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

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Unplanned reuse of wastewater for human consumption: The Tula Valley, Mexico

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23.1 INTRODUCTION

In irrigation, water is frequently used with low efficiencies (< 50%), seldom realizing that the “lost” water often recharges aquifers that are being used for several purposes. This results in unplanned water reuse together with concerns that depend on the quality of the irrigating water. This situation is illustrated by the Tula Valley case study that shows how an “inefficient” use of wastewater turned out to be a successful, though unplanned, example of water reuse in a semi-arid area. Environmental and economic conditions were dramatically improved while a new drinking water source was provided. However, in order to maximize the advantages while reducing future risks, special management – described in this chapter – is required.

Payne was the first to report, in 1975, that 90-100% of the aquifer in Tula Valley was formed by Mexico City’s wastewater. Later, in 1995, the British Geological Survey and the National Water Commission (BGS-CNA, 1998) quantified the phenomenon as at least 2 194 560 m^3/d (25.4 m^3/s). It was then realized that more than 400,000 people were using the infiltrated wastewater as a water supply. Several projects were launched to assess the potability of the aquifer water, to find proper potabilization methods and even to look for new water supply uses. This chapter describes the results of some of those projects.

Water Reuse - An International Survey: Contrasts, issues and needs around the world by B. Jimenez *et al.* ISBN: 9781843390893. Published by IWA Publishing, London, UK.

23.2 DESCRIPTION OF THE PROBLEM

Mexico City has around 21 millions inhabitants and is formed by the Federal District (Mexico's capital) and 18 municipalities in the State of Mexico. Mexico City uses 6 652 800m^3/d (69 m^3/s) of water, of which 5 356 800 m^3/d (62 m^3/s) are supplied through the water mains, 604 800 m^3/d (7 m^3/s) are pumped on site from the local aquifer (for agricultural irrigation) and 691 200 m^3/d (8 m^3/s) come from treated wastewater. Reclaimed water is used for recreational purposes, lawn irrigation, industries (cooling mainly), car washing and to fill the Texcoco lake for recreational and environmental purposes.

Because Mexico City is located in a closed basin at 2,240 meters above sea-level (masl), three collectors were built to get rid of the wastewater and avoid floods caused by storm water: the Central Collector (conveying 55% of the wastewater); the El Gran Canal (30%) and the Western Interceptor (the remaining 15%). These collectors discharge their contents to the Tula, El Salado and El Salto rivers respectively, all located in the Tula Valley. In total, 518,400 m^3/d (60 m^3/s) are being disposed of, 75% of which is combined industrial and municipal wastewater and 25% excess rain water. In the Tula Valley 4492,800 m^3/d (52 m^3/s) of wastewater are used to irrigate and the rest (691 200 m^3/d or 8 m^3/s) is sent out of the Valley through the Tula River (Figure 23.1).

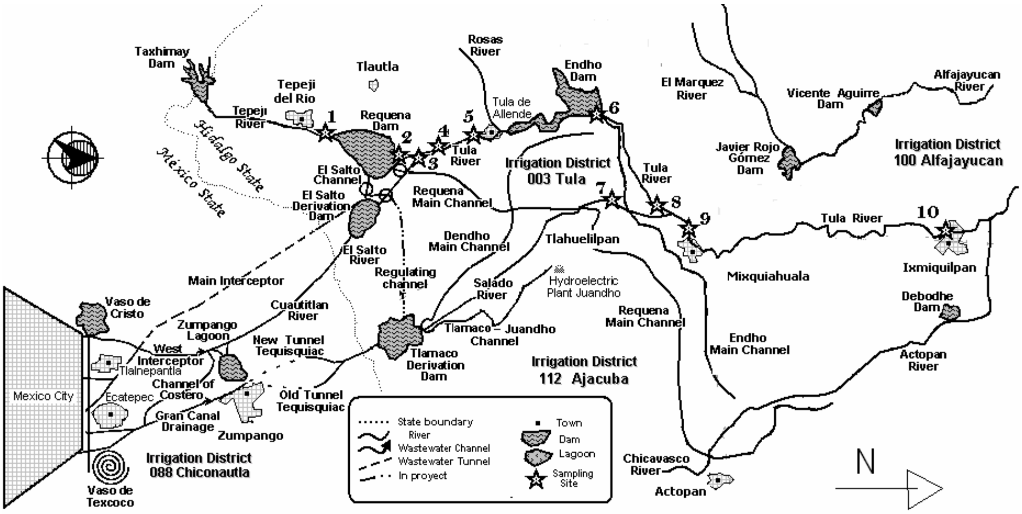


Figure 23.1 Sewerage conduits and disposal sites for Mexico City wastewater.

23.3 STUDY AREA

The Tula Valley (also colloquially known as the Mezquital Valley) is located north of Mexico City with an area of around 4 100 km^2. In the south of the valley (near Mexico City) the altitude is 2 030 masl, while to the north it is 1 990 masl. The Tula Valley is semi-arid to arid, with a mean annual temperature of 17°C, precipitation (from June to September) of 450mm and evapotranspiration of 1750mm. More than 400 000 people live in the valley, 43% in three cities (Tezontepec de Aldama, Actopan and Tula) and the rest in 294 localities. The economy is mainly based on agriculture and commerce. Industrial activity is limited to 5 industrial plants (one power generation plant, one refinery, two cement plants and one pheno-chemistry plant). As mentioned above, irrigated agriculture in the valley is based on wastewater. At the beginning of the 1990s a maximum wastewater irrigated area of 90,000 ha was registered but in 2004 the area had seemed to have decreased to 76,119 ha owned by 73,632 farmers (CNA, 2004).

Figure 23.2 Flood irrigation in the Tula Valley.

Farmers resort to furrow and flood irrigation (Figure 23.2) and thanks to wastewater, Tula soils (originally poor in organic matter and nutrients) receive 56 kg P/ha.yr, 1,200 kg N/ha.yr and 5,200 kg of organic matter measured as BOD/ha.yr, thus increasing productivity by 150% for maize, 100% for oats, 94% for tomatoes, 71% for alfalfa and chilli, and 67% for wheat. The reliability of the wastewater means that 2-3 crops per year can be grown instead of 1. For this reason, land with access to wastewater is rented at 455 USD/ha.yr instead of 183 USD/ha.yr in areas using just rain water (Jimenez, 2005). The main crops are alfalfa and maize (60% of the total) followed by oats, barley, wheat and beans. Small quantities of vegetables, such as chilli pepper, Italian squash and tomatoes are also produced, mainly for local consumption (Siebe, 1994). Health effects caused by the wastewater used to irrigate have been documented in several papers (Blumenthal *et al*., 1991; Siebe and Cifuentes, 1995; Cifuentes, 1998 and Blumenthal *et al.*, 2001) and refer to a considerable increase in helminthiases diseases, especially in children under 15 years.

23.3.1 Development of the irrigation area

Wastewater was sent to the Tula Valley for the first time in 1789 and it first began being used for irrigation in 1896 in a small region near Tlaxcoapan and Tlalhuelilpan and expanded towards Mixquiahuala. At that time, wastewater was conveyed by the El Salado River. The wastewater's economic impact soon became evident and the government decided to officially acknowledge it in 1920. The implementation of a complex irrigation system ensued. The Tequisquiac tunnel was built to convey most of the wastewater through the El Gran Canal to the El Salado River. Nowadays the irrigation system encompasses 9 dams (3 with "first-use" water from perennial rivers and irrigation drainage water, and 6 storing wastewater), 575 km of primary channels, 283 km of secondary ones and thousands of kilometres of interconnections into parcels. One of the wastewater dams is Endhó, with a capacity of 50 Mm^3. Sixty two percent of the primary channels and almost all the secondary ones (Figure 23.3) are unlined, allowing the infiltration of 25% of the conveyed wastewater. Using field data, the BGS (1998) estimated that the Requena and the Endho main channels have an infiltration rate in the unlined sections of 0.4 and 1.4 m/d, respectively, while in the lined parts it is only 0.1 m/d. Wastewater infiltration from channels is equivalent to 8 219m^3/km.d.

