# Basin of Mexico: A History of Watershed Mismanagement

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**Abstract.**— Mexico City Metropolitan Zone (MCMZ) is located within the Basin of Mexico. Because of its large population and demand for natural resources, several authors have questioned the viability of the city, especially in terms of water resources. These are reviewed at the regional and the local scales. It is concluded that a multi-basin management approach is necessary to integrate a water management strategy capable to meet near future challenges in water demand by the MCMZ.

## Introduction

Humans have occupied the Basin of Mexico for about 2,000 years. The long-term history of the basin is one of growth, collapse, and cultural rebirth and reorganization. The causes of such changes are rooted on depletion of local supplies of natural resources and dependance on resources imported from other regions (Aguilar et al. 1995).

At present, the Mexico City Metropolitan Zone (MCMZ) is one of the largest megalopolis on Earth. It extends over the Federal District, and neighboring municipalities in the state of Mexico (figure 1); it concentrates 25% of the population in the country, and a 40% of the national gross product. Widespread land cover transformation is occurring at a rapid rate due to urban growth, deforestation, agriculture, and ranching. Competition for available land and water resources is likely to generate environmental conflicts (*sensu* Crowfoot and Wondolleck 1990) among the different stakeholders of the MCMZ and neighboring river basins.

Perhaps, water will be the limiting natural resource for a sustainable development of Basin of Mexico. According to Downs et al. (in press), existing water resources will be insufficient for the needs in the year 2015, so additional sources will have to be developed. On the other hand, other threats to the MCMZ are silting up of the drainage system, and citywide flooding resulting from deforestation (Ezcurra and Mazari-Hiriart 1996).

In this paper, we examine water management issues in the MCMZ at two scales: (1) regional, encompassing the Basin of Mexico and neighboring watersheds; and (2) local, focusing in the mountain ranges located within the conservation land of the Federal District. The two scales are needed for devising the needed sensible strategies towards integrated assessment and management of water resources.

MCMZ is in one sense an ongoing experiment. Clearly, a watershed management approach is needed for a more sensible use of the natural resources and to avoid an environmental crisis in the Basin of Mexico and neighboring river basins. Nonetheless, the problems of the MCMZ are not unique. The combination of natural resource constraints, environmental impacts, and the incapacity of governments to respond and solve rather complex problems can be found in both developed and developing countries.

## Basin of Mexico

### Natural Setting

The Basin of Mexico is located at the southern end of the Mexican *Meseta Central*, along the Transverse Neo-volcanic Axis. It covers an area of 7,500 km$^2$ and encompasses the Federal District and parts of the states of Mexico, Hidalgo, Tlaxcala, and Puebla (figure 1).

The basin originated from late volcanic activity and upland formation. As lava and ash deposits closed the natural drainage outlets to the south, volcanic ridges built up around the eastern, southern, and western margins of a central lacustrine depression (Sanders 1979). At present, the basin is an elevated plain (2,240 m above sea level) bounded by high mountain ranges: Sierra Nevada to the east, which is formed by Popocateptl and Iztaccihuatl, the highest volcanoes of the basin (5,465 m and 5,230 m, respectively); Sierra de Las Cruces (4,000 m) to the west; Sierra Chichinautzin (4,500 m) and Sierra del Ajusco (4,000 m) to the south; and a series of low discontinuous ranges and to the north (Los Pitos, Tepotzotlan, Patlachique, Sierra Guadalupe and Sierra Santa Catarina).

The location of the Basin of Mexico along the Transverse Neo-volcanic Axis constitutes a boundary fringe between the Neartic and Neotropical biogeographic regions. Addi-

