Environmental Effects of Aquifer Overexploitation: A Case Study in the Highlands of Mexico

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ABSTRACT / There are several environmental processes occurring under aquifer overexploitation conditions. These processes include groundwater table decline, subsidence, attenuation and drying of springs, decrease of river flow, and increased pollution vulnerability, among others processes. Some of these effects have been observed on the Upper Basin of the Lerma River. The Lerma River begins in the SE of the Valley of Toluca at 2,600 m asl, in the wetland known as Lagoons of Almoloya del Río. This wetland is made up of a group of lagoons, which are an important aquatic system from an environmental point of view. The water inflow of this wetland is a discharge of springs, which occur between the fractured volcanic material of the mountain range and granular volcanic–continental deposits of the Valley of Toluca aquifer. The intensive exploitation of the Valley of Toluca aquifer to supply urban and industrial water to Mexico City and Toluca began in 1950 and is responsible for a steady decline of piezometric levels of 1–3.5 m/yr. Other effects of this exploitation—the drying of the wetland, the decrease of river flow and the land subsidence— caused serious ecological and social impacts. The authorities declared this aquifer as overexploited in order to reduce the exploitation and preserve the availability of water resources in this important region.

The environmental impacts of aquifer overexploitation have been observed in numerous places around the world (Llamas 1992). In these places, the adverse consequences have been proven, one of the most important being the desiccation of wetlands and rivers, with subsequent loss of the aquatic ecosystem, which is of great ecological value due to its wide biodiversity (Rodriguez-Estrella and Lopez-Bermudez 1992, Martinez-Alfaro and others 1992, Cruickshank 1995). Other effects are a decline in the groundwater level, subsidence, the drying-up of springs, a decrease in river flow and a deterioration of water quality, among others (Martinelli and others 1998, Celik and Afsin 1998, Scott and others 1999).

The region of the Upper Course of the Lerma River (Central Mexico) is a representative example of the overexploitation problem. The Upper Course of the Lerma River, giving rise to the Upper Basin of the Lerma River, is situated in an area known as the Mexican Highlands (Figure 1). This area is an important center for industrial and agricultural activity, with a high population density and enormous demands for water, which are being met almost exclusively from groundwater. Moreover, added to this problem, is the exportation of groundwater from this basin to Mexico City, for part of the city's water supply. This water exportation to Mexico City is done at a rate of 14 m³/sec, a volume taken from the aquifers of the valleys of Toluca and Atlacomulco-Ixtlahuaca, both located in the Upper Basin of the Lerma River. Of these two valleys, the one subject to greater exploitation is the Valley of Toluca (CCRECRL 1993).

The lagoons of Almoloya del Rio are located in the Valley of Toluca (SE sector), giving rise to the Lerma River, and make up the only natural wetland of the Upper Basin of the Lerma River, situated at an altitude of 2237–2600 m asl.

These lagoons have, for many centuries, represented a way of life for the inhabitants of the area as their activities were based on hunting, fishing, and gathering of aquatic flora and fauna. On the other hand, this area is an important natural reserve, because of its biodiversity (Albores 1995, CCRECRL 1997, Boehm and Sandoval 1999).

The deterioration of the ecosystem of the Lagoons of Almoloya del Rio is related to the exploitation of the groundwater resources at rates higher than the natural recharge, giving rise to the overexploitation of the Valley of Toluca aquifer.

This paper aims to establish, in the most pragmatic possible way, the effects of the overexploitation of the

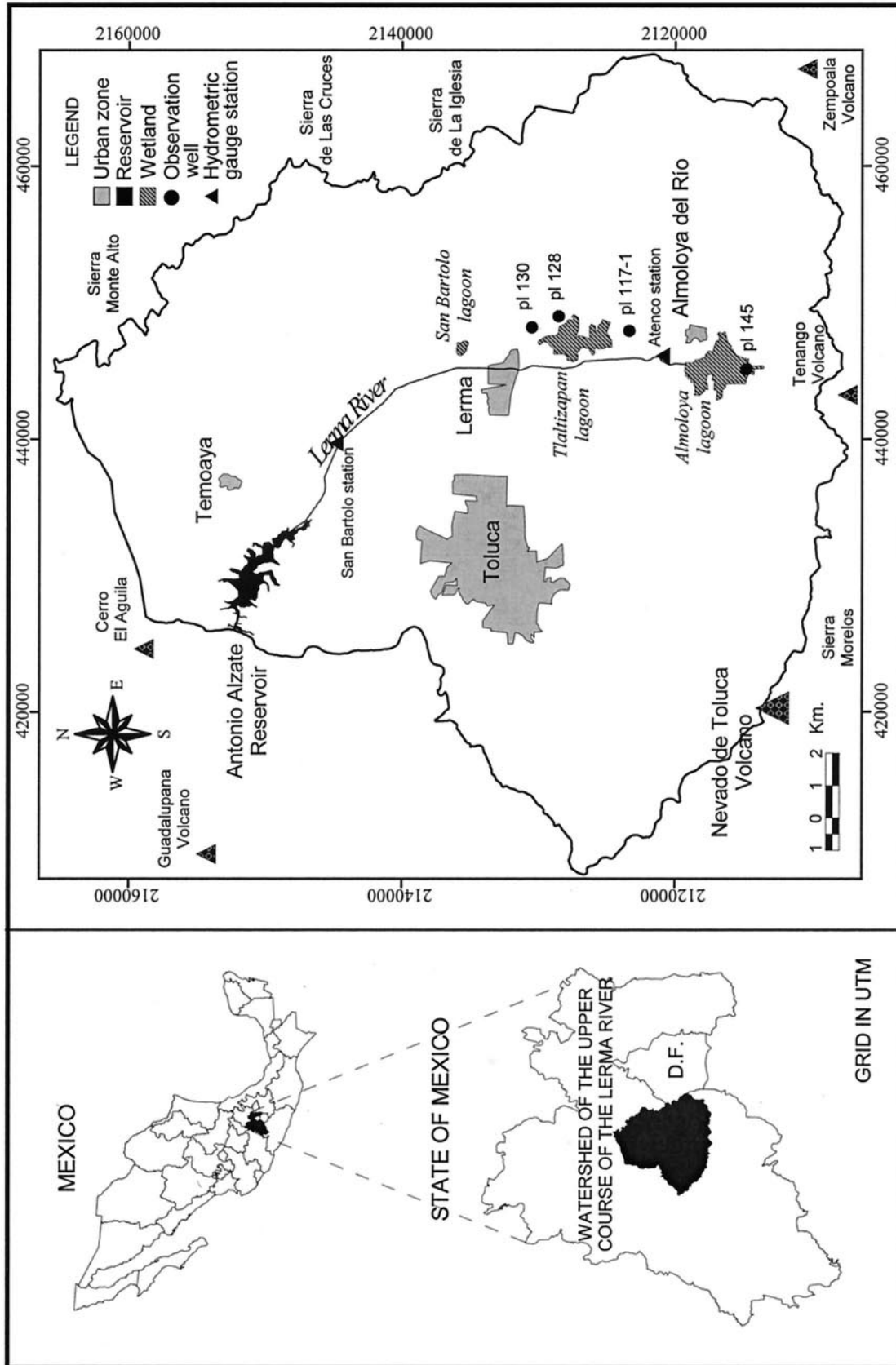*Author to whom correspondence should be addressed; e-mail: esteller@coatepec.uaemex.mx

