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Urbanization and Sustainable Potable Water Supply: Implications for Aquifer Preservation and for Interbasin Water Transfers

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Abstract

Urbanization, or the concentration of population in cities, is an irreversible social and economic fact. It exists in all continents, in developed and developing countries. In Latin America, for example, the urban population is close to 75%. Potable water demand normally exceeds, in large cities, the total recharge of the local aquifers, usually the first source for water supply, requiring aqueducts to transfer water from not urbanized neighboring basins, creating at times water conflicts between urban and rural populations.
A general model for grand vision planning is presented to determine, for typical cities from 1 to 20 million inhabitants, the scale of its local aquifer mining and depletion, deducting from the urban withdrawal the total aquifer recharge. Along with the evaluation of aquifer life, increasing groundwater withdrawal costs are compared to the costs of building aqueducts from neighboring basins.
The general model, comprising a city model, an aquifer and wellfield model, and an aqueduct model, is presented in figures showing population density versus precipitation, showing also water requirements and aquifer recharge rates. Real cities can be represented in these general figures, showing regions of aquifer sustainability, aquifer overdraft, and necessary imported water. The model is applied to three Mexican cities with 1, 4 and 20 million inhabitants.
The model is based in the statistics for large cities published by international organizations, in the estimation methods of aquifer water balance and recharge reported in the groundwater literature, and in aqueduct models previously developed and published by the authors.
It is concluded that most large cities require importation of preferably surface water from neighboring basins, through aqueducts, in amounts depending of their specific hydrological and geohydrological condition.

Keywords: Urbanization; Sustainability; Potable water supply; Aqueducts; Aquifers

1. INTRODUCTION

Urbanization was common to all major ancient cultures. In our modern world, it is an irreversible social and economic fact. The understanding of the long term sustainability of cities and its relation with the availability of water, requires a general modeling of the urban environments -the cities-, of its water requirements, and of the costs and exploitation possibilities of the locally or distantly available water sources.
The large cities, with its concentration of industrial, commercial and government activities, and education and health services, attract permanently new inhabitants, in addition to its natural growth. They require, to fulfill their economic and social purposes and to provide health and wellbeing to its inhabitants, significant amounts of water, which should be distributed in space and in time, with equality. The required amounts of water are often not available in the city surroundings, and the growth of the large cities has often been made possible by the intensive use of groundwater, which cannot be permanent. In order to give sustainability to a particular large city, the supply sources for its water requirements must be foreseen and made sure.
Water imports to cities have a long history. The cities of Rome, and gallo-roman Lugdunum (Lyon), in France, for example, were supplied by numerous aqueducts, in spite of being located in riverbanks. Constantinople had also long aqueducts supplying water to its numerous underground cisterns. The cities of Paris and New York developed since the XIX century systems of aqueducts and reservoirs to supply their water needs. Large hydraulic works, as the ancient and modern aqueducts, or the Grand Canal of China or the Canal du Midi, have been built as required since ancient times. We should not be surprised if modern large cities require large hydraulic works.
We can take the following conceptual approach:

1. Define the cities by its population, area, population density and average precipitation.
2. Define the city´s water requirements.

3. Define its primary water source, normally groundwater, and the annual recharge as a function of precipitation and recharge area.
4. Define the possibility of satisfying the city's water requirements with local sources.
5. Define a wellfield model, with its water extraction costs, for the local aquifer, and for other possible external supplying aquifers.
6. Define an aqueduct model, to convey the water imported from external sources, surface or underground, with its basic characteristics: distance to the source, positive or negative altitude difference between source and destination, total dynamic head required, and cost per cubic meter.

2. CITY MODEL

A city is defined here by its population, city area, population density δ (Demographia, 2016), average annual precipitation $\boldsymbol{P}$ [mm/y] (WMO, 2021) and water requirements, $\boldsymbol{D}$, expressed in Mm^3/y, or in m^3/s, or in mm/y. Its aquifer is defined by its annual recharge $\boldsymbol{R}$ [mm/y], and by its recharge area, normally assumed to vary between one and two times the city area, as cities may be surrounded by foothills, woods or even flatland contributing to its aquifer recharge. The water requirements $\boldsymbol{D}$ can be further separated in groundwater or surface water, and in locally supplied or imported water.
We consider here that the requirements of imported water for large cities can be defined with the knowledge of just two variables: its density and its average precipitation: sustainable groundwater withdrawals depend on aquifer recharge, for which precipitation is the main controlling variable (Rivera, 2014). In Figure 1, a number of reference cities around the world are shown, with their densities and precipitations.
For large cities, a per capita demand $\boldsymbol{d}$ of 274 l/hab/d (liters per inhabitant per day), represents 100 m^3/hab/y (m^3 per inhabitant per year). Therefore, 1 M (million) inhabitants will require 100 Mm^3/y, or 3.2 m^3/s of continuous supply. If we assume that the systems supplying the city will operate 80% of the time, or 7 000 hours per year, the installed capacity of the systems should be 4 m^3/s per M inhabitants.
If we assume a population density of 5 000 hab/km^2 (inhabitants per km^2), a common figure in large Latin American and European cities, the required urban area will be 200 km^2 per M inhabitants, and the required water supply per year will be 500 000 m^3/km^2, or a uniform water depth of 0.5 m/y, or 500 mm/y, that is, $\delta/10$.
If we assume now a typical precipitation of 1 000 mm/y, and an aquifer recharge area equivalent to twice the city area, we will require an effective recharge coefficient of 0.25 in order to satisfy the city's water requirements. This coefficient is greater than the average vertical recharge coefficients in rural areas, which range, in general, excluding extremes, from 0.10 to 0.20 (Rivera, 2014; Walton, 1970; Xu and Beekman, 2003; MWR, 2009). Vertical recharge coefficients of 0.15, for example, may seem large for urban environments. However, in these environments, new horizontal recharge is induced by the deepening of the water table or piezometric surface, which is generally the situation in city aquifers. In addition, leaks in the water distribution, wastewater and stormwater systems induce an additional incidental vertical recharge. Considering the three recharge components, vertical, induced horizontal and induced vertical, a total recharge coefficient of 0.15 will not be uncommon.