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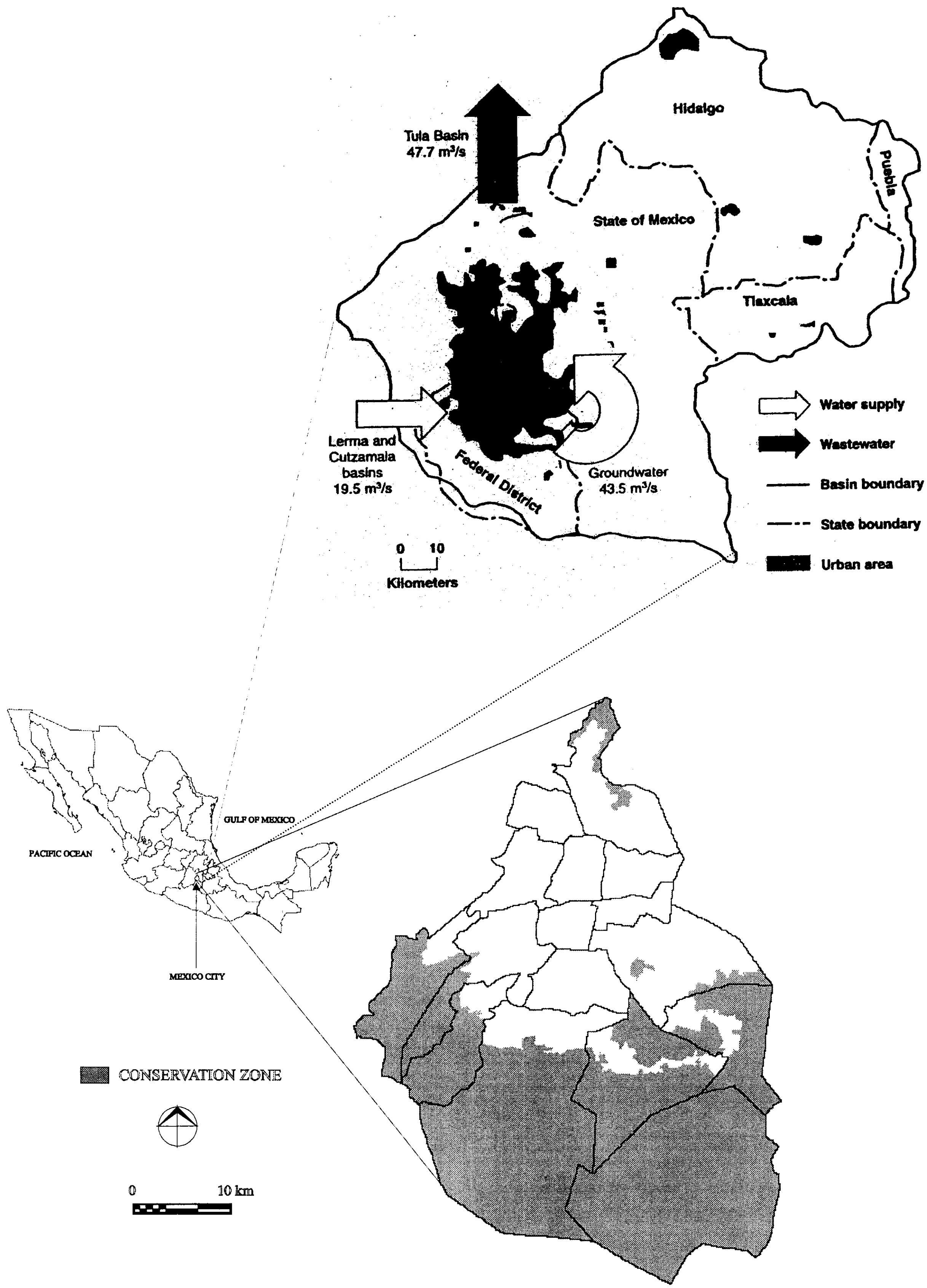


Figure 1. Study area and water management flows in the Mexico City Metropolitan Zone.

tionally, the tropical location of the Basin of Mexico, its internal geologic discontinuities, and the high altitude sierras, and isolated valley bottoms are covered create different patches originally covered with distinct vegetation types. Indeed, the lacustrine, transition, and mountain zones are correlated with a diverse flora and fauna.

Hence, three major environmental zones exist within the basin (Aguilar et al 1995, Ezcurra and Mazari-Hiriart 1996, Mazari-Hiriart and Mackay 1993): lacustrine, transition, and mountain. The lacustrine zone can be divided in three subzones: (1) lake system, an important resting habitat for migratory waterfowl; (2) saline lakeshore, characterized by halophyllous plants; (3) deep-soil alluvium, covered by sedges and swamp cypress. Clay deposits characterize the parental material of the lacustrine zone. These deposits are divided in upper and lower formations (30 to 70 m thick) by a hard layer (Capa Dura) of silt and sand. Furthermore, the clay layers are considered an aquitard because it is considerably less permeable that the Capa Dura or underlying sediments

The original lacustrine system covered 1,500 $km^2$. It comprised a sequence of five shallow lakes with a north south alignment: Zumpango, Xaltocan, Texcoco, Xochimilco, and Chalco. The lacustrine system was interconnected and drained to the Texcoco lake, but during extreme droughts, the lakes may have been separated by desiccation. The northern lakes (Zumpango, Xaltocan, and Texcoco) were saline, while the southern ones (Xochimilco, and Chalco) of fresh water, owing to the greater precipitation and springs located in that area of the basin.

The transition zone corresponds to the area between the lacustrine clays and the mountains. It encompasses five subsystems: (1) thin-soil alluvium, dominated by grasses and agaves; (2) upland alluvium, occupied by oaks and acacias; (3) lower piedmont, cloaked by low oak forests; (4) middle piedmont; covered by broadleaf oaks; (5) upper piedmont, covered by oaks and oak-pine woodlands.