(a) Primary Requena canal near Doxey, lined (b) Secondary canal near Tlaxcoapan, unlined

Figure 23.3 Irrigation channels in The Tula Valley.

Field irrigation also produces aquifer recharge because most of the crops have a water demand of less than 1 $m^3/m^2 \cdot yr$, while the applied rate to wash soil salinity is 1.5-2.5 $m^3/m^2 \cdot yr$. It is estimated that both phenomena, wastewater transport and excess irrigation rates, recharge the aquifer to at least 2 194 560 m^3/d or 25.4 m^3/s (Figure 23.4).

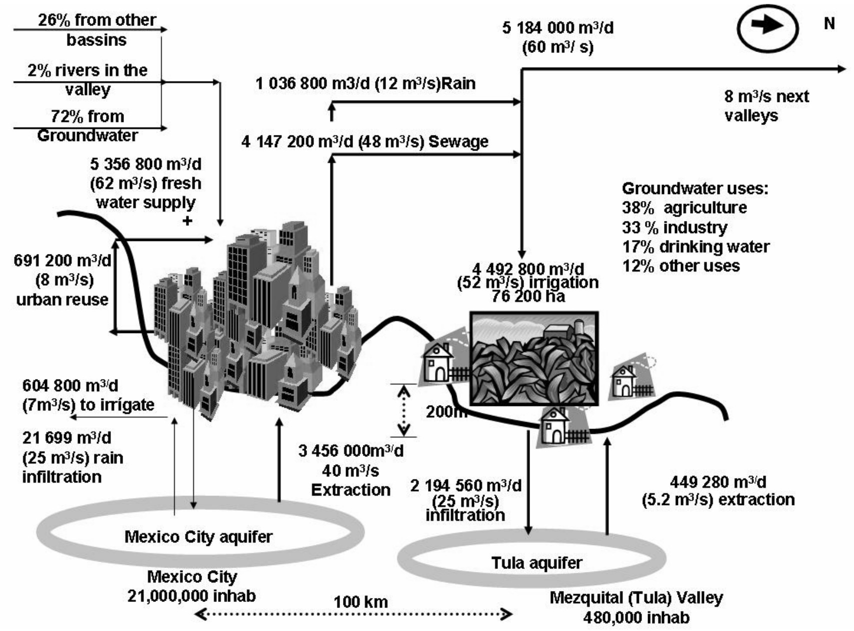


Figure 23.4 Water Balance in the Mexico and Tula Valleys.

23.3.2 Groundwater

The Mezquital valley is part of the Mexican plateau. It is surrounded by igneous extrusive rocks mountains at the south east and by limestone marine sediments and intensely folded limolites at the northwest. The central part of the valley is formed by erosion deposits that originate from the surrounding mountains and volcanic layers. Soil layers are randomly arranged with an undefined stratigraphical order, due to the non homogenous erosion and deposit periods as well as to important orogenic and tectonic land movements. For this reason, hydrogeology is very complex. In general, and according to the BGS-CNA 1998, there are three aquifers (a) Superior (b) Tarango and (c) El Doctor. The Superior aquifer is shallow, unconfined and of a variable depth. It is located irregularly in alluvial deposits. It is permeable and recharged with rainwater, wastewater and lateral groundwater flow. The Tarango aquifer (or Inferior aquifer) is the most important due to its storage and abstraction. It is recharged mainly with wastewater and some rainwater, stored in its deepest parts. The Tarango aquifer is located in volcanic ash sediments with variable granulometry and basaltic layers. Its permeability varies from 0.1 to 50 x 10^{-2} m^2/s and has a mean value of 0.015 m^2/s. In some parts the aquifer is semi-confined with groundwater depth of only 0.3 m, while in others the depth is 268 m. Several new springs have been formed from this aquifer. It is believed that the Tarango formation is interconnected with the Superior Aquifer. Finally, the third aquifer, El Doctor, is also recharged with wastewater and a significant volume is abstracted from it. Due to the complexity of the geological structure, in the Tula Valley there are also thermal springs in the lower (mainly) and upper regions. The groundwater flow is, in general, from south to north in the Tula area and from south to east in the Actopan river basin. Due to wastewater recharge for more than one hundred years, the aquifer level rose 15–30 m from 1938 to 1990 and dozens of new springs have appeared with flows varying from 8 640 to 51 840 m^3/d (0.1 to 0.6m^3/s). As mentioned, recharge was estimated to be at least 2 194 560 m^3/d (25.4 m^3/s), a value 13.4 times the natural recharge value (BGS-CNA, 1998).

23.3.3 Hydrology

The biggest rivers in the area are the Actopan, Tula and Salado (Figure 23.5). The Tula River is the main one and is known in its upper part as Tepeji River. It discharges to the Requena Dam, which also receives wastewater from the Central Collector through the El Salto River. Depending on the season of the year, water from the Tula River is either used to irrigate or is partially stored at the Endhó Dam, located west of Tula City. After Tezontepec de Aldama City, the Tula River merges with the El Salado River which contains, almost exclusively, wastewater collected by El Gran Canal. In the north and near Ixmiquilpan, the Tula River has the Actopan River as an influent. At the end of the valley, the Tula River joins the San Juan and the Hondo river taking the name of Moctezuma River which is one of the main tributaries of the Panuco River that discharges into the Gulf of Mexico.

All along their course, the Tula, Actopan and Salado rivers receive wastewater discharges from the 297 localities of the Tula Valley (sewer coverage is only 30% and wastewater treatment capacity almost nil) as well as water from the irrigation drainage channels (which is in fact wastewater used to irrigate and thus treated through the soil) as well as water from the newly formed springs. Downstream, irrigation drainage water is mixed with river water; the local population perceives the mixed water as first use or clean water.

In the past, the rivers did not receive water from aquifers due to the arid conditions. Nowadays, however, the Tula and the Actopan rivers receive 164 160 m^3/d (1.9 m^3/s) from groundwater plus another large volume from drainage channels. For all these reasons the base flow of the Tula River increased from 138 240 m^3/d (1.6 m^3/s) in 1945 to 1 097 280 m^3/d (12.7 m^3/s) in 1995. The spatial variation of the water quality in the Tula River based on all the aforementioned interactions is shown in Table 23.1.

