waste was deposited and from where it was collected and transported for sale to the Tlaltelolco market. It was used for pelt tanning or as a fertilizer (Johansson, 1988; León Portilla, 1988). Nonetheless, the growth of the Aztec population and other inhabitants of the Mexico basin eventually polluted the lake complex. Lake water quality deterioration led to Moctezuma seeking consent from Nezahualcóyotl (Texcoco's ruler) to use Chapultepec springs as Tenochtitlán's freshwater supply. The pollution of the lake also played a role in Tenochtitlán's submission when the Spaniards cut off the channel that took fresh water from Chapultepec to Tenochtitlán.

Despite these early concerns, pollution of the lake continued and the lake now receives large quantities of municipal and industrial wastewater, solid residues, and other wastes. Thus, the overall effect of the high human population density and extensive industrialization of the basin is serious contamination of soil, air and water in the area. In 1990, 90% of local factories lacked pollution control systems (INEGI, 1990b) and the development of thermal inversions in Mexico city is common (5–25% of the year, Ezcurra, 1991). The latter, with dust storms and industrial pollution, cause major health problems for inhabitants of the Texcoco basin. In addition, there is a decrease in visibility for air traffic, an important fact since Mexico City International Airport is located in this region (Hiriart and Graue, 1969).

With regard to wastewater pollution, twelve streams discharge wastewater in the basin of Texcoco (INEGI, 1990b). Southern and western permanent rivers discharge a mixture of rain and wastewater (SHCP, 1969). Texcoco receives domestic sewage from Ciudad Nezahualcóyotl, Mexico City and other urban areas. Texcoco wetlands and ponds are fed by rain mixed with residual wastewaters (60%), rain water (30%), and rivers (10%).

'Lake' Nabor Carrillo is fed by the Xochiaca, La Compañía and Churubusco rivers. All are polluted with wastewaters from Ciudad Nezahualcóyotl and other urban areas of Mexico City. This hypertrophic reservoir is also polluted with heavy metals, especially zinc and lead (Vázquez, 1991).

The Churubusco River transports wastewater from the south-east of Mexico City to Texcoco. En route, it receives additional domestic and industrial wastes. With and without secondary treatment, local agriculture and industry use its water.

Residual and treated wastewaters are now important resources to Texcoco (CONAGUA, 1991). Wastewater is used to wash saline soils, notwithstanding unsatisfactory results (because when wastewater irrigation stops, salinization returns). Additionally, wastewater irrigation contributes heavy metals (lead and zinc) and other toxins (e.g., ABS – alkyl benzene sulphonates–, and boron) to soil pollution (Guajardo, 1985). Treated water is also widely used in the area.

Part of Churubusco River wastewater is secondarily treated by activated sludge treatment and facultative stabilization ponds. Removal efficiencies can reach 85–90% of BOD_5 and 99% removal of coliform bacteria. The water quality is adequate for agriculture and reduces the use of potable water for irrigation of Texcoco plantations (CONAGUA, 1991; SARH, 1988a). A tertiary wastewater treatment pilot plant was built to provide a higher water quality for Texcoco industrial, recreation, and municipal use and aquifer recharge. Water from secondary treatment plant effluents (activated sludge and facultative stabilization ponds) and 'Lake' Nabor Carrillo is used. This reservoir now operates as a stabilization pond (SARH, 1988b).

According to SEDUE (1986), Texcoco is one of the most polluted industrial areas of Mexico. The main industries are metallic and non-metallic factories, foundries, and industries producing cement, pharmaceuticals, glass, fertilizers, textiles, chemical products, sulphuric acid, paper and cellulose, automobiles, and power. The atmosphere is polluted by suspended particles (up to 300 $\mu g/m^3$, most from the erosion of dried soils), ozone and sulphur dioxide (Fuentes, 1991).

The 'Valle de México' thermoelectric power plant is probably the main source of air pollution around the area of Texcoco. It started in 1963. Fortunately, in 1990, the plant was changed to burn natural gas. Nevertheless it has been estimated that the plant daily releases 8.47 kg. SO_x and 7.77 ton NO_x to the atmosphere. The plant also contributes to water pollution by using $3.96 \times 10^6 m^3$ of deep-well and secondarily-treated wastewater in its cooling towers. The polluted water (with oil, detergents) is then discharged without additional treatment to the north-eastern area of Lake Texcoco (Mendoza, 1992; SEDUE, 1990).