Figure 1. Location of the State of Mexico, showing the Upper Course of the Lerma River, the Lagoons of the Almoloya del Rio, and the observation wells locations.

aquifer on the wetland, on the Lerma River, as well as on the land subsidence.

Materials and Methods

One of the main initial stages for analysis of the basin's functioning is a physiographic understanding of the basin. In this paper, the physiographic characteristics of the watershed were obtained through digital elevation model (DEM) processing with a resolution of 90 m. The information source corresponds to the contours on the geographic map of the State of Mexico (IGECEM 1995). The DEM of the Upper Course of the Lerma River, where the Valley of Toluca is located, was produced through GIS Arc/INFO software, ver. 7.1.2 [Triangular Irregular Network (TIN) module] and ArcVIEW 3.0a.

For the study of the piezometric evolution of the Valley of Toluca aquifer data from the existing piezometric monitoring network, 66 observation wells, run by the National Water Commission [Comisión Nacional del Agua (CNA)], were used. In addition, hydrometric data from the Atenco and San Bartolo gauge stations, located in the wetland area, also operated by the CNA, were used.

In order to determine the flow of the Lerma River up to the limit of the José Antonio Alzate reservoir, a hydrological estimation was carried out, based on the data from the three hydrometric gauge stations that are found in the basin above the reservoir, as there is no one station that is pertinent for the whole tributary area. The time period for records used corresponds covered 1974–1990.

The evolution over time of the wetland surface area was based on aerial photographs (1970 flight, scale 1:25,000; 1971 flight, scale 1:10,000; 1989 flight, scale 1:5000; and 1995 flight, scale 1:5000) and orthophotos (1983 flight, scale 1:10,000; 1989 flight, scale 1:5000; and 1995 flight, scale 1:5000).

Field surveys were also carried out to locate and geoposition cracks and differential collapses of the land.

Study Area

Geographic–Geologic Framework

The Valley of Toluca is located in the central area of Mexico, more specifically in the central zone of the State of Mexico, and is one of the highest in elevation in the Mexican Highlands. The Valley of Toluca, located in the Upper Course of the Lerma River (Figure 1), has an average elevation of 2570 m, up to the José Antonio Alzate reservoir, which is the first receiving body for water coming from the Lerma River. At ap-

proximately 9 km downstream from the dam, at an altitude of 2570 m, the Upper Course of the Lerma River ends where the tectonic steps of the Valley of Atlacomulco-Ixtlahuaca descend (CCRECRL 1997).

The Valley of Toluca covers an area of around 700 km^2, with the main axis running north–south with a length of almost 35 km, and the shorter axis running east–west about 20 km. The northern borders are the Guadalupana volcano, the Cerro El Aguila, and the Sierra Monte Alto; to the south the Tenango and Zempoala volcanoes; to the east the Sierra de Las Cruces and La Iglesia; and to the west the Nevado de Toluca and Sierra Morelos. Figure 2 shows a relief map of the watershed of the Upper Course of the Lerma River. The energy in the relief shown in the southern portion should be noted, from the Nevado de Toluca volcano, and on the eastern side, due to the presence of the Sierra de Las Cruces.

The Upper Course of the Lerma River is located in tropical latitudes (parallels 19°05' and 19°50'N), but its high altitude, as well as the adjacent mountains (Sierra de Las Cruces and the Nevado de Toluca), and without continental climate characteristics give rise to a more temperate climate—semicold and cold. The average monthly temperature varies between 5°C (at places above 3000 m in altitude) and 20°C (areas situated in the valley). The rainy season starts in the mid-May and lasts until mid-October. Average annual precipitation is highest on the sides of the Nevado de Toluca, where isohyets of 1200 mm can be found, decreasing towards the valley with averages of 900 mm. The highest records of precipitation come in the month of June, after this month there is a lack of rain, which generally coincides with the month of August; this period is called the mid-summer draught. Using Köppen's climatic classification (Miller 1982), the Valley of Toluca presents a C(w2)(w)bi(g) climate, which corresponds to a subhumid temperate climate, with a long summer, winter rain of less than 5%, isothermal and maximum temperatures before the summer solstice.

