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Water in Mexico City: what will climate change bring to its history of water-related hazards and vulnerabilities?

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Water in Mexico City: what will climate change bring to its history of water-related hazards and vulnerabilities?

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ABSTRACT This paper describes the risks that Mexico City faces from flooding and water scarcity, how these risks developed over time and how climate change will affect them. It begins by discussing the climatic and hydrological conditions that explain the abundance of water resources and the droughts and floods that have affected the city and its surrounds for centuries. It then presents the water-relevant implications of climate change for the city and considers who is likely to be most impacted. Floods, droughts and other water-relevant hazards are the result not only of "nature" (and now of human-induced climate change) but also of past and present socio-environmental changes. This helps explain why Mexico City's population, infrastructure and systems are less able to cope with climate change.

KEYWORDS governance structures / socio-ecological resilience / urban vulnerability / water systems

I. INTRODUCTION

On a rainy August day in 2008, Hurricane Dean delivered 79 millimetres of rain in three hours to Mexico City, the capital of Mexico. This overwhelmed its deep drainage system, the capacity of which had been much reduced by lack of maintenance. The result was a flood of water, sewage, mud, waste and trash. A new record for heavy rainfall was set, and what ensued was perhaps a record for a traffic jam, with a chaos of collisions as the city's 4 million cars sought their way through the flooded streets. In some areas, the flood waters rose by 80 centimetres, trapping drivers in their cars until rescue officials arrived.

But floods and traffic jams are an ongoing theme in Mexico City, which has been facing recurrent floods, droughts and other hydrological and climate-related hazards since pre-Hispanic and colonial times.(1) As is the case in many other urban areas in the country and globally, Mexico City is already unable to cope with the types of climate hazards (e.g. floods, droughts) that global warming is expected to aggravate.(2)

During the twentieth century, different transformations took place within and around the city that might further challenge its viability. These transformations were driven by socio-environmental processes operating at regional, national and international levels (changes in the hydrological cycle, urbanization and climate change, respectively). For

1. Palerm, Angel (1973), "Obras hidráulicas prehispánicas en el sistema lacustre del Valle de México, México", SEP–INAH, Mexico; also Sanders, William, Jeffrey Parsons and Robert Santley (1979), *The Basin of Mexico. Ecological Processes in the Evolution of a Civilization*, Academic Press, New York, 561 pages.

2. Satterthwaite, D, S Huq, M Pelling, A Reid and P Romero Lankao (2007), *Building Climate Change Resilience in Urban Areas and Among*

Mexico City, transformations in climate meant an increase in mean rainfall as well as an increase in frequency and intensity of extreme events such as floods, droughts and heat waves.[3] Downpours and storms, for instance, increased from one or two to six or seven per year during the twentieth century.[4] As shown in Figure 1, most of the meteorological hazards facing the city in recent years are related to water, and floods are the most common water-related hazard.

In order to fully understand the urban impacts of global warming, it is necessary to focus not only on exposure to climate hazards but also on whether and why the city, its population and water systems are negatively affected, in other words, vulnerable.[5] Vulnerability can be considered as the degree to which a system (Mexico City), its population and its infrastructure are likely to experience harm due to exposure to a hazard, either a perturbation or a stress factor.[6] The most vulnerable individuals, groups and places are those that experience the greatest exposure to hazards, but also those most sensitive or likely to suffer from exposure and with the weakest capacity to adapt. Adaptive capacity, therefore, is a multi-dimensional phenomenon determined by such factors as:

- the ways in which the socio-ecological system in question (in this case Mexico City) amplifies or attenuates the impacts of the hazard, as a result of its socio-environmental history and the macro-forces or stresses (e.g. climate change, economics and politics) that are interacting to affect the system;

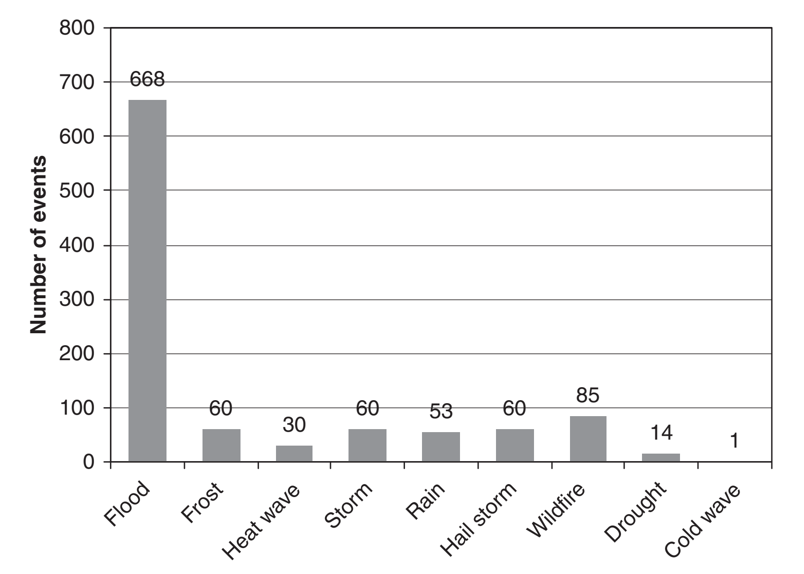

FIGURE 1
Mexico City: hydro-meteorological events resulting in disasters (1980–2006)

SOURCE: Based on data from La Red (2008), "Desinventar", accessed 20 December 2008 at http://www.desinventar.org/.

Urban Populations in Low- and Middle-income Nations, IIED Research Report commissioned by the Rockefeller Foundation, IIED, 112 pages.

3. Secretaria del Medio Ambiente (SMA), Gobierno Distrito Federal (2008), *Programa de Acción Climática de la Ciudad de México 2008–2012*, SMA, Mexico, 170 pages.

4. See reference 3.

5. Turner II, B L, R E Kasperson, P A Matson, J J McCarthy, R W Corell, L Christensen, N Eckley, J X Kasperson, A Luers, M L Martello, C Polsky, A Pulsipher and A Schiller (2003), "A framework for vulnerability analysis in sustainability science", *Proceedings of the National Academy of Sciences* Vol 100, No 14, pages 8074–8079; also de Sherbinin, A, A Schiller and A Pulsipher (2007), "The vulnerability of global cities to climate hazards", *Environment and Urbanization* Vol 19, No 1, April, pages 39–64.

6. According to Turner et al. (2007) (see reference 5, page 8074), hazards are "…*threats to a system, comprised of perturbations and stress (and stressors), and the consequences they produce. A perturbation is a major spike in pressure (e.g. a tidal wave or hurricane) beyond the normal range of variability in which the system operates. Perturbations commonly originate beyond the system or location in question. Stress is a continuous or slowly increasing pressure (e.g. soil degradation), commonly within the range of normal variability. Stress often originates and stressors (the source of stress) often reside within the system. Risk is the probability and magnitude of consequences after a hazard (perturbation or stress).*"

- individual/household resources (e.g. income and other asset bases) and, in urban contexts, the extent and quality of infrastructure and public services and the entitlement of populations to those resources and services; and
- the quality and inclusiveness of governance structures and community organizations that provide or manage safety nets and other short- and longer-term responses.

The aim of this paper is to describe both Mexico City's exposure to flooding, water scarcity and other hazards that climate change is likely to aggravate, and some of the environmental and socioeconomic determinants of its vulnerability to these. It describes the climatic and hydrological conditions that explain the abundance of water resources, the droughts and the floods that have recurrently affected the Valley of Mexico Basin for centuries. It also presents the water-relevant implications of climate change for the city (Section II). Floods, droughts and other water-related hazards are the result not only of "nature" but also of past and present socio-environmental changes, as described in Section III. Section IV considers what parts of Mexico City's population, infrastructure and systems are most vulnerable, providing some reasons why this is so. Section V presents some closing remarks and reflections.

II. THE BASIN OF MEXICO CITY: HYDROLOGICAL AND CLIMATIC CONDITIONS

Mexico City is located in the lower part of the Mexico Valley Basin, a "naturally" enclosed depression, around 2,200 metres above sea level, in the central part of the trans-Mexican volcano belt. The basin is surrounded by mountains that reach just above 5,000 metres. The average annual temperature is 15°C, with a variation of 8°C between summer and winter. Most of the average annual precipitation (between 600 millimetres in the northern areas and 1,200 millimetres in the southern areas) occurs between May and September, with little to no precipitation during the remaining months.

