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Mexico City's Water Management: In search of sustainability

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Abstract

Mexico City is facing water supply problems as its population increases and aquifer overexploitation needs to be stopped. Because of its geographic location the City has continuously faced water related problems such as floods and lack of the resource. Currently the closest water sources have been already tapped and more water will be needed in the near future in order to satisfy the ever increasing demand as the aquifer systems located under the City provide nearly 75% of the total water supply. Water from the aquifers is extracted at a higher rate than they are replenished, causing a mean decline in the groundwater table of one meter per year. A high percentage of water used is exported to the *Pánuco* basin without being reused; thus, authorities are trying to implement a program to artificially recharge the aquifer using reclaimed waste water and wells in order to reduce aquifer overdraft and as an alternative to meet the ever increasing water demand. Although the main focus of the present paper is to analyze the artificial recharge program, other water policies such as efficient water use and leak detection in the water supply network will be analyzed as well along with a comparison between importing water from other river basins and use of reclaimed waste water is realized and a new approach is proposed in order to improve water management in the Basin.

Contents

1 Introduction 1

2 Water Management in the Basin of Mexico 2
2.1 Aquifer exploitation . . . 3
2.2 Consequences of aquifer overexploitation . . . 4

3 Improving water supply in the City 5
3.1 Artificial recharge . . . 6
3.2 Total cost of the project . . . 7
3.3 Risks associated with an artifical recharge program . . . 8

4 Water tariffs 8
4.1 Opportunity cost of water in the aquifer . . . 9

5 Discussion 12

6 Conclusions 13

List of Tables

1 Costs associated with an artificial recharge program . . . 7
2 Costs of importing water from possible water sources . . . 10
3 Unitary costs of possible water sources (1987 pesos) . . . 10
4 Inflation rates and costs for future sources (1988-1997) . . . 11
5 Total costs of alternative sources for 1997 in USD . . . 11
6 Unitary cost of water for alternative sources . . . 11

List of Figures

1 Location of the Basin of Mexico . . . 2
2 Land subsidence rate in downtown Mexico City (1891-1973), after NRC (1995). . . . 5
3 Landsubsidence in the Historical Center of Mexico City, after Figueroa-Vega (1988). . . . 6
4 Possible water sources for the Mexico City Metropolitan Area . . . 9

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Mexico City's Water Management: In search of sustainability

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1 Introduction

This paper analyzes current water policies in Mexico City and its Metropolitan Area (MCMA), which is the most important economic entity in Mexico. The MCMA, which by the end of the last century had a population of nearly 20 million people, obtains most of its water from the aquifer system that lies beneath it. One of the largest challenges that Mexico City's authorities face nowadays is how to provide enough water in a sustainable manner given the ever increasing water demand. This is not a new problem and attempted solutions include importing water from other basins since the 1930s (Ramirez-Sama, 1990; NRC, 1995) as well as implementing efficient water use programs, monitoring and repairing leaks in the water supply network, and substituting the use of first use water by treated wastewater (Fuentes-Mariles, 1997; DGCOH, 1997). These actions have reduced the water supply problem, but aquifer extraction is greater than natural aquifer recharge. Due to this overexploitation, aquifer reserves are diminishing, causing land subsidence in the city. Land subsidence damages existing infrastructure such as the water supply network, sewage system and buildings.

By the year 2010 a water supply deficit of 10.4 m^3/s is expected and authorities are considering importing an extra 5 m^3/s from the Cutzamala river basin and the remaining 5.4 m^3/s from the Tecolutla river basin (DGCOH, 1997). In order to achieve sustainable water management in Mexico City, the challenge consists of improving current water supply without continuing the actual overexploitation of the aquifer and stopping the importing of water from other river basins. In the past water demand has been met by importing water from other river basins; however, importing more water from other sources is questionable, both economically and politically (DGCOH, 2000). In order to reduce problems related to aquifer overexploitation and to increase water supply, an artificial recharge program has been proposed in order to increase aquifer recharge in Mexico City as a means to achieving sustainable management of the resource (Ramirez-Sama, 1990; DGCOH, 2000, 1997; DGCOH and Lesser, 1991).

Excessive groundwater extraction can have a number of side effects. It is important to distinguish between reversible side-effects, such as water table or piezometric surface decline from those which are quasi-irreversible, such as land subsidence, as reversibility plays an important role in sustainability (Simonovic, 2001).

2 Water Management in the Basin of Mexico

Mexico City is located in the Mexican Valley Basin (referred to in the remainder part of the paper as the Basin of Mexico or the Basin) which is located in the central part of Mexico, as shown in Figure 1. Originally, the Basin did not have a natural exit and storm water accumulated in its center in four lakes which formed a large shallow lake in the rainy season. In the XIXth century, the Basin was connected to the Pánuco Basin through the Nochistongo and Tequisquiac tunnels in order to drain it. Floods have been a serious problem in the City throughout its history, almost causing its perdition in 1629 in a flood that lasted over 5 years (Perló-Cohen, 1999). Due to this vulnerability to floods, a series of dams have been built on the western mountain range of the Basin, known as *Sierra de las Cruces*. These dams regulate the peak floods of the main streams located on this Sierra and then release their water to the sewage system, mainly to the *Interceptor del Poniente* which is part of the deep sewage system built in the 70's to reduce the risk of floods in the City. Accordingly, there are no appropriate sites to build dams which can store the excess water in order to increase the water supply. One possibility could be to study whether these dams could be used for water supply, an issue that is not analyzed in the present work.

