Vulnerability of Mexico City’s water supply sources in the context of climate change

Sandra Martinez, Stefanie Kralisch, Oscar Escolero and Maria Perevochtchikova

ABSTRACT

In the context of growing urbanization and climate change, the issue of how to best secure and increase future water supply in developing countries is key. To support informed decision-making in Mexico City, a comprehensive study was conducted to assess the potential effects of climate change and the vulnerability of water sources. The infrastructural, environmental and administrative factors affecting the water available from each source were identified and evaluated, and then combined with the likely impacts in regional water availability estimated using results from two global circulation models and two emission scenarios. The results obtained indicate that the water sources outside Mexico City, such as the Cutzamala and Lerma systems, are the most vulnerable. The current situation is likely to become worse as result of climate change, as projections suggest a 10–17% reduction in water availability by 2050. When responsible agencies decide the strategies to secure and increase water supply, they will have to consider the prevailing and potential conflicts, the local water demand, the contribution to the city’s greenhouse gas emissions and future changes in water availability.

Key words | adaptation, availability, climate change, vulnerability, water management, water supply

INTRODUCTION

In the context of growing urbanization, megacities have been identified as global risk areas (Kraas 2008). The sheer increase in population density and the extreme dynamism of urban sprawl make them foci of vulnerability and bring a high degree of complexity to the task of providing basic urban services. In many regions, urban growth entails the intensive use and contamination of water resources in the city and its periphery, followed by the development of long-distance water imports (Morris et al. 2005; Martinez et al. 2009). Water providers face a lack of financial resources and administrative capacity for maintaining the ageing infrastructure and developing new sources in order to respond to the challenge of growing water demand (Hamouda et al. 2009).

In addition, the long-term changes in temperature and precipitation on the one hand and higher climate variability and the increased occurrence of extreme weather events on the other threaten to exacerbate the situation. Forecasts of increases in global temperature of 1.4–6 °C during this century are widely accepted in the scientific community (IPCC 2000). The effects of these changes have been increasingly evident and dramatic all around the world. While attempts to agree on mitigation mechanisms under the Kyoto protocol have fallen short in several ways, in recent years the political agenda has focused on adaptation to climate change. In this framework, cities and local governments face the challenge of generating reliable local data from regional climate tendencies in order to create local climate change adaptation programs.

With about 8.8 million inhabitants and a total of 20 million in its metropolitan zone, Mexico City is one of the world’s largest urban conglomerates. Numerous authors have discussed Mexico City’s water problems from different perspectives (Birkle et al. 1998; Tortajada 2006; Carrera-
Hernández & Gaskin 2009; Gonzalez-Reynosa et al. 2010) and its water management has been characterized as inefficient, unsustainable and inequitable (World Bank 2015). The drinking water supply coverage of the Mexico City Water System (Sistema de Agua de la Ciudad de México (SACM)) has been decreasing constantly since the year 2000, but at 91.6% it lies well above the national average (Conagua 2012b). Nevertheless, this figure does not refer to continuous water provision, as many people receive drinking water only intermittently; such is the case for more than 900,000 people in the district of Iztapalapa alone.

These borderline conditions are likely to worsen in the future. Studies that explored the potential effects of climate change on water availability in Mexico warn about reduced water supply in the future (Maderey & Jiménez 2000; Magaña & Conde 2000; Rivas Acosta & Montero Martínez 2013; Haro et al. 2014). For the Mexico City valley in particular, a decrease in water availability is to be expected (Mendoza et al. 2008).

Meanwhile, the metropolitan area keeps on growing at its periphery and it is estimated that its total population will reach 29 million by 2030 (World Bank 2015). The issue of how to best secure and increase future urban water supply is urgent and needs comprehensive assessment. In this study, key factors contributing to the vulnerability of water supply sources in Mexico City were identified and assessed, and the potential impact of climate change on these factors and the resulting water availability were estimated. The objective was to achieve a wide assessment to feed the decision-making process and to provide the basis for identifying possible adaptation actions to respond to changing regional water availability.

**MEXICO CITY’S WATER SUPPLY**

Mexico City lies in a closed basin at an altitude of approximately 2,240 m a.s.l., surrounded by volcanic mountain ranges. The region faces the lowest per capita water availability (74 m³/year) and the highest population density in the country (Conagua 2009a). The main drinking water source is the Mexico City Metropolitan Zone (Zona Metropolitana de la Ciudad de México (ZMCM)) aquifer, as designated by the National Water Commission (Conagua, Comisión Nacional del Agua). This aquifer underlies the city (Figure 1). A total of 549 wells operated by the SACM (SACM well system) abstract approximately 14 m³/s of groundwater from this aquifer.

