# The unintentional and intentional recharge of aquifers in the Tula and the Mexico Valleys: The Megalopolis needs Mega solutions

*Blanca JIMENEZ*
*Instituto de Ingeniería, UNAM and Mexican Academy of Sciences*
*MEXICO*
*bjimenezc@iingen.unam.mx*

ABSTRACT

Mexico City has 21 million inhabitants and is located in a closed basin at 2240 masl. Since the Aztec period Mexico City has been a megacity and water availability has never been considered in planning the city. As a result, today, Mexico City faces two important challenges: (a) to stop local groundwater overexploitation and with it problems related to soil subsidence, and, (b) to control the impact that the disposal of the huge amount of wastewater produced has on the downstream valley, possibly by reusing it. This paper describes these two challenges highlighting that not all of the observed impacts are negative. As a result of Mexico City using nearly 86 $m^3/s$ (1,956 MGD) of water, 60 $m^3/s$ of wastewater are produced and disposed of at the Tula Valley. In this valley the non-treated wastewater is used for agricultural irrigation of 95,000 ha, significantly increasing soil productivity. However, diarrhoeal diseases at this site have multiplied 16 fold in children under 15 years of age. Combined with the agricultural use of wastewater, non-intentional recharge of the Tula aquifer is occurring and has completely changed the environment in the valley. The aquifer formed is even considered as a new water source for Mexico City. For these reasons Mexico City will become its own “downstream user”. The main lesson learned for the city is that urban areas need to be planned with consideration given to water supply and disposal in order to be prepared for both the benefits and the negative impacts.

**Keywords:** Agricultural reuse, groundwater incidental recharge, human consumption reuse, megacities, soil subsidence, urban water cycle, water management.

# INTRODUCTION

In Mexico, nearly 70% of the population uses groundwater as a source of drinking water. This is because most people live in the centre and northern part of Mexico where surface water sources are scarce, not reliable throughout the whole year or are of low quality. Additionally, this is the area where most of the irrigated land and industries are located. As a result there is great competition for water resources. At a national level, the amount of water extracted from the subsoil is around 900 $m^3/s$, representing nearly a third of the total volume for consumption. In total, there are 653 aquifers. The intense use of groundwater in the central and northern part of Mexico is creating an increasingly worrying situation. The number of overexploited aquifers increased from 36 to 102 between 1975 and 2003 (Aboites *et al*., 2008). Overexploitation has not only impacted on the availability of water but also the cost of supply and its quality, and resulted in the need to pump water from deeper levels. In 2005 there were 18 aquifers affected by saline intrusion. 17 of these experienced a significant increase in salt content, at least 8 were affected by wastewater infiltration, 2 were had high iron and/or manganese concentrations, 4 were polluted by fluorine and 3 by arsenic (CONAGUA, 2008 and Aboites *et al*., 2008).

As part of this complex situation, a significant amount of water used for agricultural irrigation is unintentionally recharging the aquifers. Irrigating water efficiencies are around 40%, therefore where soil is permeable this is resulting in the artificial recharge of groundwater. A significant amount of the water used for irrigation is wastewater. In 1995, a total of 102 $m^3/s$ (2,328 MGD) of wastewater were used to irrigate 257,000 ha throughout the country (Jiménez and Chávez, 2005a). One example of this situation is Mexico City. The wastewater produced by the 21 million inhabitants living there is being used to irrigate a valley located downstream and to the north of the city. Wastewater is used to irrigate and the excess water is recharging the aquifer, resulting in the unplanned reuse of wastewater and its consumption by nearly 500,000 inhabitants. In addition the new aquifer formed is considered to be a possible source of water for Mexico City.

## MEXICO CITY WATER USE

Mexico City was founded by the Aztecs in 1325 and was named Tenochtitlan. When the Spanish arrived, in 1519, Tenochtitlan was a "megacity" with an area of 15 km$^2$ and 200,000 inhabitants. Tenochtitlan was located in what is known nowadays as the Valley of Mexico, a natural closed basin with five lakes. The city was located on an island connected to the land by four streets (Figure 1) that were also used as dykes to separate saline from fresh water. Due to urban expansion and the artificial drying of the valley, nowadays only small parts of two lakes (Texcoco and Zumpango) remain.

**Figure 1.** Tenochtitlan City (From Santoyo *et al*., 2005).

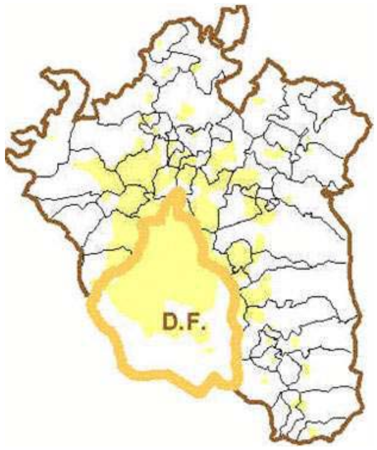


**Figure 2.** DF and the 37 municipalities of the State of Mexico, forming Mexico City

At the present time, Mexico City has 21 million inhabitants, has a surface area of 8,084 km$^2$ (2,598 inhab/km$^2$ and is responsible for 21% of GDP (gross domestic product) of the country (Jiménez, 2008). The intense economic activity combined with the large population living in a valley located at high altitude (2,220 masl) has created a complex water problem, related not only to supply but also wastewater disposal. The mean annual temperature is 15 °C, with mean pluvial precipitation of 700 mm, varying from 600 mm in the north to 1,500 mm in the south. The pluvial season is well defined; it extends from May to October and is characterized by intense showers lasting for short periods during the day. One single storm may produce 10-15% of the mean annual pluvial precipitation. As a consequence, in the Mexico Valley there are few perennial rivers most of which carry water only during the rainy season (Jiménez, 2009).

