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Water management in the Basin of Mexico: current state and alternative scenarios.

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Abstract

Water management policies in the Basin of Mexico, where Mexico City and its nearly 20 million inhabitants live are analyzed in this paper. After a brief description of how water has been managed, possible water management plans are discussed in order to change water management in the Basin and a call is made for a change in the defensive attitude towards water taken to date. As the aquifer's replacement cost is considered to be the proxy for the implementation of water tariffs, it is determined based on the cost of future water sources and found to be 0.65-0.72 USD/m^3, which is twice the amount currently charged in the Federal District (0.34 USD/m^3), where 45% of the City's domestic water users are found. As another alternative, the development of an artificial recharge program is also analyzed and found to be a plausible way to increase water supply at a unitary cost of 0.605 USD/m^3. Despite the presence of these alternatives, it is suggested that water management in the Basin needs to change from a water supply approach to a water demand approach.

1 Introduction

The Basin of Mexico, where Mexico City and its Metropolitan Zone (MCMZ) are located, has had a contradictory approach towards water management, as it has struggled to drain the lakes that once covered this region while at the same time it started to transport water from adjacent basins in the late 1950s. In addition, the large amounts of water extracted from the Basin's aquifer have caused drawdown of the groundwater table and consequently, land subsidence which reaches 40 cm/yr in some areas.

The water resources management approach taken to date needs to change as other options, preferable to transferring the Basin's water problems, need to be found. Accordingly, this work analyzes the existing water management policies in the Basin, giving a brief description of how this contradictory approach has evolved over time. As water tariffs are expected to cover the aquifer's replacement cost, this cost is determined based on the cost of taking more water to the MCMZ from different water sources that have been considered in order to increase the total water supply. As part of these possible solutions, an artificial recharge program is also considered and the requirements of its successful development and implementation are discussed.

2 The Basin of Mexico

Mexico City is located in the lower part of the Basin of Mexico, in the central region of Mexico, (Fig. 1) with a mean elevation of 2240 meters above sea level (masl) and enclosed by four different mountain ranges: to the west, the *Sierra de las Cruces*, to the south the *Sierra Chichinautzin*, to the east by the *Sierra Nevada* with peaks above 5000 masl, and northwards by the *Sierra de Pachuca* (Fig. 1). Due to its geographic location, the City has struggled to protect itself from floods since its early times, while water supply problems arose during the XXth century. As the Basin is enclosed by these mountain ranges, during the rainy season a large shallow lake was formed, covering a large area that extended from *Mixquic* in the south to *Zumpango*, near the Basin's limit to the north. This lake system was a problem even before the arrival of the Spaniards, solved by the Basin's inhabitants with the construction of the *Albarradón de Netzahualcóyotl*, which in fact protected the City (at that time named *Tenochtitlán*) from flooding in 1449 (Mathes, 1970).

Due to the City's flood-prone condition, plans to divert the Basin's rivers or to drain the Basin's lakes were continuously developed. The first of these projects was conceived in 1555, when Ruy Gonzalez proposed to divert some rivers in order to stop them from feeding the lakes (Mathes, 1970). After the most severe flooding since the arrival of the Spaniards in the Basin occurred on June of 1607, a plan to both divert rivers and drain the lakes was envisioned by Enrico Martinez on October of that same year (Mathes, 1970). The lakes, which originally covered an estimated area of 1,575 km^2, were reduced to 230 km^2 in 1861 and 95 km^2 by 1891; in the 90s, the estimated area covered by the lakes was 13 km^2 (DGCOH, 1994). This has been caused by the development of a complex drainage system in the Basin, which in fact drains the entire Basin, converting an endorreic Basin into an artificial exorreic system.

2.1 The Basin's drainage system

Despite the efforts undertaken to drain the lake throughout the City's history, it was not until 1900 that a long term solution was completed, when the *Gran Canal del Desagüe* (Grand Drainage Canal, Fig. 1), whose construction works started in 1886, was finished (Perló-Cohen, 1999). Later in time, a series of dams were built on the western mountain range of the Basin (*Sierra de las Cruces*, Fig. 1) between 1930–1940, while in the 1960s different rivers that crossed the city were piped and more dams were built in the *Sierra de las Cruces* to protect the City from flash-floods (DGCOH, 1994). The system of dams was designed to drain their reservoirs to the *Interceptor del Poniente* (Western interceptor) and take them out of the Basin, to the *Salado* river, a tributary of the *Pánuco* river, which discharges to the Gulf of Mexico (Fig. 2). As the City grew, a new drainage system was required and between 1965–1975 the first 68 km of the *Drenaje profundo* (Deep drainage, Fig. 1) were built and by the end of the 90s it comprised a total of 181 km, with diameters between 3.20 to 6.50 meters (DGCOH, 1994).

The way in which the drainage system has been developed provides for drainage of the entire Basin (Fig. 1): The western system drains the western regions, the deep drainage system the southern and central areas, while the *Gran Canal* first receives the water that flows in the eastern rivers and further downstream receives the waters from the northeastern region of the Basin.

2.2 Water supply: a briefing

Water demand in the Basin of Mexico is satisfied by two different types of sources, the first of which is comprised of water withdrawn within the Basin: groundwater, rivers and springs. The second source is comprised of water brought from other basins through two water supply systems: The *Lerma* and *Cutzamala* systems, which were developed in order to increase the city's water supply and which withdraw water through extraction wells and a series of dams located west of the Basin of Mexico (Fig. 2). As the Basin comprises five political entities (Fig. 1), different governmental agencies are in charge of water supply, the most important being the *Comisión Nacional del Agua* (CNA) and the recently formed *Sistema de Aguas de la Ciudad de México* ((SACM), formerly known as *Dirección General* *de Construcción y Operación Hidraulica (*DGCOH)). The CNA has under its charge the *Gerencia Regional de Aguas del Valle de México* (GRAVAMEX), which in conjunction with the SACM operates the water-supply infrastructure for the MCMZ. The always increasing water demand has been driven by the continuous growth of the City as shown in Table 1 and detailed in the following paragraphs.