The area under study is located specifically in the physiographic province called the Neovolcanic Transmexican Axis (Deman 1976), an area made up of a strip of volcanic material, calcoalkaline type, whose age dates it in the Upper Cenozoic. The lithological sequence is made up of various types of tertiary volcanic rocks, mainly basalt and andesite, as well as pyroclastic matter and breaches, abundant in the mountain ranges surrounding the valley (Figure 3). Lacustrine and alluvial sediments can be identified in the valley and are interspersed with clastic deposits of volcanic origin. The age assigned to these deposits is Late Pliocene–Quaternary (Honorio and Hernandez 1982, Herrera and Sánchez 1994).
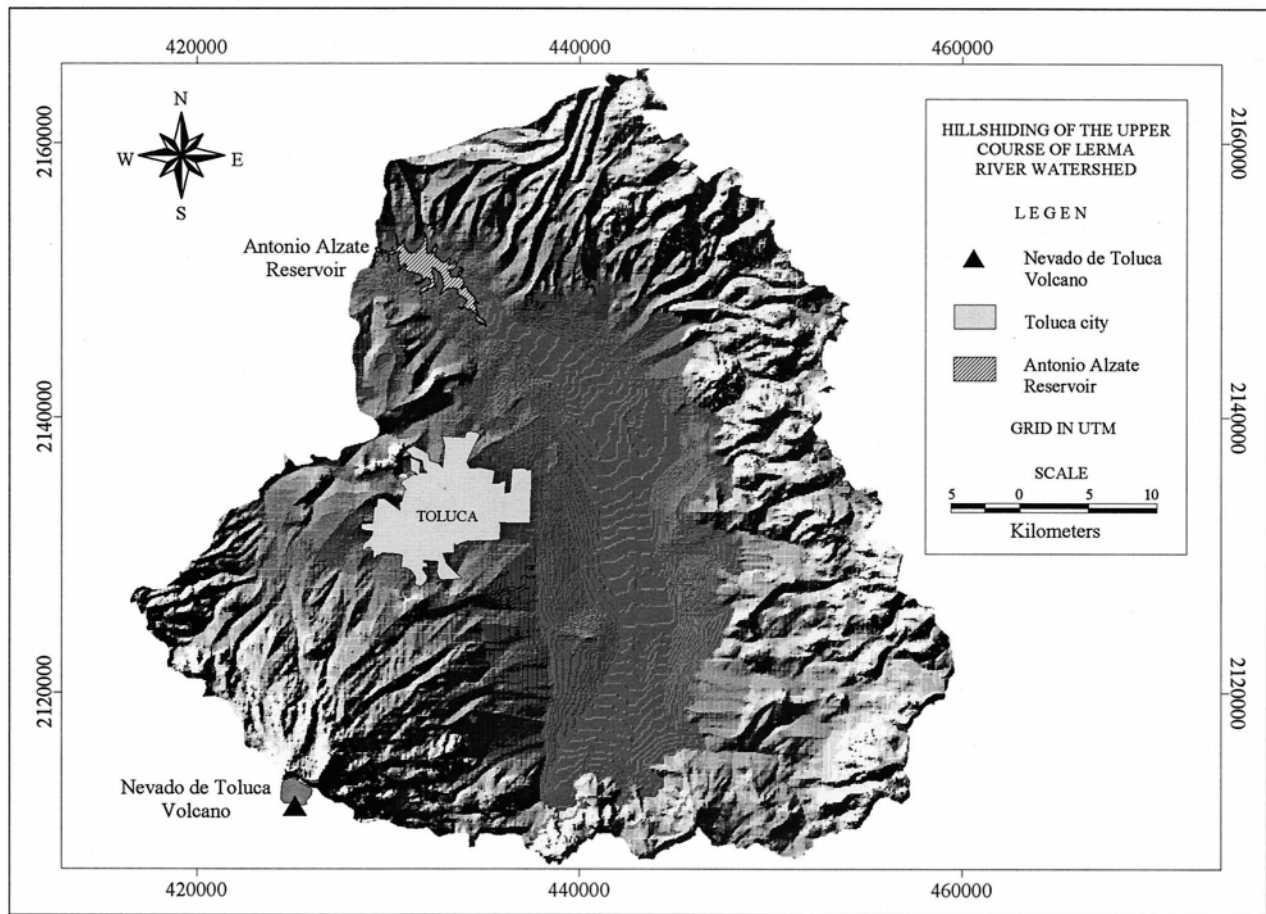
Figure 2.   Relief map of the watershed of the Upper Course of the Lerma River.

Surface hydrology and hydrogeology

The data obtained from the DEM allowed the definition of the main physiographic features of the Upper Course of the Lerma River. Table 1 shows the results obtained in estimating these features.

For the period 1974–1990, the annual volume of Lerma River for a dry year (1982–1983) was 98 hm^3/yr, for a wet year (1976–1977) 267 hm^3/yr, and for an average year 171 hm^3/yr, with minimum volume in March and maximum in September (Figure 4).

With reference to the hydrogeology, it must be pointed out that two aquifers can be defined in the basin, the border aquifer, made up of fractured volcanic rocks, which form the mountainous elevations, and the valley aquifer, formed by granular materials of volcanic-sedimentary origin. The clastic aquifer, known as the aquifer of the Valley of Toluca, is made up of material which is noticeably heterometric, with a predominance of gravel, sands, and conglomerates with lime–clay matrix, although intercalations of pyroclastic and tuff layers can be distinguished.

The clastic materials rest on a base of consolidated volcanic matter of a variable nature, predominantly basalt and andesite (Unitecnia, 1996). These basalts and andesites represent a continuation of the volcanic deposits that form the mountain ranges and make up the fractured aquifers whose main function is to recharge the Valley of Toluca aquifer.

The hydraulic parameters of the aquifer of the Valley of Toluca cover a wide range of values, due to the lithological and geometric variability of the deposits. However, it is possible to differentiate areas with a transmissivity function: the area corresponding to the foot of the mountain Sierra de Las Cruces (NE), with values that reach up to 13,000 m^2/day, the Lerma sector (S) with a mean transmissivity of 950 m^2/day, the area of Almoloya del Rio (SE) with values around 22,000 m^2/day and the central section with a transmissivity that varies between 90 and 400 m^2/day. The storage coefficient fluctuates between 0.3 and 0.9% (CCRECEL 1993).