The Basin extends northwards to the Pánuco basin, northeast to the Tecolutla basin, southward with the Amacuzac basin and southwest to the Lerma Basin and four political entities (Federal District, State of Mexico, Tlaxcala and Hidalgo) have jurisdiction over it. An integrated approach for water management in the Basin is difficult as each state has its own government. This is exacerbated by the fact that Mexico City and its Metropolitan Area is comprised of two political entities: the Federal District and the State of Mexico.

Figure 1: Location of the Basin of Mexico

Water sources in Mexico City are the aquifers and water imported from the Lerma and Cutzamala river basins. Dams built near the City in order to protect it from floods temporarily store the water which is then exported to the Pánuco basin through the deep drainage system. Therefore, the only water available for recharge within the basin is the water drained by the deep drainage system and the sewage system.

The water used in the Mexico City Metropolitan Area (MCMA) is approximately 60 m^3/s, of which 43 m^3/s are provided by the aquifers, 10.6 m^3/s by the Cutzamala system, 5.3 m^3/s by the Lerma System and 1.4 m^3/s by surface sources located within the Basin of Mexico (DGCOH, 2000). The current water supply infrastructure covers 97% of the inhabitants of the Federal District and 90.5% of the population living in the State of Mexico (DGCOH, 1997). According to the increase in population, by the year 2010, a total supply of 70.7 m^3/s will be needed; thus a water supply deficit of 10.4 m^3/s is expected if the current infrastructure remains without change. The only options to increase the water supply to the City are importing water from other river basins or through artificial recharge of the aquifer using treated storm waters and wastewaters. Artificial recharge of the aquifer using wastewater in Mexico City is currently under trial using water treated up to a tertiary level in a recharge pond. The current flow that is being recharged by this facility is 0.02 m^3/s (DGCOH, 1997) while the other recharge facility which is an injection well located in the southern part of Mexico City recharges the aquifer at a rate of 0.06 m^3/s (DGCOH, 1997).

The sewage system in Mexico is a combined system, as storm water and wastewater flow through it. The total flow is estimated to be 54 m^3/s, which is comprised of 42.8 m^3/s of wastewater and 11.2 m^3/s of storm water (DGCOH, 1997). A small amount of the total flow (4.75 m^3/s) is used for irrigation in certain parts of the basin, while the remainder is exported to the Tula river basin (DGCOH, 1997). The waste water quality is typically domestic waste water, although some industrial contaminants are present (DGCOH, 1997).

2.1 Aquifer exploitation

Water related problems in the City are caused by its geographical location, characterized by a simultaneous excess and lack of water. Excess run off from rainfall in the rainy season is exported to the Gulf of Mexico, while water is imported from the *Lerma* and *Cutzamala* basins to satisfy the always increasing water demand. The aquifers beneath Mexico City have been progressively exploited since the mid nineteenth century, gradually becoming sub-artesian with groundwater table levels having declined by approximately 80 m (Edmunds et al., 2002).

Pumping of the major aquifers began in 1847 when the first wells were drilled in the Basin (Ortega and Farvolden, 1989). Water extraction from the aquifer in the 1950's was 13.7 m^3/s, while water imported from the *Lerma* Basin had reached 6.0 m^3/s (Mazari and Alberro, 1990). By 1990, groundwater was delivered from 3537 officially registered wells within the Metropolitan Area (NRC, 1995), and as exposed previously, current pumping policies have caused a decline in the groundwater table levels of up to 3 meters per year in some areas (DGCOH and Lesser, 1991) and associated to this drawdown, land subsidence has occurred, as will be presented in the following section.

2.2 Consequences of aquifer overexploitation

Land subsidence in Mexico City, was discovered as a result of a polemic about the subsidence of the gates of *San Lázaro*, at the beginning of the main sewage channel of the city (Figueroa-Vega, 1984). In February of 1925, Roberto Gayol demonstrated to the Association of Engineers and Architects of Mexico that the problem was just the result of the general subsidence of the bottom of the valley. He presented as evidence two precision levelings made in 1877 and 1924 of a monument located near the Cathedral (Figueroa-Vega, 1984), attributing the phenomenon to the effect of the recently built drainage system.

When authorities realized that land subsidence was associated with heavy pumping, several wells located in the centre of the city were closed in 1952, while new ones were drilled in the southern regions of the Basin (i.e. *Chalco, Tláhuac and Xochimilco*) (Ramirez-Sama, 1990). Likewise, water pumping rates in those regions have caused land subsidence (NRC, 1995). A clear example of land subsidence in the central part of the City is the *Ángel de la Independencia*, which at the end of its construction in 1910 had nine steps and by the end of the last century a total of 14 steps were added to its staircase, as the city has sunk around it.