Climate has been a key determinant of the basin's hydrological peculiarities. Scholarship on climate and climate variability in the basin of Mexico during the last 600 hundred years points to the alternation of wet years (and floods) with drought episodes, some of them severe and protracted, in some cases lasting more than 10 years. Between 1450 and 1900, 136 droughts occurred;(7) more recent studies indicate four periods of serious drought between 1948 and 1996; and two more droughts were registered between 1997 and 2006.(8) During the last century, the city has experienced increases of up to 1.6°C in its mean temperature, largely due to the heat-island effect that is the result, among other things, of land use changes and transformations in the hydrological cycle (Section IV).

The Mexico Valley Basin used to have a very large number of springs in the lakes, foothills and mountains, with an excellent system of aquifers that still meet 68.5 per cent of the requirements of its enterprises and 18 million inhabitants. Mexico City has suffered from recurring floods, often the result of episodes of short-term heavy rainfall, precisely because it is located on the basin floor, much of it on sites where lakes once existed. The lake system used to act as natural drainage for precipitation run-off,

7. Mendoza, B, E Jauregui, R Diaz Sandoval, V Garcia Acosta, V Velasco, G Cordero et al. (2005), "Historical droughts in central Mexico and their relation with El Niño", *Journal of Applied Meteorology* Vol 44, May, pages 709–716.

8. See reference 3; also CENAPRED, cited by Arredondo Brun, J C (2007), "Adapting to impacts of climate change on water supply in Mexico City", accessible at hdr.undp.org/en/reports/global/hdr2007-2008/papers/; and La Red (2008), "Desinventar", accessible at http://www.desinventar.org/.

which was carried down by rivers and streams from the higher elevations that surround the basin. The abundant water supply and the propensity to flood, which represent simultaneously one of the chief advantages and one of the most perilous dangers of the basin, are determined by at least three peculiarities in the structure and functioning of the hydrological cycle:[9]

- the mountains that surround the Mexico Valley Basin – basalt and andesite rock formations – are highly permeable to precipitation, thus determining both the high levels of aquifer refill and the formation of abundant springs and water sources, at least until the first half of the twentieth century;
- the mountains and hills were covered in mixed forests of diverse species of oak and pine, as well as *madronos*, alder, cypress, shrubs and grasses.[10] Forests served as barriers against the wind and water erosion of the soil, and also contributed to a dynamic equilibrium between the proportion of water precipitated, filtered, evaporated and drained off to the bottom of the basin. They were hence key in moderating the scale of surface run-off and thus of floods; and
- even into the twentieth century, the basin floor was covered by a series of extensive and shallow lakes, which dried up as a result of evaporation. The sedimentary layers of these lakebeds registered periodic cycles of replenishment and desiccation, during the wet and dry years, respectively. The process was accelerated by the interaction of changes to the hydrological system with land use changes caused by primary activities and urban growth. The depth of the lakes, between one and three metres, tended to increase during the rains and diminish during the dry season. The lake system also contributed to the dynamic equilibrium between precipitation, run-off, evaporation and infiltration; it dampened the impact of the floods that have always affected the lower part of the basin, precisely where the Aztec capital Tenochtitlan and – afterwards – Mexico City were situated.

A seemingly infinite number of rivers and seasonal streams used to flow from the mountain regions into the lake system, and they were a source of water for the irrigation of ranches and plots of land, and for factories. They periodically flooded the city and other areas of the basin during the rainy season. Today, many have either dried up or have been encased and converted into sewers.

Thus, the Valley of Mexico experienced a succession of dry and wet periods and a hydrological cycle in which precipitation, infiltration and evapo-transpiration maintained a dynamic equilibrium: a cycle based on unique ecological factors such as mixed forests and a system of lakes.

Besides being affected by the environmental transformations described below, the climatic and hydrological conditions of the basin are projected to be influenced by global warming.[11] Results from general circulation models suggest changes in means and in extremes that threaten to disrupt the balance of the system still further. With a predicted increase in mean temperatures of up to 4°C, together with a predicted decrease in mean precipitation of up to 20 per cent by 2080 (Table 1), Mexico City can expect a more intense hydrological cycle, which is likely to affect the levels of the aquifers that still provide Mexico City with most of its fresh water. The expected increase in the evapo-transpiration rate, along with decreases in the precipitation run-off and aquifer recharge rates will decrease the availability of fresh water for the city's inhabitants and economic activities.

9. The hydrological cycle is a conceptual model that describes the storage and movement of water between the biosphere, atmosphere, lithosphere and hydrosphere. Water can be stored in any one of the following reservoirs: atmosphere, oceans, lakes, rivers, soils, glaciers, snowfields and groundwater. Water moves from one reservoir to another through processes such as evaporation, condensation, precipitation, deposition, run-off, infiltration, sublimation, transpiration, melting and groundwater flow.

10. See reference 1, Sanders et al. (1979), pages 88–89.

11. Jauregui, E and A Tejeda (2001), "A scenario of human thermal comfort in Mexico City for CO2 conditions", *Atmosfera* Vol 14, pages 125–138.

TABLE 1
Expected changes in precipitation and temperature in Mexico City

Federal District: 2020 scenario		**State of Mexico: 2020 scenario**	
Total annual precipitation will diminish 5–10%	Mean annual temperature will increase 1.8–1.2°C	Total annual precipitation will vary +5 to –5%	Mean annual temperature will increase 0.8–1.2°C
Federal District: 2050 scenario		**State of Mexico: 2050 scenario**	
Total annual precipitation will diminish 5–10%	Mean annual temperature will increase 1–2°C	Total annual precipitation will vary +5 to –15%	Mean annual temperature will increase 1–2°C
Federal District: 2080 scenario		**State of Mexico: 2080 scenario**	
Total annual precipitation will diminish 5–20%	Mean annual temperature will increase 2–4 °C	Total annual precipitation will diminish 5–20%	Mean annual temperature will increase 2–4 °C

SOURCE: INE (2008), accessed 12 January 2009 at http://www.ine.gob.mx/cclimatico/edo_sector/estados/futuro_mexico.html.

Expected changes in extremes include the alternation of more intense droughts and heat waves with short episodes of intense rain (storms, hailstorms). These climate hazards might aggravate water shortages and floods, as well as increase risks from waterborne diseases.(12) Yet, the future potential impacts of these hazards will depend among other things on the ways in which the city's socio-ecological system currently amplifies climate impacts (as described in Section III), and the vulnerability and adaptive capacity of the city, its water system and its population (Section IV).

III. SOCIOECONOMIC AND ENVIRONMENTAL ANTECEDENTS

Hazards such as floods and droughts are created not only by natural processes. History reveals that the vulnerability of urban water systems and users may have been centuries in the making,(13) and results from such socio-environmental processes as the construction and operation of water infrastructures, and land use changes induced by agriculture, logging, cattle and urbanization. It is necessary to consider how the main transformations that result from these processes have reduced the resilience of Mexico City's water systems and populations during the pre-Hispanic, colonial, and "Porfiriato"and post-revolutionary eras.(14)

a. Pre-Hispanic period

During the pre-Hispanic era, the Aztec state and society applied different mechanisms to take advantage of water: they re-routed rivers and constructed terraces, dams, reservoirs, canals, irrigation ditches and other infrastructure. They built terraces and *chinampas*, a very productive and sustainable method of crop cultivation developed by previous lakeside civilizations/communities.(15) They also developed lacustrine transport systems, and used water as a source of sustenance for diverse species of fish, amphibians and birds, as well as for recreation, consumption and domestic activities.

The Aztec state constructed and operated an impressive hydraulic system, composed of roads, dikes, locks and aqueducts, to cope with or adapt to existing climatic and hydrological conditions. It had two objectives: to control the level of the lakes, in order to protect their

12. See reference 3.

13. Hilhorst, D (2004), "Complexity and diversity: unlocking social domains of disaster response", in Greg Bankoff, Georg Frerks and Dorothea Hilhorst (editors), *Mapping Vulnerability: Disasters, Development and People*, Hopkins University Press, pages 52–66; also Ávila García, P (2006), "Water, society and environment in the history of one Mexican city", *Environment and Urbanization* Vol 18, No 1, April, pages 129–140.

14. All of Section III draws on Romero Lankao, Patricia (1999), "Obra hidráulica en la ciudad de México y su impacto socio-ambiental, 1880–1990", Instituto Mora, Mexico, 163 pages.