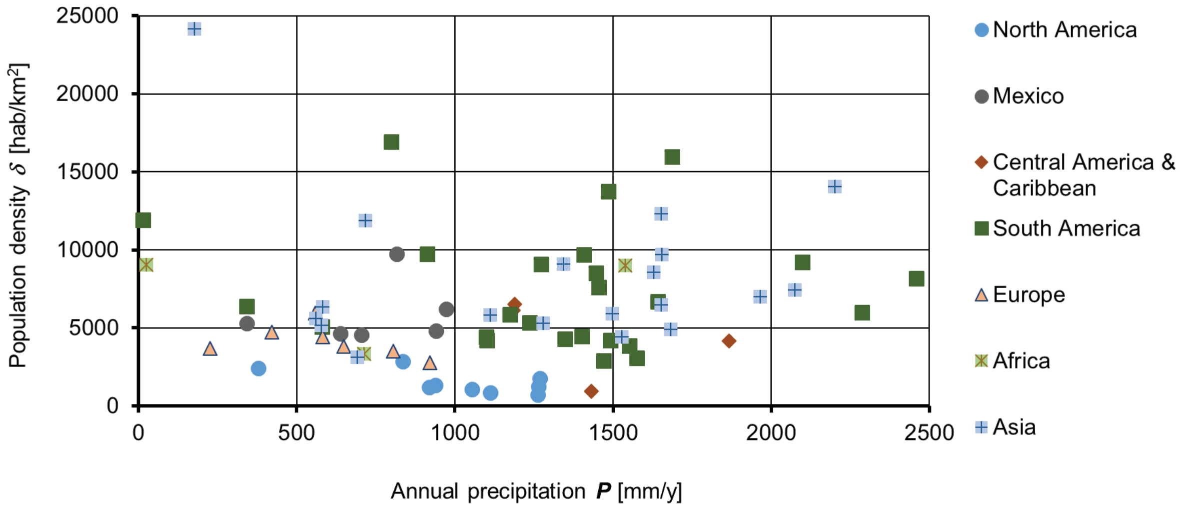

Figure 1. Population densities δ [hab/km^2] versus annual precipitation $\boldsymbol{P}$ [mm/y] for cities around the world.

We can conclude that cities with population densities like the one indicated above have typically exceeded the total recharge available and are either overdrafting their local aquifers, or importing water to satisfy their requirements. Assuming an average total recharge coefficient of 0.15, an aquifer recharge area twice the city area, and a precipitation of 1 000 mm/y, we can state that cities with densities greater than 3 000 hab/km^2 will necessarily have to import water. If the cities receive only 500 mm of precipitation, only those with densities below 1 500 hab/km^2 will be able to supply its water requirements from its local aquifers.

3. GROUNDWATER POSSIBILITIES TO SUPPLY LARGE CITIES

In order to evaluate the groundwater possibilities to supply large cities, Figure 2, equivalent to Figure 1, is presented. If we assume, as in the City Model, an aquifer recharge area of twice the city area, the aquifer recharge volume or available groundwater corresponding to a certain precipitation will be duplicated for the city area, that is, for the city's population density. We have drawn in Figure 1 the straight line ***R***, linearly dependent with precipitation, which represents a total recharge coefficient of 0.15 for the total aquifer's recharge area. We have also drawn the straight line ***2R***, corresponding to twice the aquifer recharge. We can define in the figure different regions, which will define the city's situation regarding its water supply. In Region I, the aquifer is in a stable condition, groundwater withdrawal not exceeding the recharge. Region II corresponds to an overdrafted aquifer, in which the withdrawal exceeds the recharge and, as a limit, can reach twice the recharge; it will require water imports, to avoid aquifer depletion and the consequences of overdrafting. Region III goes up to the point in which 100% of the rainfall is needed to satisfy the city's water requirements. Region IV requires more water than available from rainfall. In Regions III and IV, water imports are a *sine qua non*.
Moving to the right in Figure 2 (increasing precipitation and aquifer recharge) means more sustainable conditions. Moving up in the figure (increasing demand and withdrawals) means less sustainable conditions.
From the figure, US and Canada cities, along with a few South American and Asian cities, favored with high precipitations, can be fully supplied with groundwater under stable aquifer conditions. European and most Latin American cities, as well as African and Asian cities, are either overdrafting their aquifers or importing water. Overdrafting aquifers is a temporary solution, not sustainable. Overdrafting can have a series of has a number of harmful to the environment and the cities infrastructure: land subsidence, saline intrusion in coastal aquifers, loss of infrastructure due to water level drawdown, water quality deterioration and necessary relocation of the withdrawing infrastructure (UNEP, 2003), and general environmental deterioration.
In the long term, to be sustainable, all cities above the ***R*** straight line will have to import water. Cities between the lines ***R*** and ***2R,*** if withdrawing only groundwater, must make a relatively rapid transition to supply their deficits with imported water. Cities in Regions III and IV, even favored by precipitation, must be importing water.