In order to study the evolution of the groundwater table, a monitoring piezometric network was developed in the city in 1984 (DGCOH and Lesser, 1991). The evolution of the groundwater table prior to 1948 may be estimated only by the fact that, according to old local drillers, many wells within the Lake zone of the city were still flowing wells at the beginning of this century (Figueroa-Vega, 1984; Ortega and Farvolden, 1989). Lesser-Illades et al. (1990) used the piezometric network which consisted of 320 monitoring wells in order to report the evolution of the static groundwater table level.

Overuse of the aquifers in the Basin during the twentieth century has caused land subsidence problems. From the beginning of the twentieth century until 1938, the land subsidence rate was 4.6 cm/yr, which increased in the following decade to 16 cm/yr, reaching a maximum value of 35 cm/yr in the period of 1948-1956. After the wells located in the center of the City were closed, the rate went down to 7.5 cm/yr and by the end of the 80's its mean value was 4.5 cm/yr (Mazari and Alberro, 1990), although some regions remained at a subsidence rate of up to 40 cm/yr (DGCOH and Lesser, 1991). By 1990, the mean land subsidence rate was 10 cm per year, while in certain parts of the city it was as high as 40 cm per year (DGCOH and Lesser, 1991). Net land subsidence over the last 100 years has lowered the central part of the urban area more than 7.5 m (Figueroa-Vega, 1984; NRC, 1995) as shown in figures 2 and 3. Some areas currently have an accumulated subsidence of more than 15 m (González-Morán et al., 1999) and up to 30 m in areas such as Azcapotzalco (Birkle et al., 1998).

Overexploitation of the aquifer in the City has generated a number of negative externalities, including (Haaggarty et al., 2001):

1. The cost to building owners of damage to their property from land subsidence due to over extraction.

2. The cost to government of damage to public infrastructure (roads, pipes, etc) from land subsidence due to over extraction.

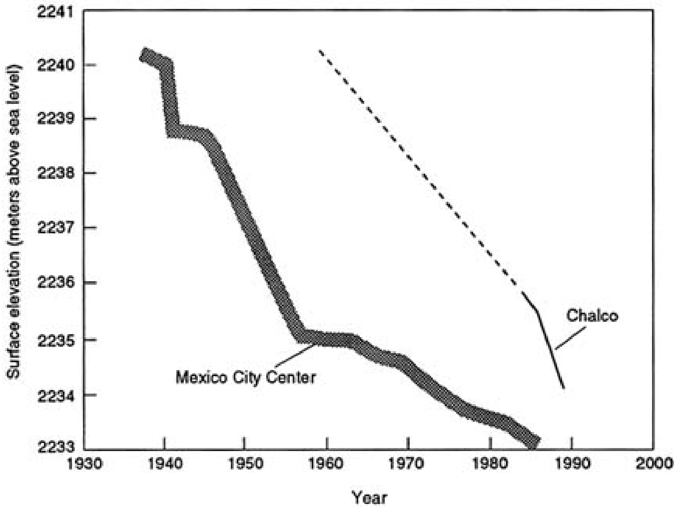

Figure 2: Land subsidence rate in downtown Mexico City (1891-1973), after NRC (1995).

3. The cost to future generations of current unsustainable use manifested through higher costs in the future or diminished quality of life.
4. The cost of foregone use of water by the surrounding communities whose water is being taken to the Federal District.
5. Raising the cost of nearby communities due to higher pumping costs caused by the lower water tables (deeper wells) which are the result of overexploitation.

Another aspect of overexploitation that has not been considered in the City is that as the aquifer is compacted, water quality is affected as well; in the southern and south-western areas of the Valley of Mexico, water quality has been decreasing. This is likely to be caused as the pore water of the overlying lacustrine clay is being drained to the aquifer as clays are being consolidated due to depressurization of the aquifer (Cortes et al., 1997). Compounding this problem, the aquitard has been considered as a protective barrier for the aquifer from surface pollution but because of overexploitation, the aquitard is cracked in some areas and may cause infiltration of pollutants to the aquifer; this phenomenon has not received enough attention, and it is assumed that the very low permeability of clay in the aquitard protects the aquifer against surface pollution (Durazo, 1996).

3 Improving water supply in the City

Mexico City's authorities are currently considering three main water policies in order to improve water management in the Basin, namely artificial recharge, water tariffs and importing water. The policies that will be analyzed in this section are the artificial recharge program and finding a proper water tariff in order to charge, at least, the opportunity cost of water to users. Finally a comparison between "new" water provided by injection of reclaimed wastewater and water imported from other