The boundary between the lacustrine and the transition zones is generally defined as the edge of the upper clay formation. If present, clays are imbedded with silts and sands in the transition zone; closer to the mountains, the transition zone consists of fractured basalt. Groundwater recharge happens in the transition zone because of its high relative to the other two zones.

The mountain zone is composed of the area above 2,700 m above sea level in the major sierras. Temperate plant communities of pine, fir, and juniper cover this zone. Snow melt from the volcanoes of the Sierra Nevada, as well as springs and runoff from summer rains from all the sierras are the main source of water to the lakes at the center of the basin.

Mean annual precipitation in the Basin of Mexico is $744.2 \times 10^6$ $m^3$ (23.6 $m^3/s$). Rainfall in the Basin of Mexico is monsoonal and presents a NE SW gradient. Also, precipitation in the sierras is about 50% higher than that of the Basin floor. Accordingly, Sierra de Las Cruces receive the highest mean annual precipitation (1200 mm/yr) , followed by Sierra del Ajusco (900 mm/yr), and Sierra Nevada and Sierra Chichinautzin (800 mm/yr). Approximately 50% of the precipitation infiltrates to the groundwater. In spite of the differences in precipitation, Sierra Nevada and Sierra Chichinautzin are as important as the other sierras because of their area.

## Land Use

High population has been an always present determinant of environmental change in the Basin of Mexico. In pre-Hispanic times, at the peak of the Teotihuacan Culture (A.D. 300-750), the basin had a population of 300,000. At the time of the Spanish Conquest (A.D. 1519), the basin's population was above 1,000,000; inhabitants were distributed over 100 settlements. At that time, the region was perhaps the largest and densest urban area in the world (Ezcurra and Mazari-Hiriart 1993).

From the 1300s to the 1500s, the Aztecs altered the hydraulic characteristics of the lacustrine zone to protect the city of Tenochtitlan, which was founded on an island at the western section of the Texcoco Lake in 1325 A.D. Tenochtitlan water supply was satisfied by artesian wells. To protect the city, the Aztecs achieved an efficient water management system in the lakes of Xochimilco, Chalco and Texcoco by means of dykes, canals and floodgates (Aguilar et al. 1995). Likewise, their settlements expanded with the establishment agricultural crops on raised parcels of land above water, known as *Chinampas* (Downs et al., in press).

The Spanish conquest launched further alterations to the lacustrine system. The basin was opened artificially in the early 1600s. The canals were converted into roads and water was drained out from the city. The alluvial plains and the piedmonts were deforested and overgrazed. Ultimately, the lakes were drained as modern MCMZ expanded and land uses throughout the basin changed during the colonial and independence periods.

Until 1930, the spatial development of the MCMZ was characterized by a pattern of concentration in the downtown area. Between 1930 and 1950, peripheral expansion of took place as household were built in the south and west sections, and industrial developments in the north section. Accelerated growth occurred from 1950 to 1980, as the city grew northwards into several municipalities in the state of Mexico, and the population soared with access to cheaper land, recently built infrastructure and basic services. Low-income housing concentrated on dry lacustrine areas on the east and northeast, while the middle class and industry settled along a major highway on the north. On the south and southwest, residential subdivisions were established on mountain slopes without control or regulations.

In 1940, urban settlements covered 90 $km^2$ (0.9% of the basin). By 1990, the MCMZ encompassed about 1,161 $km^2$ or 12% of the Basin of Mexico. Population of the MCMZ was estimated to be 15 million in 1995, although the growth rate is decreasing (Ezcurra and Mazari-Hiriart 1996). Nowadays, however, flows of people and materials between the MCMZ and other major cities (Toluca at the west and Cuernavaca at the south) have created a megalopolis that extends beyond the boundaries of the basin. From 1953 to 1980, the average growth rate of MCMZ was 5.2%.

## Water Management

### *Water Supply*

The main aquifers in the Basin of Mexico are composed of alluvial and volcanic materials of variable thickness (100 to 500 m). Due to artesian pressure, the aquifer's original hydraulic gradient and water flow was upward, through the overlaying clay aquitard. However, groundwater utilization has changed the hydraulic regime and the gradients and flow in the upper deposits are downward, toward heavily pumped zones (Mazari and Mackay 1993).

Groundwater pumping in the MCMZ started in 1847. By 1925, groundwater extraction had generated a 1.25 m subsidence in some sections of Mexico City. This phenomenon was accelerated by 150 deep production wells that were drilled in 1940. A ban on new wells in the city area was issued in 1954, and some existing wells were relocated to the north and south of the basin (respectively, the well fields of Teoloyucan-Tizayuca-Los Reyes-Chiconautla, and Xochimilco-Tláhuac-Chalco). Although these changes reduced subsidence in the central MCMZ, they have increased subsidence in the Chalco-Xochimilco area (Mazari and Mackay 1993). The subsidence rates have stabilized at about 6 cm/yr in the downtown area. Nevertheless, sinking is occurring at a higher velocity (15 to 40 cm/yr) along the limits of the urban area. Some areas in downtown Mexico City have sunk 9 m since the early 1900s.