Table 1. Population and water supply evolution in Mexico City 1900-2000

year	Population[a]	Water supply (m^3/s)
1900	345,000	0.77
1950	3,136,000	14.30
1990	15,785,000	61.59
2000	18,396,677[b]	65.00[a]

[a] Data from INEGI(2002), [b] INEGI (2007)

Population and water supply in the Basin increased drastically throughout the XXth century, as in 1899, water supply to Mexico City was only 0.77 m^3/s, provided by the *Hondo* river (52%) and springs located west of the City, in the *Desierto de los Leones, Santa Fe* (20%) and in *Chapultepec* (28%) (Marroquín-Rivera, 1914). However, by 1900 this water supply was not enough and an aqueduct was built to bring water from *Xochimilco*, a wetland located in the southern part of the Federal District and documented in Marroquín-Rivera (1914). These days, the regional aquifer system represents the main water supply source from which water started to be extracted in 1847 (Ortega and Farvolden, 1989). However, it was not until 1930 that a large number of wells were drilled and by the end of that decade, drawdown of the water table made it necessary to drill deeper wells; despite the drawdown caused by these wells, another 58 were drilled in the Federal District between 1940–1946 (Bribiesca-Castrejón, 1960). The drawdown caused by the existing wells in the Federal District triggered the development of the *Lerma* system, which takes water from the upper *Lerma* basin, south of *Toluca* (Fig. 2). This system, which started its operation in 1951 conducts the water taken from different springs and extraction wells in the *Toluca* valley (upper Lerma Basin) through a 60 km aqueduct which ends in a distribution tank in Mexico City and provided 3.5 m^3/s in 1952, after starting its operation in September 1951 (Bribiesca-Castrejón, 1960). By this year another 33 wells were drilled in the *Xotepingo* area, with which the total water supply was 14.3 m^3/s; however, leaks were estimated to be around 14% or 2.0 m^3/s (Bribiesca-Castrejón, 1960).

During the 50s more wells were drilled in order to increase the City's water supply: the *Chiconautla* system, located 32 km north of the Federal District, in the State of Mexico, started to extract water in 1957 through 40 wells at a depth of 150 m (Bribiesca-Castrejón, 1960), while southwards the first stage of the *Peñón del Marqués* system was finished in 1958 and by 1959 it comprised 13 deep wells which extracted 1 m^3/s. Simultaneously, water withdrawals in the *Lerma* system were augmented in order to provide a total flow of 6 m^3/s; with all these actions, in 1960 the total water supply to Mexico City was 22 m^3/s (Bribiesca-Castrejón, 1960), of which 13.6 m^3/s (62%) were withdrawn from the Basin's aquifer. Despite these actions, more water was needed and during the 60s more wells were drilled: within the Basin 40 wells were drilled at a depth of 150 m to supply an additional 2.5 m^3/s in the *Tláhuac-Chalco* area, while 32 additional wells were drilled in the *Lerma* basin, which provided an extra 2.5 m^3/s in 1960 and to which 45 more wells were added in 1964. Water from rivers was also withdrawn: in the southern region of the Federal District, a flow of 0.02 m^3/s was provided by the *Magdalena* river (DGCOH, 1995).

As the City continued to grow, more water was needed and more wells were drilled in the *Lerma* basin, which in 1974 provided 14 m^3/s, causing large drawdown rates in the *Toluca* and *Ixtlahuaca* valleys pueswhich in turn caused a reduction in the extraction rates. In this same year, seven lines of wells called *Pozos de Acción Inmediata* (wells for immediate action, or PAI by its spanish acronym) were drilled as a "temporary solution" to the City's water supply problem and which to this date continue to extract water, causing drawdown rates of 2.5 m/year north of the Federal District (Carrera-Hernández and Gaskin, 2007). As this water was still not enough, in 1976 the *Cutzamala* system started to be built in order to bring water from the *Cutzamala* river (Fig. 2) through a 127 km aqueduct and seven reservoirs which used to be part of the hydroelectrical system *Miguel Alemán*. The water supplied by the *Cutzamala* system needs to be pumped 1200 m in order to reach the MCMZ using five different pumping stations and was designed to provide water to the two political entities over which Mexico City extends: the Federal District and the State of Mexico.

By 1990, groundwater was delivered from 3537 officially registered wells within the MCMZ (NRC, 1995). Water supply to the MCMZ in the 90s, estimated from data available in the CNA by considering that private wells extract 50% of their allowed volumes was 61.59 m^3/s, a value that when the entire Basin is considered only reaches 65.66 m^3/s. By considering only the MCMZ, extraction from the aquifer was 40.76 m^3/s (66%), followed by water brought from the *Cutzamala* system, with 14 m^3/s (23%), and the *Lerma* system with 5.8 m^3/s (9%), while surface waters accounted only for 2% of the total water supply: 90 springs provided 0.87 m^3/s, while the *Madín* basin supplied 0.37 m^3/s and the *Magdalena* river 0.19 m^3/s. For this period, the PAI wells, which were drilled as a temporary solution in the 70s extracted a total flow of 4.57 m^3/s, mainly from the *Teoloyucan* and *Tizayuca-Pachuca* well lines (Fig. 1) which accounted for 2.61 m^3/s. In addition, a number of unaccounted extraction rates is present, as several illegal wells are present in the Basin (NRC, 1995).