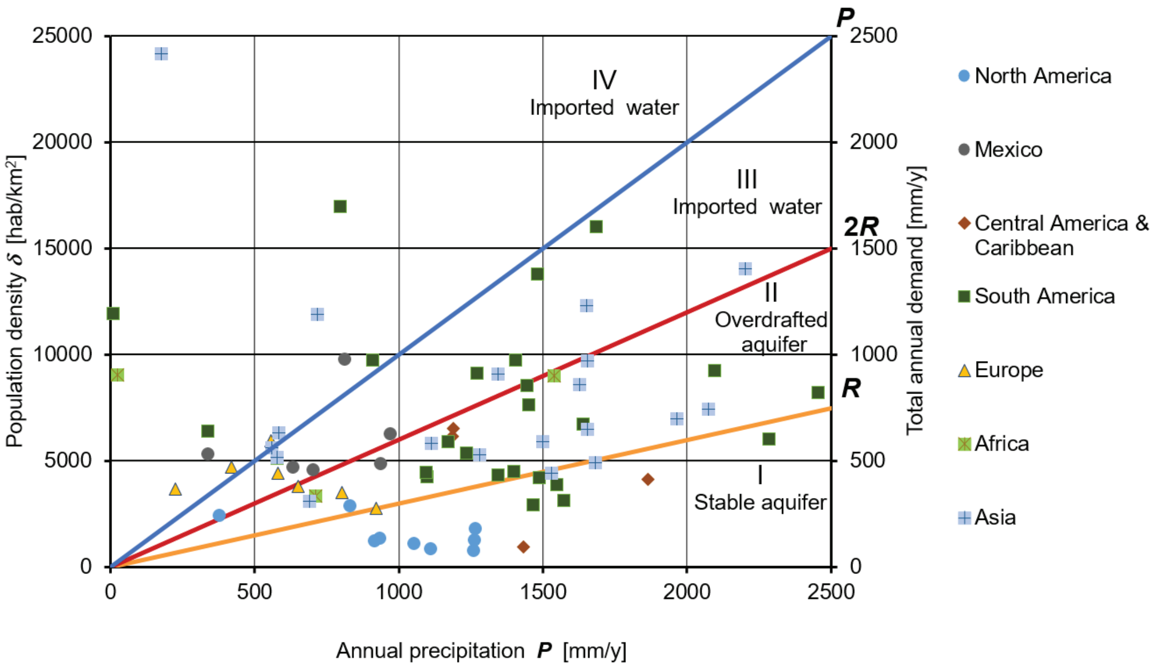

Figure 2. Population densities δ [hab/km^2] versus annual precipitation ***P*** [mm/y] for cities around the world, showing regions of aquifer stability (Region I), aquifer overdraft (Region II), and required imported water (Regions III and IV).

The general conclusion offered by Figure 2 is clear: for the densities of most large cities, 1, groundwater is not sufficient to satisfy the population's water needs; 2, a number of city aquifers are being overdrafted and risk depletion and no future availability; and 3, as a general rule, with few exceptions, large and dense cities require water imports from neighboring watersheds.

4. AQUIFER MODEL

Aquifers, the groundwater reservoirs, from which generally high quality water can be extracted economically, show a large geological, sedimentary and hydraulic variety. They have defining variables as permeability, K, depth, b**,** transmissivity, $T = K\ b$, and storage coefficient, $\boldsymbol{S}$. They are classified hydraulically as free or unconfined, semiconfined, or confined; and geologically as alluvial, in fractured rock, or karstic. In free or unconfined aquifers, the water table is at atmospheric pressure. In confined aquifers, generally deeper and overlain by quasi-impermeable layers or aquitards, their hydraulic depth is an imaginary surface, called piezometric surface. The aquifer's annual recharge is calculated with a water balance or hydrologic equilibrium equation, evaluating inflows, outflows, and changes in storage. The water balance, comparing withdrawals to total recharges, will define the groundwater deficits (Freeze and Cherry, 1979; Hiscock, 2005; Todd, 1980). The aquifer dimensions, in area and depth, together with its storage coefficient, will define the available groundwater, which compared with the groundwater deficits will define the aquifer remaining life.