15. *Chinampas* are areas of raised land created from alternating layers of mud from the bottom of the lake with plant matter/other vegetation. These "raised beds" or "swimming gardens" (Humboldt) measured between two and four metres wide and 20 to 40 metres long. They rose about one metre above the surface of the water and were separated by narrow canals, which allowed farmers to move between them by canoe. The *chinampas* were extremely fertile pieces of land and yielded on average four crops annually. In order to plant on them, farmers first created "seedbeds", or

capital city, Tenochtitlan, and its agriculture from floods; and to supply Tenochtitlan with the abundant water from the springs of Chapultepec, as well as to irrigate agricultural fields. It should be noted that at its peak, during the late fifteenth century, Tenochtitlan's population was estimated at half a million, making it one of the world's largest cities at the time. The basin's population reached an estimated 1.5 million inhabitants, distributed in more than 100 towns.

The Aztecs cleared forests, modified and controlled the level of the lakes, re-routed rivers, filled or drained the lakes to gain land, and thereby accelerated erosion and the impact of floods. The Aztecs' environmental transformations of the basin's hydrological cycle resulted in stronger floods, affecting their economy and quality of life, but their actions did not have the far-reaching impacts of those of later populations.(16)

reed rafts, where they planted seeds and allowed them to germinate. Once germinated, the seedlings were replanted in the *chinampas*. This cut down the growing time considerably.

16. Ezcurra, E, M Mazari-Hiriart and A G Aguilar (1999), *The Basin of Mexico: Critical Environmental Issues and Sustainability*, United Nations University Press, Tokyo, 216 pages.

b. Colonial period

During the colonial era (from the destruction of Tenochtitlan and its hydraulic system until the final quarter of the nineteenth century), the not-necessarily successful reconstruction of the pre-Hispanic hydraulic system was undertaken on behalf of the vice-regal authorities.(17) Indigenous communities and Spaniards developed different coping mechanisms. They used and re-routed bodies of water; they dried out lake areas and constructed dams, canals and water reservoirs; they built and maintained ranches, plots of land, orchards and haciendas, and irrigated agricultural systems such as the *chinampas*.(18) A range of features distinguished water use and management during this period.

The first feature was the construction, between 1607 and 1788, of the Nochistongo canal, designed to drain Lake Zumpango and the feared Cuautitlán River, located to the northeast of the basin. The so-called "royal drainage channel of Huehuetoca" was the first hydraulic work designed to do more than just control the water; it also had the first "hydrological footprint",(19) designed to drain water away from the basin.

Attention was also given to the problems of sanitation in Mexico City. The city relied on a series of filtration tanks and pipes connected to a system of open channels, generally located in the middle of the streets, which transported sewage and household wastewater from west to east towards a large dike or watercourse (the San Lázaro) that ran from the southeast to the northeast of the city. Since the inhabitants of the city used it to dispose of their waste, trash and other debris, it was often clogged; the channels also became a source of cholera, typhus and other disease that repeatedly afflicted the population.

Because they were open systems, the aqueducts and the public supply sources contributed to a further deterioration in the quality of the water supply. Water use upstream affected the users located downstream. As a result, the water was often "contaminated" and didn't reach the required standards for drinking and cleaning.

Water sources were abundant during the colonial era, but unevenly distributed, creating problems of "scarcity". Natural springs in places such as Chapultepec, Desierto de Los Leones, Churubusco and Guadalupe provided for an average daily consumption of 264.6 litres per person; but while some districts had a number of public wells, others lacked

17. See reference 1, Palerm (1973).

18. See reference 1 Palerm (1973); also Rojas, T, R Strauss and J Lameiras (1974), "Nuevas noticias sobre las obras hidráulicas prehispánicas y coloniales en el Valle de México", SEP/INAH, Mexico.

19. Drawing on the concept of "ecological footprint"*, the notion of "hydrological footprint" refers to the environmental effects of cities that go beyond the areas they occupy and that result in enormous urban demands for water from external zones and also in "sending out" large quantities of waste or sewage waters from urban water uses. *See Rees, William E (1992), "Ecological footprints and appropriated carrying capacity: what urban economics leaves out", *Environment and Urbanization* Vol 4, No 2, October, pages 121–130.

even one. Poor inhabitants to the east of the capital suffered from water shortages and scarcity, particularly during the dry season; but in the more affluent sectors to the west, where some had access to private wells, water was wasted in spills from aqueducts and wells and also by the wasteful practices of some users. This spatial inequality and waste are prevalent even to this day. The impact of this inequality was intensified by the unparalleled transformation of the regional hydrological cycle and its effects on the economy and quality of life. Pluvial and wind erosion were accentuated, accelerating the drying up of the lakes and intensifying the force and impact of the floods.

c. The "Porfiriato" and post-revolutionary period

A system of water use and management that was created during the dictatorship of Porfirio Díaz (1876–1911) was consolidated by the regimes stemming from the 1910 Mexican Revolution, and lasted until the beginning of the twenty-first century. The Porfiriato regime introduced a water supply that relied on the operation of artesian wells. It included a closed distribution system, which improved the quality of fresh water, and a 26-kilometre long aqueduct that carried water from Xochimilco in the southeast, then outside the city, to the *tanques de dolores* (storage tanks west of the city). The regime also completed the project to drain the basin of Mexico City that had been contemplated since the seventeenth century. For its time, the mostly open main drainage channel, or Gran Canal, and the closed network of combined secondary and tertiary drainage, was a state-of-the-art system aimed at coping with floods and improving the sanitary conditions of the city. The Gran Canal, which is 48.1 kilometres long and has a drainage capacity of 15 cubic metres per second, connects to the Tequixquiac drainage tunnel, which is 9.5 kilometres long and located 40 kilometres from the (then) city, and removes the water completely from the valley into the Tula River. The tunnel and canal combine to form a system that captures the residual waters and rainwater through six principal collectors (primary system), five from west to east and one from south to north, which connect the secondary system of drains to the Gran Canal.

The Porfiriato era hydraulic system, much of which still remains operational today, set various milestones. It consolidated a centralized, state-centered system of water management, while local institutional structures and political participation remained fragmented. The water authorities favoured the requirements and interests of the capital over the priorities of local economic sectors and other regions connected to the city through the hydraulic system. With it, the artificial unification of those spaces of the basin covered by the system was initiated, including zones linked to the city through the provision and removal of water through supply, sanitation and drainage infrastructures.[20] This initiated a complete modification of the basin's hydrological cycle, whereby rainwater no longer followed the path of infiltration, storage in water aquifers, stagnation and evaporation in lakes – at least not in the same proportions. A significant amount of the water was removed, consumed and wasted, and another portion could not arrive at its final destination – lakes and aquifers – because a system of pipes captured and removed it from

20. See reference 14, Romero Lankao (1999); also Perló, M and A E González (2005), "¿Guerra por el agua en el Valle de México? Estudio sobre las relaciones hidráulicas entre el Distrito Federal y el Estado de México", UNAM–PUEC, Mexico, 143 pages.

the basin, along with all of the residual water left there. Furthermore, groundwater extraction initiated during the last quarter of the nineteenth century resulted in subsidence and in a failure of the Gran Canal. (This later led to the construction of the gravity-fed deep drainage system). Hence, an absurd situation was created whereby storm and wastewater was (and is currently) pumped out of the basin, while 34 per cent of the total drinking water is brought from increasing distances, with increasing energy and money expenditure and increasing greenhouse gas emissions as it has to be pumped up into the basin.(21)

The post-revolutionary governments extended and consolidated the Porfirian system. They constructed new artesian wells as well as systems that transferred or imported water from the Lerma Basin (1951) and the Cutzamala Basin (1982), located to the west and southwest of the Mexico Valley Basin (Figure 2). Applying a supply approach as principal management strategy, they expanded the water distribution and drainage systems, but often, supply was exceeded by demand and the patterns of urban growth. In 1970, the government inaugurated the "system of deep drainage", which drains from the basin 200 (and sometimes as much as 300) cubic metres of residual and rain waters per second from domestic,

21. The amount of electricity used to pump the total volume of water from the Cutzamala system to the treatment plant located to the west of the city of Toluca is equivalent to the amount of energy consumed by the city of Puebla, which is inhabited by about 1.5 million people. This is because the water is transferred for a distance of 60 to 154 kilometres and is then pumped up more than 1,000 metres, requiring 102 pumping stations, 17 tunnels and 7.5 kilometres of canals. See Tortajada, C (2006), "Who has access to water? Case study of Mexico City Metropolitan Area", thematic paper for *Human Development Report 2006*, accessible at hdr.undp.org/en/reports/global/hdr2006/papers/.