2.3 Consequences of groundwater extraction

The main problem caused by the large extraction rates of water from the aquifer system is land subsidence. This is not a new problem as it was discovered in 1925 by Roberto Gayol, who used two precision surveys made in 1877 and 1924 of a monument located near the City's Cathedral (Figueroa-Vega, 1984), attributing the phenomenon to the effect of the recently built drainage system. When the large extraction rates were associated with land subsidence, wells located in the central part 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*) (Ramírez-Sama, 1990). 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 due to the fact that the monument's foundations lay in a hardened sand lense interbedded within the lacustrine deposits on which the City is built.

From the beginning of the XXth 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 80s its mean value was 4.5 cm/yr (Mazari and Alberro, 1990); however, 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, although some areas still had a rate of 40 cm/yr (Strozzi et al., 2003; 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) and some areas currently have an accumulated subsidence of more than 15 m (González-Morán et al., 1999) or even 30 m (Birkle et al., 1998). These large subsidence rates have damaged existing infrastructure such as the subway lines which need to be periodically fixed and the water supply and sewage network, increasing the amount of leaks.

Another aspect of the large groundwater extraction rates 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 by the pore water of the overlying lacustrine clay being drained to the aquifer as clays are being consolidated due to depressurization of the aquifer (Cortés et al., 1997). Compounding this problem, the lacustrine sediments, which have been a protective barrier for the aquifer from surface pollution are cracking in some areas, which may cause infiltration of pollutants to the aquifer (Durazo, 1996).

The effects of extensive groundwater extraction are also seen in the Valley of Toluca, in the upper Lerma Basin, where the groundwater table has been lowered. This situation has altered the regional groundwater flow pattern, reversing vertical hydraulic gradients in the Valley floor (Rudolph et al., 2006).

3 Analysis of water management policies

Paradoxically, policies and drainage infrastructure have been developed in an opposite direction taken by water supply policies: on one hand, all runoff is taken out of the Basin by a system that has been developed throughout the XXth century, while on the other hand, water is now being withdrawn from other basins, as currently 23% of the current water supply is brought by an aqueduct that extends for more than 100 km and over an elevation difference of 1200 meters. The problem lies in that the City continues to grow and more water will be required; in fact, a water deficit of 9 m^3/s is expected by 2010 (DGCOH, 1997). Accordingly, water authorities are looking at other options to augment water supply, comprised of three main water policies: (1) artificial recharge of the aquifer system, (2) water tariff enforcement and (3) import water from other basins. These water policies are analyzed in this section, and then an estimate of the aquifer's replacement cost is done by considering the existing alternatives if the aquifer were not present.

3.1 Artificial recharge

As previously explained, almost all runoff generated within the Basin is drained by the *Interceptor del Poniente* and a small amount is used for water supply. A possible option to increase water supply is by reusing water within the Basin through artificial recharge of the aquifer with reclaimed water. This approach is currently under trial in the Basin at two different locations: the first one recharges 0.02 m^3/s through a recharge pond, while the second one recharges the aquifer through an injection well at a rate of 0.06 m^3/s (DGCOH, 1997), using water that has been treated up to a tertiary level.

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 and 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 in the irrigation district *Chiconautla* while the remainder is exported to the Tula river basin (DGCOH, 1997). The waste water quality is typically that of domestic waste water, although some industrial contaminants are present (DGCOH, 1997).

A previously developed study (DGCOH, 1997) is used here as a reference for an artificial recharge project in the Basin. This study suggests taking wastewater 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 Drainage Canal will be taken before water coming from *Los Remedios* river mixes with it, as this contains industrial wastewater, making it harder and more expensive to treat it to proper standards for recharge.

Treated water will be recharged in the *Sierra Chichinautzin* between *Xochimilco* and *Tláhuac*, located in the southeastern part of the Federal District (Fig. 1). The costs included in this item are pumping costs, cost of pipes to transport water from the treatment plant to the 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 at that time was of 0.0023 USD/m^3 (DGCOH, 1997).

In the study of reference, capital, operation and maintenance costs were calculated and reproduction of that part of the study is not made in this work. The capital costs (CC) obtained on that study were of 711.984 million USD, while the Operation and Maintenance (O & M) costs were of 0.34 m^3/s (1997 costs) in addition to the unitary costs of the recharge facilities of 0.0023 USD/m^3. These costs are converted to current (2008) unitary costs by applying Mexico's annual inflation rate for the period and by amortizing the CC through the 50 years that are considered to be the project's life span. Accordingly, the unitary price of injecting reclaimed waste water is of 0.605 USD/m^3.

At this point, it should be emphasized that 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 (World Health Organization, 2002). 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 order to avoid point pollution of the aquifer system.

3.2 Water tariffs

One of the policies suggested in order to achieve a better management of water resources is charging appropriate water tariffs which is a water demand control tool. 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 generally considered that users should pay at least this cost (NRC, 1995), which is the value that is sacrificed to obtain a given asset (in this case water). Another way to assign a value to the Basin's aquifer system is to determine its replacement cost, which is the approach presented in this work, and calculated by considering alternative water sources for the City. These water sources have been suggested previously in papers dealing with the City's water supply, such as Ramírez-Sama (1990) and NRC (1995).