Our reference aquifer will be a deep aquifer, as in most cities, with a depth of 300 m, and a pumping head of 200 m. This aquifer is in between two withdrawal conditions: its equilibrium condition, namely, with its water withdrawal being equal to its recharge, and the condition of a highly stressed, intensively used, and overdrafted aquifer, with a withdrawal volume of twice the recharge volume, or 100% overdrafted. We assume that water withdrawals in aquifers below or near large cities have already surpassed and are not far from duplicating the recharge volumes, as the easy availability of local groundwater normally delays the consciousness of overdrafting and its negative effects, and extends the response time for the withdrawal control and limitation, and for the preparation of alternative supply projects. We are establishing a withdrawal limit of twice the recharge as this figure normally promotes alerts. As the alternative supply projects are normally expensive and can give rise to water conflicts, the overdrafting of the local aquifer, once acknowledged, have a tendency to continue for many years, see decades.

5. WELLFIELD MODEL

In order to calculate a reference unit cost for the groundwater withdrawal, a wellfield model is required. We will assume a wellfield with a minimum well separation of 1 000 m, for a minimum disturbance between neighboring wells. The typical well is fully penetrating, 300 m deep, with a pumping head of 200 m, a borehole diameter of 50 cm, a pipe diameter of 30 cm, a flow of 80 l/s, operating 7 000 h/y (80% of the time), with an annual yield of 2 Mm^3. Fifty wells are therefore required to supply water to 1 M inhabitants, which, as stated above, require 100 Mm^3/y or an installed supply capacity of 4 m^3/s. The wellfield model can fit in a large city with a high population density or in its close surroundings. If the density is 10 000 hab/km^2, 1 M people require 100 km^2. If there are 50 wells in this surface, there will be 2 km^2 per well, and a separation of 1 400 m between wells, higher than the minimum distance established.

The cost of a well is estimated at 1 000 USD/m, including the pumping equipment. Linear cost amortization in 10 years means 0.015 USD/m^3. The energy cost, assuming 0.10 USD/kWh, is 0.09 USD/m^3. The total cost at the wellhead is 0.105 USD/m^3. Considering 0.015 USD/m^3 for the amortization of the minimum collection infrastructure, that is, pipes leading to tanks, we have a total cost of groundwater of 0.12 USD/m^3. This figure can easily be duplicated, as the real wells in wellfields are not optimal, as we have assumed. We can therefore assume a minimum cost of groundwater of 0.24 USD/m^3.

If the city, as assumed, is overdrafting its aquifer, other costs should be considered, as overdrafting has a number of costly consequences, as mentioned above: land subsidence, saline intrusion in coastal aquifers, loss of infrastructure due to water level drawdown, water quality deterioration and necessary relocation of the withdrawing infrastructure, and environmental deterioration. All these costs are difficult to evaluate. We will try to evaluate the subsidence cost, to have it as a reference for the environmental and infrastructure costs: if we assume a minimum infrastructure construction cost in a city of 1000 USD/m^2, and a subsidence of 0.1 m/y, the city infrastructure will have to be replaced in 100 years, after which 10 m of subsidence will have accumulated. If we assume now that this subsidence and the need to replace infrastructure happens in 10% of the city area, we have a cost of 1 USD/m^2/y. If δ = 5 000 hab/km^2, one person requires 200 m^2 of city area, and 100 m^3/y, or 0.5 m^3/m^2/y. The subsidence cost of every cubic meter of withdrawn groundwater will be 2 USD/m^3, higher than any other water cost. A similar cost could be calculated for saline intrusion, which can lead to total aquifer loss, or for the general environmental deterioration.

6. AQUEDUCT MODEL

Considering the above conclusions, we must now compare the costs of locally supplied and imported water. Using a model developed by the authors, using the present construction, large steel pipe fabrication and installation costs, plus power and energy costs evaluated for 10 years at a 10% interest rate, the costs for a buried aqueduct built with welded steel pipe can be obtained, for flows of 1m^3/s and 4 m^3/s, in USD/m^3, for different lengths and height differences between water levels at the source and at the destination, as follows (Autrique and Rodal, 2019):

Table 1. Unit costs, for water conveyed by aqueducts, in USD/m^3, for different distances (aqueduct lengths) and water level elevation differences between source and destination, and for flows of 1 and 4 m^3/s.

km \ m	0		100		200		300	
	1m^3/s	4m^3/s	1m^3/s	4m^3/s	1m^3/s	4m^3/s	1m^3/s	4m^3/s
10	0.037	0.030	0.093	0.085	0.148	0.141	0.205	0.197
25	0.091	0.072	0.146	0.128	0.202	0.183	0.262	0.242
50	0.181	0.143	0.236	0.199	0.291	0.254	0.356	0.316
75	0.270	0.214	0.325	0.269	0.381	0.325	0.450	0.391
100	0.359	0.285	0.415	0.340	0.470	0.396	0.544	0.465