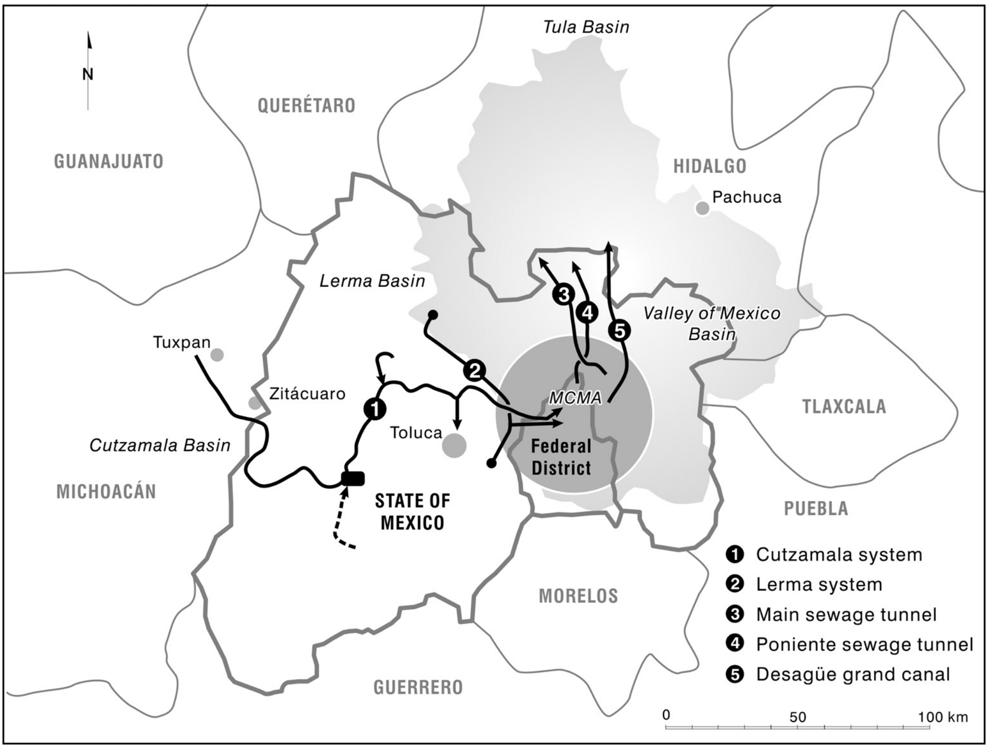

FIGURE 2
The mega-basin of Mexico City

SOURCE: Adapted from AEGR (2004), GIS services.

TABLE 2
Sources of potable water supply in the metropolitan zone of Mexico City (cubic metres per second)

Source	1950	1960	1970	1980	1992	2002*
Internal (well, springs, rivers)	10.8	16.6	26.0	41.8	44.4	45.2
Lerma		4.4	10.0	8.4	5.3	5.9
Cutzamala	–	–	–	–	10.6	14.9
Total	**10.8**	**21.0**	**36.0**	**50.2**	**60.3**	**66.0**

SOURCES: Romero Lankao, Patricia (1999), "Obra hidráulica en la ciudad de México y su impacto socio-ambiental, 1880–1990", Instituto Mora, Mexico, 163 pages; also *Arredondo Brun, J C (2007), "Adapting to impacts of climate change on water supply in Mexico City", accessible at hdr.undp.org/en/reports/global/hdr2007-2008/papers/.

commercial and industrial users, including highly contaminating sectors such as paper and cement.[22]

Currently, the drainage system of Mexico City has a primary network of 2,087 kilometres of sewage pipes and a secondary network of 10,237 kilometres of pipes, 68 pump stations, numerous dams, reservoirs and regulation tanks, 111 kilometres of open canals, 42 kilometres of "drainage rivers" and 118 kilometres of deep collectors (interceptors) and tunnels. There are also 25 treatment plants in the Federal District and 45 in the municipalities of the state of Mexico, with a total installed capacity of 10.2 cubic metres per second. Only 9 per cent of the water is treated,[23] and evidence suggests that the untreated portion might contaminate the sub-soil and even the aquifer system.[24]

According to the most recent information available at the metropolitan level, about 66 cubic metres of fresh water per second is supplied to the city, of which 68.1 per cent is from local sources and 22.5 per cent and 8.9 per cent from Cutzamala and Lerma, respectively (Table 2). Included in the water supply system are 12,278 kilometres of secondary distribution lines, a primary network of 1,074 kilometres of pipes, 275 storage tanks of around 1.94 cubic metres each and 183 pump plants. The domestic sector consumes 72 per cent of the supplied water, the industrial sector 16.2 per cent and the commercial and service sector 11.6 per cent. Proposals are underway to use 25 cubic metres per second from the Mezquital Valley aquifer, which since 1896 has used Mexico City's sewage waters to irrigate agricultural fields.[25] Yet, high concentrations of nitrates (up to 19.6 milligrammes/litre) and total coliforms (more than 2,400 colony-forming units/100 millilitres in some boreholes) cast health concerns onto whether that option is feasible.[26]

IV. UNDERLYING VULNERABILITIES

This section describes the features of the city and its water system that make it vulnerable to water and climate hazards, and the impact that land use changes induced by primary activities and urbanization have had on vulnerability. It also presents some of the socioeconomic determinants of vulnerability, such as individual and households endowments, the extent and quality of water infrastructure and services, and the quality of the city's governance structures.

22. Programa de las Naciones Unidas para Medio Ambiente (PNUMA) (2003), "GEO Ciudad de México, perspectivas del medio ambiente", PNUMA, Mexico, 154 pages.

23. GDF (2007), "Programa para el manejo sustentable del agua para la Ciudad de México", accessed 1 September 2009 at www.sma.df.gob.mx/dgpcp/pdf/ProgAgua_Cd.

24. See reference 22; also Mazari-Kriart, M, B Torres-Beristain, E Velazquez, J J Calva and S D Pillai (1999), "Bacterial and viral indicators of faecal pollution in Mexico City's southern aquifer", *Journal of Environmental Science and Health Part A*, Vol 34, No 9, pages 1715–1735.

25. Together with post-revolutionary agrarian policies, the use of these waters contributed to the development of agricultural irrigation systems and to major increases in corn and alfalfa yields. Yet, the levels of contamination by sewage water have resulted in two negative impacts: restrictions on the cultivation of vegetables and increasing production costs for farmers. For instance, instead of planting alfalfa every 6–8 years, farmers need to plant it every 4–6 years. See Romero Lankao, Patricia (1999). An example of the proposals to use the waters of Mezquital's aquifer can be found in R Pérez, R Jiménez, B Jiménez and A Chávez (2009), "¿El agua del Valle del Mezquital, fuente de abastecimiento para el Valle de México?", accessed 1 September 2009 at http://www.bvsde.paho.org/bvsaidis/saneab/mexicona/R-0069.pdf.

TABLE 3
The basin of Mexico City: water balance according to two calculations

Annual precipitation	Evapo-transpiration	Aquifer recharge	Surface run-off	Availability	Over-exploitation
213 m^3/s*	171 m^3/s	23 m^3/s	19 m^3/s	40 m^3/s	22.2 m^3/s
226.7 m^3/s** (746mm)	163.2 – 179.1 m^3/s	29 m^3/s	29.1 m^3/s	48.1 m^3/s	19.1 m^3/s

SOURCES: *Departamento del Distrito Federal (DDF) (1982), "El sistema hidráulico del Distrito Federal. Un servicio público en transición, México", DDF, Mexico; also **Arredondo Brun, J C (2007), "Adapting to impacts of climate change on water supply in Mexico City", accessible at hdr.undp.org/en/reports/global/hdr2007-2008/papers/.

a. Features of the water system that amplify the city's vulnerability

As a result of the socio-environmental changes described above, both the current water system and the city have unique characteristics that amplify the impacts of rains, floods and other hazards that climate change is expected to aggravate. The first is the profound transformation of the hydrological cycle by the engineered systems described earlier, which has created irreversible changes in the regional water balance as well as changes in the basin's climate. Mexico City is now over-exploiting its water resources by between 19.1 and 22.2 cubic metres per second, depending on the calculations (Table 3). This creates two kinds of vulnerability. Problems of water availability (scarcity), created by human actions, make water users vulnerable to the changes in the availability of water that are expected from climate change. According to projections where no consideration is given to global warming, between 2005 and 2030 the population of Mexico City will increase by 17.5 per cent, while between 2007 and 2030 available water will diminish by 11.2 per cent.(27) The situation might get worse if – as expected – climate change brings lower precipitation. Those water users who already face recurrent shortages during the dry season or when droughts hit Mexico City will be especially affected. For example, 81.2 per cent of people affected by droughts during 1980–2006 live in Netzahualcoyotl, one of the poorer municipalities of the city.(28)

The other vulnerability is related to the continuous downward displacement of groundwater levels, which historically has caused subsidence and continues to do so in some areas, thus undermining the foundations of buildings and urban infrastructure and increasing their vulnerability to such hazards as heavy earthquakes and rains (the intensity of the latter will be aggravated by climate change). As mentioned earlier, the location of the city puts its residents at risk from floods regardless of economic or social position – floods are the main source of disaster for 70 per cent of the sub-sections (delegations and municipalities). But not all of the population is equally affected. For example, 36.1 per cent and 32.7 per cent of people reported to be negatively affected by floods are located in the municipalities of Tultitlan and Chimalhuacan, respectively, (Table 4), which became part of the city during the 1960s and 1970s, increasing their populations by 7.2 and 23.5 times, respectively, between 1970 and 2000.(29) There have been problems of access to and quality of the water infrastructure ever since.