Mexico City has extended into the so called Metropolitan Area. This includes the Federal District (DF), but also the 37 municipalities of the State of Mexico (Figure 2). Currently, there are more people living in the 37 municipalities of the State of Mexico (around 60% of the population) than in the Federal District.

**Water sources and use**

At the present time, Mexico City uses 85.7 $m^3$/s (1,857 MGD) of water (Figure 3); 48% of this is supplied through the network, 19% pumped by farmers and industries directly from local aquifers and the remainder, 9%, is treated wastewater used for lawn irrigation, industrial cooling, landscape irrigation, fountains, car washing and the filling of lakes and canals for recreational and environmental use. First use water (78 $m^3$/s) comes from: (a) 1,965 wells that pump 57 $m^3$/s from the local aquifer; (b) local rivers located in the southern part of the city (1 $m^3$/s); (c) the Lerma region (5 $m^3$/s); (d) the Cutzamala region (15 $m^3$/s). Water is used mostly for municipal purposes (74%), followed by fresh water irrigation (16%), self-supplied industries (2%) and for non drinking water reuses (1%). Agriculture takes place over 40,000 ha of the valley to produce flowers and vegetables that are sold in the city.

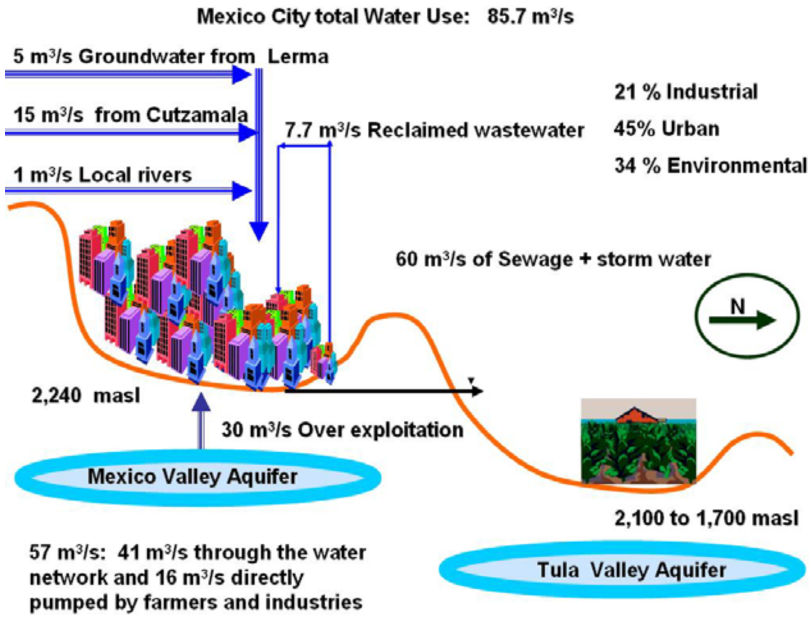


**Figure 3.** The water sources of Mexico City

To manage water, the Federal District has a public water utility that runs the commercial service privately, while the 37 municipalities of the State of Mexico all manage their water via public institutions. This poses a challenge to the integrated management of water (Jiménez 2008).

## Municipal use

Water services cover 89% of the population within the DF and a lower and varied percentage in the municipalities of the State of Mexico. The service is provided through a water network but also through the use of water tanks. People not connected to the network - but considered in the water supply service figures - receive a limited amount of water twice per week at no cost that they may need to carry considerable distances from water tanks or distribution sites to their homes. These distances may be small when compared to rural areas but they are significant on the urban scale. In the Federal District alone, the number of people not connected to the network is around 1.15 million. No data is available for the municipalities of the State of Mexico (SACM, 2006 and Jiménez 2008a). Distributed water is treated only with chlorine for groundwater sources while for surface water sources alum coagulation, sedimentation and chlorination are applied.

The 57 $m^3$/s of municipal water consumption represents a daily *per capita* water use of 255 L. However, 40% of water leaks from the mains, so it is estimated that, on average, people actually receive 153 L/*capita*.d, a value that falls within the 150-170 L/*capita*.d range recommended by WHO (1995). In fact, the actual use of water varies according to social class. The upper classes, representing 5% of the population, use more than 4 times the amount used by members of the lower classes connected to the network, but 300 times more than people receiving water through via tanks. In general in Mexico, tap water is considered unsafe to drink. In fact there is no reliable information demonstrating its safety. Public data is reported by the Federal District Water Works System on the internet for the whole Federal District and relates only to the bacterial and free residual chlorine content for some sites within the network. The federal government occasionally also provides data. As an example, COFEPRIS (the entity responsible for surveying the quality of potable water at a national level) reported in 2009 that the water distributed in the Federal District through the network fulfilled the amount of free chlorine set by the norm in 94% of the samples and that 7.5 % of the total population was at bacteriological risk when consuming tap water due to the presence of faecal coliforms. The population at risk was concentrated in only 3 of the 16 neighbourhoods comprising the Federal District (Tláhuac, Milpa Alta and Xochimilco). These neighbourhoods are located in the south and are part of the semirural area of the city, where tap water comes from local wells and the sanitation services are based on latrines functioning sporadically and discharging to the subsoil (Duran *et al*., 2010).

Official information concerning the chemical characteristics of drinking water is even less readily available. In 1994, it was reported that only 64% of the drinking water from the Federal District fulfilled the required physicochemical parameters. These parameters were colour, alkalinity, hardness, total solids, ammonia and organic nitrogen, iron and manganese. The delegations with problems were those located east and south east. In addition, data from some isolated academic studies show that drinking water prepared from groundwater contains nitrates and organochloride compounds at higher concentrations during the dry season compared to the rainy season (Mazari-

Hiriart *et al.*, 1999). The total trihalomethane content was below the Mexican drinking water norm (NOM-127-SSA1-1994, DOF, 2000) of 200 μg/L but exceeded the maximum allowable value of 80 μg/L established in the United States (EPA, 2004). These same authors reported the presence of total coliforms, faecal coliforms, faecal *Streptococcus*, and other pathogenic bacteria before and also after chlorination. They isolated 84 microorganisms of 9 genera associated with human faecal pollution. One of these was *Helicobacter pylori* (associated with gastric ulcers and cancer) an organism 15% less susceptible than normal water indicators to chlorine (Mazari-Hiriart *et al.*, 2002).

