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The changing climate and domestic water consumption in Mexican cities

El clima cambiante y los consumos domésticos de agua en ciudades de México

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Abstract. Supplying enough drinking water for household consumption in Mexican cities such as Guadalajara, Monterrey, or Mexico City is a major challenge. With an urban population that has grown significantly since the second half of the 20th century, water demands are increasing faster than supply. Urban water consumption is determined by socioeconomic factors such as population size, income level, or hydraulic infrastructure, but also by climatic conditions. Access to water resources in Mexican cities is unequal since wealthier people tend to consume more. Climate is also important in water consumption since the maximum temperature regulates water demand, and its effect is detectable in the warmest periods of the year, before the start of the summer rainy season. The above suggests that the formation of urban heat islands (UHIs) could increase water demand and consumption. However, in Mexico, the per-capita water consumption in large cities has tended to decrease in recent decades because the water supply has not increased at the rate of the number of users. In this way, the main climatic regulator of water consumption is meteorological drought, which results in low water availability and, frequently, socioeconomic drought. Therefore, better urban water management should include strategies for using climate information, where urban supply is prioritized.

Keywords: domestic water consumption, peak temperature, urban heat island, urban water supply, surface water.

Resumen. La provisión de suficiente agua potable para consumo doméstico en urbes mexicanas como Guadalajara, Monterrey o la Ciudad de México es un gran reto. Con una población que ha crecido significativamente desde la segunda mitad del siglo XX, las demandas de agua aumentan más rápido que la oferta. Los consumos urbanos de este recurso están determinados por factores socioeconómicos como la población, el nivel de ingresos, o la infraestructura hidráulica, pero también por condiciones climáticas. El acceso al agua en ciudades de México es desigual, pues tiende a consumir más quien más recursos económicos tiene. El clima también es importante en el consumo de agua, pues el factor temperatura máxima es un modulador de la demanda y su efecto es detectable en los periodos más cálidos del año, previo al inicio de la temporada de lluvias de verano. Lo anterior hace pensar que la formación de islas de calor urbanas (UHI) pudiera incrementar la demanda y los consumos de agua. Sin embargo, en grandes ciudades de México, estos consumos per cápita tienden a disminuir en décadas recientes porque la provisión de este recurso

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no aumenta al ritmo con que crece el número de usuarios. Así, el principal modulador climático de los consumos de agua es la sequía meteorológica, pues su ocurrencia da como resultado una baja disponibilidad de agua y, con frecuencia, sequía socioeconómica. Por lo tanto, una mejor gestión hídrica urbana debe incluir estrategias de uso de información climática, en donde se priorice la provisión a las ciudades.

Palabras clave: consumo doméstico de agua, temperatura máxima, isla de calor urbana, abastecimiento de agua urbana, agua superficial.

INTRODUCTION

Access to drinking water is one of the major challenges facing urban areas, mainly due to the accelerated growth of the urban population, which already accounts for the largest percentage of people worldwide (United Nations, 2012; World Bank, 2023). It is becoming increasingly difficult to meet urban water demands, not only in quantity but also in quality, especially in the context of climate change (UNESCO, 2020; He *et al.*, 2021). Access to water in large cities is limited, not only in areas where it is scarce due to an arid or semiarid climate (Eakin *et al.*, 2007), but even in large cities where rainfall is relatively abundant (e.g., Carvalho de Melo *et al.*, 2021). The problem of supplying water to cities is complex and depends on various socioeconomic and climatic factors, so resource management schemes should consider a growing population and the effects of a changing climate (e.g., Soto, 2012).

Water supply issues in cities will grow as the urbanization process proceeds unless there are changes in water management and demand (Koop and Van Leeuwen, 2017). For example, the World Meteorological Organization (WMO) recommends a daily water consumption per capita of around 100 liters to meet their basic needs. However, consumption per capita in Mexican cities is almost always above this volume (Torregrosa *et al.*, 2015; Medina-Rivas *et al.*, 2022). In Mexico's high-income areas of large cities, water consumption can exceed 300 L/inhabitant/day, in contrast to low consumption in poor sectors, where drinking water supply is deficient, and people frequently lack even the recommended minimum. As cities exceed international recommendations for water consumption, water resource managers continue making efforts to meet the growing demands rather than reduce consumption (Morales Novelo & Rodríguez Tapia, 2007; Aguilar-Barajas & Ramírez, 2021). This approach has led to a deficit that has been increasing over several decades and which has frequently led to socioeconomic drought conditions, even in the absence of a meteorological drought (Sisto *et al.*, 2016; Magaña, 2016).

Water consumption patterns in cities are largely dependent on socioeconomic factors, although they are also influenced by climatic conditions (Soto *et al.*, 2012). Periods of meteorological drought pose the greatest threat of socioeconomic drought. Despite this, water management planning based on climate forecasts is almost non-existent, and, in the best of cases, information on negative rainfall anomalies is only used to justify rationing measures implemented when water availability is low (Magaña, 2016). In this way, a risk problem involving water management can be explained only under a naturalistic approach, where the issue is the lack of sufficient rainfall.

In some places, the maximum temperature has been found to regulate water consumption on scales from days to months and even years (Chang *et al.*, 2014). Temperature rises in the hot dry season induce increases in water consumption. Therefore, one of the current concerns in urban areas is how to meet water demands under climate change, considering that some climate scenarios point to drier and hotter conditions (IPCC, 2021; Torregrosa *et al.*, 2015). The hydrological cycle and water availability scenarios are highly uncertain (Caretta *et al.*, 2022), so there are still few adaptation projects in the face of this threat. In the case of water for Mexican cities, these projects are only implemented in response to the emergency, seeking new sources of supply. It is still uncommon for water management measures in urban areas to consider that the changing climate affects water demand, such as the urban heat island (UHI) effect.

Although climate change due to UHIs has been widely documented (e.g., Oke *et al.*, 2017), its effects on water consumption are less well-known (e.g., Guhathakurta & Gober, 2007; Scott *et al.*, 2009). In Mexico, the work of Jáuregui (1973, 1997, 2004) clearly showed the existence of UHIs in the country's main cities, with temperature increases of 2 °C to 3 °C in urban areas over periods of 50 years or less. In Mexico, the local climate change process began after the 1960s or 1970s due to an accelerated urbanization process. For example, the Valley of Mexico Metropolitan Zone (VMMZ) increased its size 5.4 times in 50 years, leading to a mean temperature increase of almost 3 °C. The size of the Guadalajara Metropolitan Area (AMG) or the Monterrey Metropolitan Area (MMZ) is 3 to 5 times what it was half a century ago, leading to temperature increases of close to 3 ºC (Jáuregui *et al.*, 1992; Jáuregui, 2009). Mexico's large cities have even experienced changes in their hydrological cycles, with more intense and frequent rainfall or heat events (Jáuregui & Romales, 1996; López *et al.*, 2022). Warmer conditions in urban areas can increase water consumption and greater water stress. However, determining the extent to which a UHI affects water consumption is not an easy task, as socioeconomic factors seem to have a greater weight in short- and long-term variations in water consumption than climate factors alone. In Mexico, water availability is lower in warm periods, so meeting the demand becomes difficult (Vargas & Magaña, 2020). Meteorological droughts (Méndez & Magaña, 2010), either short or prolonged, further complicate water management in cities. In dry months or periods of warm and dry meteorological drought, the water supply to cities becomes critical. If the UHI causes a temperature rise, the water demand is expected to increase. Therefore, the main objective of this article is to analyze the impact of a changing climate, such as the one induced by a UHI, on household water consumption, particularly regarding the effect of meteorological droughts. Therefore, this analysis considers the natural variability of the climate in terms of months to years and decades. A better understanding of the relationship between climate and water demands will allow us to estimate the importance of planning water resource management using climate information and may even lead to recognizing UHI mitigation strategies. Mexico City (CDMX, in Spanish), the Guadalajara Metropolitan Zone (GMZ), and the Monterrey Metropolitan Zone (MMZ) will be considered as case studies.