26. Jiménez, B, A Chávez, J Barrios and R Pérez (2000), "Impact and potential of re-used water in the Mezquital Valley", *Water* Vol 21, June, pages 34–36.

27. Partida, V and C Anzaldo (2009), "Escenarios demográficos y urbanos de la zona metropolitana del Valle de México", accessible at www.conopo.gb.mx/publicaciones; also CONAGUA (2008), "Estadísticas del agua en México", accessible at www.conagua,gob.mx.

28. According to data from La Red (2008), of the total 1,461,000 people reportedly affected by droughts at the city level during that period, 1.2 million lived in Netzahualcoyotl, the fourth most populous and second densest municipality in Mexico City, and dominated by the working class. It is also considered among the most dangerous places in Mexico due to the rampant crime in the area.

29. Molina, Mario and Luisa Molina (editors) (2002), *Air Quality in the Mexico Megacity: An Integrated Assessment*, Kluwer, Netherlands, Table 3.2, page 64.

TABLE 4
Number of floods and people affected during 1980–2000

Municipality	Number of floods	%	Number of people affected	%
Azcapotzalco	12	1.80	0	0
Coyoacan	18	2.69	23	0.001
Cuajimalpa	10	1.50	0	0
Gustavo A Madero	30	4.49	231,000	8.34
Iztacalco	8	1.20	0	0
Iztapalapa	53	7.93	63,480	2.29
Magdalena Contreras	17	2.54	0	0
Milpa Alta	8	1.20	22,400	0.81
Alvaro Obregon	33	4.94	1,250	0.05
Tlahuac	16	2.40	0	0
Tlalpan	24	3.59	1,000	0.04
Xochimilco	23	3.44	34,000	1.23
Benito Juarez	19	2.84	0	0
Cuauhtemoc	27	4.04	1,000	0.04
Miguel Hidalgo	21	3.14	0	0
Venustiano Carranza	12	1.80	100	0.004
Tizayuca	2	0.30	0	0
Atenco	3	0.45	0	0
Atizapan de Zaragoza	10	1.50	320	0.01
Coacalco	12	1.80	0	0
Coyotepec	2	0.30	700	0.03
Cuautitlan	3	0.45	8,000	0.29
Chalco	43	6.44	9,670	0.35
Chiautla	2	0.30	150	0.01
Chicoloapan	8	1.20	650	0.02
Chiconcoac	1	0.15	0	0
Chimalhuacan	24	3.59	906,200	32.70
Ecatepec	58	8.68	76,200	2.75
Huixquilucan	7	1.05	0	0
Ixtapaluca	21	3.14	164,580	5.94
Naucalpan	33	4.94	2,021	0.07
Netzahualcoyotl	36	5.39	96,940	3.50
Nicolas Romero	3	0.45	0	0
Papalotla	1	0.15	0	0
La Paz	8	1.20	15,000	0.54
Tecaimac	2	0.30	0	0
Tenango del Aire	1	0.15	400	0.01
Teoloyucan	3	0.45	2,000	0.07
Tepotzotlan	1	0.15	0	0
Texcoco	4	0.60	1,600	0.06
Tlalmanalco	5	0.75	0	0
Tlalnepantla	19	2.84	100,000	3.61
Tultepec	3	0.45	400	0.01
Tultitlan	12	1.80	1,000,200	36.09
Zumpango	2	0.30	0	0
Cuautitlan Izcalli	8	1.20	32,000	1.15
Total MCMA	**668**	**100**	**2,771,284**	**100**

NOTE: 12 municipalities were excluded because they didn’t register any flooding. The number of people affected was the number of persons needing immediate assistance during the emergency, including displaced persons and evacuees.
SOURCE: Own calculations based on data from La Red (2008), “Desinventar”, accessed 20 December 2008 at http://www.desinventar.org/.

Another unique characteristic that amplifies the impacts of rains, floods and other hazards is that the water system essentially configured a mega-basin (Figure 2) by artificially unifying not only the urban areas covered by supply and drainage but also all the regions connected to the city through water supply and sanitation.[30] This, together with such factors as land use changes, has made Xochimilco, Lerma and Cutzamala vulnerable to water scarcity, floods and other climate hazards. For example, the springs in lakes Xochimilco and Lerma, which began to help meet the city's demand for water in 1911 and 1951, respectively, dried up.[31] The lakes reduced in volume and size and Lake Xochimilco is now maintained with treated water. Both lakes have become dumps for sewage water, for trash generated by domestic users and, in Lerma, for chemicals generated by industrial activities.[32] There is a downward displacement in the groundwater levels along the aquifer zones of 1–1.5 metres annually, as well as soil subsidence, which results in damage to infrastructure and property. The vulnerability of these areas to floods and waterborne diseases has also increased, thus becoming an indirect source of vulnerability for Mexico City.

The transformations in these regions have had negative impacts on the livelihoods of the local populations. For instance, between 1950 and 1990, the *chinampas*[33] practically disappeared from Xochimilco, the agricultural areas diminished by 73.7 per cent, and the average corn yields fell from 1.7 to 1.1 tonnes per hectare. Greenhouse production became the principal "agricultural system" in the area. This does not mean that agriculture disappeared but, rather, that local populations changed their livelihood strategies, which historically have been diversified. By the end of the nineteenth century, local populations combined three agricultural systems: *chinampas*, ravines and terraces.[34] Currently, the *chinampas* are a source of other livelihood strategies; farmers build nurseries and greenhouses there, as well as houses. They combine this with selling agricultural products and working in the formal and informal sectors (driving minibuses, or working as housekeepers and street vendors).[35] While allowing the Xochimilco population to "survive", these diversification strategies are generating greatly increasing socio-environmental deterioration and disaster risks in the area. As local populations increasingly build their homes in areas of the lake system in order to be closer to opportunities for diversified income streams, they are also more affected by, and vulnerable to, various kinds of environmental deterioration and its social implications: the contamination of the lake with sewage water primarily from domestic installations; soil subsidence; and tremors and floods.

The third characteristic is the combined flow of the city's sewage and captured rainwater towards the Mezquital Valley, amounting to 45 and 16–200 cubic metres/second, respectively. Although Mezquital benefited in a contradictory way from the use of sewage water,[36] the drainage caused the drying up of the Mexico basin lake system, the springs and countless seasonal streams. Paradoxically, as shown in Figure 1, even this profound modification of the drainage system did not succeed in controlling the perennial floods that periodically affect different areas and sectors of the capital, above all those located in zones and municipalities not covered by drainage, or with drainage of low quality, like the zones of irregular urbanization.

30. See reference 20, Perló and González (2005), which also refers to the concept of "aguapolis", to define this process.

31. This draws from Romero Lankao (1999), see reference 14.

32. In the Valley of Lerma, the network of sewers rose from an average coverage of 48 per cent in 1993 to 82 per cent in 2000, but with great differences in coverage among municipalities, varying from 3 per cent to 90 per cent. Less than one-third of the industrial residual water receives treatment. See Gobierno del Estado de México (1993), "Programa regional Cuenca Alta del Río Lerma", in *Anexo del Atlas Ecológico de la Cuenca Hidrológica del Río Lerma*, *Vol I*, Gobierno del Estado de México; also Gobierno del Estado de México (2005), "Programa hidráulico integral del Estado de México", accessible at http://www.edomexico.gob.mx.