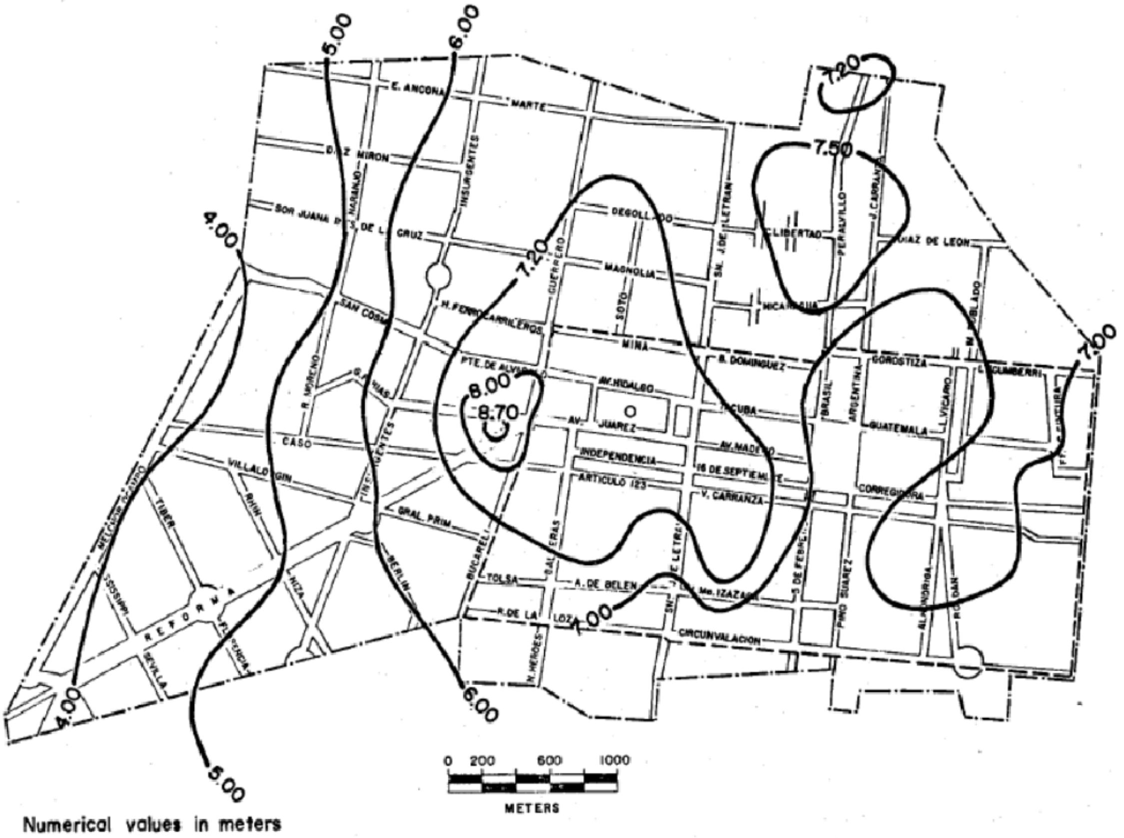

Figure 3: Landsubsidence in the Historical Center of Mexico City, after Figueroa-Vega (1988).

basins is realized based on costs associated to each of these projects and their net present costs.

3.1 Artificial recharge

Although in recent studies authorities have proposed an artificial recharge program (DGCOH, 2000) a formal proposal of this type of project was presented earlier (DGCOH, 1997). The present subsection is primarily based on this report.

Artificial recharge methods include surface infiltration systems and injection wells. Surface recharge systems work well in situations where soils are permeable from ground surface to the water table and where adequate land area is available at reasonable cost to accommodate the recharge facilities (Pyne, 1995). Where low permeability soils are present between ground surface and the water table, or where land availability at reasonable cost is limited, surface recharge may not be viable (Pyne, 1995). Mexico City is built over a thick deposit of clay with very low permeability, thus the use of surface ponds is not a viable option, and artificial recharge of the aquifers in the City will be made using injection wells and treated waste water. Waste water will be treated up to a tertiary level in order to guarantee the quality of the water remaining in the aquifer in order to prevent human diseases caused by drinking reclaimed waste water; the water is injected to the aquifer as this provides

Table 1: Costs associated with an artificial recharge program

Type of cost	ammount
Capital	711,984,000 USD
Operation and Maintenance	0.34 USD/m^3

an additional treatment buffer in the process. In this regard, I consider important to pinpoint the necessity of properly locating the injection wells in order to guarantee a certain residence time of injected water in the aquifer as treated waste water should not be immediately extracted from the aquifer by extraction wells located near the injection wells. In order to verify this restriction, the use of a groundwater flow model is required; however, this is out of scope of the present paper and will be the subject of future work.

Waste water will be taken from the Churubusco River and the Grand Sewage Canal as they provide the highest quality and the quantity required (10 m^3/s). Water from the Grand Sewage Canal will be taken before water coming from Los Remedios River mixes with it, as the latter contains waste water from industries, making it harder and more expensive to treat it to proper standards for recharge.

In the study of reference (DGCOH, 1997) capital, operation and maintenance costs were calculated and reproduction of that part of the study is not made in this paper. Thus, only final costs obtained will be shown, as follows:

The annualized capital cost (considering 5 years) is 141,901,600 USD/yr, which added to the annualized operational and maintenance costs of 107,222,400 USD/yr yields a total of 249,124,000 USD/yr, which is the annual cost of treating 10 m^3/s. Accordingly, the unitary treatment cost of each cubic meter is 0.79 USD (1997 prices) for the first five years, and 0.34 m^3/s for the following years (DGCOH, 1997). Inflation rates were obtained from TCB (2001).