In response to the rising water demand and declining water tables, additional well systems were installed for importing water from outside the city borders, in the states of Hidalgo and Mexico. The Chiconautla system, located 32 km north of the city center, conducts an estimated flow of 1.3 m³/s from 41 wells in the Cuautitlán–Pachuca aquifer. In addition, 2.8 m³/s are pumped by the Immediate Action Well (Pozos de Acción Inmediata (PAI)) system, composed of 156 wells distributed over seven well fields located outside the city boundaries. The PAI system, operated by Conagua, had originally been constructed as a temporary solution to ease water stress in the 1970s, but is still running.

Two major water import schemes from outside Mexico City are in place. The Lerma system was developed between the 1940s and 1980s to import water from the upper Lerma basin, situated in the neighboring State of Mexico. Groundwater is pumped by 250 active wells in the Toluca Valley and Ixtlahuaca–Atlacomulco aquifers, which provide 70% and 30% of the extracted volume, respectively. Currently, an estimated flow of 7.8 m³/s is transferred via an aqueduct to Mexico City.

The Cutzamala system was built in three stages starting in 1982 and is the only important surface water source. Water is collected behind seven dams located in the Cutzamala River basin and is conducted via a 127 km aqueduct toward the State of Mexico and Mexico City, spanning an elevation difference of more than 1,200 m. The system is operated by Conagua through their regional office, the Mexico Valley Water Basin Agency (Organismo de Cuenca Aguas del Valle de Mexico) reportedly delivering 9.6 m³/s of water to Mexico City and approximately 6 m³/s to the State of Mexico.

There are other minor water sources for Mexico City within the city borders. There is a system of 18 springs that outcrop in the Sierra del Ajusco mountain range in the south of the city. Surface water sources within the city have been almost entirely converted into stormwater and sewage drains, the only one currently being used for drinking water supply is the Magdalena River. Owing to the low water volume (approximately 0.8 m³/s) and lack of data, these two sources were excluded from the study.
CONCEPTUAL FRAMEWORK

The concept of water supply sources is understood in this study to encompass (i) the catchment areas taking into account the environmental component, (ii) the infrastructure considering the technical component and (iii) the socio-administrative framework involved in each source.

The term catchment area corresponds to the hydrological catchment for the surface water sources and to the areas delimited by Conagua (2009b) for each aquifer in the case of groundwater (Figure 1). The environmental dimension of the evaluation refers to those processes that affect natural water availability in the catchment areas, e.g. land use change, erosion, soil and water degradation, groundwater drawdown etc. The infrastructure evaluated takes into account the well fields, dams and principal conduction systems until the point of delivery to Mexico City. The city's water distribution system was not included. With respect to the administrative dimension, the legal, social, institutional
and economic situation related to each supply source was evaluated.

In the literature there are different approaches to assess the vulnerability of water resources. The analysis of vulnerability to climate change usually combines the system’s sensitivity with its resilience or the capacity for adaptation. In Mexico, Mendoza et al. (2008) defined climate change vulnerability indices for hydrologic areas using the hydrologic balance, intensity of water use and the storage capacity of the hydraulic infrastructure; Rivas Acosta & Montero Martínez (2013) combined indicators of exposure, sensitivity and adaptive capacity using a geographic information system in order to map hydrologic vulnerability in a river basin under different climate change scenarios. Likewise, Conagua (2007a) assessed the vulnerability of different regions to drought. Another approach is focused not on resource vulnerability, but on the water users or different social and economic sectors and their sensitivity and adaptability to changes in water availability (Soto Montes de Oca & Herrera-Pantoja 2009).

In this study, vulnerability is defined for each of the water supply sources as the likelihood that drinking water supply to Mexico City will decline in the future. A vulnerability index was constructed by searching for specific variables that determine vulnerability in the three dimensions of environment, infrastructure and socio-administrative framework.

**METHODOLOGY**

A method to assess the vulnerability of water supply sources to climate change was developed and applied in this study (Figure 2). First, extensive diagnostics of the present conditions were performed, namely the state of the infrastructure, the environmental state in the catchment areas and the administrative situation of each source. Then, the climate change impact on regional water availability was estimated. Based on the results of these two steps, the vulnerability index was evaluated using multi-criteria analysis.

In terms of diagnostics, it is important to mention that we mainly used official data and reports provided by the water authority and local water providers. The official character of the information was considered important, as the results were directed to inform political decision makers.
Climate change scenarios

For the climate change scenarios, temperature and precipitation data were obtained from the Atmospheric Science Institute of the National Autonomous University of Mexico (Universidad Nacional Autónoma de México), which geostatistically down-scaled different global models to a scale of 10 x 10 km and projected them onto high-resolution historical climate data (period 1950–2000) (CCA UNAM 2008). From all the relevant and applicable models, MPI-ECHAM5 (Max Planck Institute for Meteorology) and UKMO-HADGEM1 (Hadley Centre Global Environmental Model Met Office, UK) were chosen, as both present a small error for the region, but differ somewhat in their estimations (CCA UNAM 2008).