Groundwater extraction supplied enough water for the population of Mexico City until the mid-1960. Nowadays, groundwater is insufficient to meet the demand. In addition, the extraction rate is higher than the natural recharge rate of the aquifer (25 $m^3/s$ during the rainy season). Although there are 1,200 registered wells (of depths from 70 to 300 m), about 40% of them are used only occasionally during droughts. External river basins complement the supply of water in Mexico City.

Current water demand is about 63 $m^3/s$ in MCMZ. Groundwater is still the main supply with 42 $m^3/s$ (extraction rates are as follows: Xochimilco, 26.0 $m^3/s$; metropolitan zone, 7.0 $m^3/s$; Texcoco 5 $m^3/s$; and Chiconautla 4 $m^3/s$). Aqueducts supply water from the external river basins of the Lerma and the Cutzamala (6 $m^3/s$ and 13.5 $m^3/s$, respectively). The remainder 1.5 $m^3/s$ is produced by surface systems within the basin (Ezcurra and Mazari 1996).

### *Wastewater*

Storm runoff, industrial wastewater, and domestic sewage are carried out of the Basin of Mexico by a combination of sewers, open canals, reservoirs, lagoons, pumping stations, and a deep drainage system. About 75% of the population in the basin have access to this system; the rest disposes sewage through septic tanks and absorption wells. It is conceivable that a significant amount of contaminants are released by the sewage system. Additionally, there are 24 wastewater treatment plants, whose capacity totals 4 $m^3/s$ (7% of the water used in the basin).

Wastewater flows northward to the Tula Basin through an open canal (called *Gran Canal*) that has been in operation since the early 1900s, and the deep drainage system (called *Drenaje Profundo*), built in the 1970s. As the city has subsided, the open canal has lost its designed downgrade so auxiliary pumping stations are needed to discharge wastewater out of the Basin of Mexico to the Tula River. The closed drainage system consists of a network of tunnels that have a depth of 30 to 300 m. this system operates mostly during the rainy season and does not require auxiliary pumping. Wastewater is discharged to the Tula-Moctezuma-Pánuco River, which flows to the Gulf of Mexico. In the Tula Basin, the wastewater is used for irrigation and to generate electricity in the Zimapán Dam.

### *Groundwater Pollution*

Contaminants released at surface can migrate or be carried down by infiltrating water towards the aquifer. Contamination sources include landfills, petroleum refining, transport, and storage, gasoline stations, electronic industries, other industrial and commercial sources, wastewater disposal.

Therefore, risk of groundwater contamination is higher in the transition zone because of its permeability and wells now draw water from zones within or near it. The main aquifer is considered hydrogeologically closed to contamination that originates in the lacustrine area, because the clays that overlie the aquifer are an effective barrier to downward migration of water and surface pollution.

The reliance on the lacustrine clays to act as an efficient barrier to contamination is based on the assumption that they are a relative homogeneous, impervious unit. However, human activities (drilling wells, excavations, abandoned wells, deep drainage system, and the subway transportation system), and natural cracks and fractures may have breached the integrity of clays. Surface cracking is known to result from subsidence.

Importantly, Mazari-Hiriart et al. (in press) have demonstrated the presence of viral pathogen indicators, as well as fecal associated bacteria populations, in drinking water supply of Mexico City. This is an evidence of groundwater contamination with serious implication for human health.

## Conservation Land of the Federal District

The conservation land of the Federal District, officially known as *Suelo de Conservación Ecológica* (SCE; figure 1), was established by a presidential decree in 1930s, along with a series of natural parks. The SCE extends over 89,000 ha (58% of the Federal District), mostly on the south and southwestern mountain ranges. It includes 25 watersheds and encompasses the main groundwater recharge areas in the Federal District, and about 50,000 ha of natural cover (fir, pine, oak, scrub, and grasslands). It is located within the boundaries of nine of administrative units, or political delegations, of the Federal District (Cuajimalpa, Alvaro Obregón, Magdalena Contreras, Tlalpan, Milpa Alta, Xochimilco, Tlahuac, Iztapalapa, and Gustavo A. Madero; see figure 2).

The Natural Resources Commission of the Federal District (Comisión of Natural Resources or CORENA) is the governmental agency responsible for managing the SCE. CORENA is currently formulating a strategy to set land-use policy for natural resource management and conservation of natural resources, to delineate a land-use pattern that maximizes consensus and minimizes environmental conflict, and to protect the natural cover, natural habitats, a and groundwater recharge areas.