Treated water will be recharged in the *Chichinautzin* sierra between *Xochimilco* and *Tláhuac*, located in the southeastern part of the Federal District. Costs included in this item are pumping costs, cost of pipes to conduct water from the treatment plant to injection wells, supply and installation of pipes, unidirectional tanks to avoid pressures below the atmospheric pressure and habilitation of wells. The total annual cost associated with the recharge facilities is 0.0023 USD/m^3 (DGCOH, 1997).

3.2 Total cost of the project

The total cost of the project is obtained by adding the treatment costs and the recharge costs, as follows:

$$\begin{aligned}\text{Total cost} &= \text{treatment costs} + \text{recharge costs}\\ \text{Total cost}_{firstfiveyears} &= 0.79 + 0.0023 = 0.80\ \text{USD/m}^3\\ \text{Total cost}_{lifetimeofproject} &= 0.34 + 0.0023 = 0.3423\ \text{USD/m}^3\end{aligned}$$

Considering a project life of 50 years, the net unitary cost of the recharge program is calculated as:

$$\begin{aligned}\text{Capital costs (t = 5 years)} &= 141{,}901{,}600\ \text{USD}\\ \text{Operation and maintenance costs (t = 50 years)} &= 107{,}947{,}728\ \text{USD}\end{aligned}$$

Thus, the annual cost for the first five years is 249,849,328 USD while for the remainder life of the project the cost is 107,947,728 USD. The present cost of the artificial recharge program (PCAR) is calculated using a discount rate of 3% as recommended by the NOAA (ASTSWMO, 1998).

$$PCAR = \frac{249,849,328}{(1+0.03)^1} + \ldots + \frac{249,849,328}{(1+0.03)^5} + \frac{107,947,728}{(1+0.03)^6} + \ldots + \frac{107,947,728}{(1+0.03)^{50}} \quad (1)$$

PCAR= 3,427,337,344 USD

3.3 Risks associated with an artifical recharge program

There are risks associated with an artificial recharge program; if aquifer recharge is done haphazardly or in a poorly planned fashion, chemical or microbial contaminants in the water could impact the health of consumers, as explained by the World Health Organization (WHO, 2001). The risk may be especially important when reclaimed water is being used, as wastewater may contain numerous contaminants (many of them poorly characterized) that could have health implications if introduced into drinking water sources. A proper risk assessment should be realized before implementing an artificial recharge program in the City. In this regard, proper information of consumers will play a vital role in the acceptance of such a program. The main issues that have to be addressed in a risk analysis should be:

1. Identification of risk parameters
2. Quantification and expose analysis
3. Dose-response evaluation and
4. Risk consequences and its management.

On this regard, the recommendations given by Nichols and Zeckhauser (1986) should be taken into account in order to avoid “risk conservatism”.

4 Water tariffs

One of the policies suggested in order to achieve a better management of water resources is water tariffs. Its implementation raises several problems, as improvement in water supply and water quality is often used as a political flag and most people think that water should be provided at almost no cost (Saaden-Hazin, 1997); however partly because of low water tariffs, inhabitants of the City are not aware of a water crisis, as water price sends a clear signal to users about the relative scarcity of the resource (González-Antón and Arias, 2001). Current tariffs in the City do not reflect the opportunity cost of water (NRC, 1995; DGCOH, 2000) and it is considered that users should pay at least this cost (NRC, 1995). In order to address this issue, in the present section a first approach1 to calculate the opportunity cost of water in the Basin is presented considering alternative water sources for the City. These