Excessive exploitation of groundwater

The western part of Mexico City is in the foothills of the Sierra de las Cruces, the southern part on lava from the Xitle volcano, and the largest and remaining part is on the bottom of ancient Lake Texcoco. Over-extraction of groundwater has led to the compaction of the lacustrine clay soils and thus to the sinking of the city. In prehispanic times, Lake Texcoco was at the lowest point of the Mexico basin. In 1803, Alexander von Humbold noted that the surface of Lake Texcoco was 1.17 m below that of Mexico City (Alcocer et al., 1993a). However, Mexico City sank more than nine metres in just the first half of the last century, and the bottom of Lake Texcoco (2,234.5 m.a.s.l.) is now 3.5 m above the lowest part of the city (2,231 m.a.s.l.) (SHCP, 1969). Although the area around 'El Caracol' has sunk because of underground brine extraction, the bottom of Lake Texcoco remains above Mexico City (Hiriart and Marsal, 1969; Marsal and Graue, 1969).

In the wet season, Texcoco acts as a natural rainfall collector and indeed has been used as surface runoff impoundment. Water storage capacity was increased by the construction of a 40 km long, 1–1.5 m high artificial barrier (the Bordo Poniente along the western border, and the Bordo de Xochiaca along the southern one). This area is generally dry from February to June, and under water the rest of the year. Since the bottom of Lake Texcoco is now located higher than the city, it constitutes a potential flood generator to Ciudad Nezahualcóyotl and other low-lying areas of Mexico City. Further, while dry, the area produces dust storms, as noted.

To exploit the saline deposits (sodium carbonate and sodium chloride) of Lake Texcoco playas (calculated as 500 km^2) for industry, Sosa Texcoco, S.A., was established in 1948. Soils impregnated with sodium carbonate were washed and the washings subsequently evaporated to give crystallized salts. To do this, a subsurface (1.5–2 m depth) drainage collection system, 'topos' (moles), was dug. Brine (up to 20 g L^{-1}) was then transferred to 'El Caracol', a 9 km^2 solar evaporator, concentrated and crystallized (González, 1956; Sosa

Texcoco, S.A., undated). To enhance production, Lake Texcoco playas were partitioned by small rectangular levees.

Additionally, Sosa Texcoco, S.A., pumped brines from 25–35 m deep. It started drilling pits in 1955 and by 1988 these numbered 520. The volume of underground brine removed was more than 50×10^6 m^3yr^{-1}. Underground brine salinity down to 60 m was 54 g L^{-1}, decreasing beyond this depth to 40 g L^{-1} between 90–150 m, 2 g L^{-1} between 200–350 m, and 1.6 g L^{-1} between 213–1,884 m. This zonation probably reflects different groundwater origins. The upper layer down to 180 m is saline fossil groundwater contemporaneous to the deposit; deeper layers contain meteoric fresh groundwater which is recharged periodically (SHCP, 1969).

Subsurface canalization, levee construction, dredging and underground brine over-exploitation has led to physical damage of the basin. The most evident consequence is a differential sinking of the Texcoco area as demonstrated by the inclination of 'El Caracol' solar evaporator. At first, brine was conducted by gravity to the centre of 'El Caracol'; more recently, it has to be pumped from one evaporation pond to another.

Highway construction

Finally, the construction of a highway from Peñón to Chinconcuac, crossing the Texcoco ecological rehabilitation area, is being considered by the government (CONAGUA, 1991). This highway will have a significant environmental impact on the first Mexican attempt at ecological rehabilitation of a degraded environment. Thus, noise (90–100 dB) will be produced by an estimated traffic of 2,000 to 5,000 vehicles per hour. Noise will disturb wildlife, so modifying their areas of feeding, mating, reproduction and nesting. Further, although access to the area undergoing rehabilitation is restricted, all highway travellers will have uncontrolled access; wildlife will be exposed to predation, illegal capture, hunting, and other disturbances. Pollution will be another consequence of highway construction. Garbage, gravel, powdered asphalt, oilcloth, soot, CO, NO_x, SO_x, etc. will impact the environment, so contaminating water, air and soil. Aesthetic pollution also will occur.

The effects of human impacts on lake biology

Humans arrived in the Mexico basin some 22,000 years ago. Since then, populations have expanded to the south and north-east. The Indian population established in the basin was so large that to get enough food it applied enormous pressure on the aquatic biota through fishing, hunting and collecting. Lacking large terrestrial herbivores in the area, fish, waterfowl, amphibians, reptiles, crayfish, and aquatic insects were extensively exploited as a protein supplement. The growth of the population, however, exceeded the productivity of the basin, and its maintenance capacity. This led to more than one period when natural resources were severely impacted by either humans or natural events (e.g., volcanism, climatic changes) in the basin (Ezcurra, 1992).