In addition, it has been shown that water quality deteriorates during distribution (Jiménez *et al.*, 2004). The water network operates at low pressure due to insufficient and intermittent water supply across the city. To have access to water all day, people must use individual storage tanks (called "tinacos") and as a result tap water is of a low quality. In order to ensure the availability of drinking water, a family of four earning 4 times the minimum wage spends 6-10% of its income on bottled water or potabilizing tap water at home (by boiling it, adding disinfectants or by using individual disinfection systems using ozone, UV-light or filters with colloidal silver). Individual disinfection systems at least double the price of disinfecting water (Jiménez, 2009).

**The need for alternative water supply options**

It is estimated that, in order to supply water to Mexico City's entire population through the network there is a need for 1-2 $m^3$/s of water. To provide an amount of 240 L/inhab.d to the entire population, an additional 5$m^3$/s are needed (Jiménez, 2009). To prevent overexploitation and inject water to control soil subsidence, at least 15 $m^3$/s of water are required. Therefore in total 22 $m^3$/s of water are needed. Where to take it from has become a major concern for the government.

As Mexico City grew, water sources other than the springs located in the Mexico Valley needed to be exploited. In 1847 –when the population amounted to around 0.5 million people– local groundwater began to be extracted from 105 m deep artesian wells. By the year 1857, there were

168 wells. Later, in 1942, when the population reached 2 million, water had to be imported from the Lerma River located in the State of Mexico, and in 1951 from the groundwater of the same Lerma basin, located 100 km from Mexico City and 300 m above its level. Finally, in 1975 when the population reached 7 million, surface water was imported from the Cutzamala region, 130 km away and 1,100 m below Mexico City's level (Jiménez, 2008a). The water transference from the Lerma and Cutzamala basins created negative environmental and social impacts. The population of the Lerma region used to depend on sustainable fisheries, but due to over-extraction of groundwater to supply Mexico City the Lerma Lake disappeared and people needed to become farmers to subsist. Furthermore, people went from using surface water as supply to water from deep wells. The Chapala Lake (the main lake in Mexico, located in Jalisco State) that was fed partly by the Lerma hydraulic system experienced a reduction in level of 5 m. To reduce overexploitation in the Lerma area, from the original amount of imported water of 7 $m^3/s$, nowadays only 3 $m^3/s$ are being sent to Mexico City. The transference of water from the Cutzamala basin amounted to 20 $m^3/s$ when the project began its operation. This volume has been reduced to 15 $m^3/s$ since 2008 (and even less in drier periods) as a result of the decrease in the amount of water stored in the dams that are part of the Cutzamala system due to the effects of the El Niño phenomenon. The lower availability of water in the whole Cutzamala dam system has also been the cause of a reduction in the amount of water available for power generation and the loss of a large area of irrigated agricultural land (Jiménez 2009). Facing this situation, the federal government made plans to incorporate additional sources of water into the Cutzamala system, but construction of the project was stopped due to social pressure. An internationally renowned movement called the "Mazahuas Women's Movement to Defend Water" was created to stop the process. The roots of this movement lie in the fact that even though the Cutzamala system has been providing water to Mexico City for many years, the people of the region still receive very limited levels of water services.

In addition to the above, the scenario of extracting additional water from the subsoil of the Mexico Valley was not optimistic either. The aquifer was overexploited by at least 117%, creating a soil subsidence problem. In fact this problem was at the origin of the decision to import water from external sources, as groundwater exploitation had led to a soil subsidence rate of 40 cm/year and the central part of the City had sunk 7 m by 1954. Following this decision, wells located in the central part of the city were shut down. Nevertheless, to cope with the water demand of a still growing population, new wells were opened in the southern and northern part of the city where it was thought they would have a much smaller effect on subsidence (Santoyo *et al.*, 2005). However, extraction from new wells with the urban settlements growing over the natural recharge area still caused the soil to subside. This has been happening at different rates over the city creating what is called "differential sinking". Differential soil subsidence in Mexico City is the source of other negative impacts, including (Jiménez, 2009):

a) The loss of drainage capacity from the sewerage system. To recover the capacity of one of the sewer drains (the Gran Canal), built to convey up to 40 $m^3/s$ of Mexico City's wastewater but in the event only able to transport 15 $m^3/s$, a pumping station was built in 2008 at a cost of 30,000 USD to raise wastewater 30 m. Before this pumping system began its operation, the wastewater that could not be conveyed by the Gran Canal needed to be transported through the Deep Drainage System. This was critical as the drainage system operated for nearly 12 years without maintenance and 400 $km^2$ of the city was at risk of flooding with 1.2 m of wastewater, affecting at least 4 million people (Domínguez *et al.*, 2005). Maintenance of the Deep Drainage System was finally performed in 2009 at a cost of around 19 million USD. In addition, the construction of an additional deep sewer had to be initialised at a cost of 1 billion USD.

b) A total of 20-30 floods in Mexico City with a mixture of pluvial and wastewater (SACM, 2006). The investment needed to recover wastewater drainage capacity in the Gran Canal alone is 305 million USD (Jiménez, 2008a and 2009). Despite all of these efforts, floods of wastewater in the city are still frequent. Some of them have had severe effects. For example, in February 2010, 4,000 houses and 485 schools were flooded in several municipalities in the State of Mexico. One sewer broke apart, resulting in a 60 m long hole. This caused the level of wastewater to rise up to

1.70 m. Several low income families lost all of their property and it cost the government 25 million pesos to repair the hydraulic infrastructure and to partially pay damages. In July 2010 new floods occurred.