DATA AND METHODOLOGY

Analyzing urban water consumption for the main Mexican cities is challenging because the information is dispersed, with reports at various spatial and temporal scales. Water data is mainly available from the National Water Commission (CONAGUA), as part of the National Water Information System (https://app.conagua.gob.mx/sistemasdeagua/). Some water availability and consumption figures can be found in metropolitan water operation systems, such as Mexico City (SACMEX) (SACMEX, 2021), the Guadalajara Metropolitan Zone (SIAPA) (CONAGUA, 2015; López *et al.*, 2022), and the Monterrey Water and Drainage Services (SADM) (SADM, 2005-2023), which include information on consumption, users, and water volumes delivered to metropolitan areas.

In this study, the evolution of water consumption is compared with data on the population growth of metropolitan areas and municipal living standards. To this end, we used information from the population censuses of the National Institute of Statistics, Geography, and Informatics (INEGI, 2005-2020 and INEGI, 2020) and information on mesh-block population density (HDX Mexico, 2018).

The climatic aspects of the urban areas are analyzed with meteorological information from CONAGUA, specifically from the observatories of Mexico City (Tacubaya, CTMDF), Guadalajara, Jalisco (GUCJL), and Monterrey, Nuevo León (OBSNL) (CONAGUA 2023a). The quarterly water demand for the MMZ was estimated based on data reported by Aguilar and Monforte (2018), who calculated the percentage of physical losses from 2000 to 2015.

The way in which UHIs have intensified was established using time series and histograms of daily maximum temperature for periods of twenty years. These data are supplemented with information on the conditions of the main water sources that supply the metropolitan areas of Mexico City (Cutzamala system), Guadalajara (Lake Chapala), and Monterrey (El Cuchillo dam) (CONAGUA, 2023b), as well as estimates of groundwater variations provided by the NASA Gravity Recovery and Climate Experiment system (GRACE) (Landerer, 2021). Records from the GRACE and GRACE-FO satellites have estimated the total monthly surface and groundwater depth from 2002 to date, with a spatial resolution of approximately 150,000 km^2.

RESULTS AND DISCUSSION

a) Urban Water Supply and Consumption

The degree of water pressure, i.e., the ratio between the concessioned water volume and the mean annual natural availability, reflects the evolution of the severity of the water crisis in Mexico (e.g., CONAGUA, 2019). In states such as Chiapas, Tabasco, and Oaxaca, where rainfall is abundant, the degree of water pressure in 2017 (expressed as percentages), for example, was low, of less than 3 % (Figure 1). In contrast, in most semi-arid regions of northern Mexico, the degree of water pressure is greater than 45 %. In urban areas, such as Mexico City and its suburbs, where the population exceeds twenty million people, the water pressure is extremely high, above 170 %, which has led to overexploitation of surface and underground supply sources. For this reason, Mexico City is experiencing a severe water crisis as the demand has increased to unsustainable levels (Ortega Font, 2009).

Despite relatively abundant rainfall in the Valley of Mexico (>700 mm/year), the number of users is so high that distant water sources, such as the Cutzamala System, are used to supply the western area of Mexico City. In the Valley of Mexico's Hydrological Administrative Region, the per-capita water availability increased from around 188 m^3/inh/year in 2004 (Breña Pujol & Breña Naranjo,

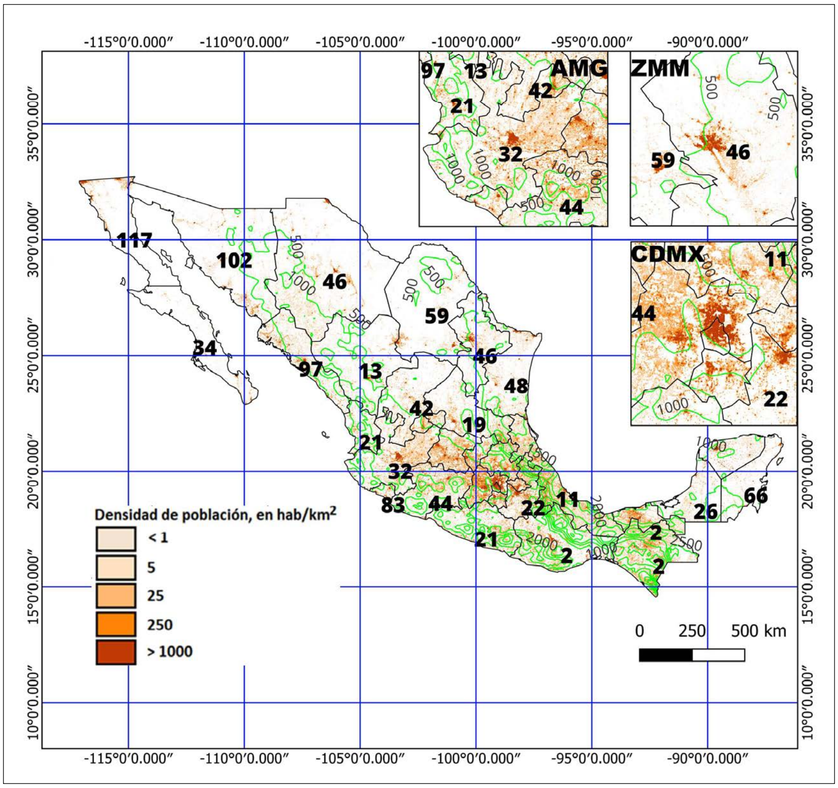


Figure 1. Population density (orange scale), annual precipitation (mm) (green lines), and degree of water pressure by state (%) (bold number) in 2017.

2007), when the population was around 8,700,000 inhabitants in Mexico City, to 73 m^3/inh/year in 2009, when the population was just over 9 million people, placing this city in an extreme scarcity scenario. Something similar occurs in the MMZ, where rainfall is generally scarce (<400 mm/year), except when a tropical cyclone enters (Magaña *et al.*, 2021). The accelerated population growth in the area has exceeded the water supply (Gobierno de Nuevo León, 2023), and, therefore, distant water sources such as the El Cuchillo Dam have been required. Lower water levels in the dam in recent years of meteorological drought have meant that supply to users is decreasing, leading to lower consumption. In Guadalajara, Lake Chapala has had to be used for decades to meet the water demand (von Bertrab, 2003; IMEPLAN, 2022). Water policy and a growing consumption rate related to population growth have challenged water supply for several years (Gleason & Flores, 2021).