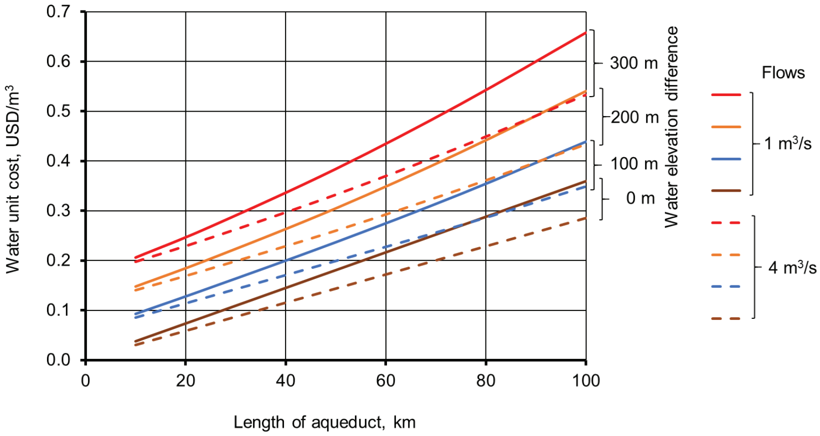

Figure 3. Unit costs, for water conveyed by aqueducts, in USD/m^3, for different distances (aqueduct lengths) and water level elevation differences between source and destination, and for flows of 1 and 4 m^3/s.

We can calculate a reference unit cost, for a 100 km aqueduct, with a 1000 m height difference and a flow of 1 m^3/s, with three stages, each one 33.3 km long and with 333 m in height difference. The total cost will be three times 0.333 USD/m^3, or 1 USD/m^3. If the water conveyed by the aqueduct is surface water, the cost of the storage dam should be added. From a recent project, the dam cost is around 0.50 USD/m^3. We will consider 1 USD/m^3 for the dam cost, as the available sites for new dams might not be optimum. We reach then a total reference cost of 2 USD/m^3 for imported surface water.
This cost should be compared with the calculated reference cost of local groundwater, 0.24 USD/m^3. However, if we add the estimated cost of the different environmental and infrastructure consequences of aquifer overdrafting, 2 USD/m^3, we will reach a cost equivalent to the import cost of surface water from watersheds distant 100 km from the city to be served and 1 000 m below the city elevation.

7. EXAMPLES

Considering the above costs and discussion, we present the cases of three Mexican cities: Mexico City, Monterrey, and San Luis Potosí. All three cities lie in the Mexican Central High Plateau, between two mountain ranges which run parallel to the Pacific and Atlantic coasts. In the central high plateau, where a large proportion of the Mexican population lives, precipitation is scarce, and most aquifers are overdrafted. The principal characteristics, data and variables for each city are shown in Table 2. Aquifer data were obtained from the Mexican National Water Commission (CNA, 2020) and from Cruickshank et al (2005) and worked out by the authors. Demands and corresponding recharges from agriculture were not considered, leaving only the urban and industrial water demands.

Table 2. Water supply and water supply related variables for the three Mexican cities studied as examples.

Concept / **City**	**Mexico City**	**Monterrey**	**San Luis Potosi**
Population, [M hab]	20.23	4.16	1.12
City area, [km^2]	2072	894	212
Density, δ [hab/km^2]	9800	4600	5300
Precipitation, *P* [mm/y]	686	589	403
Demand, *d* [m^3/hab/y]	110.7	98.3	113.4
Total Demand, *TD* [Mm^3/y]	2240	409	127
Recharge area, [km^2]	6105	2100	418
Vertical recharge, *VR* [Mm^3/y]	311	129	40
Horizontal and Induced recharges, [Mm^3/y]	777	62	24
Total recharge, *TR* [Mm^3/y]	1110	191	64
Aquifer area, [km^2]	6105	2100	418
Aquifer thickness, [m]	188	200	240
Water table depth, [m]	86	20	120
Aquifer volume, [Mm^3]	30400	420000	3000
Aquifer storage coefficient, *S*	0.053	0.013	0.060
Drawdown, [m/y]	1.40	0.10	2.00
Groundwater Withdrawal, *GWW* [Mm^3/y]	1530	200	99
Deficit, *Def* [Mm^3/y]	420	9	35
Aquifer life * [y]	36	152	43
Recharge area / City area	2.95	2.35	1.97
Vertical recharge coefficient	0.074	0.104	0.237
Total recharge coefficient	0.265	0.154	0.380
Local groundwater [Mm^3/y]	1530	200	99
Local surface water [Mm^3/y]	40	0	8
Total Local water [Mm^3/y]	1570	200	107
Imported groundwater [Mm^3/y]	170	109	0
Imported surface water [Mm^3/y]	500	209	20
Total Imported water [Mm^3/y]	670	318	20
Total supply, groundwater [Mm^3/y]	1700	200	99
Total supply, surface water [Mm^3/y]	540	209	28
Total supply [Mm^3/y]	2240	409	127
TD / TR	2.01	2.14	1.98
GWW / TR	1.38	1.05	1.55
GWW / TD	0.68	0.49	0.78
Def / TR	0.38	0.05	0.55
Def / GWW	0.28	0.05	0.35
Def / TD	0.19	0.02	0.28
Supply from local water, [%]	70	49	84
Supply from surface water, [%]	24	51	22

* Aquifer life = 0.5 (Aquifer volume) ***S*** / (2 ***Def***), where 0.5 is a volume shape factor and 2 is a safety factor.