Likewise, one relatively optimistic (A1B) and one pessimistic (A2) scenario were chosen from the SRES-series (IPCC 2000). The A2 is a scenario with a higher atmospheric CO₂ concentration and temperature increase. It is defined by continuous population growth; the economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and slower than in other storylines. In the A1B scenario atmospheric, CO₂ concentration is stabilized at 650/750 ppm. This scenario represents a world of rapid economic growth and technological progress. The population peaks in the mid-century and declines afterward, and there is a rapid introduction of new and efficient technologies, as well as a balance across fossil and non-fossil energy sources.

Combining two models and two scenarios, complemented by the historical climate data, five data series of monthly rainfall and temperature were obtained for the years up to 2050 for each catchment area.

Estimation of impacts on water availability

The potential impact of climate change on the water availability was estimated by applying a simple water balance for the Cutzamala catchment and the areas corresponding to the ZMCM, Toluca Valley and Ixtlahuaca–Atlacomulco aquifers. Water availability, expressed as the sum of recharge and runoff, was calculated for both, the rainy and the dry season, as the difference between precipitation and evapotranspiration (ET).

\[
(\text{Runoff + Recharge})[m^3] = (\text{Precip}[mm] - \text{ET}[mm]) \times \frac{\text{area}[km^2]}{1,000}
\]

Changes in ET were calculated for each area and season by using the Coutagne (1954) formula.

As no hydrometric data were available for the region, the change in the aggregated parameter (runoff + recharge) was used to represent the change in water availability between historical average conditions (baseline) and the scenarios for 2050.

Vulnerability assessment

Based on the diagnostics performed on the water supply sources and a literature review on vulnerability indices, key vulnerability factors were obtained. In a first step, these factors were grouped into three dimensions and were summarized into variables that can be used as potential indicators of vulnerability.

To combine this objective and instantaneous view with practical and long-term system knowledge, a group of experts from the water sector (consultants and former Conagua officials) was convened to participate in a survey and a workshop. As an introduction, they were given an overview of the diagnosis, the variables identified and the expected impact of climate change on the water balance for each source. During the subsequent group discussion, an interesting first feedback of the practitioners on the results was obtained and the list of key variables was adapted, resulting in a final set of nine vulnerability indicators.

The indicators were organized into a semi-quantitative evaluation matrix which the participants individually completed with values from 1 to 10, reflecting each variable’s perceived impact on the water availability of a source. The value 1 was associated with the least pressure on water availability and values close to 10 would express the highest pressure. Using multi-criteria analysis, these individual assessments were translated into an overall hierarchization matrix, comprising each variable’s value, weight and level of confidence for each source. The sum of the resulting...
values in each dimension constitutes the infrastructure, environmental and socio-administrative vulnerability for each source. The sum of all the values for each source constitutes the total source vulnerability.

RESULTS

Impact of climate change on water availability

As shown in Figure 3, the different time series result in fairly different estimations of climate parameters for 2050. In comparison with the historical baseline, the HADGEM1 model foresees a decrease in summer precipitation and, at least in the A1B scenario, an increase in winter precipitation. This tendency is reversed in the ECHAM5 model. These differences reflect the uncertainty associated with the application of different global climate models (Kosow & Gaßner 2007; CCA UNAM 2008).

The mean annual temperature is predicted to increase between 1.3 and 1.9°C, a tendency that is also observed for mean monthly temperatures throughout the year (Table 1, Figure 3). The greatest increases in mean monthly temperature (max. 2.2°C) are predicted for the Cutzamala
area during the summer season. The temperature rise leads to an increase in annual ET (0.2–6%).

Decreases in mean annual rainfall of 1.3–5.1% were calculated for 2050 for all scenarios, except for the ECHAM-A2 combination, which estimated an increase in total annual rainfall of 0.4–2.7%. Nevertheless, the mean annual value is not relevant for the water balance. Instead, the seasonal distribution has to be considered, where the expected changes are much more drastic, but not unanimous between the models. For the HADGEM1 model, total rainfall during the wet season is predicted to decrease between 2 and 5%. In the dry season, predictions indicate an increase of 6–8% for the A1B scenario, but a reduction of 4–5% for the A2 scenario. In contrast, the ECHAM5 model predicts slightly higher rainfall amounts for the summer season (even up to 11% for the A2 scenario in the Cutzamala area) and a noticeable reduction in winter precipitation (between 12 and 23%).

From the climate parameters and based on the water balance, the climate change induced alterations in annual water availability were calculated for the year 2050 (Table 1). Annual water availability in all three catchment areas is estimated to decrease by 10–17% in three of the four future scenarios. For these combinations, the pessimistic scenario A2 consistently entails a more drastic decrease in water availability than the moderate A1B. In contrast, the ECHAM5/A2 scenario shows a smaller impact in water availability, with reductions of 3–7.5%. However, important seasonal climate change impacts can be expected for this combination. For example, this combination presents a rather adverse seasonal rainfall distribution, as the precipitation increases in summer and strongly decreases in the dry season. An effect that could not be included in the calculations is the likely increase in inter-annual climate variability, i.e., a higher frequency and duration of droughts.