In the three metropolitan areas referred to, the number of water users has grown faster than the population (Figure 2). The case of the MMZ stands out, where the increase in the number of water outlets in the MMZ was almost 105 % in the period 2005–2022. Between 2014 and 2018 alone, the number of water outlets in the MMZ went from 1.1 to 1.6 million, a nearly 45 % increase in less than five years. Mexico City and the GMZ had smaller increases in the number of outlets in the same period, in the order of 16 % and 37 %, respectively. Thus, the recent annual growth rates in the number of users are around 1 % in Mexico City, 2 % in the GMZ, and 5 % in the MMZ. However, the trends for the mean annual increase in domestic water consumption are 0.6 %, 0.9 %, and 3.5 % for CDMX, GMZ, and MMZ, respectively.

There are various water consumption estimates for the inhabitants of metropolitan areas in Mexico. In the MMZ, in the early 21st century, one inhabitant consumed an average of 180 L/day; however, the current daily water consumption per capita is only 130 L/day. However, metropolitan averages generalize consumption levels and mask the contrasts

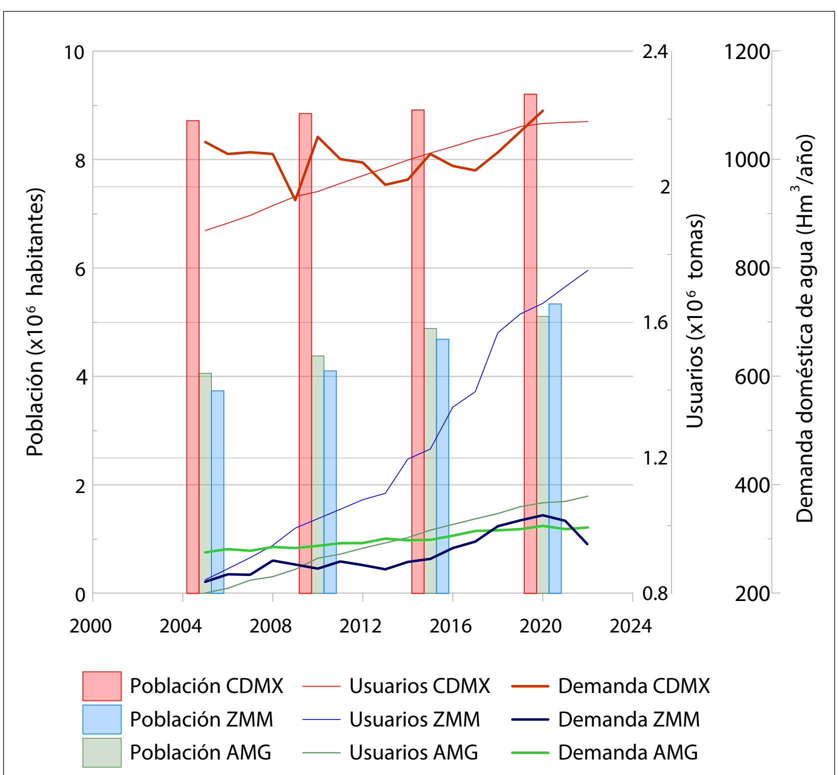


Figure 2. Population, in millions of inhabitants (bar), number of water users in millions of outlets (thin line), and annual mean demand for water for household use (2005–2020) (thick line) for Mexico City (red), the Guadalajara Metropolitan Zone (green), and the Monterrey Metropolitan Zone (blue).

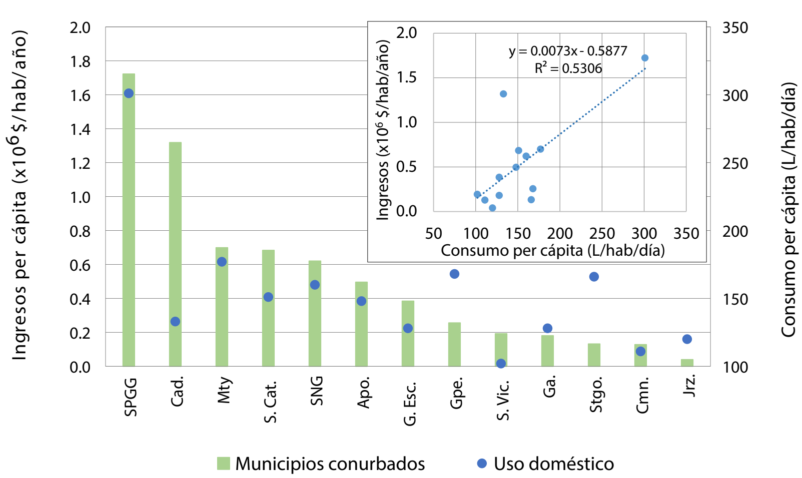
in their spatial distribution, largely driven by the socioeconomic conditions between one area of the city and another. For example, in San Pedro Garza García, the municipality with the highest socioeconomic level in the country, the average consumption per capita is more than 300 L/inh/day, while in municipalities with a lower economic income, water consumption is less than 115 L/inh/day (Figure 3).

In Mexico City, water consumption ranges from more than 200 L/inh/day to less than 100 L/inh/day (Ortega-Font, 2011; Gobierno de la CDMX, 2019). As in the case of the MMZ, the highest consumption in Mexico City occurs in neighborhoods with a high income in the west and parts of the city center, such as the municipalities of Miguel Hidalgo, Azcapotzalco, Benito Juárez, or Cuauhtémoc, with around 200 L/inh/day (Medina-Rivas *et al.*, 2022). In other areas of central or eastern Mexico City, such as the low-income municipalities of Iztapalapa, Tláhuac, and Milpa Alta, consumption is less than 100 L/inh/day (Figure 4). Regions with the highest maximum temperatures would be expected to consume more water, as in other parts of the world (Chang *et al.*, 2014). However, in Mexico City, the maximum temperature has less influence on consumption than the economic factor. Temperature averages above 28 °C in March and April in the east-center of Mexico City, where less water is consumed, contrast with 25 °C in the west, where consumption is higher. The limited access to drinking water in eastern Mexico City in hot weather has adverse impacts on the health of its inhabitants (Vargas & Magaña, 2020).

Mean water consumption can vary significantly from year to year, depending on availability, largely driven by the amount of precipitation received, as well as limited or differentiated access to drinking water. Although water supply has been increasing in the study areas, it has been much lower than the growth rate in the number of users, leading to lower consumption per capita, not because users consume less water but because it reaches household outlets in smaller volumes.

b) Trends in Climate and Water Consumption

Household water consumption tends to increase in warmer regions or in the warm season as people use more water for bathing and cooling (Eakin *et al.*, 2007). In spring and summer, increases in maximum temperatures require more water to maintain



Note: SPGG, San Pedro Garza García; Cad, Cadereyta Jiménez; Mty, Monterrey; S. Cat, Santa Catarina; SNG, San Nicolás de los Garza; Apo, Apodaca; G. Esc, General Escobedo; Gpe, Guadalupe; S. Vic, Salinas Victoria; Ga, García, Stgo, Santiago; Cmn, Carmen; Jrz, Juárez. The box shows a linear fit between water consumption per capita and income in the MMZ. Data Sources: SADM (2022), INEGI (2019).