Obviously, desiccation has been the main impact upon the aquatic biota. The drastic modification of the hydrologic balance, initiated with the Tajo de Nochistongo, adversely altered the regional ecology and caused the extinction of most of the natural resources, thus affecting both the ecological and socio-economic equilibrium (Leyva, 1985).

From classical texts and the literature, we know that the Mexico basin was inhabited by a rich diversity of aquatic biota. Many taxa have been depicted and described (see Alcocer-Durand and Escobar-Briones, 1992; Alcocer et al., 1993a). Moreover, Deevey (1957) referred to the first representation of a corixid in a Nahuatl text. Several species that have diminished or disappeared from Lake Texcoco, such as those of crayfish, frogs, molluscs, turtles, water snakes, salamanders, fishes, and others have also been recorded (Alcocer and Williams, 1993). Unfortunately, such studies are merely taxonomic descriptions and do not allow for any evaluation of biotic resources.

Among typical Mexican fishes, *Girardinichthys viviparus* (Goodeidae) or yellow fish, and the silverside *Chirostoma jordani* (Atherinidae) used to be abundant not only in Lake Texcoco but also in the whole lake complex. Now, they are threatened by over-fishing (Granillo, 1985; Leyva, 1985), habitat reduction and pollution. Fortunately, they still inhabit a few places. Although 'Lake' Nabor Carrillo is one such place (*G. viviparus*), pollution endangers its survival. Both species are also living – at least in 1992 – in Chapultepec lake (Alcocer-Durand and Escobar-Briones, 1992; Alcocer et al., 1993b); however, their existence has been jeopardized by the introduction of *Tilapia* and carps by the Mexico City government to promote public relations.

Probably, the most significant biological resource in Lake Texcoco is its waterfowl. Sixty-eight waterfowl species have been recorded, plus sixty-five associated with marginal wetlands. Thus, avian richness is 133 species. Although bird numbers are augmented in autumn and winter by the arrival of migratory birds from Alaska, Canada and United States (SARH, 1987), the highest number of species and individuals is reached in the first half of spring (Chávez and Huerta, 1985; González, 1985). Before 1985, the number of migratory birds reaching Texcoco was estimated at less than 20,000 individuals, but after 1985 the number has increased to at least 350,000 individuals annually (Valero, 1985).

Currently, planes at Mexico City International Airport landing on the dried bed of Lake Texcoco disturb birds through noise and pollution. However, illegal hunting on wetlands also threatens the rich avian resource. Local people have developed an ingenious lethal weapon for bird hunting, the 'armadas'. These consist of several tubes (up to 100) loaded with gunpowder and birdshot or grapeshot that work as a primitive rifle. The tubes are located in three series: the first, parallel to the water surface, the second, at an acute angle, and the third, at 90°. The weapon is carefully hidden near the water's edge. At dawn, the birds are attracted with baits until several arrive. Then the first series is fired to kill or wound as many as possible; those not reached by the first discharge are caught by the second or the third. Most birds are wounded and then killed. This hunting technique kills many non-edible birds, thus affecting the whole avian community. In spite of the increased number of birds in recent years, bird numbers have decreased compared to numbers at the beginning of the century. Although Lake Texcoco represents the most important faunistic refuge to waterfowl in the Mexico basin (SARH 1987), it is certainly not a safe one because bird hunting clubs have increased their membership.

Around the 1970s, many people exploited aquatic resources other than waterfowl, such as the 'axayacatl' and the 'ahuautle'. The first is corixid adults (Insecta: Hemiptera), the second, their eggs. 'Axayacatl' is sold as bird food and is most abundant from August to November. The 'ahuautle' is a typical Mexican Holy Week dish, and can fetch a very high price. The eggs are deposited on submerged *Distichlis spicata* put in place for this purpose (Alcocer-Durand and Escobar-Briones, 1992; Hutchinson, 1993). Another resource is the 'acuitzil', *Cambarellus montezumae* (Decapoda: Astacidae); it is eaten as food. Over-exploitation and habitat reduction are again the reason for the decline of these biotic resources. Another over-exploited biological resource is the famous 'axolotl', the ambystomatid salamander *Ambystoma velasci/lacustris*. The type locality of this species is Lake Texcoco (Brandon, 1989).