3.3 Replacement cost of the aquifer system

Alternative water supply sources currently under 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 (NRC, 1995; Ramírez-Sama, 1990). The first four alternatives consist of importing water from other basins, while the last alternative consists of replacing clear water used for irrigation by reclaimed waste waters. These future water sources are shown in Fig. 2 and are as follows (Ramírez-Sama, 1990):

1. Temascaltepec Basin: Water flowing in the *Temascaltepec* 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*. The total flow that can be provided by this source is 7 m^3/s.
2. Tecolutla Basin: This source will use part of the *Necaxa* hydroelectrical system to pump 15 m^3/s; accordingly, this water will not be available in the *Necaxa* and *Apulco* hydroelectrical dams, diminishing their electricity generation.
3. Amacuzac Basin: The estimated flow from this source is 15 m^3/s, which will diminish the electricity generation of the hydroelectrical dams *El Caracol*, *Infiernillo* and *La Villita* as this river is a tributary of the *Balsas* river.

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^3/s.
5. Taxhimay Dam: The water stored in this dam is currently used for irrigation and it is being proposed that it could be used as a domestic water supply, if waste water is used in those fields that currently make use of the dam's water. The available flow is estimated in 5 m^3/s.

The costs associated with each water supply project and the costs associated to lost electricity generation are summarized in Table 1, while the unit costs per cubic meter are shown in Table 2, which are expressed in Mexican pesos of 1987, as detailed in Ramírez-Sama (1990).

Table 1: 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

The prices shown in Table 1 are converted to current (2008) unitary prices following the same procedure as the one for the artificial recharge program, as shown in Table 2:

Table 2: Inflation rates and costs for future sources (1988-1997)

Year	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997
Inflation[a] (%)	125.43	20.32	26.54	22.84	15.58	9.77	6.97	34.77	35.26	20.82
Taxhimay	0.17	0.20	0.25	0.31	0.36	0.40	0.42	0.57	0.77	0.93
Oriental	0.16	0.19	0.24	0.30	0.35	0.38	0.41	0.55	0.75	0.9
Amacuzac	0.18	0.22	0.28	0.34	0.39	0.43	0.46	0.62	0.84	1.02
Tecolutla	0.18	0.22	0.27	0.34	0.39	0.43	0.46	0.62	0.84	1.01
Temazcaltepec	0.19	0.23	0.29	0.35	0.41	0.45	0.48	0.64	0.87	1.05

Year	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
Inflation[a] (%)	15.20	16.67	9.51	6.39	5.03	4.56	4.68	4.00	3.63	3.97
Taxhimay	1.08	1.26	1.38	1.46	1.54	1.61	1.68	1.75	1.81	1.89
Oriental	1.04	1.21	1.33	1.41	1.48	1.55	1.62	1.69	1.75	1.82
Amacuzac	1.17	1.37	1.5	1.59	1.67	1.75	1.83	1.9	1.97	2.05
Tecolutla	1.16	1.36	1.49	1.58	1.66	1.74	1.82	1.89	1.96	2.04
Temascaltepec	1.21	1.41	1.55	1.65	1.73	1.81	1.89	1.97	2.04	2.12

[a] Inflation rates were obtained from Banco de México (2008).

If current electricity tariffs for pumping of public drinking water (Tariff 6 of the Comisión Federal de Electricidad: 1.16 MXN/kWh) are considered, the current unitary costs of these five different sources are as shown in Table 3:

Table 3: Total costs of alternative water sources

Water source	2008 prices (MXN/m^3)	2008 prices (USD/m^3)
Taxhimay	2.41	0.22
Oriental	3.39	0.31
Amacuzac	7.07	0.65
Tecolutla	8.69	0.80
Temazcaltepec	7.61	0.70

From Table 3 it can be inferred that the cheapest source is the *Taxhimay* source, while the most expensive water source is the *Tecolutla* basin. It should be stressed that externalities (e.g. problems associated with groundwater extraction such as drawdown of the groundwater table and land subsidence) are not considered as part of these costs. These problems need to be quantified, as well as socio-ecological problems that can arise by importing water from these sources which are not included as part of these costs. It should be noted that in this analysis, current prices are used and no attempt was made to compound or discount costs and benefits for future conditions, as done by Donovan et al., (2002).

As previously explained, the Basin's aquifer system provides a total of 40.76 m^3/s, but due to the uncertainty in determining actual water extraction rates, this value ranges between 36 m^3/s and 44 m^3/s as the percentage of water that users actually extract from their allowed volume is unknown. The uncertainty in determining the total flow of groundwater extractions was shown by Carrera-Hernández and Gaskin (2007), as although the CNA has developed a database with groundwater extractions (REPDA), it is incomplete (i.e. it does not contain all the wells operated by the SACM); in addition, the REPDA only contains allowed water extractions (for both surface water and groundwater), not actual extractions. In order to determine the replacement cost of the aquifer, the estimated cost of other sources to supply the same amount of water in both quantity and quality is required. If the lower bound of the extraction rate is considered (36 m^3/s), then water needs to be imported from the *Amacuzac, Tecolutla* and *Oriental* basin for a total of 37 m^3/s. Accordingly, the replacement cost of the aquifer system would be the weighted average of prices for each cubic meter imported from these three different sources (Table 3), thus:

$$RC = 0.65\frac{15}{37} + 0.8\frac{15}{37} + 0.31\frac{7}{37} = 0.65 \text{ USD/m}^3 \quad (1)$$

This unitary price was obtained by considering the Oriental Basin, which is not a feasible option. The project that the authorities have tried to develop is the Temascaltepec project, which, if substituted in (1) instead of the Oriental Basin, yields a unitary cost of 0.72 USD/m^3.