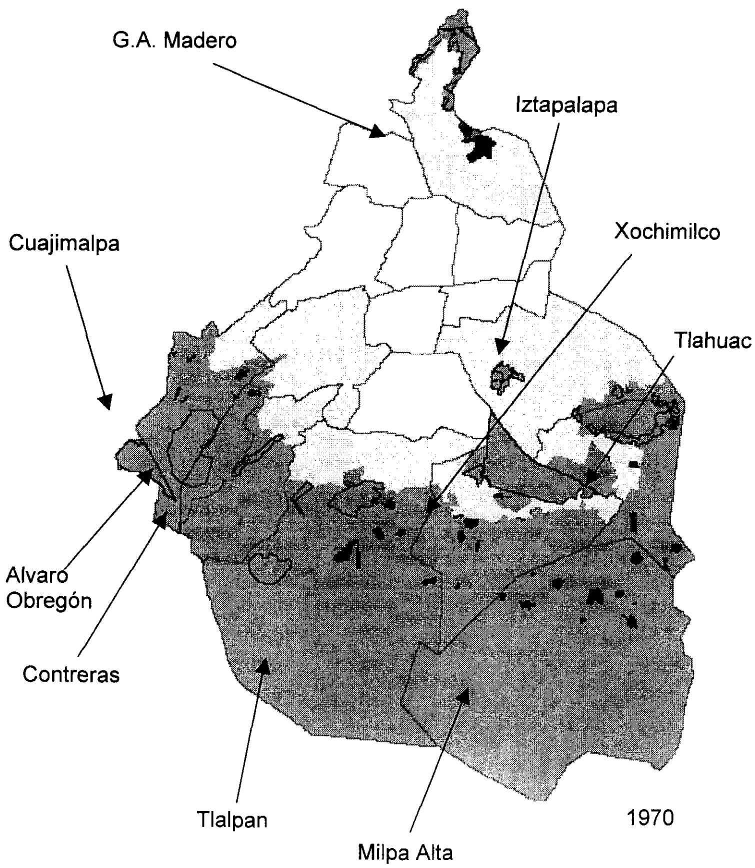


Figure 2. Land-cover transformation in the conservation zone of the Federal District (black). The names in the figure are those of the political delegations.

## Water Balance

A water budget analysis shows that about 50% of the SCE present water surplus. When the SCE is divided according to water surplus categories, it is evident that the largest proportion of the SCE is either moderate (12,380 ha) or high (15,540 ha), while the categories low and very high occupy a smaller area (8,610 ha and 7,720 ha, respectively).

The relative importance of the vegetation for the hydrological cycle of the basin is related to their area and relative amount of water surplus. Practically, the total area covered with fir forests, alpine grassland, and riparian forests, as well as half of the area covered with grasslands. About 50% of the area covered with pine forest have average water surplus, while a similar percentage of oak forests have lower than average water surplus (figure 3a). Thus, pine and fir forests are the most important vegetation types, followed by alpine grasslands and riparian forests, grasslands, and oak (figure 3b).