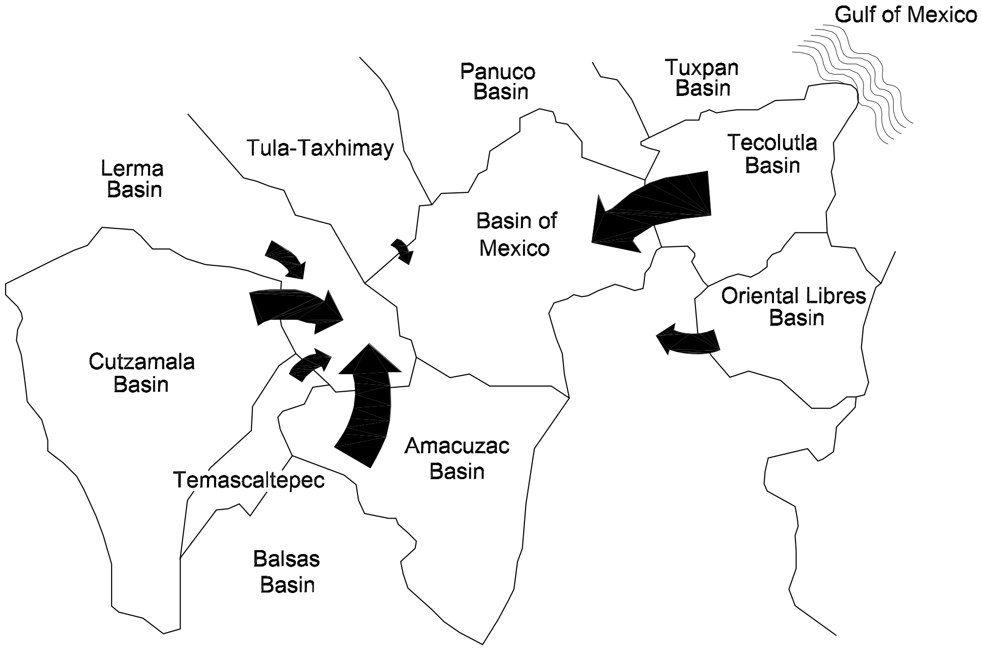

Figure 4: Possible water sources for the Mexico City Metropolitan Area

water sources have been suggested previously in papers dealing with the City's water supply, such as Ramirez-Sama (1990); Fuentes-Mariles (1997); NRC (1995) just to name a few. Water use efficiency in the City is not achieved by users as most people are not aware of a water crisis, mainly because water tariffs are too low. As opportunity cost is considered to be a proxy for water tariffs, in the following section this cost is calculated in order to suggest a minimum water tariff for consumers in the City.

4.1 Opportunity cost of water in the aquifer

The opportunity cost of water in the aquifer is the cost of obtaining water of comparable quality and in equal quantity from some alternative source (Kulshreshtha, 1994). Thus, alternative water supply sources currently in consideration by the City's authorities will be used to calculate the opportunity cost of water in Mexico City's aquifer. There are currently five different alternatives to supply more water to Mexico City (Fuentes-Mariles, 1997; NRC, 1995; Ramirez-Sama, 1990). The first four alternatives consist of importing water from other basins, while the last alternative consists in changing clear water used for irrigation by reclaimed waste waters. These future water sources are shown in figure 4 and are as follows:

1. Temascaltepec Basin: In order to use the water from this basin, water flowing in the *Temazcaltepec* river will be stored in the El Tule dam in order to pump it a total height of 250 m to the *Valle de Bravo* dam through a 15 km long tunnel. The construction of this infrastructure will suppress the opportunity of using the water from the *Temascaltepec* river in the hydroelectrical plants of *Santa Bárbara* and *Tingambato* (Ramirez-Sama, 1990). The total flow that can be provided by this source is 7 m^3/s.

Table 2: Costs of importing water from possible water sources

		Taxhimay	Oriental	Amacuzac	Tecolutla	Temascaltepec
flow	m^3/s	5	7	15	15	7
Annual volume	$m^3 \times 10^6$	157.68	220.75	473.04	473.04	220.75
Construction costs	M$	401.93	632.61	1360.06	1346.75	664.38
Energy used to pump water	kWh/m^3	0.452	1.356	3.834	3.100	4.424
Affected energy	kWh/m^3	-	-	0.507	2.650	0.325
Annual energy	MkWh/yr	71.27	299.33	2053.47	2719.98	1048.34

2. Tecolutla Basin: To import water from this source, a series of dams and conductions will have to be built. This source will use part of the *Necaxa* hydroelectrical system to pump 15 m^3/s. The amount of water that will be pumped to the Federal District will not be used in the *Necaxa* and *Apulco* hydroelectrical dams, diminishing their electricity generation (Ramirez-Sama, 1990). The flow that this source would provide is 15 m^3/s.

3. Amacuzac Basin:In order to import water from this Basin, several dams have to be built as well as conduits and pumping stations for the 15 m^3/s that this external source can provide. This flow will diminish the electricity generation of the hydroelectrical dams *El Caracol*, *Infiernillo* and *La Villita* (Ramirez-Sama, 1990).

4. Oriental Libres Basin: Water imported from this source will be taken from the aquifers located in the closed basin where the towns of *Oriental, Libres* and *Zacatepec* are located. The flow available from this source is 7 m^3s (Ramirez-Sama, 1990).

5. Taxhimay Dam:The water stored in this dam is currently used for irrigation and it is being proposed that it could be used to supply water for urban use, using waste water for irrigation instead of the water provided by the dam. A total flow of 5 m^3/s can be supplied by this source (Ramirez-Sama, 1990).

To compare the alternative sources costs with the cost of the recharge project, prices shown in table 2 have to be expressed in 1997 costs. In order to do so, the inflation rate for each year will be used from 1988 to 1997, as shown in table 5. These costs are also shown in USD for 1997 in table 5.

The net present costs for the alternative water sources are calculated in order to obtain the opportunity cost of water. The procedure is similar to that of section 3.2: a project life of 50 years, a discount rate of 3% and it is assumed that capital

Table 3: Unitary costs of possible water sources (1987 pesos)

Energy for pumps	$\$/\text{m}^3$	0.041	0.122	0.345	0.279	0.398
Affected energy	$\$/\text{m}^3$	0.000	0.000	0.046	0.238	0.029
Op. and Maint.	$\$/\text{m}^3$	0.023	0.014	0.023	0.023	0.023
Construction costs	$\$/\text{m}^3$	0.306	0.345	0.345	0.341	0.361
Total costs	$/m	0.370	0.481	0.759	0.881	0.811

Table 4: Inflation rates and costs for future sources (1988-1997)