Figure 3. Water consumption (L/inhabitant/day) in the MMZ at the municipal level and annual income per capita for 2019.

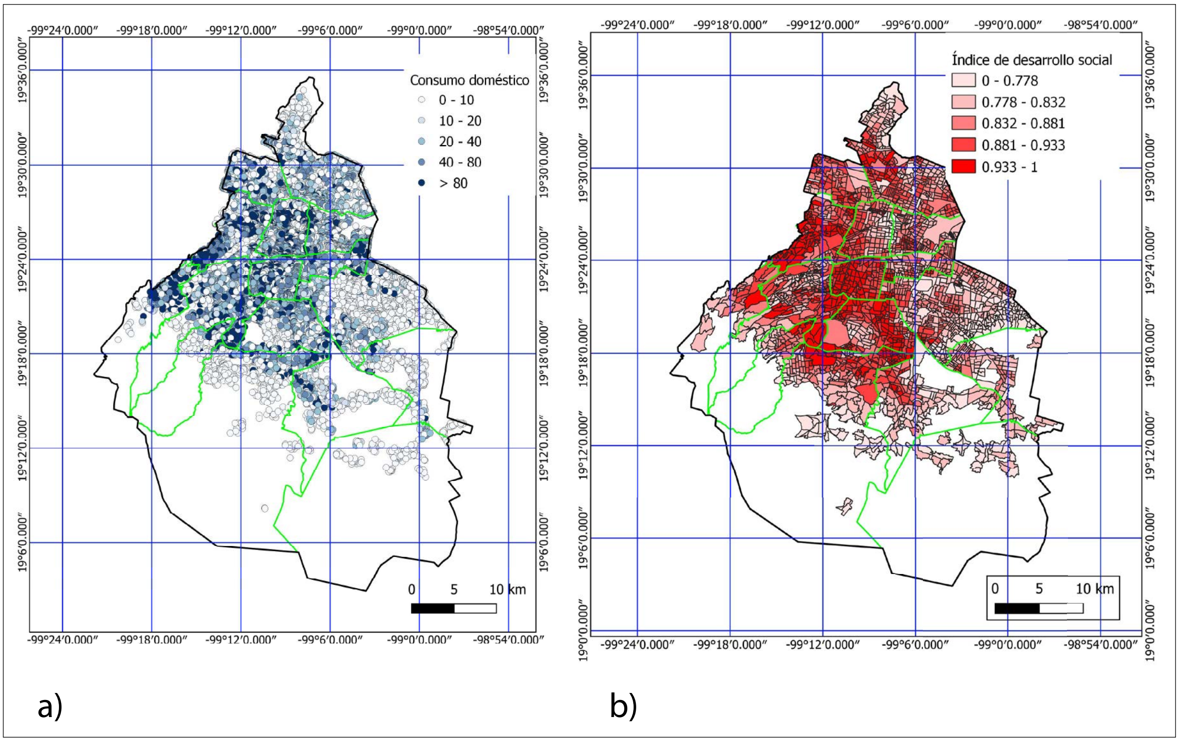


Figure 4. a) Water consumption (m3/neighborhood/day) in the second two-month period of 2019 at the neighborhood level in various municipalities of Mexico City. b) Social Development Index (SDI) by AGEB, related to the socioeconomic level of the population (EVALÚA, 2020), where the SDI is as follows: Very low, from 0 to 0.778; Low, from 0.778 to 0.832; Medium, from 0.832 to 0.881; High, from 0.881 to 0.933; Very high, from 0.933 to 1. c) Mean maximum temperature (°C) in Mexico City in March and April. The blue line indicates the borders of the urbanized region in 2015.

comfort and health levels. The annual cycle of maximum temperature in Guadalajara, Monterrey, and Mexico City shows that the spring-summer is the warmest period. In Guadalajara, for example, the mean monthly maximum temperature in May reaches 34 °C, but in certain years, the monthly average in April can exceed 40 °C (Figure 5). In Monterrey, the mean maximum temperatures between June and August are around 35 °C, but in certain years, average monthly maximum temperatures may be close to 40 °C. In Mexico City, the warmest months are in spring, between March and May, with maximum temperatures around 26 °C, but in the warmest years, the maximum temperature exceeds 30 °C. On some days, maximum temperature values can be higher than 32 °C, and the tendency is for the UHI effect to lead to more frequent heat-wave episodes (Jáuregui, 2009).

The trend in these metropolitan areas is toward a rising temperature, as urban development imposes significant land-use changes that induce a UHI (Jáuregui, 1997; Vargas & Magaña, 2020). Histograms of daily maximum temperature for consecutive 20-year periods between 1960 and 2020 show that urban growth has induced more frequent episodes of maximum temperature above 35 °C in Guadalajara (Figure 6a), above 36 °C in Monterrey (Figure 6b) and above 30 °C in Mexico City (Figure 6c). For the GMZ, the number of episodes with temperatures above 35 °C has almost doubled in three decades, with peaks of almost 40 °C recorded on certain days. In the MMZ, temperatures above 35 °C are frequent, and the warmest episodes can be up to 45 °C, which involves a very high risk to human health (Vargas-Huipe & Rodríguez-Van Gort, 2023). In the case of Mexico City, temperatures of more than 30 °C have

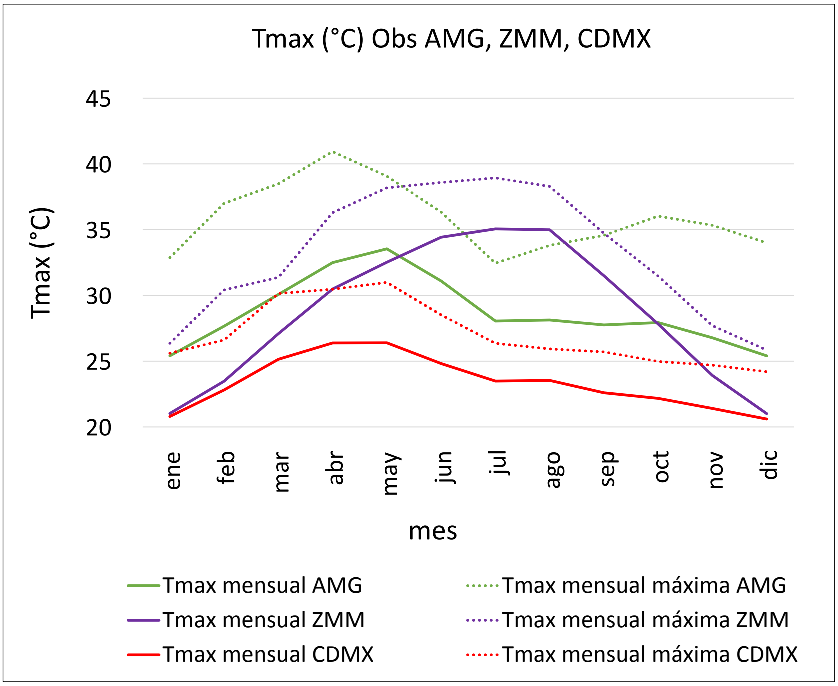


Figure 5. Climatology of the mean monthly maximum temperature (°C) (solid line) and the mean maximum temperature of the warmest months (dotted line) in the GMZ (green), the MMZ (purple), and CDMX (red).

become more frequent, with maxima reaching 34 °C. In all cases, these extremes tend to occur in dry periods, when water for urban consumption is scarcer.

