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Water Resources Development,
Vol. 26, No. 4, 677–689, December 2010

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Impacts of Water-management Decisions on the Survival of a City: From Ancient Tenochtitlan to Modern Mexico City

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ABSTRACT *Water-management decisions can influence city sustainability. The actions implemented based on these decisions can mitigate, and even prevent, certain water-related risks. Likewise, they can also intensify already existing dangers or generate new ones. Water-management decisions are linked to the institutions that make them, to their capacity for solving specific water-related problems, and to perceptions about which water problems should take priority. Mexico City's inhabitants have been exposed to insufficient water supply, low water quality, a lack of sanitation services and catastrophic floods since the city was originally built. These risks have forced city authorities, at different times, to implement measures to prevent them. This article analyses how water-management policies have developed over the centuries, and how these policies have affected the city inhabitants, and the environment. The study uses as an example the history of water-management decisions and practices in Mexico City. It also points out relevant future directions for water policy.*

Introduction

Water is an essential resource for human survival and development. For this reason, government authorities must ensure equitable water distribution, adequate quantity and quality of water supply, and wastewater treatment. Throughout history, water-management authorities have set their own diverse priorities and objectives to deal with the issue. These priorities have driven their decisions and practices to solve water-related problems. In turn, these decisions and practices have influenced the perceptions of society and have been also used by authorities as a measure to exercise their power.

Not all water-related problems that endanger the health of the population and the sustainability of cities have been addressed by authorities. The government's recognition that these water-related problems should take high priority within the public agenda has historically been subject to outside forces: the economic and political interests of business elites, political parties, and civil servants. These groups continually compete with each other to drive public policy by imposing their own perceptions and private interests.

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0790-0627 Print/1360-0648 Online/10/040677-13 © 2010 Taylor & Francis
DOI: 10.1080/07900627.2010.519503

To the present day, water management has given priority to the *supply* of water. Providing this essential resource to as many people as possible has always been considered the highest political priority—more important than guaranteeing safe water consumption or sustainable water management. Thus, government responses have focused on increasing people's access to water, no matter if it means transporting the water from ever-distant sources. This response, however, does not consider the externalities generated by an increasing water demand, by water source degradation and by water quality reduction. Moreover, for several decades, water prices have been subsidised, making it appear to the public that water is a free, abundant resource with minimal costs of distribution. This erroneous perception has sadly contributed to irrational and wasteful water consumption.

Nonetheless, perceptions are changing. The supply-oriented approach that considers water a finite resource whose problems can be solved through the construction of great infrastructure projects and the use of technological advances has been changing very slowly. Currently, water-management decisions and practices are based on a demand-oriented approach. This approach views water as a finite and vulnerable resource with an economic value that must be paid by users to reduce its wasteful consumption, and whose management should be based on the participation of all users (United Nations, 1992).

Some effort has been made to advance water management through the implementation of the integrated water resources management (IWRM) model. Although this model is focused on establishing comprehensive and integrated water management, it presents some challenges when trying to incorporate dynamic interactions between biotic, social, economic and political components into the decision-making process (Global Water Partnership (GWP), 2009). For example, it is not entirely clear how IWRM can be implemented in the real world, how land and water management can be integrated, how collaboration among government institutions and other stakeholder can be promoted, and how to deal with the mismatch between the spatial delimitation of watersheds and aquifers and established political boundaries (Biswas, 2008).

To date, there is no consensus on how water can be managed more effectively and efficiently. The perceptions and self-interests (economic–political) of authorities, elite power groups and society as a whole have determined how water resources have been used, or misused, throughout human history—its allocation, distribution and use. Hope still lies in the belief that technology will be key in facing past and future water-related risks. This expectation has proved to be too optimistic; technological advances alone are insufficient to guarantee a sustainable water supply and clean wastewater disposal.

Water-management decisions and practices throughout human history have had both positive and negative outcomes: some water-related risks have been mitigated and even prevented, while certain *existing* risks, or *new* dangers, have been intensified or created. These new dangers include water conflicts, water pollution, water scarcity, water-borne diseases and groundwater over-exploitation. With the goal of improving current city water management, by learning from past successes and failures, this article analyses how water-management policies have changed over centuries, and how these policies have affected city inhabitants and the environment. The study uses as an example the history of water-management decisions and practices in Mexico City and addresses whether the city's water-management policies are sustainable in the long-term, identifying relevant future directions for water policy.

The ever-changing environment and social transformation of this city started with its foundation in Pre-Colombian times. The Basin of Mexico was artificially opened in the

1600s, and currently has four artificial drainage systems. It is expected that another artificial drainage system will be completed in 2010, with the construction of the East Drainage System. Of the six interconnected lakes that originally served as a water source for the citizens of Mexico City—and also as a protection mechanism for the Aztecs—today only Lake Texcoco and Lake Xochimilco still exist, although drastically reduced in size. Water from the other lakes was extracted at the beginning of the 20th century. Most rivers were channelled, and the few that were not are today highly polluted because they carry wastewater from Mexico City to the sea. Additionally, the aquifer of Mexico has been dangerously overexploited, and the hydrological cycle of this Basin has been severely modified due to changes in air humidity, temperature, precipitation and the aquifer's natural cycle of recharging.