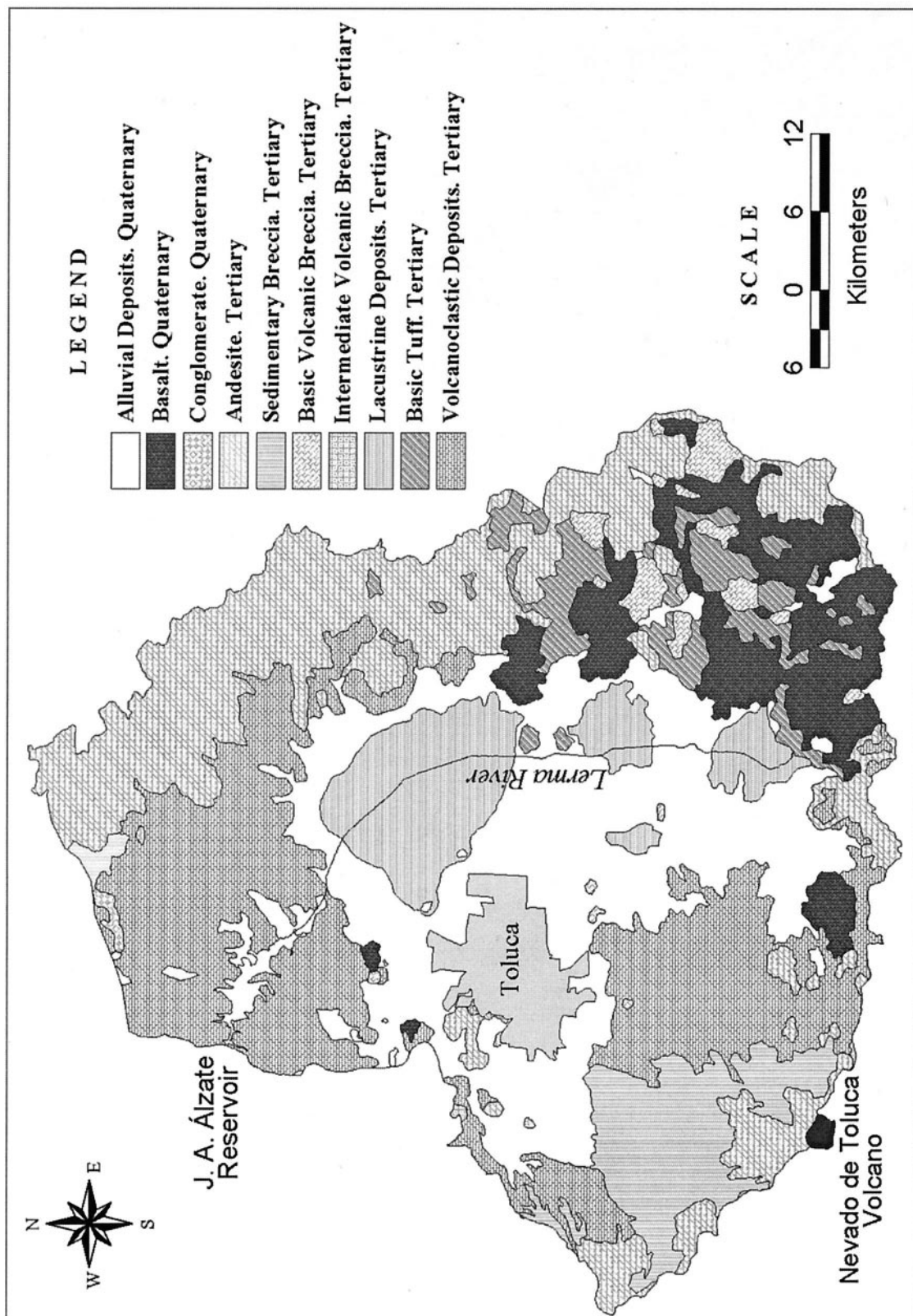The system is made up of various levels of superimposed aquifers that come together to make up a mul-

LEGEND

Alluvial Deposits. Quaternary
Basalt. Quaternary
Conglomerate. Quaternary
Andesite. Tertiary
Sedimentary Breccia. Tertiary
Basic Volcanic Breccia. Tertiary
Intermediate Volcanic Breccia. Tertiary
Lacustrine Deposits. Tertiary
Basic Tuff. Tertiary
Volcanoclastic Deposits. Tertiary

SCALE

6   0   6   6   12

Kilometers

J. A. Álzate Reservoir

Lerma River

Toluca

Nevado de Toluca Volcano

N
E
S
W

Figure 3. Simplified geological map of the watershed Upper Course of the Lerma River.

Table 1 Physiografic characteristics of the watershed of the Upper Course of the Lerma River

Upper Course of the Lerma River watershed		Comments
Surface and perimeter	$S = 2117.88 \ km^2$ $P = 241.79 \ km$	The surface (S) and perimeter (P) of the watershed was obtained under the use of GIS and DEM.
Coefficient of compactness	$K_c = 1.481$	The obtained value of compactness coefficient indicates that the river watershed tends to a square.
Circularity ratio	$R_{ci} = 0.455$	This coefficient corroborates the proximity of the form of the watershed with a square.
Length ratio	$R_e = 1.07$	In agreement with the obtained value it is inferred that the watershed is predominantly flat but with portions with important slopes values.
Hypsometric curve	$H_{max} = 4{,}549$ masl $H = 2{,}848$ masl $H_{min} = 2{,}556$ masl	From this analysis the maximum (H_{max}), minimum (H_{min}) and average ($\bar{H}$) altitude of the watershed were obtained. In agreement with the form of the hypsometric curve it is inferred that the watershed is an eroded one and could be classified as a valley.
Watershed slope	$\bar{m} = 8.54\%$ $m_{min} = 0.00\%$ $m_{max} = 50.00\%$	The average ($\bar{m}$), minimum (m_{min}) and maximum (m_{max}) watershed slopes were obtained. The analysis of slope ranks inferred that the 52.52% of surface is classified as flat with smooth slopes, the 30.15% as smooth to medium sloped, 11.33% is strongly sloped and 8% as steep land.
Drainage characteristics of the watershed	$\overline{Rb} = 4.36$ River order: 5 (Horton-Strahler)	The value of the average ratio of bifurcation ($\overline{Rb}$) of the channels is 4.36. With this value of bifurcation, it is said that the geologic structure of the watershed does not distort the drainage model.
Main river characteristics	$L = 50.2 \ km$ $S_{river} = 0.11\%$ $S_h = 1.16$	In the case of the Upper Course of the Lerma River, from its origin to the Alzate dam, the river has a length of 50.2 km and an average slope of 0.11%. The river presents a hydraulic sinuosity of 1.16. Since the value of the hydraulic sinuosity is little than 1.25 and that length of the reach is greater than ten times the cross section of the channel, is said to be in a straight river.

tilayer aquifer, but the existence of a certain hydraulic continuity allows one to consider a single-flow system. Nevertheless, there are significant differences in hydraulic charge.

The hydraulic balance (Figure 5) that has been established for the aquifer defines some total inflow of 380 hm³/yr, of which 101 hm³/yr come from lateral recharge from the Nevado de Toluca, 198 hm³/yr come from lateral recharge from the Sierra de Las Cruces, and 81 hm³/yr from direct infiltration of precipitation. The outflow of the system is estimated at 385 hm³/yr; this discharge is produced by lateral flow towards the Valley of Ixtlahuaca-Atlacomulco, with a value of 2 hm³/yr, and through pumping, which is estimated at 383 hm³/yr. The overall balance of the aquifer indicates an imbalance between inflow and out-
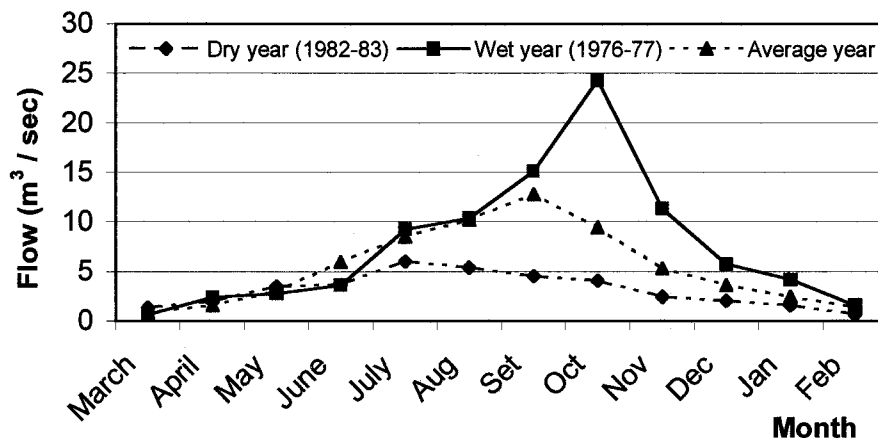