This result shows that the unitary price that should be charged to users ranges from 0.65-0.72 USD/m^3. In order to compare this cost with the price currently being charged to domestic users, a supply of 180 liters/day/person is considered, as suggested in Mexico City's Master Water Plan with 4.4 persons sharing a water intake (DGCOH, 2000), yielding 45 m^3 on a bi-monthly basis (users in Mexico are charged every two months). The current water tariff being charged to domestic users varies across political entities in the City, as well as within the income level (by regions), as shown in Table 4.

Table 4. Unitary tariffs (USD) based on a bi-monthly water consumption of 45 m^3

Municipality	Population[a]	Income level		
		Low	Middle	High
Federal District (DF)[b]	8,720,916	0.34	0.34	0.34
Tlalnepantla[c]	683,808	1.10	1.19	1.19
Naucalpan[c]	821,442	0.79	0.82	0.84
Atizapan de Zaragoza[c]	472,526	0.68	0.78	0.83
Cuautitlan Izcalli[c]	498,021	0.46	0.55	0.55
Huixquilucan[c]	224,042	0.80	0.80	0.80
Cuautitlan[c]	110,345	0.56	0.56	0.56

[a] Data from INEGI (2007).
[b] Costs were obtained from the Sistema de Aguas de la Ciudad de México (2008)
[c] Costs were obtained from Comision del Agua del Estado de Mexico (2008)

According to Table 4, water tariffs based on a bi-monthly consumption of 45 m^3 ranges from 0.34 to 1.19 USD/m^3. It is interesting to note that the lowest water tariff is registered in the Federal District, and that no difference is made in order to distribute this tariff in the entity that comprises 45% of Mexico City's inhabitants. This contrasts with the tariffs proposed in December 2007 for the municipalites that comprise the State of Mexico; however these tariffs represent an increase of approximately 40% and were recently proposed (December 2007). The largest water tariff is charged in the Municipality of Tlalnepantla, which was the first municipality of the State of Mexico that became part of the MCMZ in the 1950s. The development of an up-to-date database of water users (and water consumption) is needed, as in the entire country only 49% of the supplied water in 2003 was charged to users (CNA, 2008). Evidently, social equity needs to be considered in order to enforce water tariffs in the City, as water is not an economic asset, but a human right. Another aspect that needs to be analyzed in this region is price elasticity of household demand as to date, no studies have addressed this issue.

4 Discussion

The way in which a given problem is approached changes with time; accordingly, water management policies in the Basin need to evolve, as policies which might have been adequate from an engineering point of view may overlook social, economic and environmental demands, which are needed in order to achieve sustainable development (Feng, 2001). Authorities are aware that a water management program including protection of the aquifer system in the Basin needs to be implemented not only in the Basin of Mexico but throughout the country, as intense extraction of groundwater in Mexico is not a unique problem of Mexico City. Groundwater represents 70% of the total water supplied to cities in the country; a fact reflected in the increase of aquifers that are in a state of severe exploitation. Out of a total of 653, the number of aquifers that show symptoms of severe groundwater extraction (such as a continuous decline of the potentiometric level) has increased from 32 in 1975, to 80 in 1985 and 101 in 2007 (CNA, 2008).

Current water management policies in the Basin of Mexico have had serious impacts both within the Basin and in others basins from where water is withdrawn. The main impact of groundwater exploitation is land subsidence, which is a widespread phenomenon in the Basin of Mexico and in the upper *Lerma* basin, where groundwater started being extracted in the 1950s. The accumulated land subsidence up to the present can not be reversed; however, land subsidence can be controlled and diminished to its greatest possible extent through the development of groundwater extraction policies. Additionally, water users in the Basin need to be informed of the current situation, as the real magnitude of the water crisis is not felt by its inhabitants. This attitude has been partially caused by subsidies provided by the Federal government as the low water prices do not reflect the existence of a water crisis; in addition, the Federal District's government does not pay the total cost of new infrastructure or of water supplied by the Cutzamala and Lerma systems as Federal funds are provided for this end (Zuluaga et al., 2001), as can be seen from the current water tariffs (Table 4).

The cost of each cubic meter that will be injected to the aquifer in the artifical recharge program, considering a project life of 50 years is 0.605 USD, (with a capacity of 10 m^3/s) . When compared to the costs shown in Table 3, makes it 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 (with 0.31 and 0.22 USD/m^3, respectively). 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 MCMZ; the prices reflected in Table 3 do not reflect the full cost of water supply from these sources as environmental impacts are not included: In the Lerma Basin, negative effects of groundwater extraction are visible by cracks in the ground and land subsidence caused by drawdown of the groundwater table, while the *Cutzamala* system has diminished energy production from the hydroelectrical plants *El Infiernillo* and *La Villita*. Social problems caused by water provided to the City are present not only in other river basins, but also within the Basin: the inhabitants of *Chiconautla* are demanding that water extracted in this region should be provided to them instead of taking it to the MCMZ as they lack access to piped water (DGCOH, 2000). The agricultural users of this region had started irrigating their crops with sewage water (Bribiesca-Castrejón, 1960) from the Grand Sewage Channel when the *Chiconautla* system started to extract groundwater from this area in the 1950s. At present it is becoming increasingly difficult for the Federal authorities to undertake unilateral decisions about water withdrawals as shown by the large opposition to the development of the last stage of the *Cutzamala* system, which consists in developing the *Temascaltepec* project: the *Mazahuas*, the ethnic group who inhabit the region of this basin have rallied against it and been actively protesting against its development. To date, they have succeeded.