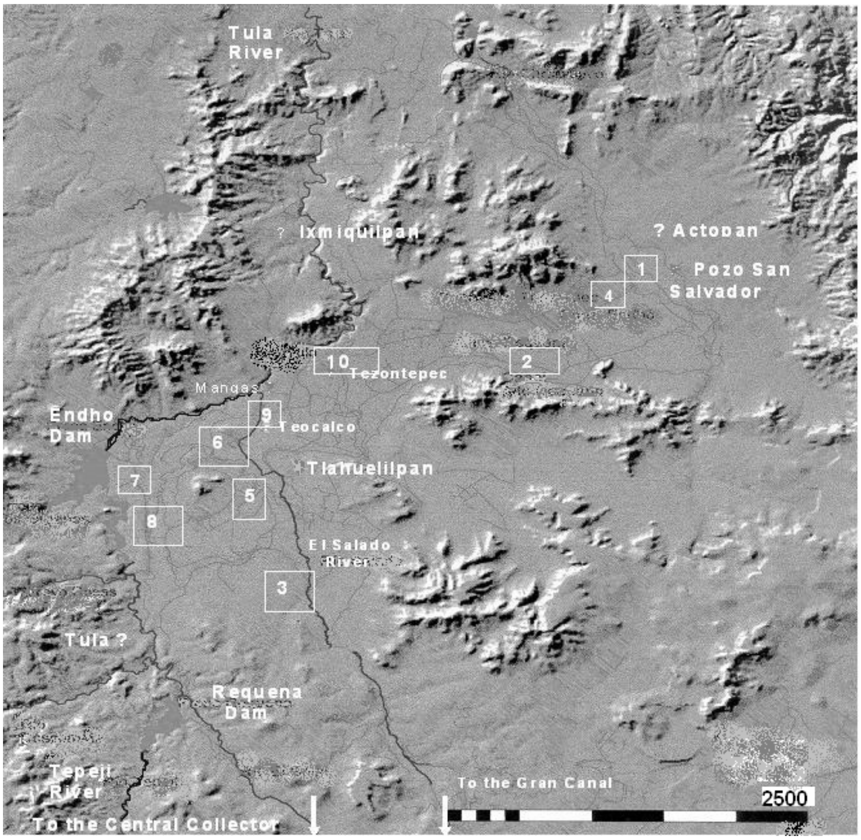


Figure 23.5 Wells and springs monitored at the Tula Valley.

Table 23.1 Water quality of the Tula River and some of its tributaries, with information from BGS-CNA, 1995.

Parameter mg/L unless indicated	Tepeji River	Central Collector	Tula River	Endhó Dam	Salado River	Gran Canal	Tula River Near Cfe	Tula River Near Teoacalco
pH[1]	7.0	7.0	7.0	7.1	7.6	7.7	7.4	7.5
Conductivity[2]	431	1114	995	1136	1590		1673	4092
O2	2.5	0.6	1.0	2.2	1.0		1.8	4.3
BOD	53	131	77	57	78	460	67	7
COD	186	315	256	204	295	210	192	208
Faecal coliforms[3]	28×10^5	6.5×10^7	6×10^7	7.8×10^4	5.2×10^6		6.4×10^6	2.01×10^4
ABS	3.4	6.7	5.2	4.2	2.6	13	1.4	0.5
Boron	1.1	1.6	1.3	0.9	1.0	25	1.9	1.8
Organic nitrogen	6.1	14.7	4.6	2.4	3.8		5.9	5.0
$N\text{-}NH_3$	2.9	8.5	8.2	10.9	18.5	23	3.4	25.9
$N\text{-}NO_2$	3.4	0.0	0.0	0.0	0.1		0.8	0.8
$N\text{-}NO_3$	0.4	0.2	0.3	0.1	0.3		12.4	8.0

[1] no units, [2] µS/cm, [3] MPN/100mL

23.4 DRINKING WATER QUALITY

Before it was realized that water used in the region was infiltrated wastewater, a change in groundwater quality was noticed in 1938. First, it was thought to be a pollution problem, and even though its chemical composition (salts mainly) was evidently very similar to that of wastewater, in 1985 the groundwater was still considered to be of “good quality”. Only more recently, in 1995, was it realized that the difference was not due to a pollution problem but to the replacement of the original groundwater by infiltrated wastewater. At the present time there are 283 groundwater wells or springs in the area producing 449,280 m^3/d (5.2 m^3/s) of water for domestic (17%), agricultural (25%), industrial (33%) and other purposes (25%). Since 1995, several studies have been performed to asses the water quality. The first covered the whole valley and was performed by the BGS-CAN. Hundreds of compounds were analyzed. Results are shown in Figure 23.6. No major problems besides faecal pollution (controlled by disinfection) and high nitrate contents were found.

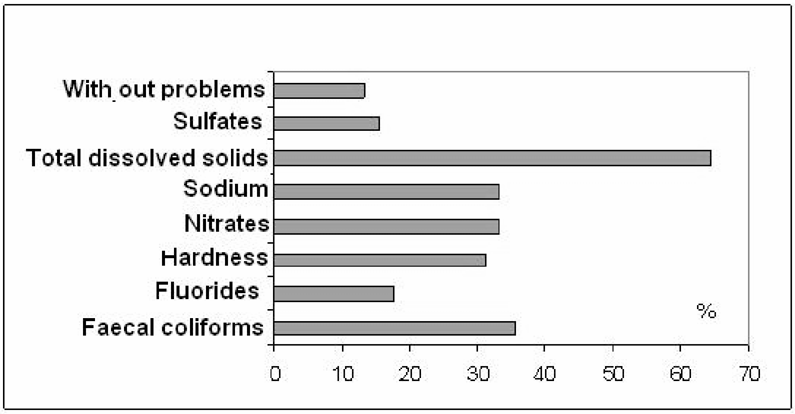


Figure 23.6 Percentage of sites with a problem in the Tula Valley by BGS-CNA, 1998.

Later, Jimenez *et al.* (1997) performed a study limited to the irrigation district 03 Tula (the oldest district in the Tula Valley – irrigated with wastewater and where the aquifer has been recharged the most). The study area was 45,215 ha. It has several springs and artesian wells (mainly near Chilcualtla, Tezontepec and San Salvador) but also some wells (near Ajacuba and Actopan) with a water level up to 90 m deep. In total, 128 abstraction sites produced 164,160 m^3/d (1.9 m^3/s) of water from springs (74%), wells (23%) and boreholes (3%). Seventeen sites were located inside the irrigated area and 50 close to the wastewater distribution channels, the rest were distributed in the irrigation fields. Prior to supply, 96% of the water was disinfected with chlorine. The study was performed in three phases.

First Phase. In 36 sites, three sampling campaigns were performed, one in the dry season and two during the rainy one, measuring the 45 parameters considered in the Mexican drinking water standard. Results showed that 37% of the supplies did not fulfil the standard due to their chloride, iron, nitrate, sulfate and/or faecal coliform content (Table 23.2). All other parameters complied with the regulation. These results were similar to those found by BGS-CNA in 1998.

Table 23.2 Number of sites that did not meet the Mexican drinking water standard (Jimenez *et al.*, 2003).

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
Without problem	13	5	

Second phase. To perform a more detailed analysis, 10 sites were selected: 6 supplying a large part of the population and located near the irrigation channels or inside the irrigated area, 2 with the influence of wastewater and 2 considered as future “clean” water supplies (Table 23.3). The selected sites supplied 39% of the population. The parameters analyzed were the pesticides used in the region for maize and alfalfa (atrazine, 2-4D, parathion methyl and permethrine), helminth ova and enteric viruses. Results showed absence of these compounds but chromatograms performed during analysis showed small peaks of non identified organic compounds.

Table 23.3 Selected sites for detailed analysis within the Irrigation District 03 Using information from: (Jimenez *et al.*, 1999).

Site	Municipality	Situation with respect to the irrigation channel or irrigation area	Flow, m^3/d	Served population
1. Bothibaji No.1;	Actopan	50 m from a wastewater distribution channel	2592	30000
2. Pozo Grande, la Noria	Actopan	200 m from a wastewater distribution channel	8640	4,000
3. El Capulín	Atotonilco	Out of the irrigated area	950	583
4. San Salvador	San Salvador	Out of the irrigated area. The site is flooded.	1728	4,000
5. Cerro Colorado	Tezontepec	1.5 km from a wastewater irrigation channel and an irrigated area. The site is flooded.	28512	72413
6. Puedhe	Tezontepec	Infiltration gallery 500 m from the Tula river. Water is used to irrigate vegetables	2333	8645
7. San Fco. Bojay	Tula de Allende	50 m from a wastewater irrigation canal	5011.2	6,000
8. El Llano 2a Sec.	Tula de Allende	20 m from the unlined Requena channel and 5 m from a wastewater channel	3024	5946
9. La Cueva 500	Tezontepec	At the bottom part of a hill	ND	-
10. El Géiser	Tezontepec	In a gorge, 500 m from the Tula River.	ND	-

ND: No data available.