Adults and larvae of *Ephydra hians* (Diptera: Ephydridae), amphipods *Gammarus* spp. (Gammaridae) and *Hyalella azteca* (Talitridae), and cladocerans (Daphniidae) used to be abundant in the shallow waters of the lake. Although not yet exploited, they could be considered a potential resource. They too are endangered.

Spirulina geitleri (Cyanophyta: Oscillatoriaceae) was cultivated in the external ponds of 'El Caracol' solar evaporator until Sosa de Texcoco, S.A., ceased operations in 1994. 'El Caracol' is regarded by Margalef (1983) as an example of a sodium carbonate alkaline lake exploited by *Spirulina*. Finally, the fairy shrimp, *Artemia franciscana* (Crustacea: Anostraca), of considerable aquacultural value, is also cultivated in Lake Texcoco.

All these biological resources are threatened by pollution of the natural or artificial water-bodies of Texcoco (Esquivel, 1989).

Conservation measures

Several measures have been proposed over the past century or so designed to conserve Lake Texcoco. In a journey from Puebla to Mexico City, Maximilian of Habsburg, the first Mexican emperor (1864–67), proposed the earliest one. His proposal was to preserve the lake as a tourist attraction (as a hunting preserve and refuge) for European noblemen. It was unsuccessful. In 1884, the government took possession of 2.200 km^2 on the eastern side of the ancient Mexico City (the area of Lake Texcoco and its surrounding land). The former president of Mexico, Francisco I. Madero (1912), decreed the land gained by the drainage of Lake Texcoco be national property and fixed a maximum level for the lake of 7.1 m (2,237.5 m.a.s.l., 270 km^2, 171×10^6 m^3 volume) above the minimum altitude of the basin.

In 1914, the Mexican government attempted to afforest the exposed northern regions of Lake Texcoco by creating the Nezahualcoyotl Reserve. However, in 1919, President Venustiano Carranza authorized the leasing of this region because of its agricultural inadequacy and the failure of the afforestation program. Nevertheless, this decree was rescinded by him the next year. During the presidencies of Emilio Portes Gil (1928–30) and Pascual Ortíz Rubio (1930–32), there were two additional and unsuccessful efforts to afforest the dried portion of Lake Texcoco. Between 1934 and 1939, the lake's surface and volume was reduced (170 km^2, 101×10^6 m^3) and its shoreline restricted to its modern boundaries by building two low-level dams, Bordo Poniente to the west and Bordo Xochiaca to the south (León, 1993; SHCP, 1969).

Water scarcity, soil erosion and salinization, the generation of dust storms, pollution and sinking ground led the Mexican government to establish, through the Secretary of Agriculture and Hydraulic Resources, the Comisión de Estudios del Lago de Texcoco (CELT) on March 19, 1971. Two years later (January 2, 1974), this commission was designated the 'Comisión del Lago de Texcoco', now the 'Proyecto Lago de Texcoco'. The main goals of this commission are the ecological regeneration of the Lake Texcoco basin, the conservation of water resources within the Mexico basin, the reduction of environmental pollution, the control of dust storms, and the provision of water to marginal towns and municipalities, industries and agriculture (Cardenas, 1985). Additionally, the commission seeks to provide a natural area to counteract industrial and urban pressures through recreation and environmental education to the inhabitants of Mexico City.

Some further actions are also planned (CONAGUA, 1991). One of the most important aims is to reduce wind erosion. The only way to protect highly saline areas from this is by permanent inundation. Other areas can be covered with different plants according to soil characteristics. Areas of moderate salinity, but unsuitable for agriculture, can be protected by salt tolerant pasture such as *Distichlis spicata*, *Suaeda nigra*, *Sesuvium* or *Atriplex*. Agriculture is the solution for the less saline soils, but it is neccesary to rotate crops. Elsewhere, erosion can be reduced by decreasing wind action by planting barriers of trees and bushes perpendicular to the direction of the prevailing winds. The most effective plant species that have been considered as tolerant to drought and saline soils include *Eucalyptus*, *Prosopis juliflora*, *Schinus moble*, *Opuntia*, *Acacia* and *Equisetum*. Two plant nurseries, 'La Almeya' and 'El Ranchito', have been created to aid the afforestation program. To build windshields, vegetation is being planted both within Lake Texcoco and along numerous tributaries. Soil improvement is also encouraged. Overgrazing is prevented by constructing enclosures or fences (Herrera, 1985a,b).

Another important activity related to water conservation and multiple use is the rehabilitation of natural and artificial reservoirs and the development of new ones. Finally, to reduce domestic demands, the use of wastewater and treated water for irrigation purposes or underground water recharge is being encouraged.

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