The main issue to be solved, not only in the MCMZ but in the entire country is the lack of long term planning. It is common knowledge in 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 term comes to an end; this problem has even been addressed and expressed in the National Hydraulic Plan for Mexico (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". 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). As put by Llamas (2005): "the good governance or management of aquifers requires the implementation of bottom-up collective institutions". The *Comisión Nacional del Agua*, (Mexico's National Water Agency, CNA) has taken a step in this direction, involving users in water management through the development of basin councils and *Comités Técnicos de Aguas Subterráneas* (Technical Groundwater Committees (COTAS)) which were proposed in the National Water Law implemented in 1992; unfortunately, the participation of COTAS in the decision making on relevant actions for aquifer management is rather small (Llamas, 2005). The development of COTAS in Mexico has been particularly successful in the State of Guanajuato, where groundwater represents 99%, 60% and 100% of domestic, agricultural and industrial water supply (Sandoval, 2004).

4.1 Development of groundwater management policies

New water policies in the city should aim to analyze whether or not a spatial redistribution of groundwater extraction is possible in order to diminish groundwater table drawdown and land subsidence in critical areas such as *Azcapotzalco* and *Tlalpan*. Another aspect that needs urgent regulation is land use change in the MCMZ, as a clear understanding of the significant impacts 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 heavy extraction of groundwater is exacerbating social and environmental costs in the Basin. Groundwater management policies can be analyzed through the development of a regional groundwater flow model which considers the effect of land cover change in the spatial distribution of aquifer recharge, as shown for the Basin by Carrera-Hernández and Gaskin (2008). This model can be used to analyze possible redistribution of wells and/or redistribution of extraction rates as well as the location of future wells in order to minimize their impact through a simulation/optimization approach.

4.2 Artificial recharge

Mexico City is built over a thick deposit of clay with very low permeability, thus the use of surface ponds to increase recharge is not a viable option and a possible alternative that needs further exploration is artificial recharge through injection wells. More water can be made available through wastewater reclamation which before being injected needs to be treated up to a tertiary level in order to guarantee the quality of the aquifer's water; reclaimed water is injected into the aquifer instead of directly distributing it in the water supply network in order to provide an additional buffer in the process. Artificial recharge has been implemented in different locations, such as in the Montebello forebay area, near Los Angeles, California where approximately 0.002 m^3/s are recharged through two large spreading ponds (Anders et al., 2004); in El Paso, Texas where recharge of reclaimed wastewater was between 0.12 to 0.19 m^3/s for the period of 1985–1989 (White and Sladek, 1990) and in Orange County, California, where the Water Factory 21 started to operate in 1976 using injection wells and reclaimed wastewater to protect its aquifer from saltwater intrusion and where approximately 50% of the injected water enters the water supply aquifer (National Academy of Sciences, 1994). Artificial recharge in the El Paso facility has raised groundwater levels by 5 m at the center of the recharge well field, where a residence time of 5 years assures the good quality of water recovered by the closest extraction wells (Sheng, 2005).

Artificial recharge of untreated wastewater has taken place north of the Basin of Mexico, in the *Mezquital* Valley, as maize and alfalfa are irrigated using wastewater from the MCMZ and where an estimated recharge of 25 m^3/s occurs to its aquifer (Jiménez and Chávez, 2004) as the irrigation district has been functioning as a large spreading pond. Removal of contaminants in the *Mezquital* valley are carried out by plants, soils and movement of water in the irrigation channels, providing removal rates similar to those of a secondary treatment plant (Jiménez and Chávez, 2004). In fact, according to Jiménez and Chávez (2004), the *Mezquital* valley is another viable option to increase water supply to

Mexico City, as they estimated a cost of 0.73 USD/m^3 including nanofiltration and transport to Mexico City, for a total flow of 6 m^3/s.

In order to implement a successful artificial recharge program in the Basin, injection wells need to be properly located in order to guarantee a given residence time of the injected water in the aquifer as treated waste water should not be immediately extracted from the aquifer. Recovery of injected groundwater is best determined by using coupled numerical groundwater flow and solute transport models which include the effects of mixing between injected water and ambient groundwater (Lowry and Anderson, 2006).

5 Conclusions

The MCMZ depends heavily on the Basin's aquifer system and current water management policies have caused land subsidence and have transferred the MCMZ water problems to other areas, as 24% of its total water supply is currently taken from a river located more than 100 km away and more 1,000 m below the Basin of Mexico. By considering alternative water sources to increase water supply, the replacement cost of the Basin's aquifer system has been determined to range from 0.65 to 0.72 USD/m^3, which is twice the amount of the water tariffs currently charged to water users in the Federal District. Although water tariffs should be enforced in order to improve water use efficiency, social welfare and equity need to be considered. The State of Mexico seems to be giving a step on this direction, as the recently proposed water tariffs (which were increased by up to 40%) are similar to the aquifer's replacement cost, and the amount to be charged depends on household income.

An artificial recharge program using reclaimed wastewater can be implemented in the MCMZ in order to control the adverse problems caused by groundwater extraction; however, authorities will have to manage it in a proper way in order for consumers to accept it. With the implementation of such a project water problems will not be transferred to other communities or river basins as has been done previously. In addition, with the injection of highly treated water, water quality in the aquifer can also be improved in those areas where certain parameters currently exceed drinking water standards. The development of a successful artificial recharge program will also depend on a regional groundwater flow model in order to simulate and guarantee adequate residence times of the injected water.

The water supply infrastructure in the City has not been improved since 2000, nor more water is currently being supplied. This has not stopped population growth and a solution needs to be found to improve water management in the City; the possible solutions should be based on managing water demand instead of increasing water supply.