33. See reference 15.

34. See reference 14, Romero Lankao (1999).

35. Romero Lankao, P, M Rodríguez and E Duffing (2004), "¿Tres procesos contradictorios? Desarrollo urbano, ambiente y políticas en Xochimilco durante el siglo XX", in M Terrones, *A la Orilla del Agua. Políticas, Urbanización y Medio Ambiente en el Siglo XX,* Instituto Mora– Delegación Xochimilco, pages 211–252.

36. See reference 25.

b. Land use changes

Although fundamental to its change, the engineered hydraulic system was not the only factor contributing to the transformation of the regional hydrological cycle and to the increasing vulnerability of Mexico City to floods, droughts and other hazards. Equally important were the land use changes induced by primary activities and urbanization. Forest exploitation and some of the agricultural and farming practices in the basin of Mexico[37] brought about deforestation and caused land surface erosion. These changing land use patterns also contributed to the accelerated desiccation of the lagoons and the obstruction of the drainage system with sediment from land erosion, while constructed surfaces negatively impacted the capacity of mountainous land areas to allow water infiltration to feed the aquifers.

Urbanization, as a determinant of land use changes, has been another factor in transforming both the hydrological cycle and the regional climate. The urban built environment is a source of heat (and a contributor to the heat-island effect), a poor storage system for water and an impediment to atmospheric movements.[38] Driven by national policies and factors that attract investment (e.g. agglomeration economies), Mexico City saw large-scale growth in urban industries followed by an increase in immigration. From the 1940s to the 1970s, import substitution policies reinforced the concentration of various urban services and compounded the political power of Mexico City. These changes were an important underpinning of increased rural–urban migration. Of comparable significance was an increasing lack of economic prospects in the rural areas, including those immediately surrounding the central city.[39] Since the 1980s, the city has become the hub of financial and service activities, co-existing with an increasingly informal economy.[40]

It is in this context that Mexico City has changed in space and over time. In the 1900s–1950s, it comprised the inner city or core area (four central delegations within the Federal District); in the 1980s, it became the Mexico City Metropolitan Area (MCMA) when the Federal District combined with 17 conurbated municipalities; and by 2003, it included 35 municipalities.[41] Yet, even beyond the limits of the MCMA, another delimitation of the city has to be considered: the mega-city region, which, similarly to the mega-basin,[42] is made of the inner city, the built-up area, five satellite cities (Toluca to the west, Querétaro and Pachuca to the north, Puebla to the east and Cuernavaca to the south) and peri-urban localities.

Notwithstanding the fast economic growth in the post-war period, the economy of Mexico City was unable to absorb all of the labour force. As a result, unemployment and underemployment persist as a structural problem. The poor lack the resources to cover the costs of such determinants of adaptive capacity as land and housing, or the operation and maintenance of urban infrastructure.[43] Between 60 and 70 per cent of the city's growth resulted from people building their own dwellings on peripheral land[44] or on land located in ravines, on hills, on river and lake beds or in mined and industrial areas. The housing, health and assets of these areas' populations are vulnerable to floods (Table 4), heavy rain, landslides, industrial pollution and accidents.[45] For instance, informal settlements in many municipalities in deteriorated mountainous areas are at risk of landslides.[46]

37. According to Sanders et al. (1979) (see reference 1), the basin used to be rich in plant species and vegetation types: a conifer forest in the mountain ridges and the higher piedmont; a moist broad-leafed forest, rich in oaks, in the lower piedmont; grasslands, aquatic vegetation and halophytes in and on the shores of the lake system.

38. The two main causes of the urban heat-island are the modification of the land surface by urban development and waste heat generated by energy usage.

39. Connolly, P (1999), "Mexico City: our common future?", *Environment and Urbanization* Vol 11, No 1, April, pages 53–78; also Izazola, H (2004), "Migration to and from Mexico City, 1995–2000", *Environment and Urbanization* Vol 16, No 1, April, pages 211–230.

40. See reference 22.

41. Romero Lankao, P (2007), "How do local governments in Mexico City manage global warming?", *Local Environment* Vol 12, No 5, May–August, pages 519–535.

42. Or "aguapolis", see reference 30.

43. See reference 2.

44. See reference 39, Connolly (1999); also see reference 22.

45. Aragón-Durand, F (2007), "Urbanization and flood vulnerability in the peri-urban interface of Mexico City", *Disasters* Vol 31, No 4, pages 477–494.

46. See reference 8, Arredondo Brun (2007).

Urban buildings, roads and infrastructure create a higher risk from floods, as these built structures prevent rainfall from infiltrating into the soil – and so produce more run-off. This problem can be mitigated by adequate storm and surface drainage. Yet, even though Mexico City has the highest levels of coverage within the country and its drainage services cover areas of recent urbanization such as Chalco and Chimalhuacan to the east, Xochimilco to the southeast and Ecatepec and Tutltitlan to the north, the services are not of the required quality. For example, the poor functioning of the sewage system in Chalco and Netzalhualcoyotl (the Compania Canal and the Xochiaca drain, respectively) results in chronic flooding with sewage in poor neighbourhoods or *colonias*.[47] As a result, local populations are affected by waterborne, gastrointestinal and skin diseases; they are also affected by cuts in electricity and piped water supplies.[48]

47. *Colonias* are similar to neighbourhoods, located within municipalities and delegations.

48. See reference 45.

c. Socioeconomic and institutional determinants of vulnerability

The capacity of Mexico City's inhabitants to cope with floods, droughts and other hazards that are likely to be aggravated by climate change is also determined by such factors as income, housing quality and access to good quality water infrastructure. Mexico City has by far the largest concentration of wealth in Mexico. It generates 32.5 per cent of national GDP, and 60 per cent of banking activity and more than three-quarters of the stock capital are concentrated there.[49] Its per capita income (US$ 13,470 in 2000 US$) is 50.6 per cent higher than the Mexican average. Mexico City, therefore, became the best place to live in the country during the twentieth century, especially during the post-war period, which resulted in high rates of population growth (Figure 3). However, as the city became less attractive as a place to live,[50] this demographic dynamic reversed somewhat during the last two decades. The annual rate of population growth slowed down and the central area, despite being relatively better served with infrastructure than the contiguous municipalities, even registered negative rates of growth (Figure 3).[51]

As in São Paolo, Rio de Janeiro, Johannesburg and other cities from high middle-income countries, wealth is unevenly distributed in Mexico City. More than half the population has an income of less than US$ 4.10 per person per day and cannot afford such determinants of adaptive capacity as food, health, education, transportation, clothes and housing (Table 5).[52]

The extent and quality of water infrastructure and services, another determinant of adaptive capacity, has different dimensions in Mexico City. As already indicated, the coverage of piped water infrastructure in the MCMA is well above the national average (97.2 per cent versus 87.8 per cent, respectively).[53] This does not necessarily translate into equal access to drinking water, in good quality services or in good quality water for all residents. While 80.2 per cent of the population in the Federal District receives piped water inside their dwellings, only 68.8 per cent of the dwellings receive the service all day long (Table 6). People who lack access, or who face shortages during the dry season, buy water from trucks, paying up to five times more per litre than served users, depending on where they live.[54] Problems of water scarcity are especially acute during the dry season. Iztapalapa, Gustavo A Madero, Iztacalco, Tlalpan, Cuauhtemoc, Ecatepec, Chalco and Netzahualcoyotl are delegations and municipalities that are especially affected by water scarcity.[55] Hence, populations within these municipalities will be more vulnerable to the reduced availability of

49. See reference 22, page 52.

50. See reference 39, Connolly (1999); also see reference 22.

51. For instance, the rates of annual growth by in-migration in the contiguous municipalities went from 23.62 per cent during the 1950s to 1.36 per cent in the 1990s. See reference 22.

52. See reference 8, Arredondo Brun (2007). For a discussion of these as indicators of the determinants of adaptive capacity, see reference 2; also Cutter, S L and C Finch (2008), "Temporal and spatial changes in social vulnerability to natural hazards", *Proceedings of the National Academy of Sciences of the United States* (PNAS) Vol 105, No 7, pages 2301–2306.