Figure 4. Interannual hydrograh estimated for the whole watershed of the Upper Course of the Lerma River. Dry year, wet year, and average year.
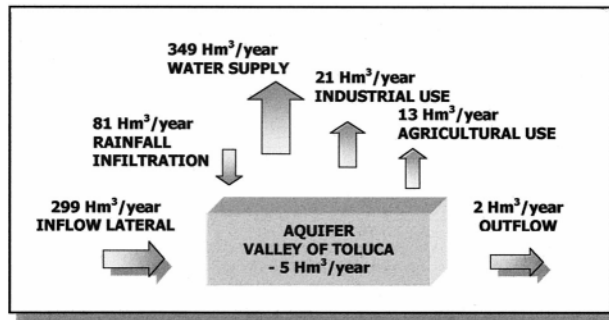
Figure 5. Diagram of the hydraulic balance.

flow, since the outflow is greater than the inflow by 5 hm^3/yr (CCRECRL 1993).

From the total extracted volume, 163 hm^3/yr is used in the same Valley of Toluca, 79% for urban water supply, 12.9% going to industrial use, and 8.1% used for agricultural activities. Moreover, Mexico City receives 220 hm^3/yr from this aquifer to cover some of its potable water needs.

The wetland, made up of the Lagoons of Almoloya del Rio, originates from a series of springs located in the contact zone between the fractured volcanic deposits that form in the mountainous rims of the valley, and the quaternary clastic material that makes up the topmost levels of the valley. These lagoons, in turn, give rise to the Lerma River. The springs are located at different points, but it is at Almoloya del Rio where the greatest concentration is found: up to 262 have been counted (Romero 1991). There is also surface runoff coming from small streams located along the watershed.

Results and Discussion

History of Hydraulic Resource Exploitation in the Valley of Toluca

The desiccation process of the wetland began as a way to control flooding and to free land for agricultural purposes. A first step was taken in 1757, but was not very successful. The subsequent works were developed from 1857 to 1870, with deepening and widening the outflow section of the Lerma River to drain the wetland area.

Several hydraulic infrastructure works were carried out, ending in the 1950s, to store the water in three reservoirs (Figure 1). The first reservoir, known as the Almoloya del Rio, Atenco, Chignahuapan, Agua Blanca, or Almoloyita lagoon, covered an area of about 50 km^2, the second reservoir, Chimaliapan or Tlaltizapan lagoon, had a surface area of 25 km^2, and the third and last reservoir, called Lerma or San Bartolo lagoon,

covered an area of 10 km^2 and was located in the municipalities of Lerma and Toluca (Albores 1995).

In the 1940s and 1950s, a series of projects were begun to hold the spring water that recharges the Lagoons of the Almoloya del Rio and in this way the Lerma River. One of these was the digging of several galleries, connected to a drain that caught the spring water. Other projects consisted of installing wells on the eastern rim of the lagoons, which started working in 1953. All of this implied exploitation of a volume of between 3.5 and 4.0 m^3/sec. The water thus obtained flowed to Mexico City through an aqueduct that passed through the Sierra de las Cruces.

Later, the prevention of loss through evaporation was added to the initial goal of flood control and freeing land for agriculture, since in a study carried out at the request of the Government of the Federal District of Mexico City in 1958, the recommendation of "reducing the piezometric level between 5 and 6 meters to avoid loss through evaporation, estimated at 90–150 $hm^3/year$" was pointed out (CCRECRL 1997).

On the other hand, around 1940, construction of the so-called Toluca-Lerma industrial corridor was begun, where intensive industrial activity was and still is being developed. This activity can be seen in the industrial production of the State of Mexico, which has occupied one of the top places in the country from 1949 to the present. This industrial activity carries with it an increase in population density in the valley, which in turn increases both industrial and urban water needs which were met by drilling wells throughout the whole valley.

The critical evolution of the water availability resulted in a presidential decree, on 10 August 1965 establishing a restriction on the use of this aquifer, but, in that same year, the demand for water in Mexico City could not be met, and an agreement was signed between the Government of the Federal District of Mexico City, the Secretariat of Hydraulic Resources, and the Government of the State of Mexico (1966–1969). This agreement allows the increased extraction from the Lerma River area, invalidating the presidential decree (Boehm and Sandoval 1999). After this agreement, the aquifer of the Valley of Toluca was under a restrictive ban, which means that no new wells can be built.

Based on this agreement, in 1970, the drilling of over 100 wells and an aqueduct of 170 km to transport water from the Valley of Toluca to Mexico City was concluded. Some of these wells are found located exactly in the transition area between the wetland and the mountain border.