Table 23.4 Monitored compounds to assess the feasibility of using the Tula Valley aquifer as a water supply for Mexico City.

Organoleptic
- Colour
- Taste

Nutrients
- NTK
- Nitrates
- Nitrites
- Ammonia nitrogen
- Phosphates

Physical
- Turbidity
- Conductivity
- Total dissolved solids
- Total suspended solids
- Total solids
- Redox potential
- Temperature
- pH

Non metals and other compounds
- Bore
- Dissolved oxygen
- Selenium
- Carbon dioxide
- Chlorides
- Total Hardness
- Cyanides
- Fluorides
- Sulphates
- Sulphides
- Total Alkalinity
  Fenoftaleina alkalinity
- Carbonates
- Bicarbonates
- Hydroxides

Metals
- Aluminium
- Arsenic
- Barium
- Cadmium
- Calcium
- Cobalt
- Cupper
- Chrome (Total)
- Iron
- Manganese
- Mercury
- Nickel
- Potassium
- Silver
- Lead
- Zinc
- Sodium

Microbiologic
- Total Coliform
- Faecal coliform
- Faecal Streptococci
- *E. histolytica*
- Helminth Ova
- *Salmonella spp.*
- *Shigella*

Organic matter
- COT
- COT total
- COT soluble
- BOD total
- BOD soluble
- MBAS

Pesticides
- Aldrine
- Chlordane
- Chlordane A
- Chlordane G
- Lindane
- Heptachlor
- Heptachlor epoxy
- Metoxychlore

Aromatic halides
- 1,2 dichlorobenzene
- 1,3 dichlorobenzene
- 1,4 dichlorobenzene
- 1,2,4 dichlorobenzene
- 1,2 dichloropropane
- Hexachlorobenzene
- 1,3 dichloropropane
- 2,2 dichloropropane
- Methylene chloride

Organic nitrogen compounds
- N – nitrosodimethylamine
- Nitrobenzene
- 2,4 dinitrotoluene
- 2,6 dinitrotoluene
- Bencidine
- 1,2 diphenilhydrazine
- N – nitrosodiphenilamine
- 2- nitrophenol
- 4 nitrophenol
- 2,4 dinitrophenol
- 3,3 dichlorobencidine

Aliphatic halogenated
- Chloroform
- Bromoform
- Dichlorobromometane
- Diclorodibromometane
- Hexachlorobutadiene
- Hexaclorociclopentadieno
- 1,1 dichloro ethylene
- Trans - 1,2 dichloro ethylene
- Triclorofluro methane
- Tetrachloro ethylene
- Trichloroethylene
- Vinyl chloride
- Tetrachloride carbon

Aromatic
- Benzene
- Ethyl benzene
- Toluene
- m – Xylene
- o – Xylene
- p – Xylene
- pyrene

Polynuclear aromatic
- Naphthalene
- Fluorene
- Criseno
- Pyrene
- Anthracene
- Benzo (a) Anthracene
- Benzo (k) fluorantene
- Benzo (b) fluorantene
- Benzo(g,h,i) pyrilene
- Dibenz(a,h) Anthracene
- Indene (1,2,3-cd) pyrene
- 2 – metilnaphthalene
- Acenaphtylene
- Acenaphthene
- 2- chloronaphthalene

Halogenated ethers
- 4 chlorophenyl phenyl ether
- Ether bis 2-chloroetthyl
- 4 bromo phenyl phenyl ether
- Ether bis (2-chloroisopropyl)

Phenols
- Phenol
- 2,4 dimethyl phenol
- Pentachlorophenol
- m-cresol
- 2-chlorophenol
- 2,4 dichlorophenol
- 2,4,5 triclorophenol
- 2,4,6 triclorophenol
- p-cresol

Phtalates
- Bis 2 ethylhexyl-phtalate
- Di-n-octyl phtalate
- di-n-butyl phtalate
- Dimetil phtalate

Other organic compounds
- Fluorantene
- Isoforone
- BHC a
- BCH b
- BCH d
- BCH g (Lindane)
- Toxaphene

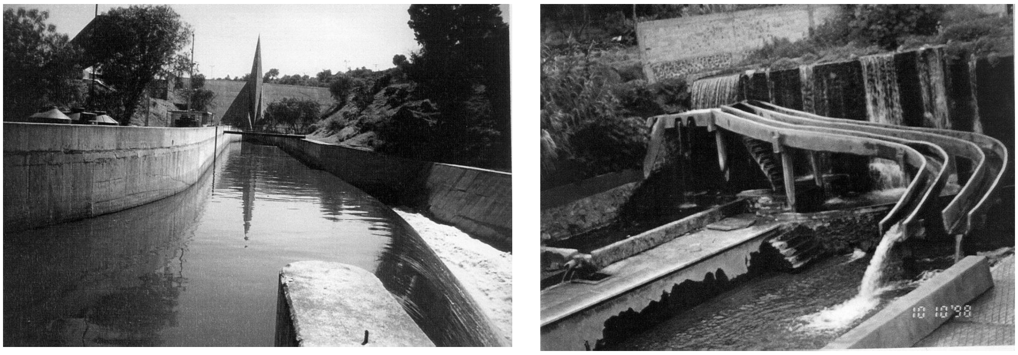
Radioactivity
- Alfa radioactivity
- Beta radioactivity

Toxicity test
- Microtox

Third phase. Based on the previous results, it was decided to include more sites (22 in total to cover 88% of the supplied population) and measure first the organic matter content (as TOC and COD). Subsequently, in those sites with high organic contents (6 sites with vertisol or with reduced compounds such as iron, manganese or nitrites), semi-volatile organic compounds were measured using the EPA SW-8270 method. No semi-volatile organic compound was detected above the detection limit (> 5ppb). Samples were also tested for toxicity using the Microtox test, with negative results.

23.5 WATER QUALITY IN THE TULA VALLEY AQUIFER

Given that no urgent or evident problems were found and that the area had plenty of water of an apparently good quality, a study was performed (Jimenez *et al*., 1999) to determine the feasibility of using the new aquifer formed as a possible future water source for Mexico City. In this third phase, 276 parameters (Table 23.4) were analyzed simultaneously by 5 laboratories (4 nationally certified, 1 also certified by the USEPA). Parameters to be analyzed were defined based on international criteria for drinking water and water reuse, the national standard for drinking water and the results of previous studies. Three sites, from the Tarango aquifer were selected (Teoacalco, Tezontepec and El Salvador, Figure 23.7a). Teocalco is a 11 232 m^3/d (130 L/s) well used to supply water to an oil refinery plant. Tezontepec is an infiltration gallery of 51 840 m^3/d (600 L/s) supplying water to 8645 people in three cities and also for recreational purposes (Figure 23.7b). San Salvador is a 3024 m^3/d (35 L/s) well that supplies 4000 people. Table 23.5 shows the results and compares them with the Mexican drinking water standard, WHO criteria (WHO, 2004), the European Union (Council Directive, 1998) and the USEPA guidelines (USEPA, 1992).



(a) (b)

Figure 23.7 Wastewater and water in excess from the aquifer: (a) The Central Collector with wastewater; and (b) recreational use of the Tezontepec water.