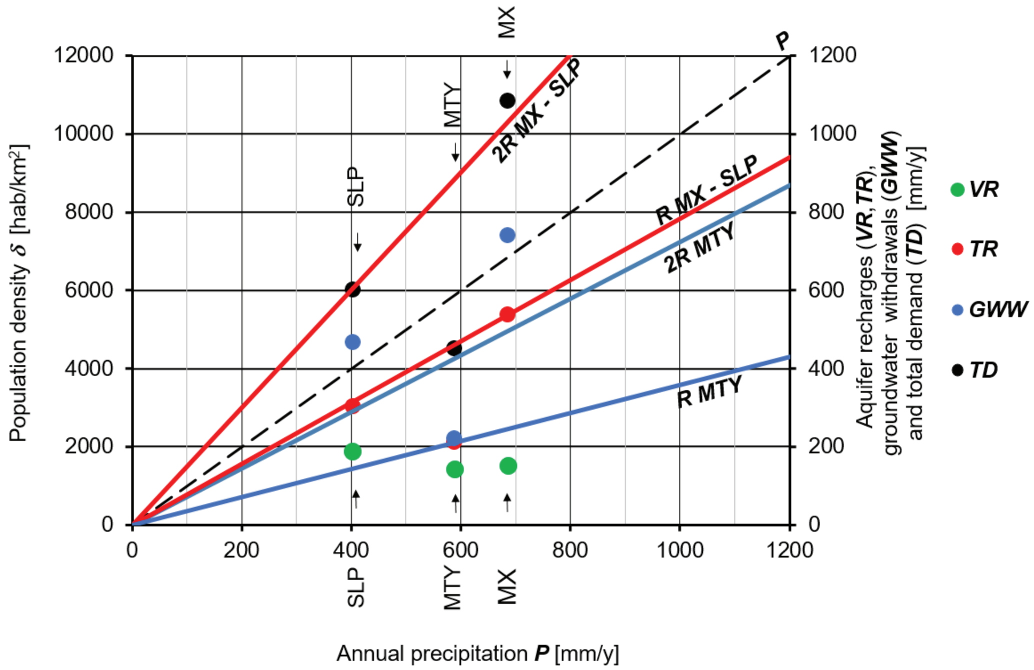

Figure 4. Population densities δ [hab/km^2] versus annual precipitation ***P*** [mm/y] for three Mexican cities, showing vertical and total aquifer recharges (***VR*** and ***TR***), groundwater withdrawals (***GWW***), and total city demand (***TD***). Groundwater withdrawals (***GWW***) at or below an ***R*** straight line (case of Monterrey) correspond with stable aquifers. Groundwater withdrawals (***GWW***) between the ***R*** and ***2R*** lines (cases of Mexico City and San Luis Potosí) correspond with overdrafted aquifers.

Mexico City, 2 200 m in elevation above sea level, lies in a closed basin, and was built in the land occupied in the past by a large lake, now dried up. Surrounded by mountains, it had in the past centuries flooding problems due to excess stormwater, aggravated by land subsidence. Excess stormwater and wastewater are now evacuated through several large deep tunnels. Mexico City water supply history has evolved classically: initially withdrawing groundwater from shallow wells in the second half of the XIX century, followed by aquifer extensive withdrawal through deep wells in the 1930s, aquifer overdrafting in the 1950-60s, and finally with imported groundwater, in the late 1950s. Infrastructure for new groundwater withdrawals, from three aquifers in the city surroundings, was built in the early 1970s, and a 127 km long aqueduct to import surface water, designed for 19 m^3/s, was finally built in the early 1980s. Groundwater withdrawals, combined with loads from city infrastructure and buildings, created land subsidence problems, as early as the 1930s, as the city lies on highly compressible clay layers. The overdraft of the four city aquifers shown in Figure 5, has not ceased (CNA, 2020; Cruickshank et al, 2005; Aguilar et al, 2015). The vertical aquifer recharge comes essentially from drainage of an overlying highly compressible clay aquitard, having caused 10 m of land subsidence in the central areas of the city, and recently in the southeast areas.

Monterrey, 540 m in elevation above sea level, is a 4 M inhabitants industrial city, has satisfied the water demand of its growing population preserving its four aquifers (CNA, 2020), shown in Figure 6, and importing water since the 1980s. Local surface water supply from nearby sources started in 1950, with major aqueducts added in the early 1980s (Linares Aqueduct, 5 m^3/s, 102 km) and 1990s (El Cuchillo Aqueduct, 5 m^3/s, 132 km). The city's permanent growth will require a new aqueduct in the near future, if the local aquifers' withdrawal sustainability policy is maintained.