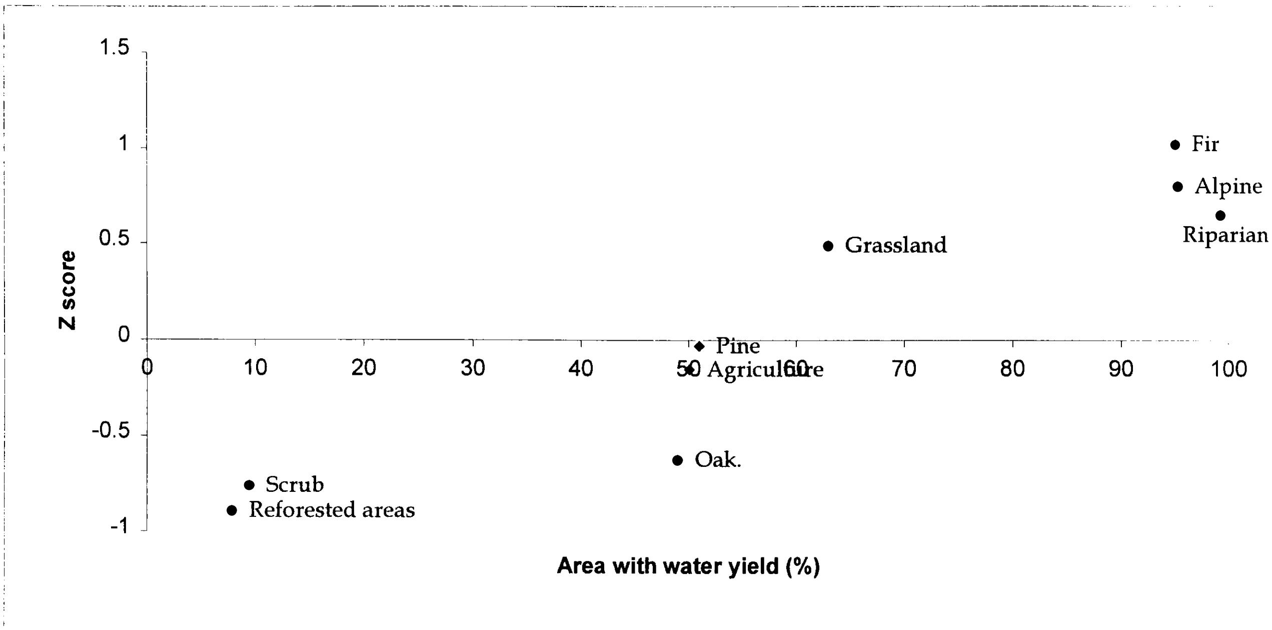


Figure 3a. Importance of vegetation types with respect to average water surplus in the conservation land of the Federal District.

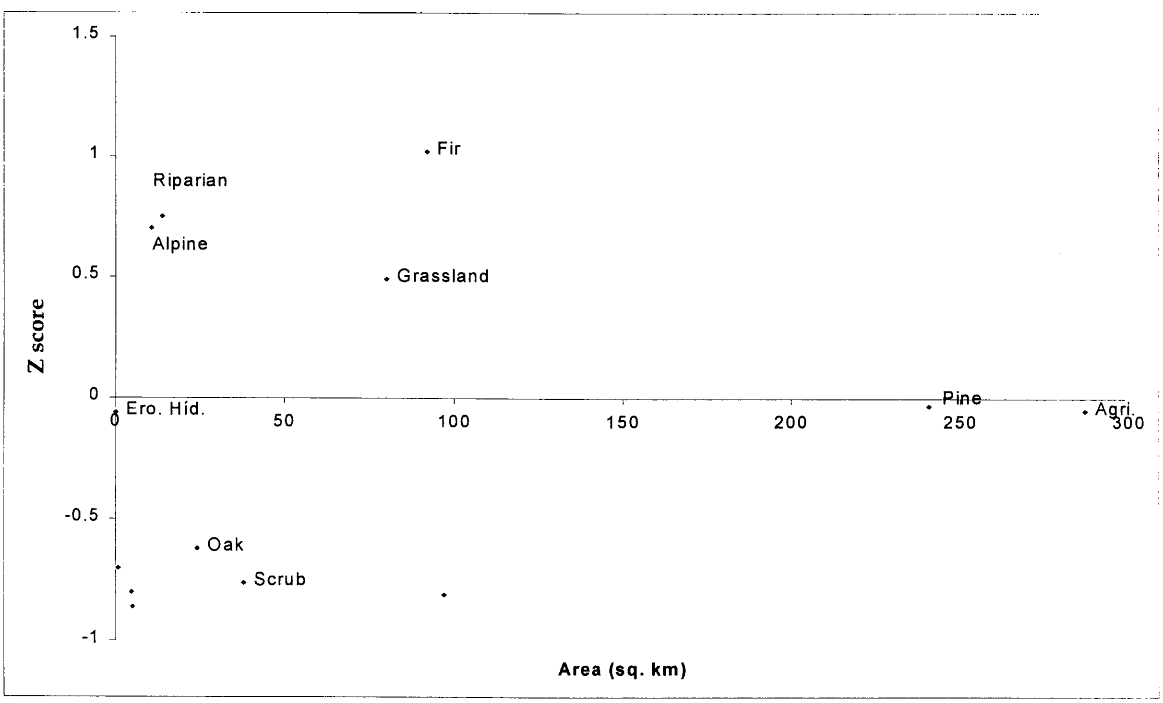


Figure 3b. Importance of vegetation types with respect to average water surplus in the conservation land of the Federal District.

## Land Use and Land Cover Change

In general, ranching, uncontrolled recreation activities, and illegal logging have affected the forested areas, while ranching, agriculture, and urban growth have reduced grassland and scrub lands. Nonetheless, the economic importance of agriculture and ranching is decreasing; indeed, the rural population working in the metropolitan area is increasing. As an aftermath, agricultural fields and ranching areas have been abandoned, and have been replaced by urban developments. In fact, urban development is occurring at a rapid rate and is occupying natural and agricultural areas. Land cover transformation, however, is not occurring at the same rate in all the political delegations of the SCE and land cover types (figure 3; table 1).

Table 1. Land cover change in the Conservation Land of the federal District (SCE).

| Land cover type | Land cover (ha) 1970 | Land cover (ha) 1993 | Change (ha) | Rate (%) |
|---|---|---|---|---|
| Forest | 38,610 | 32,160 | -6,450 | -0.7 |
| Urban | 1,870 | 9,680 | 7,810 | 6.1 |
| Grassland | 11,090 | 14,400 | 3,310 | 1.0 |
| Agriculture | 35,910 | 31,230 | -4,680 | -0.5 |
| Scrub | 1,110 | 1,830 | 720 | 1.9 |

The political delegations can be grouped with respect to the proportion of SCE within their boundaries, remaining natural cover, and annual rate of land cover transformation (estimated for the period 1970 to 1997; figure 3; tables 1 and 2). Milpa Alta and Tlalpan form the first group. They included the larger proportions of SCE, both have extensive natural cover (> 50 km$^2$), and present low annual transformation rates (< 1%). The area decreed as SCE is smaller in the rest of the political delegations.