Table 23.5 Parameters above the national or the international criteria for drinking water.

Parameter	Criteria or Standard	Teocalco,	Tezontepec	San Salvador
Total Coliforms MPN/100 mL	MEXST = 2 USEPA(1)WHO & EU = 0	16± 21	27± 27	228± 222
Faecal Coliforms, MPN/100 mL	MEXST, USEPA, WHO, EU(2) =0	1.3±1.3	4.2±9.0	88±88
Boron, mg/L	WHO = 0.5 EU= 1	0.55 ±0.14	0.63±0.1	0.2+0.2
Lead, mg/L	MEXST = 0.025 USEPA = 0.015 WHO & EU = 0.01	0.02±0.02	0.02±0.03	0.014±0.014
Mercury, mg/L	MEXST, WHO & EU = 0.001 USEPA= 0.002	0.001±0.0009	0.001±0.002	0.0004±0.0004
Chlorides, mgCl$^-$/L(3)	MEXST, WHO = 250	149±16	179±17	264±63
Sodium,mg/L (3)	MEXST, WHO & EU = 200	176±98	168± 73	215± 105
Total hardness, mg $CaCO_3$/L(3)	MEXST = 500	324±37	452±15	492±19
Nitrates mgN-NO_3/L	NOM-127 & USEPA = 10 WHO & EU = 11(4)	24±24	17±17	19±18
Ammonia, mgN-NH_4/L	MEXST = 0.5	0.7±0.7	0.08±0.06	0.07±0.07
Sulfates, mg $SO_4^=$/L	MEXST = 400, WHO = 500	109±8.0	130±55	147±78
MBAS, mg/L	MEXST = 0.5	0.2±0.2	0.14±0.3	0.2±0.7
Total dissolved solids,	MEXST = 1000 EU = 1500	945±100	1038±188	1179±125

MEXST: Mexican drinking water Standard or NOM 127 SSA1USEPA: Environmental Protection Agency of USA

WHO: World Health Organization EU: European Union

1) 5% positive for samples during one month (2) as *E. Coli*

(3) Criteria or standard due to esthetical or operational nuisances 4)11 mgN-NO_3/L = 50 NO_3

23.5.1 Comparison with wastewater

To really appreciate the aquifer water quality, it is useful to compare it with: (a) the original quality of the wastewater, (b) the quality of the water supplied in Mexico City, considered as one of the best in the country, and (c) the water quality produced by biological secondary treatment. Table 23.6 compares the mean characteristics of Mexico City's wastewater with that of Teocalco, Tezontepec and San Salvador sites in the Tula Valley. Table 23.6 also shows the difference between values in the wastewater and groundwater expressed as a percentage. It can be seen that in general, during the passage of wastewater through soils, organic matter, metals and nutrients are considerably reduced while ion salts (like Ca, Mg and Sulfates) are considerably increased. The soils of Tula were found to be acting as an unplanned Soil Aquifer Treatment or SAT (Bower, 1989).

At this stage aromatics, chlorinated benzenes and nonylphenols were considered the more conspicuous compounds found, both in wastewater and groundwater samples, as some of these classes have been reported as endocrine disrupters in the literature. Quantitative estimates for these are shown in Table 23.7, and even though their concentration in groundwater is low and in most cases below the detection limits, they were nevertheless present. The logical question then is: how will the groundwater quality evolve with time?

Table 23.6 Characterization of Mexico City's wastewater and percentage (%) difference with water in three sites of the Tarango aquifer.

Parameter in mg/L unless indicated	WHO criteria	Mexico City Wastewater	Teocalco		Tezontepecc		San Salvador	
		Value range	Mean value	D,%	Mean value	D, %	Mean Value	D, %
Fecal Coliforms, MPN/100 mL	0	10^{04}-10^{8}	2	99.9	4	99.9	88	99.9
Salmonella (3 varieties), CFU/mL	0	ND-positive	ND	100	ND	100	ND	100
E. histolytica, cysts/L	0	0-1.5	ND	100	ND	100	ND	100
Shigella, CFU/mL	0	0 - positive	ND	100	ND	100	ND	100
Helminth ova, ova/L	0	12-90	0	100	0	100	0	100
Turbidity, NTU	0.1$^{(1)}$	100 - 249	1	99	1	99	1.5	99
Total suspended solids	-	83-153	3.8	97	3	97	4.1	97
Total dissolved solids	1000$^{(1)}$	758-860	945	**-11**	1038	**-22**	1179	**-39**
Conductivity, μmhos/cm	-	1437-1689	1577	**-1**	1698	**-9**	1918	**-23**
BOD	-	200-451	4	99	8	98	5	98
Total organic carbon	-	35-188	18	84	28	75	11	90
Total COD	-	450-496	11	98	23	95	14	97
Soluble COD	-	274	9	97	4	99	15	95
MBAS	-	5.9-6.2	0.2	97	0.15	98	0.2	97
Aluminium	-	1.3-5.5	0.08	98	0.09	97	0.07	98
Arsenic	0.01	ND-0.008	0.002	50	0.004	0	0.002	50
Boron	0.5$^{(2)}$	1-1.2	0.5	55	0.6	45	0.29	74
Cadmium	0.003	0.0030	0.00015	95	0.00015	95	0.0015	50
Calcium	-	41-44	80	**-88**	73	**-72**	110	**-159**
Chromium	0.05	0.042	0.004	90	0.004	90	0.004	90
Copper	2	0.05-0.07	0.015	75	0.02	67	0.01	83
Iron	0.3$^{(1)}$	1-1.2	0.04	96	0.15	86	0.09	92
Lead	0.01	0.09-0.1	0.02	98	0.02	98	0.01	99
Magnesium	-	24-29	30	**-15**	64	**-146**	46	**-77**
Manganese	0.4	0.03-0.2	0.004	97	0.01	91	0.004	97
Mercury	0.001	0.001	0.0006	40	0.001	0	0.0004	60
Nickel	0.02	0.08-0.15	0.015	87	0.01	91	0.01	91
Potassium	-	25-41	35	**-6**	31	6	22	33
Sodium	-	198-206	175	13	167	17	215	**-6**
Chlorides	250$^{(1)}$	155-248	149	26	179	11	264	**-31**
Cyanides	0.07	0.005-0.01	0.008	**-7**	0.006	20	0.008	**-7**
Fluoride	1.5	0.7-4	0.5	79	1.1	53	0.3	87
Sulfates	-	21-51	109	**-203**	130	**-261**	147	**-308**

Parameter in mg/L unless indicated	WHO criteria	Mexico City Wastewater	Teocalco		Tezontepecc		San Salvador	
		Value range	Mean value	D,%	Mean value	D, %	Mean Value	D, %
Sulfides	-	3-3.5	1.2	63	1.0	69	1.7	48
Total Kjeldahl Nitrogen	-	37-38	1.5	96	1.6	96	1.3	96
Ammonia nitrogen	-	24-32	0.7	98	0.08	100	0.07	100
Nitrates	11	ND -1	24	**-47900**	18	**-35900**	19	**-37900**
Nitrites	0.9	ND -0.001	0.008	**-1500**	0.006	**-1100**	0.01	**-1900**
Phosphorus	-	2.7-3	0.1	96	0.2	93	0.2	93
Bicarbonates, mg /L	-	485	585	**-22**	642	**-34**	572	**-19**
Total Hardness, mg /L	-	210-220	324	**-51**	452	**-110**	492	**-129**
Ethylbenzene	0.3	1.2	ND	100	ND	100	ND	100
p. cresol (methyl phenol), µg/L	-	46.5	ND	100	ND	100	ND	100
Chloroform, µg/L	0.2	0.2-0.8	ND	100	ND	100	ND	100
Tetrachloroethylene µg/L		2	ND	100	ND	100	ND	100
o – Xylene, µg/L	0.5	3.8-4	ND	100	ND	100	ND	100
m – Xylene, µg/L	0.5	9.2	ND	100	ND	100	ND	100

(1) Value set on the basis of acceptability aspects

(2) Provisional guideline value because calculated guideline value is below the level that can be achieved through practical treatment methods, source protection, etc,

ND: Not detected

Table 23.7 Selected organic compounds in wastewater and groundwater at the Tula Aquifer (µg/L), with data from Capella, 1997.