The last works built were in the first lagoon, the Almoloya Lagoon, based on the construction of two
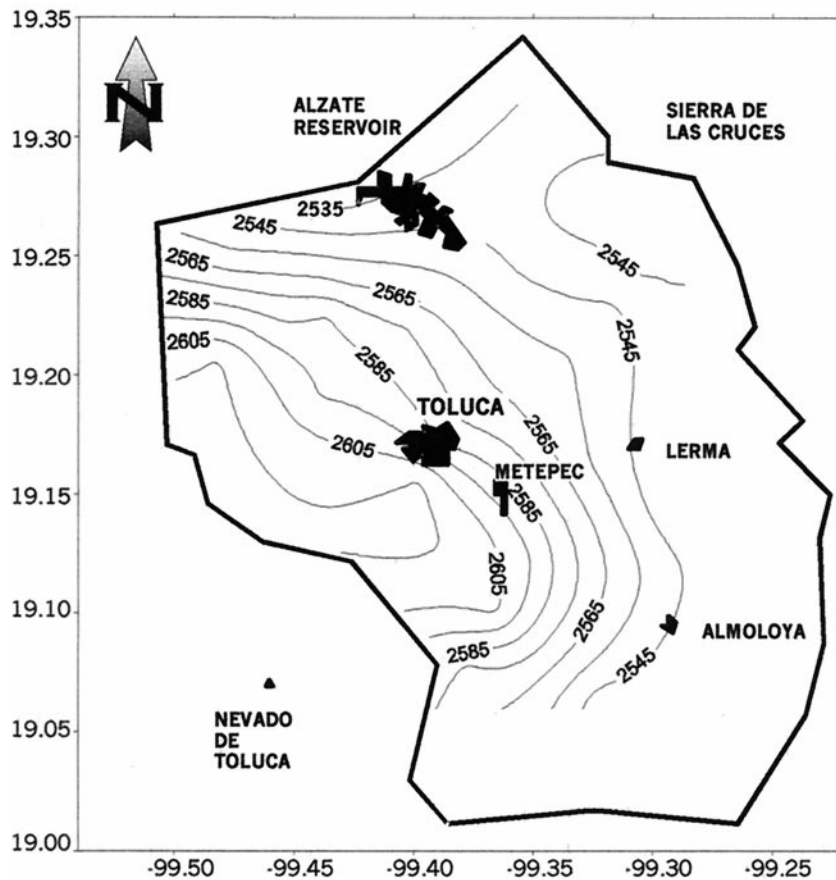
Figure 6. Water table map for October–November 1996 (in meters above sea level, contour interval 10 m).

reservoirs within the lagoon. One reservoir is the CUMAC, built in 1975, with Canadian financing meant to help preserve the ecosystem, and the outer reservoir, which encompasses the first, was begun in 1991; 8 km have been built, leaving 1.8 km still to be constructed. These works and other canal works are being carried out by the Secretariat of Agricultural Development of the State of Mexico (SEDAGRO). The purpose of this latter reservoir and the canal works is to reduce the flood area to a defined surface, to allow for the cultivation of lands and exploit rain water to store irrigation in the dry season (Díez-Perez 1998).

Piezometric Evolution

On the piezometric map, corresponding to the period of October–December 1996 (Figure 6), it can be seen that the main recharge comes from the Nevado de Toluca and that the circulation of groundwater is towards the center of the valley, being distributed in three directions, towards SE and E to the foot of the Sierra de Las Cruces, and towards **N** in the direction of the Valley of Atlacomulco-Ixtlahuaca. The main characteristic that can be observed is the influence of the set of wells

installed at the foot of the Sierra de Las Cruces to withdraw water for use in Mexico City, which means that the volume coming from the Sierra de las Cruces towards the valley has been intercepted by these wells, neutralizing their influence of recharge towards the internal area of the valley.

The exploitation process of groundwater is reflected in the map of equal decline contour lines between 1971 and 1996 (Figure 7). A piezometric depression cone in the area of Toluca City, with a maximum reduction rate of 3.5 m/yr, can be seen from this map. In the case of the area that covers the wetland, the map shows that the decreases have not been so important, but they have been hydraulically and ecologically significant. With relation to this important piezometric decline, the appearance of cracks and differential collapses in the land can be seen in different areas of Toluca City, causing damage to housing and roadways. These subsidence structures can be put into two different groups according to their direction—N–S and SE–NE—with variable vertical displacements, going from a few centimeters up to half a meter, and an average length of 500 m. The first effects of this subsidence on the land were detected
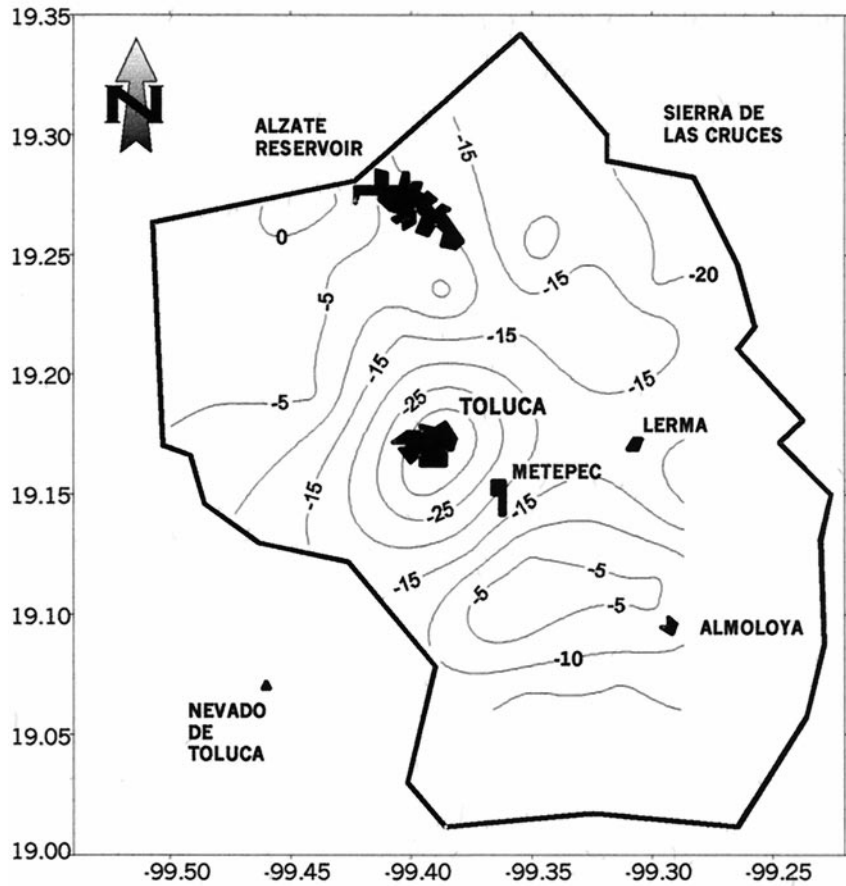
Figure 7. Map of equal decline contour lines between 1971 and 1996 (in meters, contour interval 5 meters).

in 1985 and currently continue, although they do not seem to be that important, as the rate of subsidence is at most between 2 and 3 mm/yr.