Water consumption in cities increases when the average monthly maximum temperature exceeds 30 °C, which often generates a comfort index considered hazardous (López *et al.*, 2022). In these periods, the sources of supply are generally at minimum levels due to low water levels or even meteorological droughts, which can translate into socioeconomic droughts.

Analyzing the trends in the quarterly maximum temperature allows us to establish the warmest periods as a function of the time of the year. In metropolitan areas, maximum temperatures have risen mainly due to rapid urban expansion. The increases amount to around 2 °C in fifty years and are clearly distinguishable for Monterrey and Guadalajara (Figure 7). In the case of Mexico City, episodes of increase in maximum temperature occurred at the beginning and end of the twentieth century in relation to changes in land use (Vargas & Magaña, 2020). With the formation of the UHI, average temperatures in the second quarter of the year (April-May-June) in the GMZ are frequently above 32 °C (Figure 7a). In Monterrey, in the second quarter (April-May-June), mean maximum temperatures are above 30 °C, and in the third quarter (July-August-September) they reach 35 °C (Fig. 7b). In Mexico City, mean temperatures in the second quarter are only above 27 °C; however, we must bear in mind that the Tacubaya Observatory, used as a reference in the present analysis, is located in western Mexico City in a relatively cooler region, so temperatures in the eastern and central areas may be at least 3 °C higher. reaching 30 °C between March and May (Figures 7c and 4c). In each case, it is not uncommon to experience periods of maximum temperatures above the average quarterly value, particularly during heat waves, as in June 2023.

Records of household water consumption in urban areas show an increase of around 10 % in the warmest quarters of the year. In the MMZ, consumption per capita increases by about 25 L/inh/day (Figure 8a) when the maximum temperature rises between 8 °C and 9 °C from the first to the second or third quarters. In GMZ, consumption increases between 10 L/inh/day and 12 L/inh/day (Figure 8b) when the maximum temperature increases 5 °C to 6 °C between the first and second

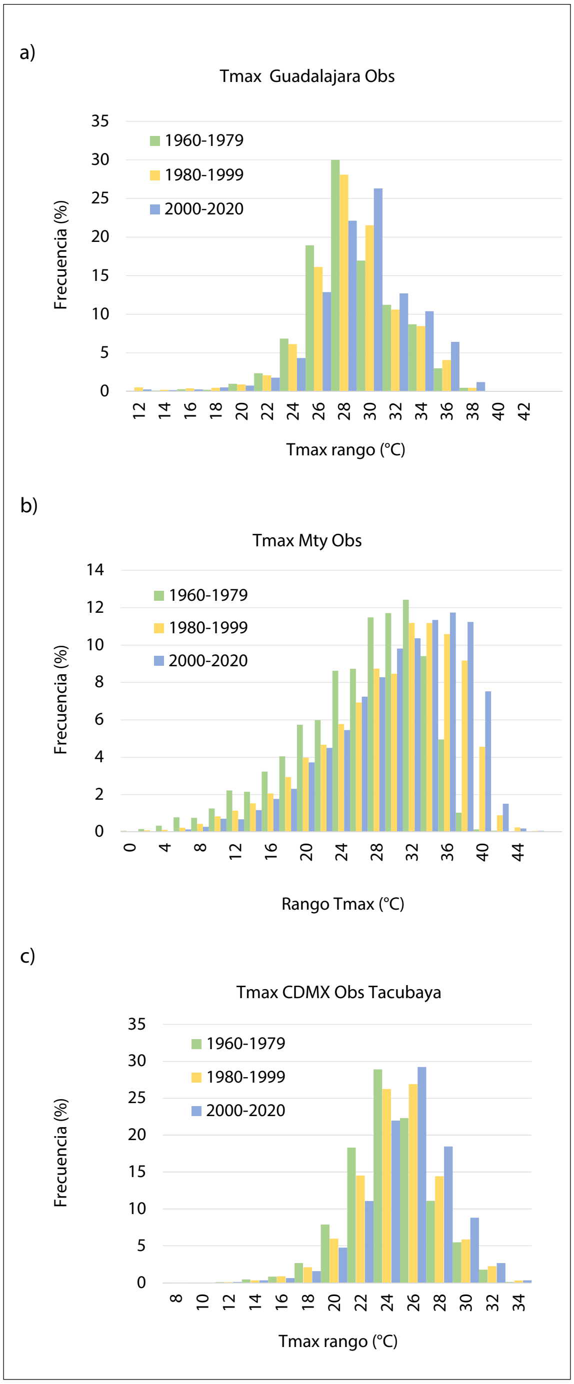


Figure 6. Histograms of maximum daily temperature (°C) in a) GMZ, b) MMZ, and c) CMDX for the periods 1960-1979 (green), 1980–1999 (yellow), and 2000–2020 (blue).

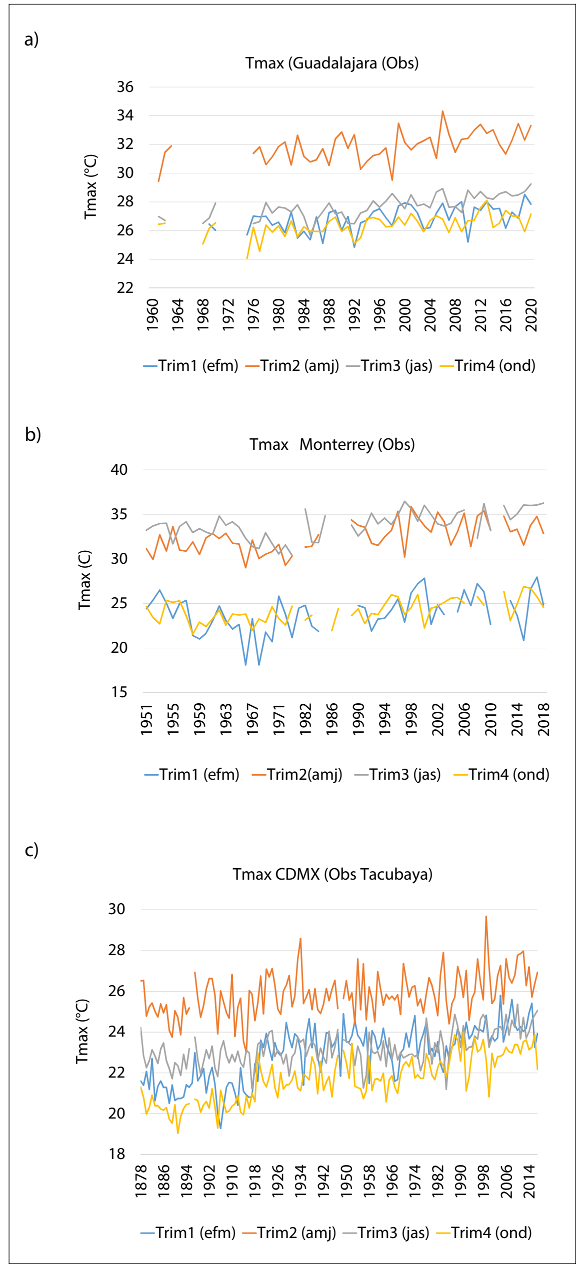


Figure 7. Mean maximum temperatures (°C) by quarter for a) GMZ, b) MMZ, and c) CDMX, obtained with data from the meteorological observatories of Guadalajara, Monterrey, and CDMX (Tacubaya).