Compound	Central Collector	Teocalco	Tezontepec	San Salvador
Methyl (1-methyl-ethyl)-benzene	5-10	< 5	< 5	< 5
1,1-oxy-bis-benzene	10-50	< 5	< 5	< 5
4-nonyl phenol	1000	5-10	5-10	10-50
1,2,4, trichlorobenzene	5-10	< 5	< 5	< 5
Benzenes	100	< 5	< 5	< 5
Phenols	1500	10	10	50
PAH	25	< 5	< 5	< 5

23.5.2 Comparison with Mexico City´s water supply

For this comparison, two wells located in Mexico City’s aquifer were selected. One is considered of good quality (Ciudad Universitaria) while the other (La Noria) is known for its faecal pollution (Cifuentes *et al.*, 2002). Figures 23.8 a, b and c show the comparison. Mexico City’s groundwater has a quality similar to that of the Tula Valley, the difference being that the latter is more saline. Results concerning the microbial content are not shown but water from La Noria had a faecal content similar to that of the other sites studied in the Tula Valley (< 100 MPN/100 mL).

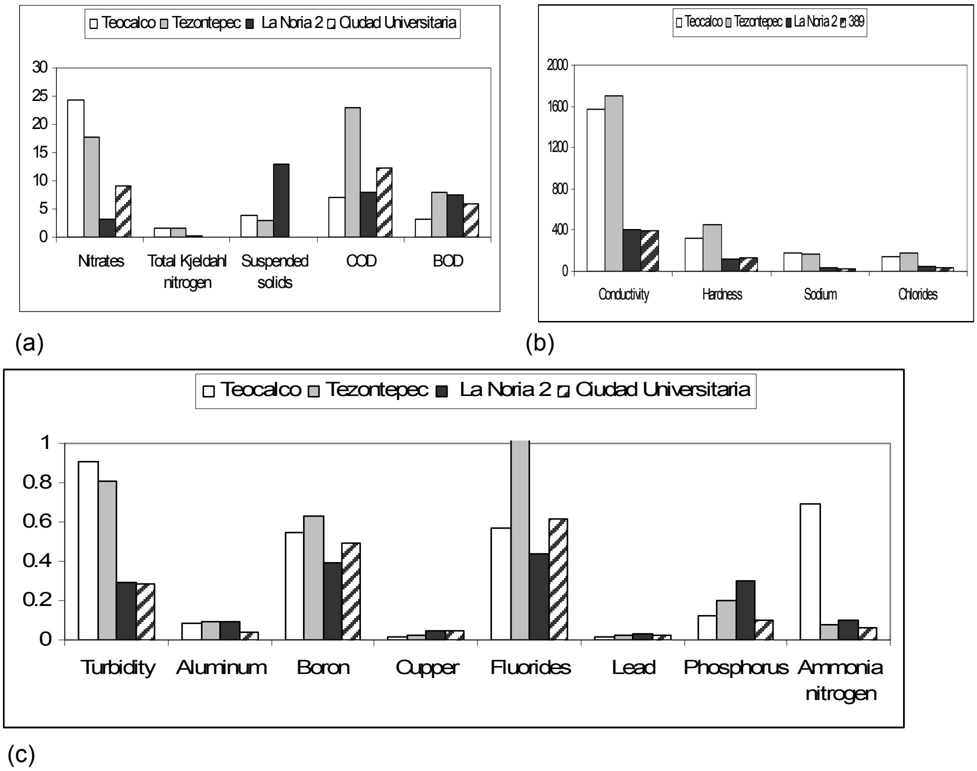


Figure 23.8 Mexico City and the Tula valley water supply quality. Content expressed in mg/L.

23.5.3 Comparison with a secondary effluent

Mexico City has several wastewater treatment plants that permit onsite water reuse. One such plant is Cerro de la Estrella which treats 172 800 m^3/d (2m^3/s) with activated sludge, filtration and chlorination. This plant is considered one of the best operated in the city. Table 23.8 compares the effluent quality with the water from Tezontepec spring (Figure 23.9). It is evident that, with the unplanned SAT in the Tula Valley, almost all the wastewater produced by the city (4 492 800 m^3/d or 52m^3/s) is treated to a better degree than at the El Cerro de la Estrella wastewater treatment plant.

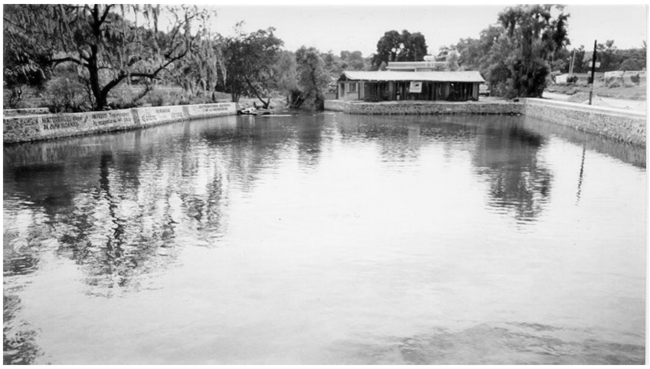


Figure 23.9 Tezontepec spring.

Table 23.8 Comparison with the effluent of an activated sludge plant.

Parameter, mg/L unless indicated	Secondary effluent	Tezontepec	Parameter, mg/L unless indicated	Secondary effluent	Tezontepec
Turbidity, NTU	4.5	1.0	Copper	0.05	0.02
Total suspended solids	23	3	Chromium	0.008	0.004
Total COD	45	23	Iron	0.13	0.02
Soluble COD	24	7	Mercury	0.001	0.001
BOD	14	8	Nickel	0.025	0.02
Faecal coliforms, MPN/100mL	9.2×10^5	4	Lead	0.02	0.01
Total coliforms, MPN/100 mL	1.1×10^6	27	Selenium	0.009	0.002
Alkalinity, mg $CaCO_3$/L	174	511	Cyanides	0.024	0.006
Conductivity, μmhos/cm	726	1699	Chlorides	68	179
Hardness, mg/L($CaCO_3$)	164	452	Fluorides	0.8	1.0
Sodium	82	168	Sulfates	67	130
Dissolved solids	496	1038	Sulfides	0.3	1
Aluminium	0.1	0.09	Nitrates	12	18
Barium	0.03	0.01	Nitrites	0.40	0.006
Boron	0.61	0.63	Ammoniacal nitrogen	1.6	0.08
Cadmium	0.002	0.002			
Calcium	27	73	TKN	3.0	1.9
Cobalt	0.05	0.01	Phosphorus	2.8	0.2