To carry out the study of evolution over time of the piezometric level in the wetland zone, four observation wells were chosen, belonging to the monitoring network that exists in the aquifer (Figure 1). Figure 8 shows the evolution of the piezometric level at these points for the period between 1968 and 1996. A gradual decline of the piezometric level can clearly be seen due to the effect of pumping groundwater and a decrease in the discharge of the springs, which are a source of recharge of the aquifer. In the case of observation well pl145, located in the area around the first lagoon (Almoloya Lagoon), stabilization of the level starting in the 1980s can be seen. This stabilization of the piezometric level is related to the construction of the CUMAC reservoir, which has allowed some recharge of the aquifer. In other zones of the aquifer, the piezometic level continues declining, with no stabilization of the level.
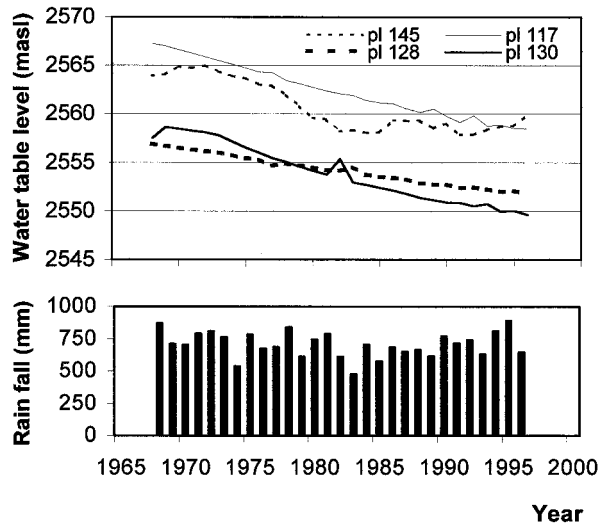
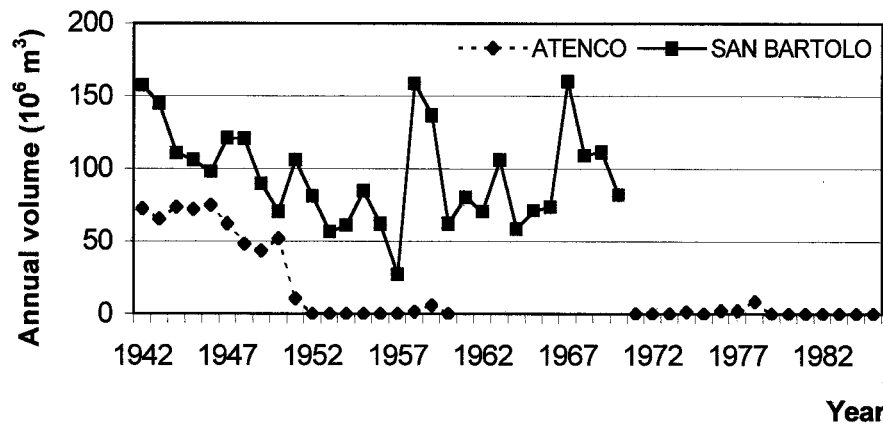**Figure 8.** Water table hydrographs. Observation wells are shown in Figure 1.

Figure 9. Evolution of water flow in Atenco and San Bartolo hydrometric gauge stations.

Table 2   Evolution of surface area of reservoirs of the wetlands of the Lagoons of the Almoloya del Rio (km^2)

| | SRH (1969) | Albores (1995) Data 1960–1970 | IPESA (1984) | | SARH (1986) |
			Wet period	Dry period	
Almoloya Lagoon	29	50	33	0.2	32
Tlaltizapan Lagoon	40	25	19	0.1	26
San Bartolo Lagoon	32	10	34	0.3	25
Total	101	85	86	0.6	83

Evolution of Surface Water Flow

As mentioned above, the three lagoons of Almoloya are primarily recharged by the water coming from springs and surface runoff. To establish the circulation between the lagoons and their outflow, the authorities installed two hydrometric gauge stations (Figure 1). The Atenco station is located between the first two lagoons and has recorded from 1942 to 1985 (although there are no data from 1961 to 1970). The San Bartolo station is located at the outflow of the third lagoon, which is considered the source of the Lerma River, and the recording period began in 1942 and ended in 1970.

It can be also seen in Figure 9, with respect to the Atenco hydrometric gauge station, that in the last decades recorded, the circulation of water between the first two lagoons was only occasional, due to the effect of the hydraulic works as well as the dam built above the Atenco hydrometric gauge station. The reservoir was put into use in April 1951, and at times, wood pieces were added to exploit water at higher levels than the concrete dam, which is 0.9 m high (crest elevation 2574.43 m asl).

In the case of the San Bartolo hydrometric gauge station, the decrease in flow throughout the 1950s was very significant, but later the decrease has not been as marked, as the lagoon and river were receiving important amounts of surface water and wastewater.

The study of the evolution of the flows of the above-mentioned two stations reflects the effect of the works that were carried out to export water to Mexico City, as well as the works for storing water from the lagoons. The hydraulic infrastructure installed modified the process of the inflow of water to these lagoons, which is why today one can consider the only source of inflow for the wetland area to be the surface-water runoff.

Decrease of Wetland Surface Area

The processes and strategies of hydraulic resource exploitation of the basin have caused a reduction in the surface area of the wetland over the years (Table 2), since the volume of water brought in from the springs has decreased and there has been a generalized decrease in the piezometric level. An example of this decrease is the Almoloya Lagoon (Figure 10), which has gone from a surface area of 23.9 km^2 in 1970 to 7.8 km^2 in 1989, although in the 1990s some of the area was recovered because of the building of the reservoirs, and therefore in 1995 this lagoon covered an area of 10.3 km^2.