San Luis Potosí, 1 800 m in elevation above sea level, a former agricultural and commercial small city, is now a major steel and automotive industrial center. Its population, at present 1 M inhabitants, is growing rapidly. The city is in a closed basin. Former rivers have been dried up by groundwater withdrawal and water table drawdown. Its overdrafted aquifer (CNA, 2020), shown in Figure 7, has been since 2015 supported by a 132 km long aqueduct (El Realito Aqueduct) conveying 1 m^3/s, but the overdraft continues, as the new imported water has supported the population growth.

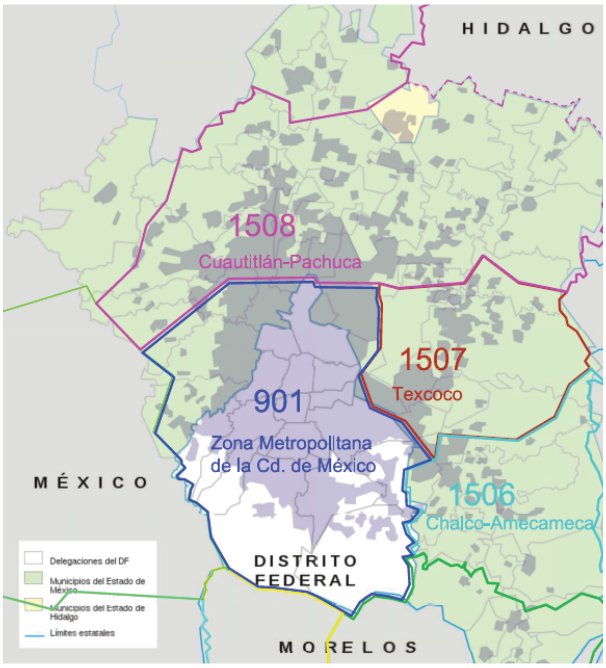

Figure 5. Mexico City (MX) and its aquifers.

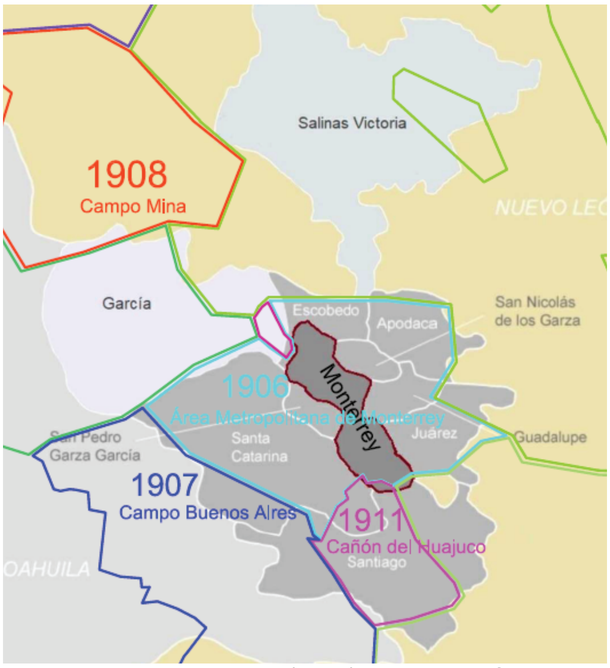

Figure 6. Monterrey (MTY) and its aquifers.

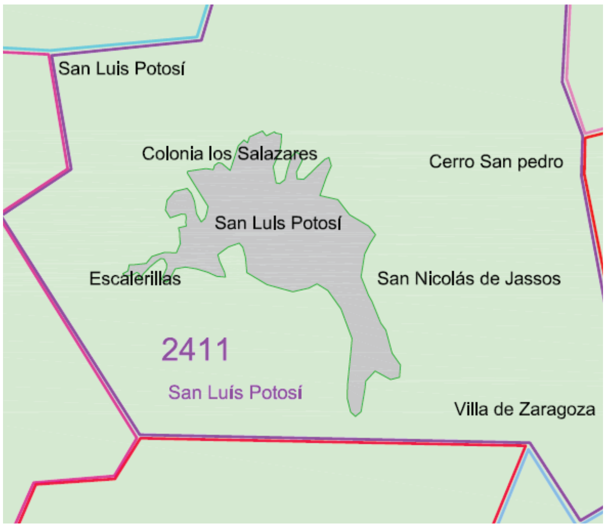

Figure 7. San Luis Potosí (SLP), city and aquifer.

The situation of the three cities regarding groundwater withdrawals sustainability is shown in Figure 4, in which the cities are labeled as MX (Mexico City), MTY (Monterrey) and SLP (San Luis Potosí). In this figure, as in the previous figures, the cities' densities and their real demands are represented versus their precipitations. For each city, along the vertical straight line corresponding to its precipitation, we show the ordinates, represented by large colored dots, relative to the city areas, in mm, of the aquifer vertical and total recharges (***VR*** and ***TR***), the groundwater withdrawals (***GWW***), and the total demand (***TD***). The difference ***GWW*** minus ***TR*** represents the groundwater deficit or overdraft, and the difference ***TD*** minus ***GWW*** represents the city's water deficit (not including the groundwater overdraft), to be covered with local surface water plus imported water. Ideally, to preserve the aquifer, the aquifer deficit (***GWW*** minus ***TR***) should be replaced by imported water from a new source.