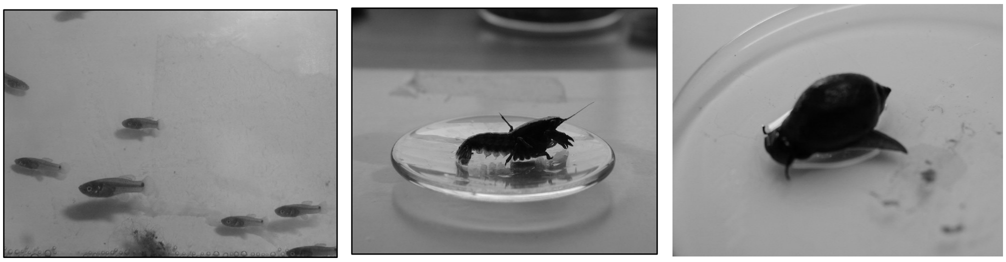
23.6 ENVIRONMENTAL EFFECTS

The use of wastewater certainly has a big impact on Tula soils. According to Siebe (1994), using FAO classification system, soils in the Mezquital Valley are of three types: (a) rendzic and melanic Leptosols, (b) calcic and haplic Phaeozems; and (c) eutric Vertisols. In general, soil pH is 6.7–8.4, conductivity is 0.41–2.22 µS/cm (with values of up to 40 µS/cm where the aquifer level is very high), clay content is 11–60%, and texture tends to be clay-loamy. Because the area irrigated with wastewater gradually increased with time as the wastewater flow from Mexico City intensified, it is possible to find areas in the Tula Valley with varying numbers of years under wastewater irrigation. This has permitted some interesting comparisons. Concerning metals, although Mexico City's wastewater contains very low levels (below the Mexican irrigation standard which is similar to that of USEPA, 1992), irrigation annually adds small amounts of metals to soils. Thus, sites irrigated for more than 80 years show a metal accumulation in the arable layer (up to 15 cm) around 3 to 6 times more than the regional baselines. For instance, Pb content has increased from 0.15 to 0.28 g/m^2, Cd from <0.009 to 0.011 g/m^2, Cu from 0.19 to 0.40 g/m^2, and Zn from 0.49 to 1.13 g/m^2. Despite this accumulation, international criteria have not been exceeded (Siebe and Cifuentes, 1995). Wastewater has also contributed to increasing the available phosphorus from low-medium levels (2–9 g P/m^2) to medium-high ones (14–25 g P/m^2) after 80 years under irrigation. For nitrogen, a slight increase has been observed from 0.22 to 0.8 kg N/m^2 (Siebe and Cifuentes, 1995; Siebe, 1998), depending on the period for which soils have been irrigated. However, unlike phosphorus, this element is easily leached, which explains its low accumulation in soils and the high nitrate content in the aquifer and the irrigation drainage (Jimenez and Chavez, 2004).

Wastewater also adds organic matter to soil to such an extent that in soils irrigated for more that 65 years it has increased from 1.6–3.6% to 3.1–6.4%. Additional organic matter increases moisture content, diluting salts, and also limits metal mobility (Siebe, 1998). Effects on crops have also been analyzed by Siebe, 1998, and Herre *et al*., 2004, reporting no yield changes on crops although a slight salinity increase in plant tissues was observed.

23.6.1 New ecosystems

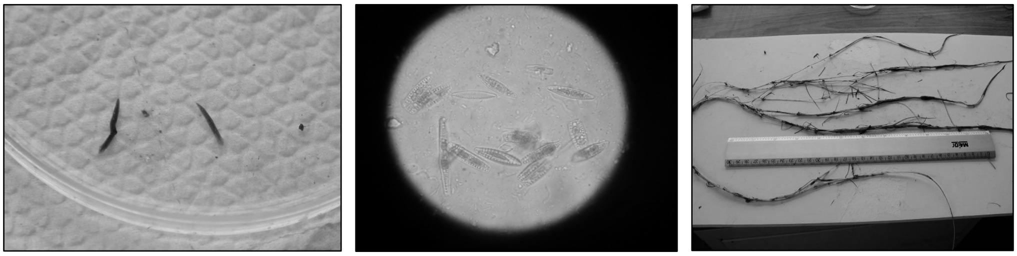
Due to the lack of water, the original vegetation in the Tula Valley was limited to Xerophila scrubs, such as mesquite, sweet acacia, yucca and a wide variety of cactus (Siebe, 1994). But nowadays, in the lower parts of the valley, where the new springs have appeared, new ecosystems have been formed. The Cerro Colorado spring is one of these springs with a flow of 51 840 m^3/d (0.6 m^3/s). It appeared in 1964 and since then new aquatic flora and fauna have sprung up (Figure 23.11). Cerro Colorado spring is used not only to supply 70,000 people, but also to wash clothes, cars and for recreational purposes. Water from the spring is even bottled with no further treatment to be sold as "spring water". Because there were some concerns about endocrine disruptors found in the water, 4 monitoring campaigns in 5 sites and at 2 depths of a small lake formed by a spring were performed to find the percentage of male and female fish in *jonesi and regalis* species (Figure 23.12). The mean distribution was 42% male and 58% female, and it was concluded that no statistically significant effects had occurred.



Heterandria jonesi (gupi) Fish

Cambarrellus sp.
(acocil mexicano)

Artropoda Physella sp
Mollusk



Planaria (*Dugesia*)
Platelminth

Diatomeas Algae

Aquatic grass *(Palustris)*
Plant

Figure 23.11 New flora and fauna in the Cerro Colorado spring.

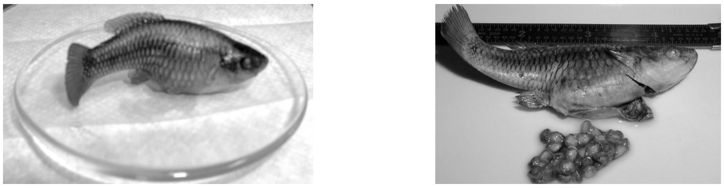


Figure 23.12 (a) Poecilidae, Heterandria, H. jonesi and (b) Goodeidae, Allotoca, A. regalis.

23.7 Water potabilization

Based on criteria set for drinking water it could not be concluded that the water represented severe health risks. But considering the origin of the water and the presence of unidentified and identified compounds in chromatograms (even at very low concentrations) it was decided to define a way to treat the water prior to its consumption in order to remove organic compounds and salts. To investigate this, membrane pilot plants were operated, one with nanofiltration membranes and the other with reverse osmosis ones, using water from Cerro Colorado spring and Teocalco well. Pre-treatment before the pilot plants consisted of sand and anthracite filtration plus a 5 μm filtration step. During the 1-year study, the treated water consistently met drinking water standards using both processes, but reverse osmosis produced an effluent with very low TDS (40–57 mg/L) and an acid pH (Jimenez and Chavez, 2004). In both cases, organic matter removal was high, producing an effluent with < 1–2 mg COT/L, with no bacteria or coliphages.

In wastewater, 60 compounds were detected (Figure 23.13a), notably 4, nonyl phenol (500–1000 ppb), 1,1,3,3 tethramethilbutylphenol (100–500 ppb), 2,3 dihydro-1,2 dimethil-1 H-Indene (10–50 ppb), 1,1 –oxyibis-benzene (10–50 ppb) and 1,1 biphenil (5 ppb), according to Capella and Pegueros, 1998. In groundwater some volatile halo compounds (alkyl benzene and chlorobenzenes) were found in very low concentrations; nanofiltration considerably removed nonylphenols and all the halo compounds, while reverse osmosis removed almost all compounds. Considering these results and based on a benefit/cost analysis, nanofiltration was selected as an adequate treatment process. Studies are still being carried out to optimize the membrane selection, complete the treatment scheme and further reduce the treatment cost.