c) Serious structural problems in buildings. As soil sinks differentially, buildings are affected. Considering only the historical buildings for which a survey has been performed, 46 severely damaged ones have been identified (Santoyo *et al.*, 2005). Due to its historical value, Mexico City Cathedral is being repaired. It is estimated that in the last 50 years, differential sinking has led to an 87 cm difference between the level of the apse and the western bell tower, partly due to overexploitation. The total investment required to redress the situation was 32.5 million USD in 2000 (Santoyo and Ovando, 2002).

d) Leaks in underground urban infrastructure. Differential sinking leads to faults in water mains, sewers, oil pipelines and tanks. No data on the effects on the last two are publicly available. For water leaks, losses are around 37-40%, resulting in a total water loss of 23 $m^3/s$ (525 MGD). This represents a cost of 56 million USD at the lowest water tariff in the city for municipal water (1 peso/$m^3$ or 0.08 USD/$m^3$).

e) Deterioration in groundwater quality. As explained above, overexploitation is causing groundwater quality to deteriorate. Different research studies (Jiménez, 2009) show that the TSS content has increased from 1,000 mg/L to 20,000 mg/L, the sodium content from 50-100 mg/L to 600-800 mg/L, the ammoniacal nitrogen content from 0-0.03 mg/L to 6-9 mg/L, and the iron content from < 0.1 mg/L to 3-6 mg/L.

f) Due to soil subsidence, the metro rails need to be levelled each year, and in some parts accumulated changes are compromising its operation.

## What are the future water supply options?

As discussed previously, at least 38 $m^3/s$ of water is needed to redress the situation. Part of this volume could come, and actually is coming, from a leakage control programme. However, considering its cost (1.5 million USD to sectorise and control pressure in the water network, plus 500,000 USD per year to repair and change deteriorated pipelines), another source of water is needed. Furthermore, over the time that is required to put this programme in place (initially estimated to be 50 years when begun 5 years ago) there is need to either transfer water from other farther basins or to implement a programme to reuse water for human consumption. Table 1 compares the cost of different alternatives including water reuse. The cheapest option, importing water from Temascaltepec (part of the Cutzamala system), is not viable due to opposition by local people. The Amacuzac and the Tecolutla options require the pumping of water from 1,700 and 1,266 m, respectively, below the level of Mexico City, and hence their feasibility is tightly linked to the future price of energy. As a result Mexico City is seriously considering the reclamation of its own wastewater for human consumption.  Among the options to reclaim wastewater, one directly uses treated wastewater in the valley and another considers its use after treatment, agricultural use, groundwater infiltration, groundwater extraction and treatment once again (presented as Tula Valley in the table below). The latter is considered the safest option and will be thus discussed in more detail in the next section.

Table 1 Cost of future water supply options for Mexico City, Jiménez (2008b)

| **PROJECT** | **USD/m$^3$ (2000)** |
|---|---|
| Amacuzac | 2.36 |
| Tecolutla | 2.13 |
| Temascaltepec | 0.75 |
| Tula | 0.72 |
| Potabilization in situ of the wastewater | 1 |
| Potabilization in situ, reinjection and extraction for water supply | 1.3 |

## MEXICO CITY WASTEWATER

Sewers collect the wastewater from 94% of the population of the Federal District and from 85% of that of the municipalities of the State of Mexico. Part of the wastewater collected is treated in local wastewater treatment plants to be reused in the City (see Box 1). The rest, 60 $m^3/s$ under average conditions, is transported out of the Mexico Basin.

***Box 1. Wastewater reuse in the Metropolitan area of Mexico City, from Jiménez (2008a)***

In the metropolitan area there are 91 wastewater treatment plants, 27 operated by the Mexico City government, 44 by different federal institutions (Ex-Texcoco Lake Commission, the Federal Electricity Commission and the army) or private companies and 20 by different municipalities of the State of Mexico (Merino, 2000). The total amount of wastewater treated by public wastewater treatment plants is 7.7 $m^3/s$ and all the treated wastewater is reused. Reuse has been performed since 1956 for landscape irrigation. At the present time, reused water is utilised to fill recreational lakes and canals (54%), to irrigate agricultural areas and parks over a total area of 6,500 ha (31%), cooling in industry (8%), diverse commercial activities - such as car washing - (5%) and to recharge the aquifer (2%). There is no data on the total amount of wastewater treated privately, but it is known that all of it is reused for lawn irrigation or cooling in industries. Considering that 100% of the treated wastewater is reused, equivalent to 12% of the wastewater produced, Mexico City is among the world's most intensive reusers of wastewater (Jiménez and Asano, 2009)[1].

One of the biggest public reuse projects is the Ex-Texcoco Lake wastewater treatment plant. This plant, built at the beginning of the 1980s, has a 1 $m^3/s$ capacity, but it only treats 0.6 $m^3/s$ of wastewater due to civil construction problems. Originally, the intention was to exchange groundwater used for agriculture with reclaimed wastewater. The project consists of an activated sludge treatment plant followed by an artificially built lake of 1,380 ha to store and improve water quality. Treated wastewater is successfully used to refill the lake creating an environment where a wide variety of birds from Canada and USA live during the winter. Recovering part of the Texcoco Lake was very important to control the alkaline dust storms that the City frequently suffered and which were created by the wind carrying the fine dust that formed on the bottom of the ancient lake. Unfortunately, a high evaporation rate in the area and the solubilisation of the salt contained in the soil considerably raised the effluent's salinity, impairing water for its use in irrigation.