In addition to the predicted impact of global climate change, during recent decades some local trends with potential effects on water availability have been observed in Mexico City. Urbanization plays a crucial role on the local climate and is overlapping and amplifying the tendencies of the expected climate change. Within recent decades, the city’s weather stations have registered an increase in annual minimum temperature (3.6 °C in the period 1961–1985 for the suburban area) and the thermal gradient (>10 °C between the city and its surroundings (heat island effect). The annual minimum temperature increase of 0.15 °C per year by far exceeds the expected impact from global climate change but will be aggravated by the latter. Many authors argue that one effect of the urban heat island is an increased occurrence and intensity of heavy rainstorms. Jáuregui (1999, 2006) report for the Tacubaya weather station in Mexico City a five-fold increase in the occurrence of extreme rain events (>20 mm/h) in the period 1940–1980, as well as an increase in the frequency of heat waves during spring, trends that during the analysis could be found also for more recent years in other weather stations in the urban and peri-urban area.

Vulnerability of water supply sources

The results obtained from the multi-criteria analysis are presented in Table 2 showing the total vulnerability for each source as well as the value obtained for each key variable, which provide interesting insights into the contribution of each component to vulnerability. The contour maps (Figure 4) summarize the situation for the different water supply sources, depicting in color the total vulnerability values for each source according to its capture area.

Despite the well-known problem of intensive groundwater extraction in the ZMCM aquifer, the external water sources were judged to present the highest vulnerability. The surface water transfer from the Cutzamala basin was assessed with the highest vulnerability value (with 8 points of a total of 10), followed by the Lerma groundwater transfer system (with 6.4 points). The SACM wells, which contribute more than 40% to the total water supply of Mexico City, had the lowest vulnerability value (5.7 points). Some details will be explored in the following sections.

Infrastructure vulnerability

The infrastructure vulnerability reflects the influence of factors of state, capacity and exposure to damage by third parties. The Cutzamala system had a high vulnerability value due to the age (55–65 years) and deteriorating state of the reservoirs and aqueducts. The storage capacity of
Table 1: Summary of changes on climate variables and water availability for the different catchment areas and scenarios for the year 2050

<table>
<thead>
<tr>
<th></th>
<th>Cutzamala catchment areas</th>
<th>ZMCM aquifer area</th>
<th>Toluca &amp; Iztlahuaca – Atlacomulco aquifers areas</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HADGEM1</td>
<td>ECHAM5</td>
<td>HADGEM1</td>
</tr>
<tr>
<td></td>
<td>Baseline</td>
<td>A1B</td>
<td>A2</td>
</tr>
<tr>
<td>Annual precipitation (mm/y)</td>
<td>987</td>
<td>862</td>
<td>892</td>
</tr>
<tr>
<td>Change June–Sept (%)</td>
<td>-5.4</td>
<td>-4.4</td>
<td>+2.6</td>
</tr>
<tr>
<td>Change Oct–May (%)</td>
<td>+6.7</td>
<td>-5.4</td>
<td>-12.1</td>
</tr>
<tr>
<td>Annual mean temperature (°C)</td>
<td>13.6</td>
<td>13.6</td>
<td>13.6</td>
</tr>
<tr>
<td>Change (%)</td>
<td>+1.3</td>
<td>+1.6</td>
<td>+1.7</td>
</tr>
<tr>
<td>Annual ET (mm/y)</td>
<td>628</td>
<td>628</td>
<td>628</td>
</tr>
<tr>
<td>Change (%)</td>
<td>+2.5</td>
<td>+1.9</td>
<td>+4.0</td>
</tr>
<tr>
<td>Annual precipitation (hm³/y)</td>
<td>1,519</td>
<td>1,580</td>
<td>4,486</td>
</tr>
<tr>
<td>Change (hm³/y)</td>
<td>-33.4</td>
<td>-70.2</td>
<td>-19.8</td>
</tr>
<tr>
<td>Annual ET (hm³/y)</td>
<td>966</td>
<td>1,092</td>
<td>2,946</td>
</tr>
<tr>
<td>Change (hm³/y)</td>
<td>+24.2</td>
<td>+17.8</td>
<td>+59.1</td>
</tr>
<tr>
<td>Runoff + recharge (hm³/y)</td>
<td>553</td>
<td>488</td>
<td>1,540</td>
</tr>
<tr>
<td>Change (hm³/y)</td>
<td>-57.6</td>
<td>-88.0</td>
<td>-58.8</td>
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<tr>
<td>Change in annual water</td>
<td>-10.4</td>
<td>-15.9</td>
<td>-10.6</td>
</tr>
</tbody>
</table>

Models, MPI–ECHAM5: Max Planck Institute for Meteorology; UKMO–HADGEM1: Hadley Centre Global Environmental Model. Met Office, UK.