Gustavo A. Madero and Iztapalapa form a second group. The extent of SCE in the two is small and is virtually devoid of natural vegetation (< 2 km$^2$), while their annual rate of land cover transformation are low (this indicates that land cover transformation in occurred before 1970). Natural cover is equally small in Tlahuac, in spite of including a larger proportion of SCE. Its annual transformation rate is extremely high (5%).

The third group, formed by Alvaro Obregón, Magdalena Contreras, and Cuajimalpa, have low annual transformation rates (> 1%). The areas of natural cover included in these political delegations are moderate (between 3 and 29 km$^2$). Finally, Xochimilco stands alone because of the extension of natural cover (50 km$^2$) and a rather high annual transformation rate is high in Xochimilco (< 3%).

Land transformation trends can be inferred from preliminary results of a suitability analysis performed for the SCE. Figure 4 shows the criteria used for zoning, and Table 2 shows the capability of the political delegations for a land use set. Hence, considering only the political delegations within water surplus, Cuajimalpa, Magdalena Contreras, and Alvaro Obregón are threatened by forestry and urban growth; Xochimilco by agriculture, ranching, and urban growth; and Tlalpan and Milpa Alta by forestry, agriculture.

Table 2. Land suitability in the Conservation Land of the Federal District (SCE).

| Delegación | SCE (ha) | Agriculture (%) | Conservation (%) | Logging (%) | Ranching (%) | Urban (%) |
|---|---|---|---|---|---|---|
| G.A. Madero | 1,600 | 19 | 70 | 3 | 65 | 15 |
| Cuajimalpa | 6,600 | 13 | 61 | 52 | 35 | 11 |
| A. Obregón | 2,700 | 18 | 66 | 37 | 31 | 6 |
| Iztapalapa | 1,200 | 53 | 55 | 0 | 34 | 24 |
| M. Contreras | 5,100 | 3 | 79 | 62 | 39 | 2 |
| Tlalpan | 26,000 | 9 | 53 | 45 | 60 | 6 |
| Xochimilco | 10,400 | 61 | 23 | 6 | 77 | 14 |
| Tlahuac | 6.700 | 50 | 13 | 0 | 73 | 16 |
| Milpa Alta | 28,400 | 19 | 55 | 47 | 49 | 4 |
| SCE | 89,000 | 22 | 50 | 38 | 55 | 8 |