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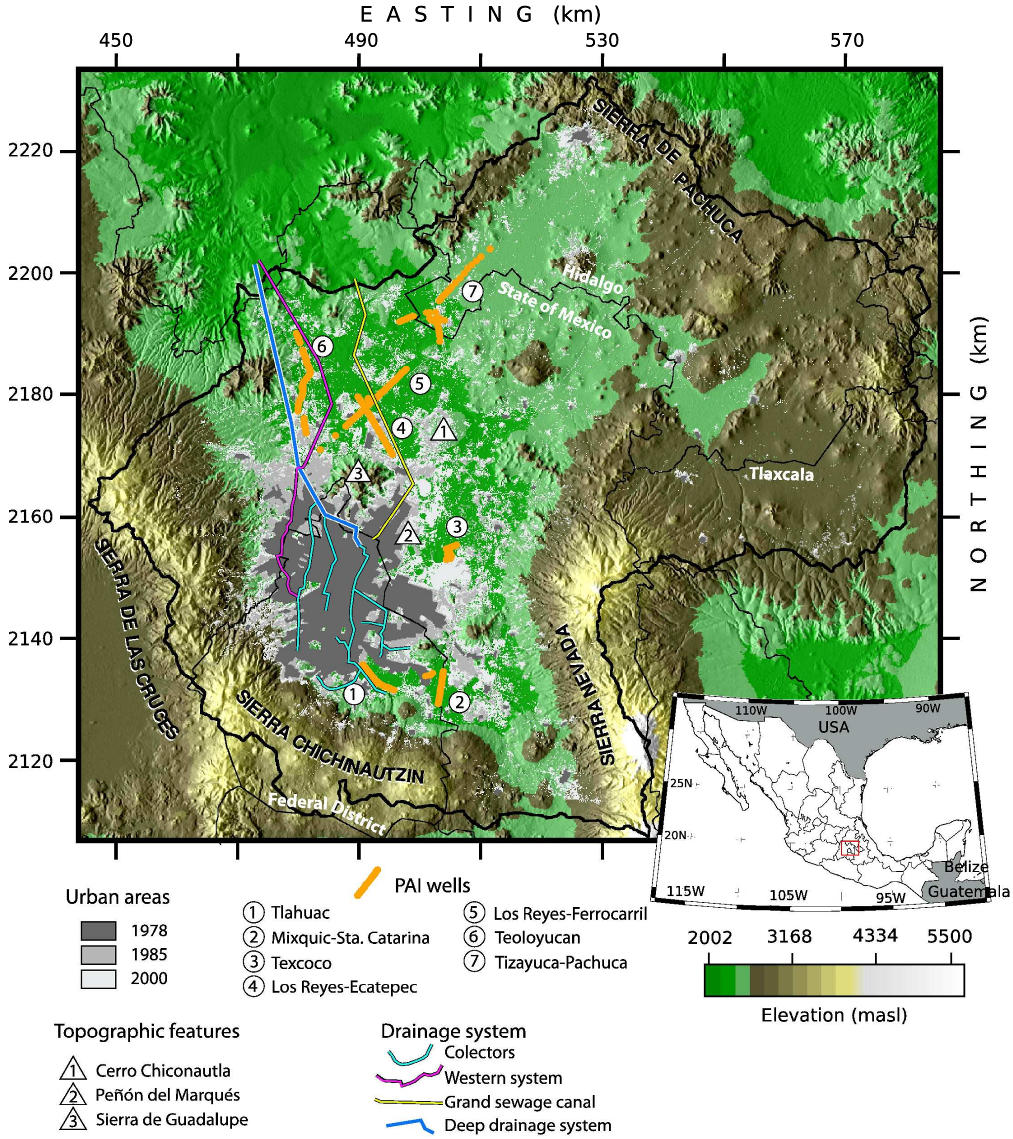

Figure 1: Location and topography of the Basin of Mexico, showing the extent of the Mexico City Metropolitan Zone (MCMZ) for 1978, 1985 and 2000. Colored lines represent the drainage network in the MCMZ, while orange dots represent the PAI wells drilled in 1974. Topography and shadowed relief derived from SRTM data.
187x212mm (600 x 600 DPI)