Scenario definitions: A2: higher atmospheric CO₂ concentration and temperature increase, continuing population growth, regionally oriented economic development, per capita economic growth and technological change are more fragmented and slower than in other storylines; A1B: atmospheric CO₂ concentration stabilizes at 650/750 ppm, rapid economic growth and technological progress, population peaks in the mid-century and declines afterward, rapid introduction of new and efficient technologies, balance across fossil and non-fossil energy sources.
some reservoirs has been reduced by about 20% due to siltation, and interruptions of drinking water service due to cracks are more and more frequent in some city sectors. In addition, this system with more than 300 km of channels and aqueducts (73 km open channels) is strongly exposed to damage by vandalism. Inspections carried out by Conagua have recorded about 1,500 illegal taps. Illegal water abstraction and damage by third parties are also important factors for the second major water import system, the Lerma system. Here, illegal taps according to Conagua cause the loss of about 2 hm³/year.

All water sources scored high vulnerability values when considering the physical state of the infrastructure. In the groundwater-dependent sources, this was attributed partially to the fact that many of the wells were drilled more than 40 years ago and to a lack of necessary investments in repair and maintenance. In the Lerma system, in the period 1997–2008 the number of wells out of service grew from 8 to 39. As for the SACM wells, constant repositioning of wells is taking place. Here, the high infrastructure vulnerability value corresponds to the fact that in the east and south of the city, where abstracted groundwater needs to be treated, potabilization plants are not operating properly. As for the PAI system, performance is low due principally to deficiencies in the design and construction of the well fields. In a 6-year period the performance declined by 20% in the Los Reyes–Ecatepec well field in the north and by 50% in the Mixquic–Santa Catarina well field in the south (Conagua 2007b).

<table>
<thead>
<tr>
<th>Vulnerability dimensions</th>
<th>Vulnerability indicator</th>
<th>Cutzamala</th>
<th>Lerma</th>
<th>PAI Wells</th>
<th>SACM Wells</th>
<th>Chiconautla</th>
</tr>
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<tr>
<td>Infrastructure</td>
<td>State</td>
<td>9</td>
<td>7</td>
<td>8</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Exposure to damage by third parties</td>
<td>7</td>
<td>7</td>
<td>4</td>
<td>2</td>
<td>4</td>
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<tr>
<td></td>
<td>Capacity</td>
<td>5</td>
<td>3</td>
<td>5</td>
<td>5</td>
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<td>Availability</td>
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<td>6</td>
<td>7</td>
<td>8</td>
<td>8</td>
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<td>nd</td>
<td>7</td>
<td>8</td>
<td>nd</td>
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<tr>
<td></td>
<td>Environmental degradation</td>
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<td>8</td>
<td>7</td>
<td>8</td>
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<td>Socio-administrative</td>
<td>Conflicts due to water demand</td>
<td>9</td>
<td>7</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Economic efficiency</td>
<td>9</td>
<td>7</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Administrative situation</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>2</td>
<td>7</td>
</tr>
<tr>
<td>Aggregated vulnerability</td>
<td></td>
<td>8.0</td>
<td>6.4</td>
<td>6.2</td>
<td>5.7</td>
<td>6.0</td>
</tr>
</tbody>
</table>

Note: scale from 1 (lowest) to 10 (most vulnerable). A higher score means a source being more vulnerable/a variable being more decisive for vulnerability.

Environmental vulnerability

Environmental vulnerability has been characterized according to the trends in water availability, water quality and environmental degradation in the catchment areas. It is in the dimension of vulnerability that the most direct effects of climate change are observed. Summing up the individual results, the environmental variables have the highest weight on total vulnerability, with a mean value of 7.9 points (Table 2).

The Cutzamala system, being a surface water source and given the estimation of climate change impact, received a score of 10 in vulnerability associated with water availability. This perception was influenced by the drought that the Cutzamala basin experienced in 2008 and that severely restricted the water supply in 11 districts of Mexico City. Likewise, the ongoing reduction in the storage capacity by reservoir siltation was a highly weighed factor.

As for the groundwater sources, all the aquifers supplying Mexico City have a long history of overexploitation (Conagua 2009a; 2012a). Dropping groundwater levels are a well-known and serious problem, affecting well performance, pumping costs and causing serious soil subsidence below the city, with great damage to urban infrastructure and buildings. The Lerma system was given a lower vulnerability score, reflecting studies and the interpretation of piezometer records that indicate that after decreasing abstraction in the system, aquifer levels have been recovering in recent years and that increased abstraction would
Figure 4 | Vulnerability score of Mexico City’s drinking water sources within the socio-administrative, infrastructure and environmental domain, obtained by averaging three indicators for each of the domains. The scores range from 13 (lowest vulnerability) to 28 (highest values).
only cause a moderate decline in piezometric levels (SACM 2007, 2009).