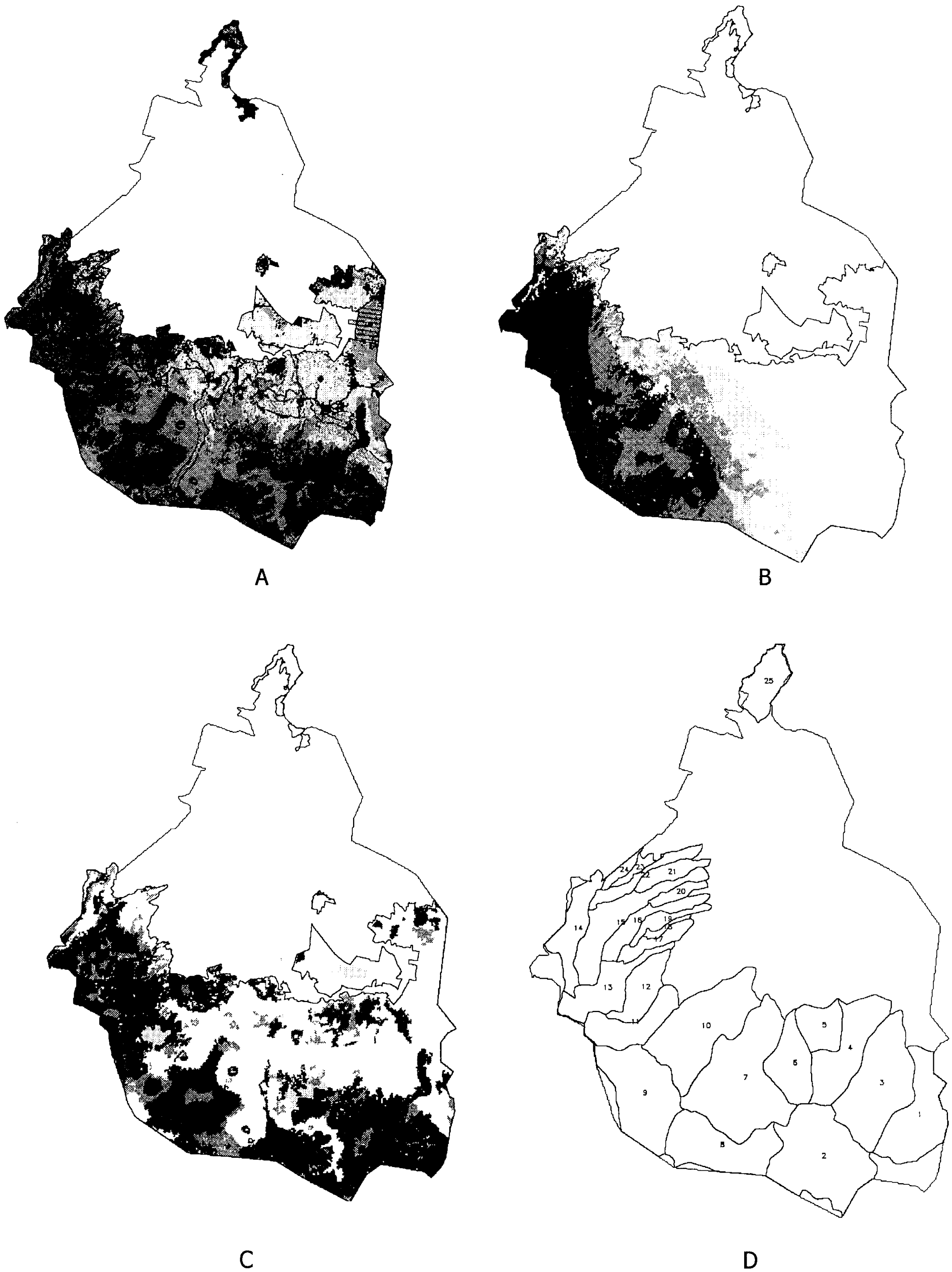


Figure 4. Zoning criteria used in the conservation land of the Federal District. A) land suitability groups (light gray=agriculture and ranching; dark gray=conservation and forestry; black=urban development; B) water surplus categories (white=null; light gray=low; dark gray=moderate; black=high); C) biodiversity importance categories (white=null; light gray=low; dark gray=moderate; black=high); D) watersheds.

## Discussion and Conclusions

Large metropolitan areas have always exerted considerable pressure on its regional environment. However, megalopolises are a 20th century phenomenon: concentrated urban growth concentrated urban growth is affecting regions at a level never seen before. It is obvious to assert that megalopolises require scrupulous allocation of available natural resources to meet the demands of rising populations. Yet, it is not yet clear how environmental sustainable these cities will prove to be.

Arguably, the biggest challenge for the sustainability of megalopolises is water supply and wastewater disposal. The MCMZ is an excellent example on a serious case of what could be called "watershed mismanagement." Nowadays, a multi-basin level approach is necessary to face the challenges in the immediate future. According with Downs et al. (in press), existing water resources will not meet the demands by the year 2015, and groundwater substitution is needed to reduce the current subsidence problems in the MCMZ. Exploitation of external hydrologic basins to supply water to MCMZ is unavoidable even with recycling of wastewaters and detection and repair of leaks in the distribution systems (losses are estimated as high as 40% of the total volume).

At the regional level, overexploitation is the major groundwater management problem, although it is important to recognize that the problem is compounded by the threat of groundwater contamination. Also, the external basin of Alto Lerma appears to be over exploited perhaps by as much as 100%, while the other, Cutzmala, is being used under its potential.

At the local scale, observed land-cover transformation rates in the SCE (table 1) seem to contradict pervious assertions that deforestation is a major threat to groundwater recharge areas in the SCE (Ezcurra and Mazari-Hiriart 1996). This apparent contradiction results from the consideration of all vegetation types in the SCE for the calculations. However, deforestation rates differ among watersheds in the SCE. It is evident that the political delegations of Cuajimalpa, Magdalena Contreras, and Alvaro Obregón are being pressured by urban growth (table 2). Therefore, it can be concluded that the watersheds with the highest water surpluses (figure 4) are threatened by urban growth. At present, most of the impacts are occurring on the oak forests in the transition zone; the area with the highest permeability in the basin. On the other hand, the political delegations of Tlalpan and Milpa Alta present lower transformation rates, generated by illegal logging, agriculture, and cattle ranching (figure 4; table 2).

Therefore, integrated water resources management plans must include the following: (1) protection and enhancement of aquifer recharge areas, (2) control of deforestation, (3) reforestation of the mountain slopes, and (4) development of additional external water resources. Importantly, as new water sources will have to be developed, research will be necessary to evaluate the withdrawal limits and environmental impacts in external basins.

The evidence presented in this paper reinforces current efforts to promote a more sensible management of water resources and the implementation of a watershed approach in the Basin of Mexico and neighboring river basins.

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