[1] This does not take into account that 100% of the non-treated wastewater is also reused, as will be presented later in the text

**Disposal of Mexico City's wastewater**

Mexico City's wastewater has been sent to the Tula Valley since 1789 where it has been used for agricultural irrigation since 1896. The use of wastewater quickly became a source of livelihoods as it enabled agriculture and, furthermore, allowed crops to be raised all year round. Realising the advantages, the farmers requested that the government send more wastewater and in 1920 a complex irrigation system was implemented. The instigation of this irrigation district by the government constituted recognition, although informal, of the use of non-treated wastewater to irrigate. Later, the farmers requested the concession of 26 $m^3/s$ of Mexico City's wastewater, at that time all that was available, and this was consented to by the president in 1955 (Jiménez 2008b and 2009). At the present time, the irrigation infrastructure is still owned by the government, in contrast to the situation of the rest of the country. It comprises nine dams (three containing freshwater and six wastewater), three rivers and 858 km of water distribution or irrigation canals. The irrigated area is around 95,000 ha. The region, colloquially known as the Mezquital Valley, has been considered by Mara and Cairncross (1989) as the largest irrigated area using wastewater in the world (Figure 4). The Mezquital Valley is located in the Tula Valley in the State of Hidalgo, 100 km north of Mexico City, and has a population of 500,000 distributed over 4,100 $km^2$ and 294 localities. The altitude of the Valley varies from 2,100 m in its southern part close to Mexico City, to 1,700 m in the northern part (Jiménez 2008a and b). The climate is semi-arid, with a mean annual temperature of 17 °C, an annual rainfall of 527 mm and evapotranspiration of 1,750 mm. The economy is based mainly on agriculture.

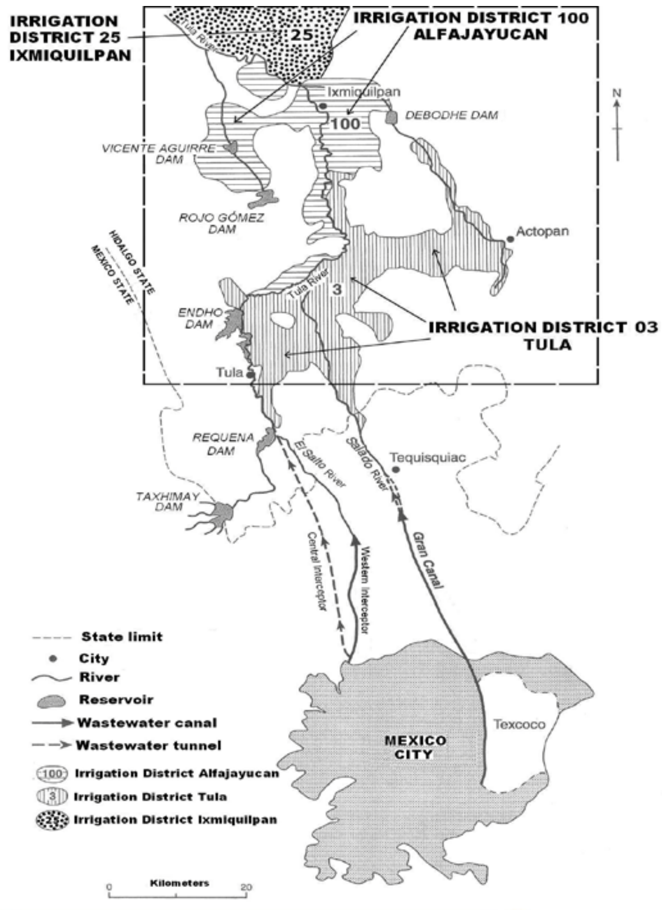


**Figure 4** Mexico City's wastewater disposal drainage system and main components of the irrigation system in the Tula Valley (Jiménez, 2008a).

In general, the agricultural soils are low in organic matter content and need water and nutrients to be productive (Siebe, 1998). This is provided by applying non-treated wastewater. Corn and alfalfa for use as fodder are the main crops (60-80% of the area), followed by oats, barley, wheat and some vegetables (chilli, Italian zucchini and beetroot, Siebe, 1994). A large proportion of the produce is sold in Mexico City, but it is also used locally. The wastewater nutrient content has improved crop yields from 67 to 150% for corn, barley, tomato, oatmeal for feed, alfalfa, chilli and wheat when compared to produce irrigated with first use water (i.e. clean water). The reliability of wastewater all year round means that 2-3 crops per year can be raised instead of one (Jiménez, 2008 b). For this reason, land with access to wastewater is rented at 455 USD/ha.yr instead of the 183 USD/ha.yr charged in areas using rain water only.

Certainly the most visible impact is the boom in the local economy. It was once a region so poor that the government considered moving the indigenous people to other sites as their land was not able to produce food. Nowadays the situation has radically changed, but even though these positive impacts are recognised, others have occurred. The two most important concern public health and aquifers. With respect to the former, Cifuentes *et al.* (1992) showed that diarrhoeal diseases caused by helminths (worms) have increased 16 fold in children under 14 years of age. Helminthiases are the cause of undernourishment which results in decreased physical and metal development (10-15 cm in height and 10-20 IQ points). The second impact concerns the incidental recharge of the aquifer with the wastewater used to irrigate. This is a consequence of the transportation and storage of wastewater in unlined infrastructure but is also due to the irrigation method and the excess of water applied to control salinity in soil. The recharge of the aquifer with wastewater has been reported since 1975, when Payne and Latorre estimated that 90-100% of the aquifer in Tula Valley was formed by Mexico City's wastewater. In 1997, the recharge rate was estimated by the British Geological Survey and the National Water Commission (1998) to be at least 25 $m^3$/s for only one of the irrigation districts. This value represents in 13 times the natural recharge (Jiménez and Chavez, 2004). For the entire valley the BGS-CNA *et al*., (1998) estimates that the rate of recharge is around 39 $m^3$/s.