In terms of water quality, conclusive data could not be found for the Lerma and Chiconautla systems. For the Cutzamala system dams, excessive concentrations of coliforms and nutrients have been reported, and deficiencies in the purification plant threaten the achievement of water quality standards (Conagua 2006). The PAI and SACM wells present water quality problems in some wells fields located in the north (high total dissolved solids, Na, Cl) and especially in the east and south (Mn, Fe, NH₄). In these areas, the increased contaminant concentrations are associated mostly with the mobilization of elements due to intensive pumping, as well as with untreated wastewater disposal and leakages from the drainage systems.

For environmental degradation, the highest vulnerability score (10) was assigned to the Cutzamala catchment given the considerable degree of deforestation and erosion and the impact of diverse contamination sources. As for the aquifer areas of the Toluca Valley, Ixtlahuaca–Atlacomulco and ZMCM, urbanization is the major driver of environmental degradation. Carrera-Hernández & Gaskin (2008) quantified the impact of urbanization on potential aquifer recharge estimating a reduction of 0.3 m³/s just for the Mexico City area. Nevertheless, this value was estimated using the 1985 land use pattern, when the urban area was more limited to the valley, where recharge to the ZMCM aquifer is estimated to be negligible due to a clay aquitard. In contrast, the ongoing urbanization of the slopes (such as the Sierra Chichinautzin in the south and Sierra de Guadalupe and Chiconautla region in the north) and illegal settlements in the conservation areas are likely to have a much stronger hydrological impact. The score of 8 for the Lerma system is associated with the rapid urbanization process in the Toluca Valley, as well as the abundance of illegal landfills in the piedmont areas around Toluca and the fact that the aquifer is largely unconfined and therefore more vulnerable to contamination.

**Socio-administrative vulnerability**

This category of indicators assesses the impact of conflicts over water, economic efficiency and the administration of the water sources. The results show that these social and management-related variables have an equally high contribution to vulnerability as the infrastructure and environmental dimension. The SACM wells, as the only major water source within city boundaries, received the lowest socio-administrative vulnerability score, whereas high values were assigned to the large-scale water transfer systems.

A major vulnerability source in these systems has been the non-consideration of water demands of the local population in the expanding areas, which has caused numerous conflicts. The social conflicts and environmental impacts in the area of the Lerma system were the reason for reducing the flow delivered to Mexico City from 14 m³/s in 1974 to less than 4 m³/s in the year 2004 (Conagua 2009a). The conflicting water demands from the Lerma system were satisfied provisionally by providing water from the aqueduct to municipalities along the way. Nonetheless, still part of the agreed compensation volume is not being delivered, and the claims for more water are expected to recur, as the Toluca and Iztlahuaca region will experience a population growth of 30% in the next 20 years.

Whereas the conflicts around the Lerma system are evolving primarily at the institutional level, they involve the organized action of civil society groups in the case of the Cutzamala system. Severe water access problems, especially in rural areas populated by the indigenous Mazahuas, and failure to implement compensation projects to improve the service infrastructure (Gómez-Fuentes 2009), triggered the conflict and so far have impeded the construction of the fourth stage of the Cutzamala system as had initially been planned.

Problems and conflicts that arise due to the unsatisfied local water demand are also reported for the fast growing municipalities bordering Mexico City, and therefore also affect the PAI well system and the Chiconautla well field. Both received the highest score (7) in administrative vulnerability. The PAI system was planned as a temporary measure and Mexico City, until today, has no water rights for the abstracted groundwater. In the case of the Chiconautla well field, the initial contract between Mexico City and the Ecatepec municipality in Mexico State had foreseen the exchange of groundwater for wastewater to be used for irrigation. As today much of the agricultural land is urbanized, Ecatepec is now negotiating to cease the water transfer. In

**References**


general, with the perspective of reduced water availability and continuously growing demands in the metropolitan area of Mexico City, various authors warn about a further exacerbation of social conflicts around water in the region (Magaña & Gay-García 2009).

The last indicator that impacts vulnerability is the economic efficiency of the systems, in which the water import systems have the highest scores. Dominating factors are the electricity costs and the infrastructure investment to assure supply, but also pending water rights payments, as in the Lerma case. In terms of high energy consumption, the Cutzamala system has been strongly disputed as 80% of the operating costs correspond to this item (1,787 million kWh) (Tortajada 2006).

**DISCUSSION**

The results show that even if the problems of each water supply source are complex, they could well be structured into dimensions and be compared on the basis of common variables following the method presented in this paper. This method provided valuable structure and clarity to the analysis but at the same time highlighted the multi-dimensional nature and interrelations of the issues.