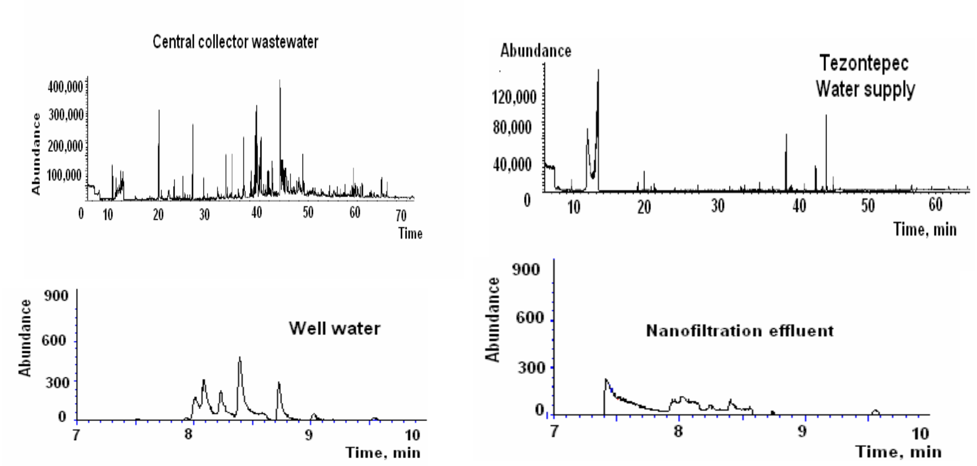


Figure 23.13 Chromatograms in wastewater, groundwater and nanofiltration effluent With information from: Capella and Pegueros, 1998 and García *et al*., 2000.

23.8 USE OF THE TULA VALLEY AQUIFER TO SUPPLY MEXICO CITY'S WATER SUPPLY

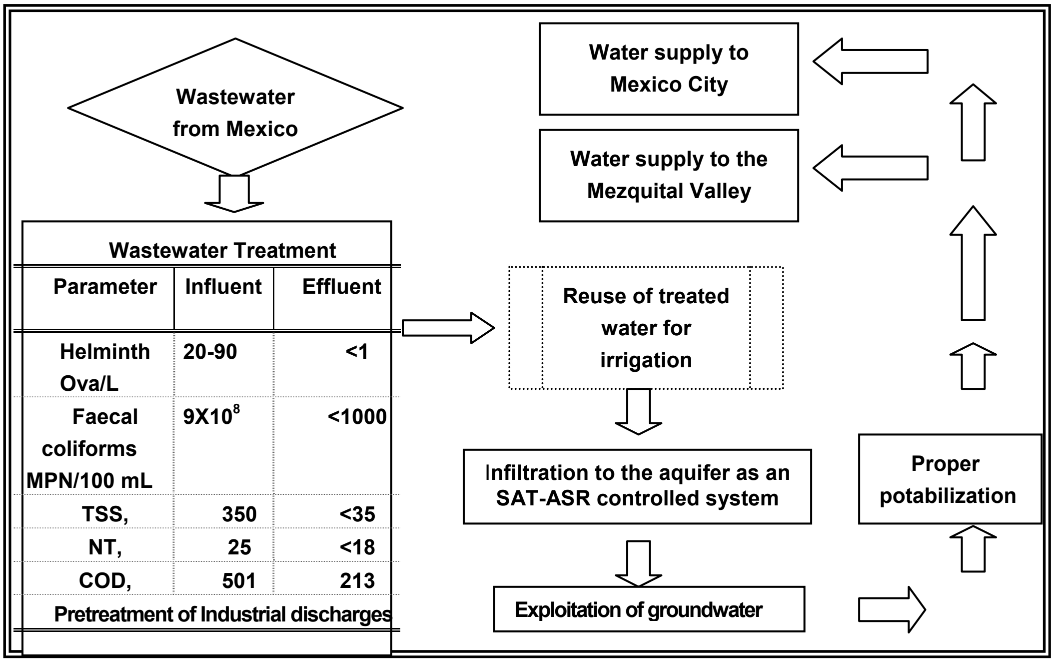
In Mexico City, around one million people lack an adequate formal water supply, and it is estimated that due to population growth an additional 864,000 m^3/d (10 m^3/s) will be needed for around 3.5 million people over the next 10 years, mainly in the northern part of the City. Due to groundwater over-exploitation, Mexico City is subsiding at rates of up to 40 cm/yr in some areas. Thus, additional water abstraction from soil is prohibited – relying on water rights markets to reallocate water from irrigated agriculture or livestock uses to the water supply of new urban developments – and a large number of wells are to be closed in order to restore hydrological equilibrium. Other options are to bring water from other valleys, some of them located 300 km away and 1700 m below Mexico City. Besides this, the Temascaltepec option, considered the most favourable one, had to be stopped due to social pressure from the regional population that rejects sending "their water to the capital", despite water being national property. Thus, new alternatives are being taken into account. One is to potabilize wastewater *in situ*, as is done in Windhoek, Namibia, while another is to bring back the water from the Tula Valley aquifer. Geohydrological studies in the Mezquital Valley have shown that there is an excess of water of at least 864,000 m^3/d (10 m^3/s). This excess is causing groundwater levels to rise, leading to soil salinization problems, flooding of the irrigation areas and 86 400 m^3/d (1 m^3/s) of water loss from evaporation. In an initial stage, 518 400 m^3/d (6 m^3/s) would be extracted for drinking purposes. This amount was set using a cautious approach in order to study the possible effects of extraction on the local groundwater availability. This volume can be produced using 90 wells (6048 m^3/d or 70 L/s each) over a 322 km^2 area near Tezontepec, Cerro Colorado and San Salvador. In this scenario the total water level depression in the Tula Valley would be around 30 m. Compared to the option of potabilizing wastewater *in situ*, this option has the advantage of enabling agriculture activities in the Tula Valley to continue and thus increase the added value of water through its successive reuse. Table 23.9 shows the comparative costs. As reference, the present cost of supplying water from the local aquifer in Mexico City is 0.02 USD/m^3 (just to chlorinate groundwater) while the cost of bringing water from a site located 151 km away and 1 100 m below Mexico City is 0.75 USD/m^3.

Table 23.9 Cost of future water supply options for Mexico City.

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

23.9 CONCLUSIONS

It is evident that infiltration through the Tula Valley soil is acting as an unintentional SAT system that efficiently depollutes Mexico City's wastewater. While the wastewater origin of the aquifer water is not causing urgent problems for Tula Valley inhabitants, it is certainly a source of great concern, especially as it is not known how long the treatment capacity of the soil will last. For this reason studies are still being carried out and additional support is required to determine the fate of pollutants and quantify soil behaviour. Also, additional studies should be done to fully determine the long-term effects of the aquifer water supply using toxicological tests in larger species, such as fish. Also, population health surveys should be carried out. With respect to water treatment, besides optimizing the process, a safe disposal method needs to be defined for the brine produced from the membrane process.



Wastewater Treatment

Parameter	Influent	Effluent
Helminth Ova/L	20-90	<1
Faecal coliforms MPN/100 mL	$9X10^8$	<1000
TSS,	350	<35
NT,	25	<18
COD,	501	213

Pretreatment of Industrial discharges

Figure 23.14 Management proposal.

Because any study will take time, it is recommended that high priority be given to controlling industrial discharges to Mexico City's sewage system, as well as treating wastewater in accordance with irrigation norms prior to its use in the Mezquital Valley; that way, the soil's treatment capacity will last longer. As defined by national standards since 1995, Mexico City's wastewater treatment should be implemented independently of the Mexico City's government decision to reuse the water from the Tula Aquifer as supply in order to protect the health of the Tula Valley inhabitants. Also, independently of Mexico City's decision, the Hidalgo state government 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 less influence. The water management proposal for the valleys of Mexico and Mezquital is presented in Figure 23.14.

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