The intense recharge of the groundwater with non-treated wastewater for more than 110 years has considerably raised the groundwater level. Between 1938 and 1990 the groundwater level rose 15-30 m and dozens of new springs appeared with flows varying from 0.1 to 0.6 $m^3$/s. In some areas the emerging water has even caused water logging, growth of hydrophilic vegetation and loss of large volumes of water due to evapotranspiration. The Tula River flow increased from 1.6 $m^3$/s to more than 12.7 $m^3$/s between 1945 and 1995 as a result of being fed by additional groundwater. All of these new sources are used as supply by the 500,000 inhabitants and for several economic activities. A total of 6 $m^3$/s are used for agricultural irrigation (38%), industry (33%), human consumption (17%), and other uses (12%), according to Jiménez and Chavez (2004). Water is extracted from 283 springs and wells. Prior to distribution to households water is chlorinated only.

In 1938, a change in the water quality of wells began to be noticed. When, in 1995, it was officially acknowledged[2] that infiltrated wastewater was the origin, several studies to assess water quality began (Jiménez 2008a and b). Up to now 5 different assessments have been performed, utilising local and internationally certified laboratories. All of these studies have highlighted the same water quality problems but have also shown the improvement of the quality of the wastewater to an extent that it could be considered similar to any other water source. Table 2 shows that problems are related mainly to a dissolved salt content greater than 1,000 mg/L, faecal coliforms and in some cases nitrates and fluorides

Table 2. Number of sites that did not meet the Mexican drinking water standards (adapted from Jiménez and Chavez, 2005).

| **Parameter** | **Sites not complying with drinking water standards** | | **Mexican drinking standard** |
|---|---|---|---|
| | % Number | % Volume | |
| Dissolved solids | 64 | 95 | 1000, mg/L |
| Sodium | 38 | 73 | 200, mg/L |
| Faecal coliforms | 42 | 25 | 0, MPN/100 mL |
| Nitrates | 31 | 12 | 10, mgN/L |
| Chlorides | 24 | 10 | 250, mg/L |
| Hardness | 31 | 9 | 500, $mgCaCO_3/L$ |
| Sulfates | 18 | 2 | 400, $mgSO_4/L$ |
| Fluorides | 18 | 1 | 1.5, mgF/L |
| No problem | 13 | 5 | |

The analysis performed covered 288 parameters including different types of pathogens, pesticides, organic compounds and toxicity tests, and showed that the water fulfilled the requirements of a regular source of water. More recent studies targeting emerging compounds showed that although these compounds are contained in Mexico City's wastewater their content in the Tula Valley aquifers and springs is not detectable in most cases or very low and confined to some areas for the others (such as carbamazepine, Gibson *et al.*, 2007; Duran et al., 2009).

[2] But not publicly

**Health effects due to the water supply in the Tula Valley**

As local people have been drinking water from the new water sources for many years a risk assessment was performed. According to health experts, the main short-term risks associated with the use of non-conventional water sources relate to the presence of *Vibrio cholerae* NO-01 and other pathogens. These occur due to the presence of faecal coliforms at a concentration greater than 2,000 MPN/100 mL (Downs *et al.*, 2000), but so far they appear to have been reasonably controlled by chlorine addition as no massive outbreaks have been reported. In contrast, high nitrate and nitrite values (up to 29 mg N/L), exceeding the Mexican drinking water norm by 3-4 times, are a concern. However, no methemoglobinemia in infants has been reported. This concurs with a recent publication prepared on behalf of the World Health Organization by Fewtrell (2004) highlighting the fact that although it is assumed in WHO guidelines that a high nitrate content in drinking water may cause methahemoglobinemia in infants, it now appears that nitrates may be only one of a number of co-factors that play a sometimes complex role in causing the disease. Research studies to assess health risks from recently detected organic compounds have not yet been performed. As a precaution they should be removed from water when found (Jiménez, 2008b).

*Will the people of Mexico City be drinking the Tula Valley groundwater?*

As discussed previously, aquifer recharge with wastewater used to irrigate occurs at a rate of at least 25 $m^3$/s. During storage, transportation and repeated use of this water to irrigate, it is depolluted by different physical, chemical and biological mechanisms, producing water at the end of the valley with a quality at least equal to the water sources used for Mexico City. The use of this water by the local population, even if its use creates ethical objections, is also proof of this situation. Nevertheless, the presence of emerging pollutants in some of the sources in the Tula Valley represents a concern that needs to be addressed independently to decide whether this water should or should not be used in Mexico City. For this reason several studies and pilot plant tests using membrane treatment processes are ongoing, so far with good results. In order for this option to be sustainable three requisites need to be met:

a) Independently of the present natural treatment of the wastewater, it is necessary to treat Mexico City's wastewater in order to fulfil the norms, control the health risks created by the use of the wastewater but also maintain the soils' depollution capacity which in some places seems to be being overloaded (Jiménez 2008b).

b) Secondly, a detailed project needs to be developed in order to assess the viability of installing several wells to extract 6 $m^3/s$ in total in an area where land is considered to be shared property. In addition, the cost of transporting water back to the city 100 km away and with a difference in height of 150 m (Jiménez *et al.*, 1997) needs to be considered in terms of future energy prices.

c) Thirdly political negotiations are needed. Although by law groundwater belongs to the nation, Hidalgo's population questions why they should return "their" water to Mexico City after having depolluted it.

The on-site reclamation of Mexico City's wastewater has a number of advantages. The first is that it allows the Tula Valley to continue using use the same amount of water. The second is that the extraction of groundwater helps to control salinisation and flooding problems observed in the lower agricultural fields of the Tula Valley due to the rise in the groundwater level[3]. The third, and this relates to Mexico City itself, is that the potabilization process is cheaper.