The combination of the academic with the management perspective allowed the identification of relevant issues and for a successful extension of perspective on both sides. This way, the priority that had generally been given to impacts over causes during the first evaluation, changed in the course of the interaction. For example, as a first step high importance was given to the siltation of the Cutzamala reservoirs and the fact that drinking water standards are threatened by high coliform and nutrient concentrations in the reservoirs. Nonetheless, a score of just 4.7 had been assigned to the variable of environmental degradation. Likewise, illegal abstractions were stressed, but the cause of the conflicts, which is the unsatisfied local water demand, was neglected. These perceptions, and hence the scoring, changed during discussion, thus the approach is considered suitable to reveal relevant connections and causal relationships between factors.

Nonetheless, one weakness of the multi-criteria analysis, as performed, is subjectivity. A significant bias could be observed between more important and disputed water sources like the Cutzamala system and smaller ones, as well as for factors that the participants were more familiar with or that had been discussed extensively in local media and politics. This bias could partially be compensated by providing more information, but is intrinsically revealing, as it is replicated in water management practice. Therefore, the value of the method for informing decision makers does not lie in the vulnerability scores alone, but the combination with the data that explain each score and the process of discussion in itself.

Climate change is very likely to directly decrease water availability from the surface water sources, but through reduced potential recharge will also affect groundwater sources in the long run. The combined analysis of climate change scenarios and the variables that characterize vulnerability under current conditions demonstrated that there are important interrelations and reinforcing effects. Some scenarios showed seasonal trends that are currently being observed and inferred to be the result of urbanization, i.e., increased summer rainfall and longer dry periods. In the Cutzamala system, these trends could have an ever stronger impact in the water quality and catchment degradation as a result of increased erosion and sediments and pollutants transport into dams. This situation could worsen with the high peak flows during extreme events that encourage siltation in the reservoirs, affecting the reservoir storage capacity and infrastructure safety. In urbanized areas, the seasonal trends could aggravate the hydrologic effects due to high imperviousness, namely an increased runoff and a reduction in the fresh water potential recharge that could exacerbate the current degradation of water quality.

On the other hand, reduced water availability due to climate change, higher water demand due to temperature increases (Akuoko-Asibey et al. 1995) and more intense summer heat waves, as well as emergency situations in drought periods are likely to increase the conflict potential related to water, which is already high under present conditions and in face of the expected population growth.

With this in mind, it can be deduced that any action that is taken today for reducing the current vulnerability of Mexico City’s water sources will also augment their resilience to climate change. For this, it is important that the
synergies between climate change adaptation policy and water sector policy are effectively explored and used.

**IMPLICATIONS FOR FUTURE WATER SECTOR POLICY**

According to the World Bank (2013) in a business-as-usual scenario, the water demand of the Mexico City metropolitan area will grow by 28% until 2030, generating a deficit of 25 m$^3$/s, or even 46 m$^3$/s when taking current overexploitation into account. Until recently, the major contributions to close the gap between future water demand and limited supply had been projected to come from infrastructure projects that import surface water from external basins. The Temascaltepec project is the expansion of the Cutzamala system to increase the flow of transferred water to 24 m$^3$/s. Three other projects refer to similarly large and even farther water transfers from the Amacuzac, Tecolutla and Atoyac rivers (Conagua 2007c). All these options involve enormous environmental costs and potential social constraints and political disruptions.

The evaluation of the existing water import systems showed that they are especially vulnerable and that considerable reductions in water availability have to be expected due to climate change and growing water demand. In addition, the excessive energy demands for these projects strongly contrast with the city’s plans to significantly reduce greenhouse gas emissions (SMAGDF 2008). Instead, a modern approach of integrated urban water management calls for a set of diverse solutions and an integration of demand, supply and wastewater and stormwater management in fit-for-purpose schemes adapted to local conditions (Mitchell 2006; Villaraigosa 2008; Martinez et al. 2011; Bahri 2012). Such schemes, combined with strategies to actively reduce water demand, could contribute more effectively to resilience toward changes in water availability in the future.

In this sense, progress toward more balanced solutions was made within the most recent planning exercise in 2012, the Regional Water Program 2030 (Conagua 2012b). This program foresees that great part of the deficit expected in 2030 can be recovered alone by demand management in the public-urban sector via reducing leakage, using reclaimed wastewater and by household water savings. Only 35% of the required water volume is expected to come from infrastructural measures, mainly from the aforementioned large import systems, and also the potabilization of the scarce internal surface water sources, the reimportation of groundwater from the Mezquital and Tula valleys and groundwater recharge.

The preference for big centralized supply sources and treatment solutions is ultimately mainly a governance issue (Wolf et al. 2014). The appeal lies in the facility of centralized financing, planning and operation by a single agency or a specific institutional construct, instead of dealing with the complexity of coordinating various smaller-scale solutions. The analysis reveals that the complex administrative structure of the city’s water supply contributes significantly to its vulnerability. Yet, this complexity cannot be avoided but has to be dealt with by shifting toward agreements between the agencies managing the water supply in Mexico City in order to support the development of adaptation strategies to climate change.