53. See reference 27, CONAGUA (2008), page 79.

54. See reference 21, Tortajada (2006).

55. See reference 22; also see reference 8, Arredondo Brun (2007).

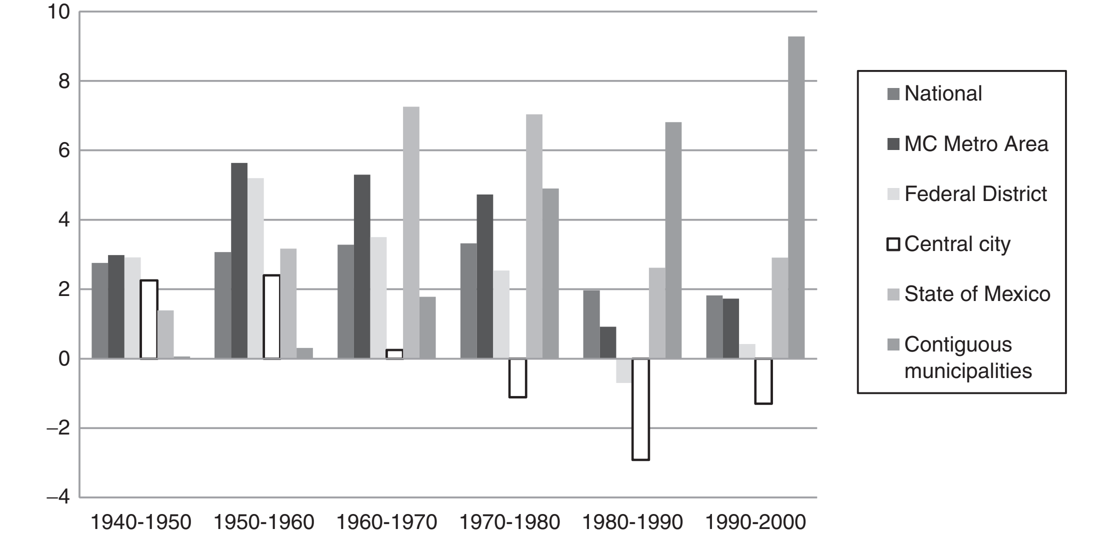

FIGURE 3
Population growth (1940–2000)

SOURCE: Romero Lankao, Patricia (1999a), "Obra hidráulica en la ciudad de México y su impacto socio-ambiental, 1880–1990", Instituto Mora, Mexico, 163 pages; also INEGI (2000), *XII Censo General de Población y Vivienda 2000*, INEGI, Aguascalientes.

water that results from the urbanization of catchment areas, from wastage, inefficient use and disputes with neighbouring states about supplies imported from distant sources. More intense droughts and the decreased availability of fresh water as a result of climate change will come on top of these stresses.

Following a trend in existence since the Porfiriato era, decisions regarding infrastructure provision have been maintained and consolidated in a manner that benefits wealthy zones and contributes to a pattern of unequal spatial access to water. As in cities of other middle- and low-income countries,[56] two tiers of access to water supply were established: the upper tier, with regular access to services, and the lower tier, with less regular access to, or less reliable, services. Sectors with less reliable services were often excluded because they were located in hilly regions that could not be reached by services; or were in areas where multiple factors interfered with reliability, such as lack of water pressure, cuts and provision by rotation. For example, although Xochimilco is located in the southeast, the water system constructed during the Porfiriato era piped water to storage tanks (called *tanques de dolores*) located in the west, and from there it was distributed to the rest of the city. In this context, it should not seem strange that domestic users such as those in Chalco consume between 20 and 80 litres per capita daily, while some users in wealthy zones of Las Lomas get on average around 600 litres per person per day.[57] This means that users located towards the east or in poorer and informal areas are faced with recurrent scarcity and, therefore, might become particularly vulnerable to existing stresses that might be aggravated by climate change.

Drainage infrastructure coverage in Mexico City is also above the national average (95.8 per cent versus 79 per cent, respectively). But

56. Smith, Laura (2002), "The urban political ecology of water in Cape Town, South Africa", accessible at http://www.queensu.ca/msp/pages/project_publications.

57. See reference 22.

TABLE 5
Average values for socioeconomic levels of population

Socioeconomic level	% of population	% of population economically active	% of population 15 years or older with at least elementary education	% of population earning at least 5 times minimum wage	% of owned households	% of households with tap water	Number of persons per room in private houses
High	4.8	51.1	82.3	28.1	64.7	94.9	1.6
Medium-high	9.1	47.5	79.5	17.0	68.7	93.1	1.8
Medium	25.1	46.1	68.8	7.5	66.5	86.1	2.1
Medium-low	20.8	45.1	60.9	3.5	64.7	70.3	2.4
Low	25	44.1	52.7	2.0	68.6	47.2	2.7
Very low	15	42.2	42.9	1.3	79.0	25.8	3.0

SOURCE: Programa de las Naciones Unidas para Medio Ambiente (PNUMA) (2003), "GEO Ciudad de México, perspectivas del medio ambiente", PNUMA, Mexico, 154 pages.

TABLE 6
Indicators of access to water at the household level, Federal District (2000)

Number of houses	% with piped water	% with piped water within the house	% who receive water every day	% who receive water all day long	% who receive water every 2 days	% other*
2,124,632	97.2	80.2	89.2	68.8	3.6	6.8

* Includes houses receiving water.
SOURCE: Programa de las Naciones Unidas para Medio Ambiente (PNUMA) (2003), "GEO Ciudad de México, perspectivas del medio ambiente", PNUMA, Mexico, 154 pages.

again, this does not necessarily translate into equal access to sanitation or to good quality services. Those areas lacking sewers simply dump their wastewater, and pollute both sub-soil and aquifers.(58) As previously mentioned, the drainage system is regularly challenged by intense, short duration storms characteristic of the rainy season, and can even collapse. The disposal of untreated wastewater has become a serious problem for the metropolitan area, especially when considering the high volumes and the nature and levels of pollutants it contains.

Another concern related to health is the quality of piped water, which can be affected by problems with the system's operation and by a lack of sanitation and drainage services in some areas. Despite the fact that measures, actions and systems exist for monitoring water quality (potability), it is doubtful that effective monitoring is being achieved, especially in the central areas of the lake system, to the east of the city, and in some areas of its aquifers. This is due to the contamination of subterranean water with bacteria, faecal matter and sulfates and to the introduction of salt waters into the aquifers.(59) These are a product of overexploitation, subsidence, fractures in and dislodging of the systems, lack of access to sanitation by some sectors, and lack of maintenance of domestic installations (e.g. water tanks). In Iztapalapa and Chalco, for example, the quality of piped water is so bad that inhabitants buy drinking water provided by trucks, which is an economic burden.(60) As mentioned earlier, climate change might aggravate the negative health implications of poor quality water and inadequate sanitation systems.

As yet, there is no accurate data on the health implications of poor water quality in some areas of the Mexico City Metropolitan Area. However, it is known that 30 per cent of enteric diseases in Mexico are related to the quality of water, and diarrhoeal diseases are the fourth most common cause of mortality among infants in Mexico City. In Xochimilco, for example, the prevalence of acute diarrhoeal diseases (14.5 per cent) is 1.6 times higher than the national average.(61)

d. Governance structures

Mexico has undertaken three national assessments (or "national communications") of climate change risks, impacts and adaptation and mitigation options.(62) These assessments were coordinated by the Ministry of Environment and Natural Resources, which is far from being politically powerful. As in other countries (e.g. India(63)), they were primarily focused on the "science" of climate change, closely associated with a top-down approach to assessing vulnerability and adaptation. Such an approach

58. According to Mazari-Kriart et al. (1999) (see reference 24), the viral indicators of faecal pollution in Mexico City's southern aquifer can pose a significant risk to public health when water is distributed and used without adequate disinfection. Also see reference 22.

59. See reference 22.

60. See reference 45, Aragón-Durand (2007).

61. See reference 22.

62. SEMARNAT (2007), *Mexico's Third National Communication to the United Nations Framework Convention on Climate Change*, INE, Mexico, 204 pages.

begins with climate change scenarios derived from global climate models, often in a scaled-down version or regional scenario form. These are then "applied" to some specific target or exposure unit (e.g. the water sector), in order to model the impacts of the scenario on that unit. This perspective has made significant contributions to the understanding of climate impacts.[64] Yet, it does not capture the complex nature of vulnerability and its socioeconomic and environmental determinants, and how they constrain the feasibility of adaptation options.