## LESSONS LEARNED

From this example there are several lessons to be learned. Perhaps the first is that you never know when you will be downstream of your own effluent. In the future, water reuse for human

[3] The rise in the water table is actually causing a loss of 0.95 $m^3/s$ of water through evaporation.

consumption may be the case for several (or at least some) populations located in arid and semiarid regions, especially if care is not taken to put precautions in place to limit population growth. In the case of Mexico City, the lesson learned should be that there was a need to prevent further population growth when it was around 8 million. Although some people argued this - and despite the fact that this occurred when the city's population had already reached 10 million inhabitants - the federal government never wanted to take this decision, in particular because in Mexico City at that time citizens did not have the right to vote. The people were ruled then by politicians directly imposed by the president. This situation has changed since 2000. In addition, other lessons have been learned, such as:

a) A megalopolis needs a mega-government not the sum (or division) of local ones. This mega-government needs the vision to define and put in place mega-solutions. However, there are no mega-universities to teach this to mega-politicians, using mega-disciplines.
b) Unusual situations provide excellent opportunities to provide innovative solutions and to move towards truly integrated management of water.
c) The so called "inefficient" use of water by agriculture, is in fact not an inefficient use, water is just being transported to another compartment of the environment.
d) There is a need to set up an ethics committee to evaluate the way in which human effects are being studied and interpreted by politicians and private companies. This committee should also investigate the cases in which cities are using other sites to depollute their water.

**Options to better manage water in the Mexico valley**

Due to the complexity of the problem there is no single solution, but rather a whole set. Some of the most important ones are:

a) The creation of a Metropolitan Water Authority. In order to integrally manage water sources in the valley it is important to have a unique water authority with a sufficient budget and the capacity to make decisions. This has long been thought of as the starting point of the solution but its implementation took a protracted amount of time. Interestingly, a metropolitan commission to manage air pollution for the metropolitan area of Mexico City was easily and quickly put in place, and its actions have significantly reduced air pollution in Mexico City. The reason for this is simple: the commission was created before independent bodies to tackle air pollution problems existed. To date, a basin water authority has been created but in practice it has faced problems reaching agreements on the way in which water should be managed.

b) The creation of an integrated water management programme. This should consider surface, groundwater, local and external sources and the quantity, quality and the uses of water over the short, medium and long term. This programme needs to be accepted by society in order to ensure its implementation independently of the political parties that govern each of the municipalities of the metropolitan area.

c) Exchange of reclaimed water with the groundwater used for agricultural irrigation within Mexico Valley. This is a programme planned from the technical perspective. However, the social and economic aspects still need to be included to allow its successful implementation.

d) Education. People must be educated in the efficient use water in order to protect and preserve its quality. These types of educational programmes need to address not only society in general, as is done at the present time, but also to target specific groups of society that have not been previously. A good example is government workers. In many public offices high consumption toilets are still used and leaks from washrooms are often uncontrolled.

e) Economic tools. In Mexico the price of water is highly subsidised. To redress this situation the Federal District has recently raised water tariffs, but this has not yet been implemented by the rest of the 37 municipalities.

f) Public campaigns to save water. The present governments (of both the Federal District and the State of Mexico) invest a significant proportion of their budget in media campaigns to encourage society to save water. However, as discussed above, the amount of water that most of the population is actually receiving and using would be classified under the category of efficient use of water for urban areas. Therefore instead of investing money on this type of campaigns greater investment should be made in leakage control programmes.

g) Rainwater harvesting. Mexico City receives significant pluvial precipitation at a total rate of 12 $m^3/s$. Rainwater is partly responsible for the urban flooding problem. Rainwater harvesting could be part of the solution for people leaving in the southern part of the city. Here, rainfall is heaviest, and the area is sufficient to collect and store water to reduce costs. It is estimated that using pluvial water as source of water costs around 10 $USD/m^3$, which can only be afforded by wealthier people. In public systems, due to the lack of storage area, it is estimated that, at the most, 1 $m^3/s$ could be obtained from pluvial water.

h) Industrial reuse. Even though industrial activity in Mexico is small (most registered companies are corporate offices, with their production sites in other parts of the country), there is still capacity to increase the industrial reuse of water to around 1 $m^3/s$. For this to be effective the cost of reusing industrial water need to be increased to match the treatment and distribution cost of reused wastewater.

## CONCLUSIONS

The main conclusion with regard to Mexico City is that there is a need to create a Metropolitan Water Authority with the participation of the different political regions, sectors and levels of government (federal, regional and local). This should be created with the intention of managing water in an integrated way. To be effective this water authority needs to have the capacity to take all decisions related to the management of water and have a sufficient budget to allow its operation. The main task of the water authority would be to elaborate a short and long-term Integrated Water

Resources Management Programme, which should consider not only technical aspects but also social and economic ones. This programme should involve views of society and include activities such as (Jiménez, 2008a) land use management, soil subsidence control, stopping and even reversing the population growth of Mexico City, protection of groundwater quality, leakage control, aggressive reuse and recycling programmes, innovative and comprehensive educational programmes, improvement of economic tools to manage water, rainwater harvesting and implementation of professional and public participation programmes. Mexico City is undoubtedly experiencing a very challenging situation concerning its water supply and wastewater disposal system which may have no precedents in other parts of the world. Nevertheless, it is highly likely that at least some of the problems discussed are already being experienced elsewhere, hence the need to create awareness of the importance of managing urban water in an integrated manner, particularly in megacities.

It is evident that infiltration through soil of the Tula Valley is acting as an unintentional SAT system that efficiently depollutes Mexico City's wastewater. While the origin of the aquifer formed in the Tula Valley is not creating evident problems to local inhabitants, it is certainly a source of great concern, especially as it is not known how long the soil's treatment capacity will last. For this reason studies need to be carried out to determine the fate of pollutants and to quantify their behaviour in soil, especially that treated with wastewater. The process selected for the Atotonilco wastewater treatment plant planned to be operating in 2012 will produce treated water with a low organic matter content which risks mobilising heavy metals and organic pollutants accumulated in the Tula soil over many years, polluting the groundwater.

Finally, independently of Mexico City's decision, the government of the State of Hidalgo should be reviewing the potabilization process applied in the area (chlorination), or as proposed by other researchers, extracting water from parts of the aquifers where wastewater has no or little influence.