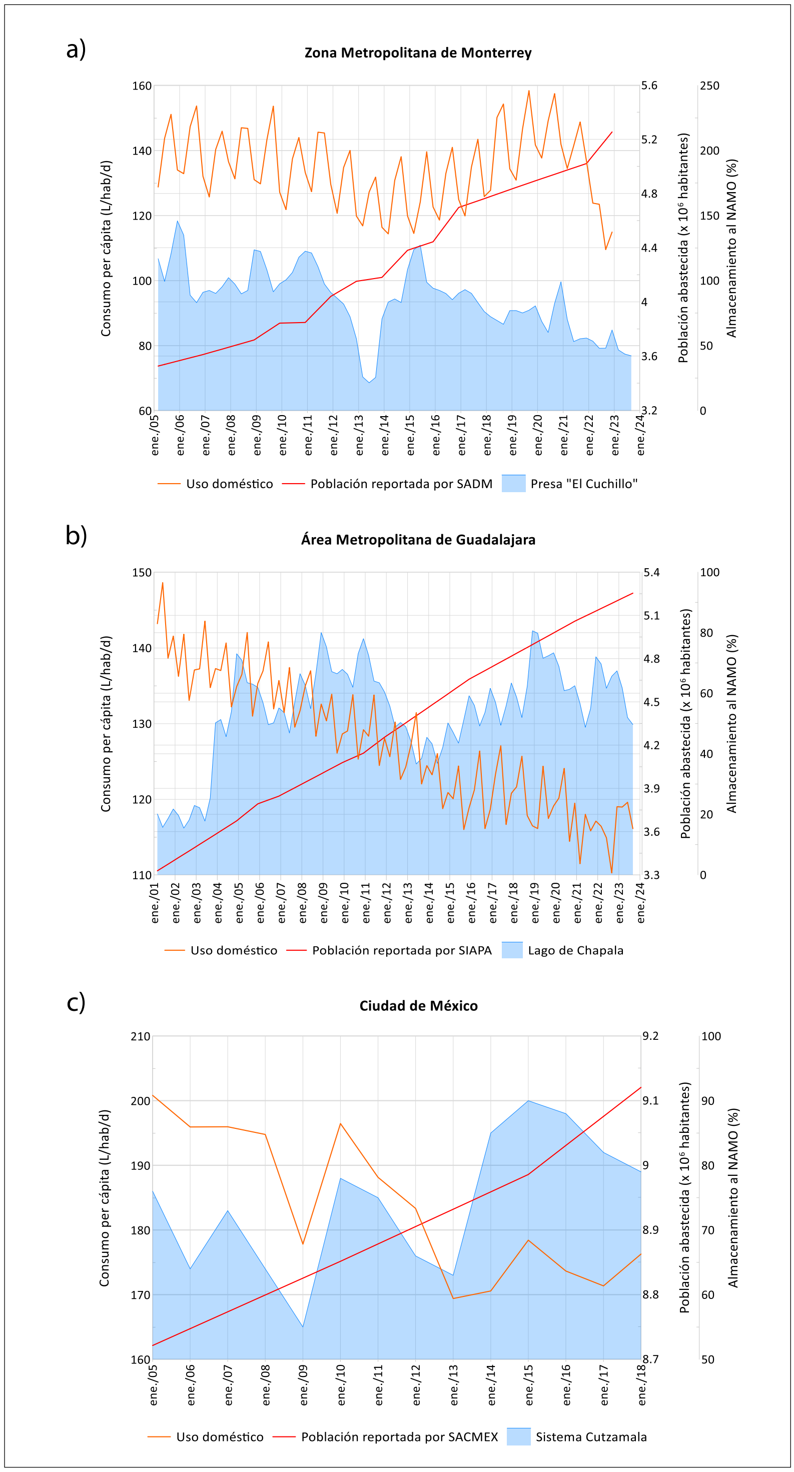


Figure 8. Household consumption (L/inh/day) (orange line), storage at NAMO (%) in the main source of surface water (blue line), and population served by the operating agency (red line): a) MMZ, b) GMZ, and c) CDMX. NAMO corresponds to the ordinary maximum water level.

quarters of the year. Thus, above 30 °C, for every °C increase in temperature, there is an increase in water consumption of around 2 L/inh/day. In Mexico City, the data do not allow a robust quarterly analysis (Figure 8c), but, as discussed below, the increases in consumption between the first and second quarters of the year are in the order of 10 %.

In recent years, household water consumption has shown low-frequency trends or variations (periods of years) related to water availability in the main sources of supply. The 2011–2013 drought in northeastern Mexico led to a 75 % decrease in the water level of the El Cuchillo dam, forcing 15 % reductions in the water volume allocated for household consumption (Figure 8a). The year 2021 also recorded a significant reduction in the water consumption per capita in the MMZ due to a meteorological drought combined with major increases in the number of users. The water storage of the El Cuchillo dam (with a maximum capacity of 159 % relative to the ordinary maximum water level [NAMO, in Spanish]), went from 125 % in 2005 to 40 % in 2023. As a result, the household water consumption was 110 L/inh/day on average, leading to a socioeconomic drought. It is worth mentioning that, since the second half of 2015, the El Cuchillo dam has shown a negative trend in its storage capacity, with reductions of approximately -7.1 % per year; this means that its level has been below 60 % since January 2021. The policy of maintaining the same sources of supply for a rapidly growing population, even under hydrological drought conditions, has resulted in a sustained increase in the dam's water deficit, translating into a socioeconomic drought in the MMZ in 2021.

In the GMZ, the water availability or levels of Lake Chapala have shown variations over periods of several years (Figure 8b), with a recovery of the water level after 2001–2003. However, the signal of very low-frequency variations in rainfall in the area have led to changes in the availability of this source of surface water. These long-term fluctuations are apparently not reflected in changes in per-capita water consumption, which systematically show a decrease related to the continuous increase in the number of users.

In Mexico City, consumption has varied according to water availability from its sources of supply, such as the Cutzamala system (Figure 8c). The trend in Mexico City is towards a lower per capita consumption facing the increasing number of users. Despite the above, the mean per-capita water consumption in Mexico City in recent years (170 L/inh/day) remains among the highest considering urban users in Mexico.