Among the water agencies, there seemed to be little awareness about the scope and impacts of climate change. In sectorial planning documents, no estimations of climate change impact or specific measures to mitigate or adapt could be found. Likewise, in documents specific to climate change, as the Mexico City Climatic Action Program (Programa de Acción Climática de la Ciudad de México) (SMAGDF 2008), Rueda (2011) observed a strong focus on the mitigation of greenhouse gases, but a neglect of climate change adaptation policies.

With the occurrence of the latest extreme events, some changes have begun to manifest. The severe drought that affected the Cutzamala basin in 2008 led to water shortages in a considerable part of the city, stimulated discussions about water management and triggered awareness about the potential impacts of climate change. The Regional Water Program 2030 (Conagua 2012b) already contains measures to deal with extreme hydro-meteorological events like droughts and storms, although, it still does not consider the impacts of climate change on water availability within its planning horizon. Actions for demand management and non-structural measures such as communication, pricing policy and improvements in billing and debt collection are being implemented. There is an increasing demand for
inter-institutional and inter-sectorial cooperation, as well as for improving knowledge of the impact of climate change in the Mexico City and the possible adaptation measures. In that sense, the formation of the Mexico City Virtual Center of Climate Change has been a first tool to promote coordinated participation and collaboration between the academic, public and private sector in generating strategies for adaptation and reducing vulnerability.

CONCLUSIONS

Informed decision-making in water sector planning requires detailed information on the current state of the system and its problems, as well as of the potential impacts of processes like climate change which threaten to exacerbate these problems in the future. To this end, this study provided a comprehensive diagnosis of Mexico City’s water sources by identifying, structuring and evaluating the infrastructural, environmental and administrative factors that may affect the available water supply volume. The diagnostics performed under present conditions were then combined with the estimated impacts of climate change on water availability in the region, using two global circulation models and two emission scenarios.

The study succeeded in demonstrating the usefulness of vulnerability assessments to identify strengths and weaknesses and to establish priority issues. The direct comparison between the sources using indicators allowed a semi-quantitative ranking of their vulnerability. The Cutzamala water transfer system was rated the most vulnerable source under present conditions and under climate change trends, whereas a lower vulnerability was assigned to the local groundwater source. Infrastructural, environmental and administrative factors contributed almost equally to the high vulnerability of the sources to decreasing water availability in the future. The current trends are very likely to be aggravated by climate change, as projections suggested a reduced water availability of 10–17% for 2050.

The trend of declining resources and ongoing population growth in Mexico City’s metropolitan zone will require the development of new water sources. When the city opts to rely on further water imports, their impact on the overall basins water balance has to be considered, as well as prevailing and potential conflicts, local water demand, the contribution to the city’s greenhouse gas emissions and future changes in water availability. Nevertheless, any effort to secure future water supply has a chance of success only if efficiency is drastically augmented, water demand is reduced and the vulnerability of the current systems is decreased, which at the same time, will increase the resilience toward climate change.

This study highlights the value of holistic analysis in exploring the implications of multiple factors and climate change scenarios in the water supply sources. We find that this approach is suited to supporting the development of strategies and adaptation policy and reducing vulnerability with a focus on the social and economic wellbeing.

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REFERENCES


CCA UNAM 2008 Guía para la generación de escenarios de cambio climático a escala regional. First Version (Conde Álvarez, Gay García, eds), Centro de Ciencias de la Atmósfera, Universidad Nacional Autónoma de México, Mexico City.


Conagua 2009b Acuerdo por el que se da a conocer la ubicación geográfica de 371 acuíferos del territorio nacional, publicado en el Diario Oficial de la Federación el 28 de agosto de 2009. Comisión Nacional del Agua, México.


Jáuregui, O. E. 1999 Las precipitaciones extremas en la Ciudad de México. Boletín Informativo 26/27 del Colegio de Pilotos Aviadores, Mexico City.

Jáuregui, O. E. 2006 Are heat waves increasing their frequency in Mexico City? In: 6th proceedings International Conference on Urban Climate (ICUC-6), 12–16 June, Gothenburg, Sweden.


Rivas Acosta, I. & Montero Martínez, M. J. 2013 Downscaling technique to estimate hydrologic vulnerability to climate
SACM 2007 Estudio del funcionamiento hidráulico de acuífero del ramal sur del Lerma y de la reposición y rehabilitación de pozos en el Alto Lerma, para el abastecimiento a la Delegación Iztapalapa. Report of the Sistema de Agua de la Ciudad de México, Mexico City.

Soto Montes de Oca, G., Herrera Pantoja, M. 2009 Estudio sobre el impacto del cambio climático en el servicio de abasto de agua de la Zona Metropolitana de la Ciudad de México. Centro Virtual de Cambio Climático Ciudad de México, Mexico City.


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