## REFERENCES

- Aboites L., Cifuentes E., Jiménez B. and Torregrosa M. (2008) Agenda del Agua. *Academia Mexicana de Ciencias*, 66 pp. México, [In Spanish]
- BGS- CNA (1998) Effects of Wastewater Reuse on Groundwater in the Mezquital Valley, Hidalgo State, Mexico. Final Report- BGS Technical Report WC/98/42
- Cifuentes, E., Blumenthal, J., Ruiz-Palacios, G. and Beneth, S. 1992. Health Impact Evaluation of Wastewater in Mexico. *Public Health Revue,* **19**: 243–250.
- CONAGUA, Comisión Nacional del Agua  National Water Commission (2008) Water Statistics CNA Ed., DF, Mexico [in Spanish]
- Durán J., Mendez J. and Jiménez B (2010) The Quality of Water in Mexico in *The Water in Mexico,* Jimenez, B., Torregrosa M L and Aboites L., Ed. Mexican Academy of Science and CONAGUA. México.
- Domínguez-Mora, R., Jiménez-Cisneros, B., Carrizosa-Elizondo, E. and Cisneros-Iturbe, L. 2005. Water Supply and Flood control in the Mexico Valley. No. 06-cd-03-10-0274-1-05, Project 5341, Engineering Institute UNAM [In Spanish].
- Downs, T., Cifuentes, E., Ruth, E. and Suffet, I. 2000. Effectiveness of natural treatment in a wastewater irrigation District of the Mexico City region: a synoptic field survey. *Water Environment Research*, **72**(1):4–21.
- Durán-Álvarez J.C., Becerril E., Castro V., Jiménez B., and Gibson R. (2009) The analysis of a group of acidic pharmaceuticals, carbamazepine, and potential endocrine disrupting compounds in wastewater irrigated soils by gas chromatography-mass spectrometry. *Talanta* **78**(3):1159-66.
- Fewtrell, L. 2004. Drinking-Water Nitrate and Methemoglobinemia. Global Burden of Disease: A Discussion. *Environmental Health Perspectives,* 1**12**(14): 1371–1374.
- Gibson R., Becerril E., Silva V. and Jiménez B. (2007) Determination of acidic pharmaceuticals and potential endocrine disrupting compounds in wastewaters and spring waters by selective elution and analysis by gas chromatography – mass spectrometry. *Journal of Chromatography A,* **1169**(1-2):31-39.
- Guillermo, A. 2000. *Geographical localization of the Mexico Basin* In Garza, G. 2000. Mexico City towards the end of the Second Millenium. Gobierno del Distrito Federal and El Colegio de México Ed., Mexico, pp. 765 [In Spanish].
- Jiménez, B. and Chávez, A. 2004. Quality assessment of an aquifer recharged with wastewater for its potential use as drinking source: “El Mezquital Valley” case. *Water Science and Technology,* **50**(2): 269–273.
- Jiménez B. (2008a) Wastewater risks in the urban water cycle. Chapter in Urban Water Security: Managing Risks. Jiménez B. and J. Rose Editors, 324 pp. *Taylor and Francis Group.* Geneve

- Jiménez B. (2008b) Unplanned reuse of wastewater for human consumption: The Tula Valley, Mexico. Chapter 23 in Water Reuse: *An International Survey of current practice, issues and needs.* Jiménez B. and Asano T. Ed., *IWA Publishing,* Inc. London. pp 414-433.
- |Jiménez B. (2009) Risks and integrated management of the urban water cycle in megacities of the developing world: Mexico City. Chapter in: Water & Urban Development Paradigms, Feyen J, Shannon K., and Neville M. Editors. *CRC Press Taylors and Francis Group,* London, UK, pp. 387-396.
- Mazari-Hiriart, M., Torres Beristain, B. Velázquez, E., Calva, J. and Pillai, S. (1999). Bacterial and viral indicators of fecal pollution in Mexico City's southern aquifer. *Journal of Environmental Science Health,* **A34** ( 9): 1715–1735.
- Mazari-Hiriart, M., López-Vidal, Y., Ponce de León, S., Calva-Mercado, J.J. and Rojo-Callejas, F. 2002. Significance of Water Quality Indicators: A case study in Mexico City. Proceedings of the International Conference: Water and Wastewater, Perspectives of Developing Countries. Indian Institute of Technology Delhi-International Water Association. New Delhi, India. December, 11-13: 407–416.
- SACM (2006). Mexico City Water Works, International Tlalocan Festival. Water and Politics. Tlalocan Proceedings, 10-15 March, Mexico City.
- Santoyo, E. and Ovando-Shelley, E. (2002) Underexcavation at the Tower of Pisa and at Mexico City's Metropolitan Cathedral. Proc. International Workshop, ISSMGE-Technical Committee TC36 Foundation Engineering in Difficult, Soft Soil Conditions, CD edition, Mexico City [In Spanish].
- Santoyo, E., Ovando, E., Mooser, F., and León, E. (2005) Geotechnical syntheses of the Mexico Valley basin, TGC, Geotecnia, S.A. de C.V. México, pp. 171 [In Spanish].
- Siebe Ch. (1994) Heavy metal accumulation in soils from the Irrigation District 03, in Tula, Hidalgo irrigated with wastewater. International Magazine of Environmental Pollution, 10:15-21 [In Spanish].
- Siebe, Ch. 1998. Nutrient inputs to soils and their uptake by alfalfa through long-term irrigation with untreated sewage effluent in Mexico. *Soil Use and Management*, **14**: 119–122.
- WHO (1995). *Drinking Water Quality Criteria,* 2$^{nd}$ Edition, Geneve Switzerland. OMS Ed.
- US EPA (2004). Guidelines for Water Reuse. EPA/625/R-04/108, USAID, Washington, D.C.