In Mexico City, water consumption is higher (>20 %) in those areas where the resource is available, that is, towards western Mexico City (Fig. 9). In the central-eastern zone, the mean maximum temperature in the warmest period of the year is frequently above 30 °C, yet increases in household water consumption are less than 10 %. One consequence of this situation is that the highest number of acute diarrheal diseases occur in the eastern part of the city due to limited access to drinking water (Vargas & Magaña, 2020).

c) Long-Term Climate Variations and Water Availability

In recent years, the decrease in per-capita consumption for large population sectors has been explained by meteorological drought conditions. Periods of negative rainfall anomalies have a major effect on surface supply sources and even on groundwater conditions. In the MMZ, the decrease in rainfall between 2011 and 2013 led to a minimum in the availability of surface and groundwater (Figure 10a). This situation apparently reoccurred in recent years (2018–2023), with significant negative anomalies in the water levels of the El Cuchillo dam and groundwater in the area, which produced a serious socioeconomic drought in the MMZ in 2021.

In the GMZ, variations in water availability do not appear to persist for more than one year, except for the effects of the 2011–2013 drought (Figure 10b). Therefore, the issues of decreasing per-capita water consumption are mainly associated with an increasing number of users and an insufficient increase in water supply.

In Mexico City, significant decreases in the water levels of the Cutzamala System were observed between 2008 and 2010, which alerted the Mexico City Water System (SACMEX). The meteorologi-

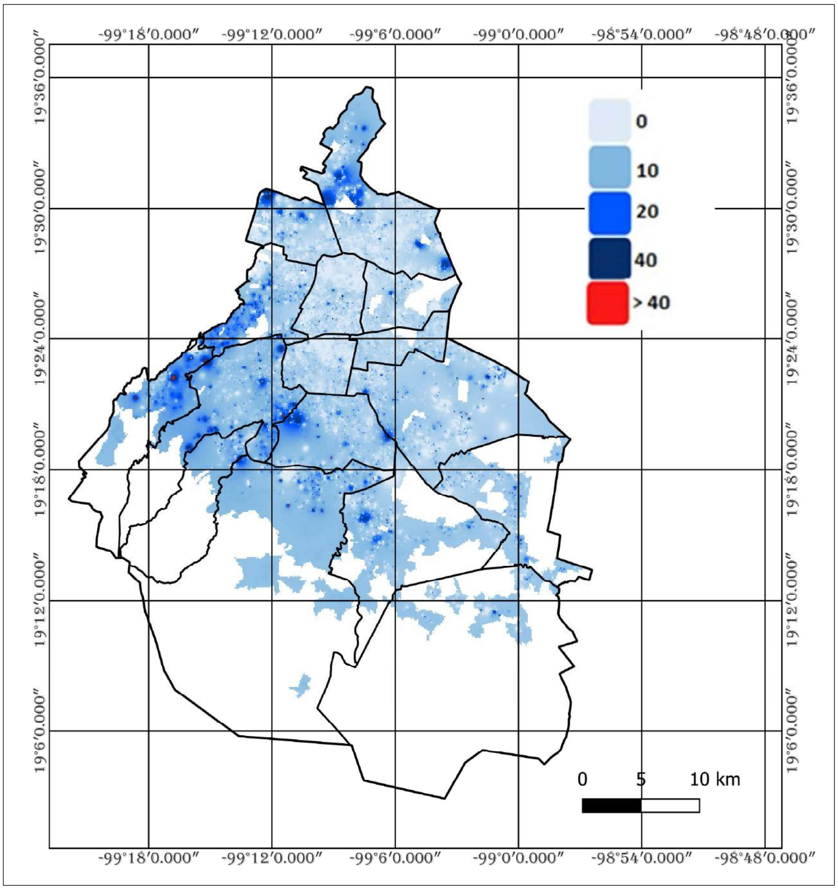


Figure 9. Change (%) in water consumption (blue scale) in Mexico City between January and February (cold two-month period) and March-April (warm two-month period) of 2019.

cal and socioeconomic drought improved thanks to major winter storms (Soto & Herrera, 2019). However, there has been a significant decrease in water sources since 2020, which has led to rationing in a large part of Mexico City (Figure 10c).

To address the climate change factor, it is necessary to review annual precipitation records spanning several decades. This can be done with precipitation data from meteorological observatories (Figure 11). As part of the natural interannual variability of the climate, there are years with low or high rainfall, frequently regulated by El Niño/ Southern Oscillation (Magaña *et al.*, 2003) and, on interdecadal scales, by the Atlantic Multidecadal Oscillation (AMO) (Méndez & Magaña, 2010). In general, the trend in the urban areas studied here is towards higher annual rainfall, although with periods of meteorological drought. Conditions previously considered a year of good rains fifty or a hundred years ago are now considered meteorological and socioeconomic droughts due to the increased water demand.

Very low-frequency variations in rainfall, with periods of around 30 or 40 years related to AMO, play a central role in water availability. There is no clear evidence that meteorological droughts are becoming more frequent or severe than in the past, but socioeconomic droughts are. Therefore, from a risk perspective, the factors that make our cities more vulnerable to rainfall deficits should be reviewed. Jáuregui and Romales (1996) found that rainfall in Mexico City tended to rise during the 20th century, which was related to the UHI. López *et al.* (2022) have proposed that, in the case of the GMZ, the trend toward a higher volume of annual rainfall results from an increase in the number of intense storms related to the GMZ urbanization process. Annual rainfall in the three metropolitan