Year	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997
Inflation[a]	1.130	0.190	0.260	0.220	0.150	0.100	0.070	0.340	0.340	0.200
Taxhimay	0.788	0.938	1.182	1.442	1.658	1.824	1.951	2.615	3.504	4.205
Oriental	1.025	1.219	1.536	1.874	2.155	2.371	2.537	3.399	4.555	5.466
Amacuzac	1.617	1.924	2.424	2.957	3.401	3.741	4.003	5.364	7.188	8.625
Tecolutla	1.877	2.233	2.814	3.433	3.948	4.342	4.646	6.226	8.343	10.011
Temazcaltepec	1.727	2.056	2.590	3.160	3.634	3.997	4.227	5.731	7.680	9.216

[a] Inflation rates were obtained from TCB (2001)

Table 5: Total costs of alternative sources for 1997 in USD

Water source	1997 prices (pesos/m^3)	1997 prices (USD/m^3)[b]
Taxhimay	4.205	0.501
Oriental	5.466	0.651
Amacuzac	8.625	1.027
Tecolutla	10.011	1.192
Temazcaltepec	9.216	1.097

[b] An exchange rate of 8.39 pesos per dollar was was considered for 1997, after DGCOH (1997)

Table 6: Unitary cost of water for alternative sources

Source	NPC (USD)	NPC/m^3
Taxhimay	722,837,396.563	0.092
Oriental	1,649,459,306.275	0.149
Amacuzac	8,279,415,221.064	0.350
Tecolutla	10,089,879,155.283	0.427
Temazcaltepec	4,632,299,995.930	0.420

costs will be paid during the first five years of the project. The values calculated in such a way are shown in table 7.

From table 7 it can be inferred that the cheapest source is the *Taxhimay* source, while the most expensive water source is the *Tecolutla* basin. However, problems associated with groundwater extraction in the *Oriental* basin will have to be studied in detail, as well as socio-ecological problems that can arise by importing water from these sources which are not included as part of these costs.

As previously determined, the aquifers provide a total of 36 m^3/s. More water sources within the Basin of Mexico are not available, and water needs to be imported. If the aquifer were not present, some other water sources would need to be exploited in order to supply water in the same quantity and quality. To supply this 36 m^3/s let us consider that water is imported from *Amacuzac, Tecolutla* and *Oriental* basins (37 m^3/s). With these sources, the opportunity cost of water would be the weighted average of prices for each cubic meter imported from the three different sources, thus:

$$OC = 0.35\frac{15}{37} + 0.427\frac{15}{37} + 0.149\frac{7}{37} = 0.343 \text{ USD/m}^3 \tag{2}$$

This result shows that the unitary price that should be charged to users is 0.309 USD. In order to compare this cost with the price currently being charged to domestic users, let us consider a supply of 180 liters/day/person as suggested in Mexico City's Master Water Plan (Fuentes-Mariles, 1997) and that 4.4 persons share a water intake (DGCOH, 2000). The current bi-monthly tariff in the city is of 0.034 USD/m^3 (DGCOH, 2000) when a consumption below 45 m^3 is registered, which is the amount of water considered to be enough in order to satisfy basic needs and equal to the consumption suggested (0.18 m^3/person/day) in two months for a common household. There is a big difference between the opportunity cost of water and the price charged to consumers, although it may be necessary in order to supply the resource to low income people; social equity needs to be considering in order to set an adequate water tariff.

5 Discussion

Overexploitation of the aquifer in the Basin of Mexico has to be stopped soon, as land subsidence is causing damages in buildings and water infrastructure; also, drawdown of the groundwater table increases pumping costs and may reduce water quality as the aquifer is compacted as described in table **??**. In order to achieve sustainability in the Federal District, authorities have to protect the aquifer as the City heavily relies on it for its water supply and it can not be substituted by a different water source. Its depletion will cause not only an environmental disaster, but also an economical one as stated by Blomquist (1992):

> When a groundwater basin is destroyed, water users not only lose the comparatives advantages of underground water storage and distribution, but they also suffer enormous financial costs. Replacement of groundwater storage and distribution capacity, even if feasible, would be an economic disaster.

The economic concentration of the MCMA has been in great measure the main cause of problems that authorities in the City have to face nowadays. Water is a vital element for life and for all activities ongoing in Mexico City, and its demand will increase as its population increases. The aquifers underneath the City are of vital importance and they have to be managed in a sustainable way; thus, all water policies implemented in the city should simultaneously satisfy social, economic and environmental demands in order to achieve this goal (Feng, 2001). Authorities are aware that a water management program including protection of the aquifers has to be implemented not only in the Basin of Mexico but throughout the country, as overexploitation of aquifers in Mexico is not a unique problem of Mexico City, as stated in the National Hydraulic Plan (CNA, 2002). Groundwater represents 70% of the total water supplied to cities in the country and by the year 2000 a total of 96 aquifers out of 653 aquifers were in a state of overexploitation (CNA, 2002). An important part in the implementation of any water policy in the city is its proper monitoring. In adition, groundwater flow has to be modeled in order to study the aquifer's response to artificial recharge and a proper water demand forecast has to be conducted, as sustainable groundwater management requires a reliable knowledge of resource availability, recharge and demand (Durham et al., 2002).