Other proof of the consequences of the drying process of the wetland is that before it started there were small islands, such as the Mirafuentes (Almoloya del Rio) and temporary islands (in the rainy season), such as San Antonio La Isla, San Juan La Isla, and San Pedro
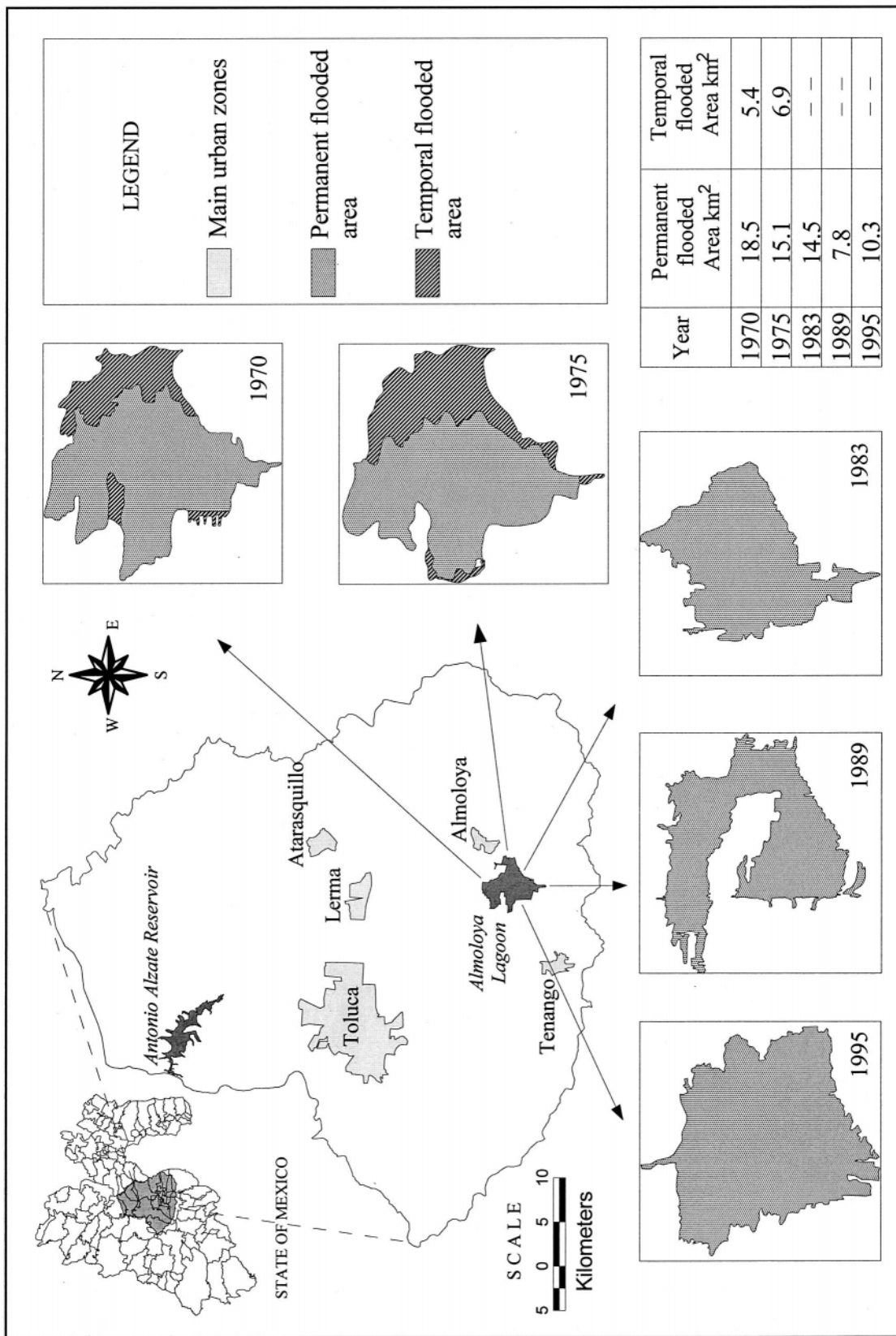
Year	Permanent flooded Area km^2	Temporal flooded Area km^2
1970	18.5	5.4
1975	15.1	6.9
1983	14.5	– –
1989	7.8	– –
1995	10.3	– –

Figure 10. Evolution over the time of the surface area of the Almoloya lagoon.

Tultepec de Quiroga La Isla, thus the origin of their names (Albores 1995). At the present time, these islands are surrounded by agricultural lands.

Water Quality

The water quality of the lagoons and that of the Lerma River has been deteriorating over time as a result of the inflow of both urban and industrial wastewater, which has combined with the effect of a decrease in water volume. This reduction in freshwater volume and the deterioration of the water quality has resulted in an important decrease in lake, fluvial, and riparian life in the region.

An example of this can be seen in a 25-km reach of the Lerma River between the Alzate Dam and the Toluca-Mexico Highway, where there is no dissolved oxygen present in the months from November to May, when the river flow is low and the organic charge levels are high [biochemical oxygen demand (BOD) of 248 mg/liter of O_2]. During the rest of the year, the values of dissolved oxygen are less than 2 mg/liter (Garrido and García-Aragón 1997).

Within the Ecological Recovery Plan for the Lerma River, developed by the Coordinating Commission for the Ecological Recovery of the Lerma River Basin of the Government of the State of Mexico and the National Program for Basin Improvement of the Federal Government, actions to widen the drainage infrastructure and the wastewater treatment were set forth and have been carried out over the past few years. The impact of these actions has resulted in some recovery of the Lerma River as an improvement in water quality of the river water has been reported (Castillo-Escalante 2000).

On the other hand, with respect to groundwater, an increase in salinity (electrical conductance increase from about 297 µS/cm in 1993 to about 978 µS/cm in 1998) and an increase in the concentration of heavy metals, such as Fe (from 0.1 to 2.51 mg/liter) and Mn (from 0.13 to 0.22 mg/liter), which are above the allowed levels for drinking water according to Mexican standards, have been seen (Esteller and others 1999). This increase in the mineralization of the groundwater could be related to the extraction of regional groundwater with a longer period of residence, since as the piezometric level decreases, an incorporation of deeper groundwater is taking place.

Conclusions

The overexploitation of the Valley of Toluca aquifer is related to the industrialization process that began in the 1940s and which has affected both the Valley of Toluca and the Valley of Mexico. This process implied a greater demand for water to cover both the industrial and drinking water needs, demands that grew as the population of the valleys grew.

This overexploitation has resulted in a drawdown of the piezometric level of the aquifer, at an average rate of 1.4 m/yr and a maximum of 3.5 m/yr, the emergence of cracks over the land surface due to subsidence, a decrease in the volume of the Lerma River, and a reduction in the wetland surface area.

The deterioration of the wetland of Almoloya del Rio is directly related to the works to exploit the springs that recharge the lagoons, works that were carried out to supply drinking water to Mexico City. This deterioration has had a huge environmental impact as it has produced a slow, but steady drying process of the lagoons, which has affected the flora and fauna of the area, as well as the use of the land, as the drained lands were used for agricultural purposes.

The steps taken up to now to mitigate the effects of overexploitation of the aquifer have not resulted in the recovery of the aquifer, making it necessary to seek other means within the framework of integrated watershed management, bearing in mind both the surface water and groundwater, as well as the reuse of treated waste water. For example, turning the exploitation of water from wells to other sources (superficial water, treated wastewater), reducing the pumping rate (Martinelli and others 1998) and artificial recharge and restoration of wetland with treated waste water (White and Bayley 1999).

Acknowledgments

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