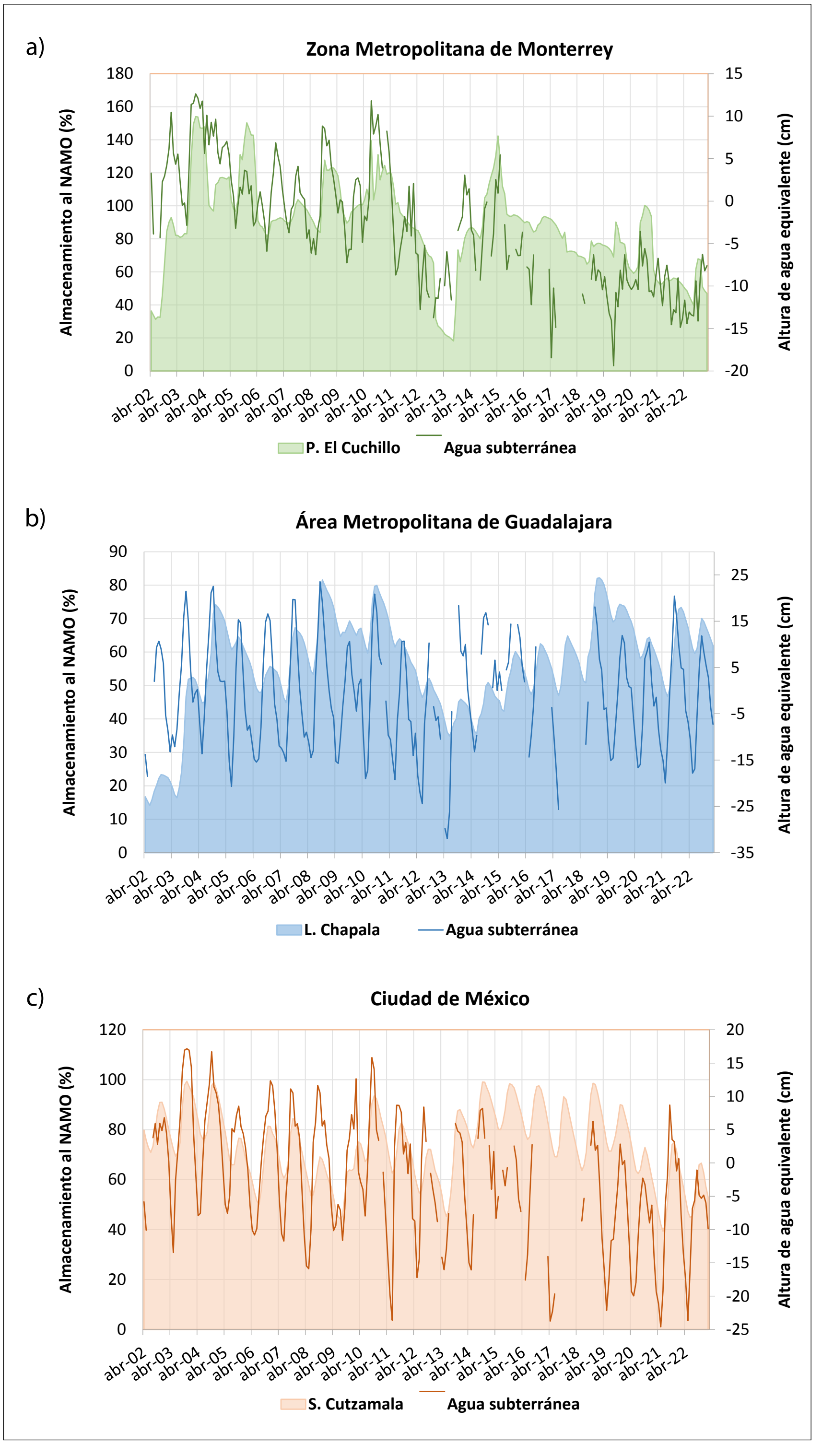


Figure 10. Changes in water availability from supply sources between 2002 and 2022. Surface water storage (%) and equivalent water height (cm) for groundwater in a) MMZ, b) GMZ, and c) Mexico City.

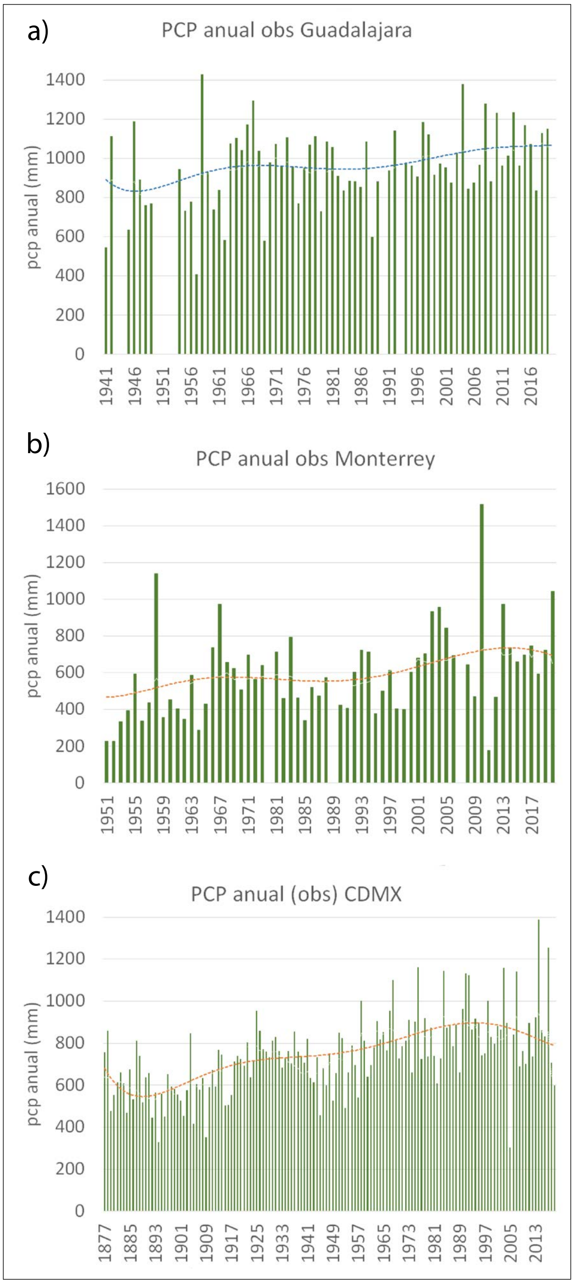


Figure 11. Annual precipitation (mm) at meteorological observatories. a) MMZ, b) GMZ, and c) CDMX. Gaps correspond to a lack of data. Smooth dotted lines denote very low-frequency variations in annual precipitation.

zones studied here has increased by 30 to 50 %, which should bring about greater water availability if an improved long-term water management strategy is implemented.

CONCLUSIONS

The decrease in water availability in large cities has led to lower consumption and, frequently, to socioeconomic droughts. Facing such a situation, the authorities resort to the naturalistic approach and speak of climate change as the main cause of socioeconomic droughts. This approach does not consider this type of drought to be an unaddressed climate risk issue in which the vulnerability of cities to meteorological drought has increased. Cities are vulnerable due to multiple factors, such as poor water management planning, excessive water consumption, or lack of investment in infrastructure. A water culture program that takes into account the changing climate is urgent for users to adapt to the fact that a finite resource is distributed among more and more people. Mexico's water crisis is serious in Monterrey, Guadalajara, and Mexico City because the household water demand has increased for almost a century as a result of population growth. Meeting these demands is complex because investment in water infrastructure has been insufficient for decades (Magaña *et al.*, 2021). However, insufficient drinking water services have adverse consequences for population health (Vargas & Magaña, 2020).

Although it is known that climatic conditions of maximum temperature influence water consumption in urban areas, the increased temperature signal due to a UHI is hard to detect, as the increasing number of users or variations in rainfall are the dominant factors. The importance of the climate factor appears when considering meteorological droughts since they affect water availability. Maximum temperatures are only reflected in per-capita consumption when the dry and warm months are contrasted with the cold or rainy seasons. The increase in water demand for household consumption could also be studied during heat-wave episodes, but better data are needed to establish the importance of these phenomena in urban water consumption. The UHI systematically increases the temperature in cities, but its effect on the per-capita water consumption in recent decades is indistinguishable.

The naturalistic discourse used to justify the water supply crisis in cities should be abandoned.

There is insistence that the climate change scenarios for Mexico are negative in terms of rainfall, without recognizing that we live in a country where the trend is towards greater rainfall; however, vulnerability to meteorological drought in Mexico increases the risks of water shortages. Underground sources are also overexploited when surface water sources drop, with adverse consequences. This issue should lead society, and mainly water resource managers, to implement alternatives and strategies for sustainable water management.

In summary, the main challenge of urban water supply in Mexico is how to meet the demand of a growing population. To date, the response has focused on the search for new sources of supply, but this has proven unsustainable. It will be necessary to build hydraulic infrastructure for water reuse while also improving water culture programs, including information and plans to adapt to meteorological droughts that can last from one season to several years.

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