We can distinguish in the figure regions with aquifer sustainability and aquifer overdraft. The region limited by the two blue straight lines "***R MTY***" and "***2R MTY***", correspond to cities with the recharge conditions (***TR*** / ***P*** ratios) of Monterrey. Its ***GWW***, groundwater withdrawal, is only slightly greater than its aquifers total recharge, ***TR***. The Monterrey aquifers are in a sustainable condition. Their expected life is long, around 150 years.

The region limited by the two red straight lines "***R MX-SLP***" and "***2R MX-SLP***", correspond to cities with the recharge conditions of Mexico City and San Luis Potosí, whose recharge lines coincide, as their ratios ***TR*** / ***P***

also coincide. It is clear from the figure that both cities are overdrafting their aquifers, as their ***GWW*** is half way between the "***R***" and "***2R***" lines. From Table 2, we can see that their aquifer lives are short, around 40 years.
To preserve their aquifers, Mexico City and San Luis Potosí should ideally reduce their aquifer deficits to zero, importing their deficit or overdraft water volumes. At present, Mexico City and San Luis Potosi import 30% and 16% of their water requirements, respectively, and their total surface water supplies, local plus imported, are 24% and 22%. To reduce their groundwater deficits to zero, Mexico City and San Luis Potosi should increase their water imports to 49% and 44%, respectively, reaching, as will be seen below, water import percentages equivalent to the city of Monterrey (51%).
The city of Monterrey, on the contrary, has been able to extract only the sustainable yield from its aquifers, but depends largely on imported surface water (51%) from two distant water basins.

8. CONCLUSIONS

1. It is clear that for the typical densities of large cities, from 5 000 to 10 000 hab/km2, the local aquifers are not able to deliver the required water supplies. The consequences are aquifer overdrafting and/or water imports from other watersheds.
2. Aquifer overdrafting is not a sustainable condition, and has several disadvantageous effects, harmful to the environment and to the cities' infrastructure: land subsidence, saline intrusion in coastal aquifers, loss of infrastructure due to water level drawdown, water quality deterioration and necessary relocation of the withdrawing infrastructure, aquifer depletion, and general environmental deterioration.
3. The delayed consciousness about aquifer overdrafting and the apparent cost differences between local and imported water have led to permanent excess withdrawals from the local aquifers, with permanent deficits, water level drawdowns, and sustainability of the cities at risk.
4. It was shown however that, if we add an estimated cost for the different environmental and infrastructure consequences of aquifer overdrafting, we will reach a reference cost equivalent to the import cost of surface water from watersheds distant 100 km from the city to be served and 1 000 m below its elevation. This reference cost for local groundwater or imported surface water is around 2 USD/m^3.
5. The conclusion of necessary imports of surface water from neighboring basins is technically very clear and simple. It is however socially and economically very complex. It can give rise to water conflicts and should be handled taking into consideration present and future agricultural and urban water requirements, promoting its efficient use, its equitable access, and preserving its sources, in quantity and quality. These conflicts should be dealt in a multidisciplinary way, from its technical and economic feasibilities to its social aspects, with the participation of all social and institutional actors, to reach long term agreements.
6. Statements from the South African Water Act (RSA, 1998) could be a useful guide for water conflicts: 1, Water is a resource common to all, subject to national control; 2, There shall be no ownership of water but only the right to use it; 3, Water required to meet people's domestic needs and the needs for the environment should be reserved; 4, The location of the water resource in relation to land should not confer preferential rights to usage.
7. Considering the above, a number of measures can be recommended:
8. Establish the present total aquifer recharge as a limit to the groundwater withdrawal to supply large cities, to allow for the gradual recovery of the aquifer. The volume of water extraction matching the recharge can be considered an "ecological withdrawal". Being an environment preservation volume, it would be similar to the "ecological flow" established for rivers downstream of dams.
9. Reserve the groundwater in basins close to cities for the water supply of the rural or small towns population and for small scale agriculture. It has been observed, from Spain to India (Llamas and Custodio, 2003), that groundwater irrigation is significantly more productive than surface water irrigation, due to the permanent availability of groundwater and its easier administration at the farm level.
10. Use preferably superficial water sources to supply the large cities, as their associated dams, aqueducts and large flows can be centrally controlled. Water from superficial sources is considered more expensive, and normally comes from neighboring or far basins. Large cities have an important proportion of the National Gross Product, and can pay for this "expensive" water.
11. The large cities could bear other "social costs", as for example "payment for environmental services" to communities for granting and preserving the surface water, or for using treated wastewater in exchange for surface water.
12. Educate and legislate to preserve and not overdraft aquifers and reserve their recharge areas. Aquifers can be kept as emergency sources for large cities during dry years, in which the surface water is scarce. They would contribute to the resilience of the cities' water supply structure.
13. Update legislations, which are not usually conceived with groundwater and aquifers sustainability in mind.

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