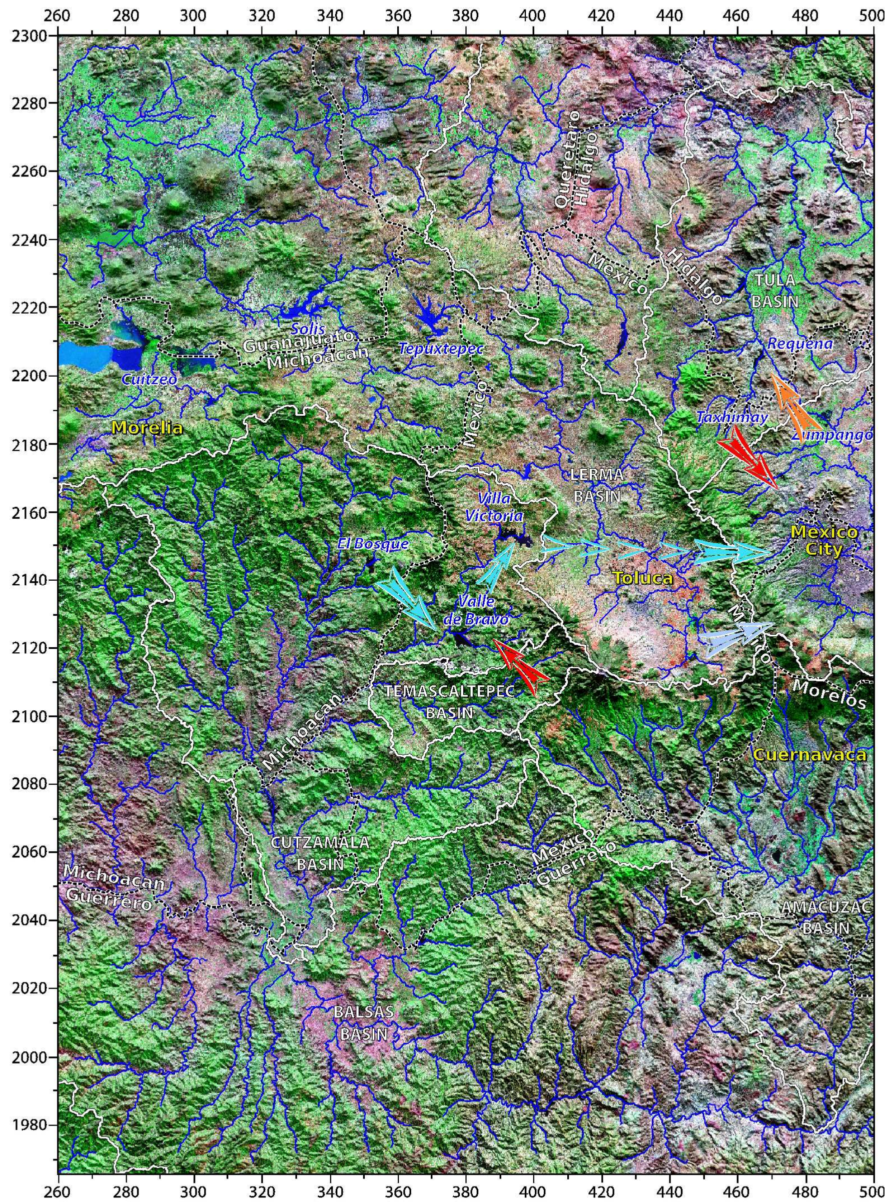

Figure 2: Current and projected water sources for the Basin of Mexico: Blue arrows represent regions from which water is currently taken, while red arrows represent basins currently under consideration to increase water supply. City names are shown in yellow. False color composite from LANDSAT-ETM+ on shaded relief derived from SRTM data.
198x272mm (600 x 600 DPI)

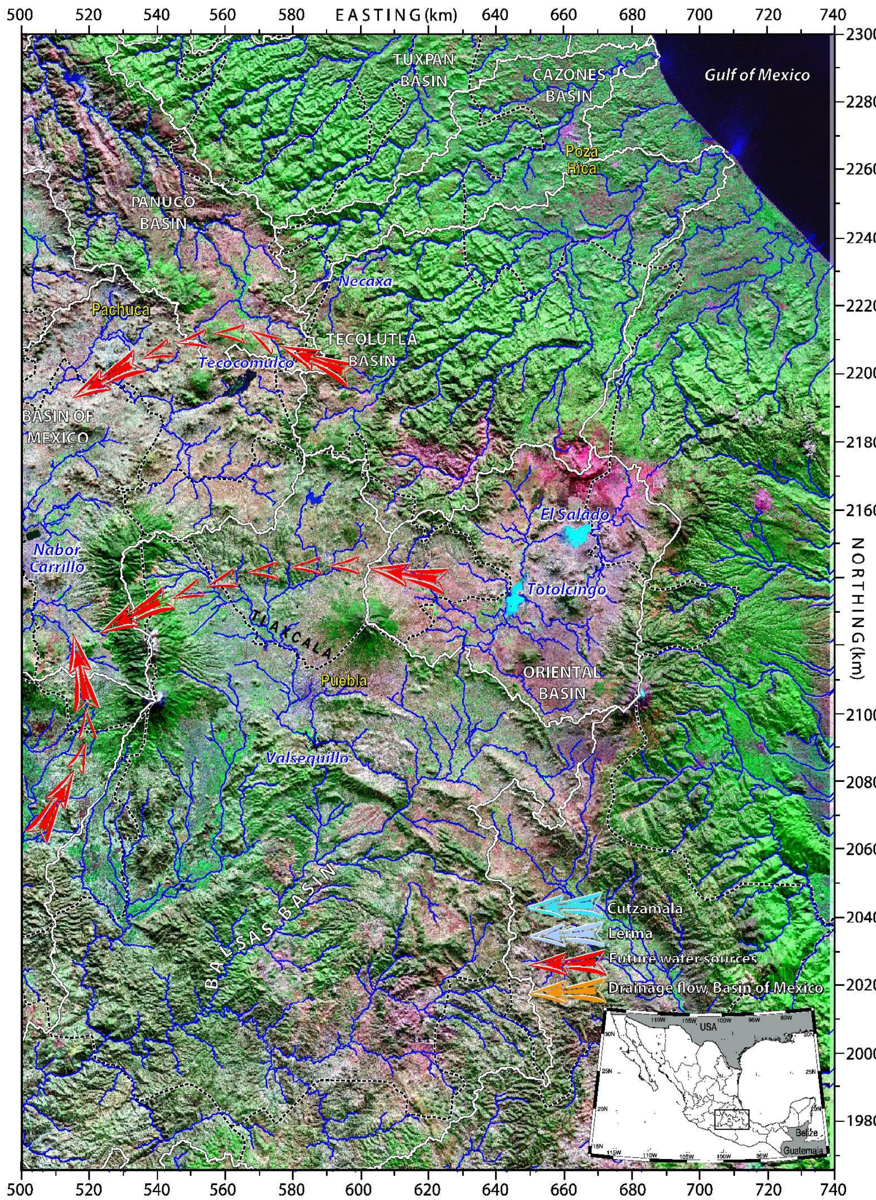

Figure 2 (continued)
200x272mm (600 x 600 DPI)