The government of the Federal District has launched two climate change programmes: the Local Strategy of Climate Action of Mexico City and the Programme of Climate Action of Mexico City (2008–2012), which has involved the consolidation of a more integrated set of strategies to reduce Mexico City's greenhouse gas emissions (mitigation) and adapt its various sectors to the impacts of climate change. Some of the actions suggested to address climate change in the water sector have been proposed many times since the 1950s, without success, including decreases in water use and the restoration and management of both urban and rural micro-basins.[65] Other actions proposed to enhance adaptation include monitoring of disasters, an early warning system and provision for disaster relief. Last but not least, energy efficiency in pumping and treatment plants and the capture of GHG emissions from untreated sewage waters are also suggested in order to reduce emissions.[66]

These studies and programmes have been undertaken in the context of two large institutional transformations: water reform and the democratization of the capital city. Democratization during the 1980s and 1990s was the result of a series of reforms that introduced an elected local assembly, an elected mayor and elected municipal governments.[67] The creation of decentralized public organizations and the opening of some areas of sector administration (e.g. metering) to the private sector marked the water reform. By 1989, after closed litigation in which neither the users nor their representatives participated, the Federal District Water Commission granted concessions to four private companies to administer the Federal District water supply system; however, this did not cover the whole MCMA, as the area outside the Federal District is still administered through distinct local, state and federal regulations.

The performance of the water supply system presents many conundrums. Water supply has improved with the installation of meters, the modernization of the user registry and more efficient collection. Meters increased coverage from 80 to 90.3 per cent between 1997 and 2001; and the collection efficiency increased from 63.5 to 83.1 per cent during the same period.[68] Yet, despite these achievements, the promoters of the reform have been unsuccessful in dealing with:

- structural features of the water system that make the city vulnerable to floods and changes in water availability through the irreversible transformation of the hydrological cycle of the basin;
- the unequal access to supply and to drainage services; and
- the unprogressive system of tariffs.

Furthermore, these reforms have not resulted in effective governance structures.[69] Likewise, there is no long-term, citywide planning for Mexico City as a whole in terms of the needed integration of disaster response into such social and economic policy processes as poverty reduction, improvements in access to affordable housing and land markets, along with

63. Revi, A, (2008), "Climate change risk: an adaptation and mitigation agenda for Indian cities", *Environment and Urbanization* Vol 20, No 1, April, pages 207–229.

64. van Aalst, M K, T Cannon and I Burton (2008), "Community level adaptation to climate change: the potential role of participatory community risk assessment", *Global Environmental Change* Vol 18, pages 165–179.

65. These actions were suggested by two water authorities: the General Direction of Hydraulic Works and the Hydraulic Commission of the Basin of Mexico City. See reference 14, Romero Lankao (1999). Yet, the actual actions resulted in increased water extraction and use (Table 2) and a lack of effective controls on urbanization and other drivers of land use changes in the conservation areas of the Basin of Mexico.

66. See reference 3.

67. Nava Escudero, C (2001), *Urban Environmental Governance*, Ashgate, UK, 267 pages.

68. Martínez Omaña, Concepción (2004), "La participación de la empresa privada en la gestión del servicio de agua en el Distrito Federal", in V Libreros et al., *Gestión del Agua en el Distrito Federal. Retos y Propuestas*, PUIC–UNAM–ALDF, Mexico, pages 17–55.

69. See reference 67; also see reference 41.

70. Wisner, B and J Uitto

more appropriate and effective zoning regulations and the involvement of local neighbourhoods in addressing risks.(70) Rather, in the context of both an historically embedded rigid hierarchy and a paternalistic approach to policy making, there is a focus on humanitarian, post-disaster assistance relief. This is illustrated by the fact that a Council for Social Integration and Help (CONAIS) was created in 2002, not to help vulnerable groups mitigate the factors that made them vulnerable but, rather, to get the necessary assistance relief after climatic disasters hit them.(71)

Policy making on adaptation is strongly constrained by other institutional factors. The political reforms outlined above did not change features such as centralization, complexity and fragmentation. The coordinating commissions and programmes created to deal with such relevant issues as urban planning and water management at the city level(72) do not seem to have allowed authorities to create much coordination thus far. There are different reasons for this. The federal government receives most tax revenues (74.1 per cent), the Federal District and delegations get 12.9 per cent and 9.1 per cent, respectively, and other entities such as the states of Mexico and Hidalgo and the municipalities get only a tiny percentage (4.5 per cent). The Federal District spends almost twice as much per capita as municipal plus state spending combined in the state of Mexico.(73) The disparity between the fiscal capacity of the federal government and the Federal District on the one hand and of the states and municipalities on the other leads to a paradox – more responsibilities are delegated to local authorities but these lack the resources to undertake effective policies. Authorities do not have a culture of cooperation, nor do they have a common and broadly shared metropolitan vision, which may be due to the effects of both election laws(74) and governing by diverse parties. Authorities involved in the management of Mexico City lack other features of institutional capacity (e.g. human resources, money and power) even to manage responses to risks let alone address the underlying causes of vulnerability.

V. CONCLUDING REMARKS: ADAPTATION OPTIONS AND CONSTRAINTS

Over the last few centuries, Mexico City has been faced with wet years and floods alternating with episodes of drought. It has also had abundant water resources. The floods and droughts have been aggravated by environmental transformations and changes in the hydrological cycle along with land use changes induced by primary activities and urban growth. They are expected to be further aggravated by climate change. This paper has shown that to fully understand the urban impacts of these hazards, it is necessary to apply an historical and sociological perspective and to analyze the socioeconomic and environmental factors determining the vulnerability of the city and the different adaptive capacities of its population.

The hydraulic cycle has been profoundly and in many ways irreversibly transformed. This has created a paradoxical situation whereby, first, not even the most sophisticated drainage system has been effective in controlling the floods that continue to affect different areas and sectors of the capital; and second, storm and wastewater is pumped out of the basin while one-third of the total drinking water must be brought in from increasing distances and with increasing investments of capital and energy (and related emissions of greenhouse gases). Besides causing changes in the basin's climate, the

(2007), "Life on the edge: a comparative study of urban social vulnerability and decentralized, citizen-based disaster risk reduction in four large cities of the Pacific rim", in H Brauch, J Grin, C Mesjasz, N C Behera, B Chourou, U O Spring, P H Liotta and P Kameri-Mbote (editors), *Globalization and Environmental Challenges: Reconceptualizing Security in the 21st Century, Volume II*", Springer-Verlag, Berlin.

71. See reference 3.

72. To deal with the lack of coordination, authorities have created climate-relevant coordinating commissions such as the Environmental Metropolitan Commission (CAM), in 1992, and the Human Settlements Metropolitan Commission (COMETAH), in 1995. The commissions function as a relatively lightweight institutional instrument mobilizing relevant stakeholders to focus on key issues. See OECD (2004), "OECD territorial reviews, Mexico City", OECD, Paris, page 71. The efforts have not been effective thus far. For every issue there is a remarkable number of plans designed by federal, state and local authorities, each of which envisions diverse time lines to implement their goals. For instance, eight programmes have been launched in recent years to deal with urban planning (key determinant of land use changes) at the metro and state level; and 44 programmes have been initiated by municipalities and delegations. "*This generates confusion in what their respective objectives should be and in how their actions should be implemented, coordinated and monitored*." (See OECD (2004) above, page 75).

73. See reference 72, OECD (2004).

74. Governors and the president are elected for a single six-year term; municipal presidents and *delegados* are limited to a single three-year period, a possible factor preventing long-term accountability in policy making.

water system has irreversibly transformed the regional water balance and the availability of water. This, in turn, makes water users vulnerable to water scarcity and more intense droughts – and climate change will aggravate both of these. A continuous downward displacement of groundwater levels and subsidence in some areas dislodges buildings and urban infrastructure and increases their vulnerability to heavy rains. The regions that provide water to Mexico City have also become vulnerable to water scarcity, floods, waterborne diseases and other hazards that global warming is expected to aggravate. These transformations have negatively affected the livelihoods of the local populations and created indirect sources of stress for the city. The capital also faces other sources of stress, namely land use changes induced by primary activities, and urbanization pathways that increase the vulnerability of urban populations to floods, landslides and disease.

Not all of the urban population is equally vulnerable. Although the city has the highest concentration of wealth in Mexico, access to many determinants of adaptive capacity is unequally distributed; and about 40 per cent of the population is vulnerable to changes in water availability, which is likely to be aggravated by climate change.

The authorities have undertaken steps to address climate change in a context of water reform and political democratization. However, these reforms have not necessarily resulted in the more effective governance structures that enhance the ability of the city and its population to cope with hazards. Hence, the challenge is to develop a long-term commitment to investing in disaster risk reduction by:

- developing the capacities to anticipate and respond to hazards;
- addressing the underlying processes of socio-environmental deterioration that reduce the city's ability to attenuate hazard impacts; and
- engaging with the socioeconomic and institutional factors underlying poverty and social exclusion that contribute to differentiated capacities to adapt (e.g. lack of effective land use control and prevention of occupation of unsuitable land, both in formal and irregular sectors).

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