Land subsidence in Mexico City is a complex and long-term problem; the accumulated land subsidence up to these days can not be reversed; however, land subsidence can be controlled and diminished to its greatest possible extent. The main problem that a successful water management program has to address is informing the users, as the real magnitude of the water crisis in the City is not felt by its inhabitants. This attitude has been partially caused by subsidies provided by the Federal government as low prices do not reflect the water crisis in the City and Mexico City's government do not pay the total cost of new infrastructure or water supplied by the Cutzamala and Lerma systems (Haaggarty et al., 2001) as Federal funds are provided for this end.

The cost of each cubic meter that will be injected to the aquifer, considering a project life of 50 years is 0.217 USD. If one takes a look at table 6 and compares the costs shown, it is apparent that the solution to Mexico City's problems would be to import water from the Oriental Basin and from the Taxhimay dam as they are "cheaper" sources. However, importing water from these basins implies transferring the City's water problems to other areas, as is the case for the two external water sources that currently supply water to the MCMA. In the Lerma Basin, overexploitation effects are visible by cracks and land subsidence caused by groundwater table drawdown while the *Cutzamala* system is diminishing the energy that is produced by the hydroelectrical plants *El Infiernillo* and *La Villita* (Ramirez-Sama, 1990) as it uses part of the hydroelectrical System *Miguel Alemán*. Social problems caused by water provided to the City are not present only in other river basins, but within the Basin as well. In some parts of the Basin. Nnear Mexico City, problems are arising as water is being extracted and supplied to the City while inhabitants who lack tapped water in those areas, such as Chiconautla are demanding that water extracted in this area should be provided to them instead of providing it to the City (DGCOH, 2000). Water Management in Mexico City has to change from a supply approach to a resource management approach, as it has been suggested in the literature (Feng, 2001; Kumar and Singh, 2001). New water policies in the city should also aim at a spatial redistribution of groundwater extraction in order to diminish groundwater table drawdown in certain areas such as *Azcapotzalco* and *Tlalpan*.

Another aspect that needs urgent regulation is land use change in the City, as a clear understanding of the significant impact of land use on groundwater can generate guidelines for sustainable groundwater management (Collin and Melloul, 2001). As urbanization grows, recharge areas decrease as the surface is covered with asphalt and concrete. Thus, the simultaneous reduction of recharge areas and overpumping of groundwater is exacerbating social and environmental costs in Mexico City.

The main issue to be solved, not only in the City but in the country is the lack of long term planning. It is common knowledge int Mexico that all projects respond to a six-year planning horizon at most, as all projects proposed by the president in turn should be completed before his presidential period comes to an end; this problem has even been addressed and expressed in the newest Mexico's National Hydraulic Plan (CNA, 2001) as one of its main objectives in order to achieve a sustainable water management:

> Water management related actions have to be taken on a long term basis in order to avoid the imposition of public administration urgencies.

This common practice has to come to an end, as the future patterns of resource extraction, production, and consumption will have to respond to long-term goals (Saaden-Hazin, 1997) in order to achieve a sustainable exploitation of the aquifers in the City. A key component in groundwater protection is the participation of citizens and users, as communities that have strong education and outreach programs, active citizen groups and which provide opportunities for citizens to be involved in planning tend to be more pro-active and more successful in protecting their groundwater resources (De Löe, 2001). The CNA has given a step in this direction, involving users in water management through the Basin Councils and the Technical Groundwater Committees (COTAS) which were proposed in the National Water Law (LAN) implemented in 1992. As a result, a total of 26 Basin councils and 47 COTAS were in function by September of 2001 (CNA, 2001).

6 Conclusions

The MCMA depends heavily on water provided by the aquifer system located beneath it and current lack of water management in the Basin has caused overexploitation of the aquifers and an anarchic use of the resource. In order to increase water supply to its ever growing population, authorities are trying to implement an artificial recharge program to avoid the increasing decline of the groundwater table and the problems associated with it.

The overall goal of Mexico City's authorities is to achieve a sustainable management of the resource; however, the problem will not be solved only with an artificial aquifer recharge program, as other water management policies have to be implemented, such as detection and repair of leaks in the water supply network and use of water tariffs. A great amount of water is lost in leaks in the water supply network, as they are as high as 37%, which represent a total of 22.2 m^3/s; if leaks were reduced to 20% a total of 10.2 m^3/s could be saved and supplied to users. This amount of water is the same amount that would be artificially recharged in case that the artificial recharge program is implemented, and is more than that which can be imported from other water sources such as Taxhimay, Oriental and Temazcaltepec. Thus, a leak detection program has to be implemented as it can be viewed as an alternative water source and its implementation is of paramount importance in achieving a sustainable use of the resource. Another measure that needs to be implemented is proper water billing and participation of water users.

In order to solve water scarcity problems in Mexico, political and institutional changes are required as sometimes the best technical solutions are not the best real-life solutions, as social welfare and equity need to be considered in any possible solution. Mexico's government is giving a step toward integral water resources management through Basin Councils and decentralization as well as stake holders' participation.

An artificial recharge program using reclaimed waste waters can be implemented in the City; however, Mexico City's authorities will have to manage it in a proper way in order for it to be accepted by consumers. With the implementation of such a project the City's water problems will not be transferred to other communities or river basins as is the case when water is imported. With a recharge program, water quality in the aquifer can also be improved in those areas where certain parameters exceed current water drinking standards.

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