These transformations have had several effects on the city population's exposure to water-related threats. Indeed, since Pre-Colombian times, Mexico City's inhabitants have been exposed to several water-related risks, including an insufficient water supply, a low quality of water, a lack of sanitation services and catastrophic floods. These problems have posed an on-going threat to the operation of the city, and to the lives of its population. City authorities, at different times, have implemented various measures to mitigate and prevent threat impacts. These actions, based on the perceptions and priorities of authorities, have focused their attention on the construction of hydraulic infrastructure to supply the city's population with water, but they have largely ignored non-structural measures. Furthermore, treatment of wastewater and the adverse health effects associated with low quality of water have not received the same level of priority that these water-related problems require to be solved.

Water-management decisions, along with improper land use, profoundly transformed the physical and environmental characteristics of the Basin of Mexico. If past and present water-management decisions and practices continue to follow the same trend—mismanagement of natural resources and ineffective urban planning—Mexico City will experience an unsustainable water-management scenario. It is imperative to identify new relevant directions for future water policy—policies that encourage greater sustainable management of water resources: water allocation, distribution, consumption and disposal.

The First Transformations of the Basin

The Basin of Mexico is naturally *endorheic*, or closed, allowing no outflow to other bodies of water. Over time, melting glaciers and precipitation on the surface formed a set of six interconnected lakes: the Lake of Mexico, Lake Zumpango, Lake Xaltocan, Lake Texcoco, Lake Xochimilco and Lake Chalco. These lakes were fed with water originating from existing rivers, streams and springs. Since these six interconnected lakes existed at different altitudes, water flowed through them towards the centre of the Basin during the rainy season. Lake Texcoco received the water flow from the other five lakes, along with drainage from the mountains, which had high concentrations of salts and minerals. Because Lake Texcoco was the lowest of the aforementioned lakes in this Basin, it was the place where the solutes from the runoff finally concentrated as water evaporated into the atmosphere. As a result, its water was saltier than even seawater. Additionally, this Basin had an extensive aquifer that absorbed excess water during high levels of precipitation, generating springs around the lakes. Conversely, during periods of drought, due to the reduction of their phreatic levels, the size of these six lakes decreased, and most of the springs disappeared (Academia de la Investigación Científica *et al.*, 1995).

Since the Spanish colonization of the Americas in the 15th and 16th centuries, the hydrology of the Basin of Mexico has been severely modified. Neither past nor present city authorities have understood the importance of preserving the hydrological balance of this Basin—its water inflows, outflows and natural storage. City authorities have been, and continue to be, concerned mainly about providing more water to inhabitants and avoiding catastrophic floods. Unfortunately, they have focused little attention on other important issues, such as the quality of the water provided, the disposal and treatment of the wastewater generated, and the transference of water-related risks beyond political boundaries.

The transformation of the Basin of Mexico started with the foundation of Tenochtitlan in 1324 by the native group known as the Aztecs. Although this city was built on a small island in the centre of the Lake of Mexico, the Aztecs quickly understood that the survival of their city depended largely on the preservation of the fragile hydrological balance of the surrounding lakes. These lakes were the base of their civilization: they protected the people of Tenochtitlan from enemy invaders and represented an important food source through harvesting, hunting and fishing.

Due to its location, Tenochtitlan was often devastated by catastrophic droughts and floods before the Spanish invasion in 1519. Nevertheless, the Aztecs faced other dangerous water-related threats, such as an insufficient water supply, low quality water and a lack of sanitation services. To gain control over the hydrology of this Basin and mitigate such water threats, authorities at the time decided to build a complex system of drains, dams, dykes and aqueducts. They constructed *chinampas*, an accumulation of aquatic plants and mud surrounded by swamps (Tortolero, 2000), to cultivate more vegetables and to expand existing land for housing. They also built dams, floodgates, drains and dykes to regulate fluctuating lake water levels during droughts and rainy seasons to diminish the impacts of flooding and to safeguard the quality of the water from lakes. Additionally, they built aqueducts to move water from surrounding springs to areas where it was needed.

The first aqueduct was built in 1416. It supplied Tenochtitlan with water from springs located further away from the Lake of Mexico. This aqueduct was destroyed by a catastrophic flood in 1449. A year later it was reconstructed with two more aqueducts. These aqueducts were also rebuilt some years later because they, too, were destroyed by catastrophic floods (Ezcurra, 1990). Another infrastructure project undertaken after the flood of 1449 was the Nezahualcoyotl dyke—a large wall built with stones, mud and soil. This dyke separated the freshwater of the Lake of Mexico from the briny water of Lake Texcoco. By retaining the freshwater, this infrastructure could supply Tenochtitlan with clean water during periods of drought. It also prevented floods during periods of rain by keeping the briny water apart from the Lake of Mexico (Musset, 1992).

Although the Aztecs tried to preserve the fragile hydrological balance of the surrounding lakes, their water-management decisions increased the population's exposure to numerous water-related risks. For example, water transference from remote springs increased the city's dependence on more distant water sources. Furthermore, Tenochtitlan was more affected by water shortages than before because the repair and maintenance of aqueducts required long periods of closure. Similarly, with the construction of the Nezahualcoyotl dyke, the city's exposure to catastrophic flooding due to insufficient maintenance, failures in the floodgates or blockage of drains was also increased.

Contrary to subsequent water-management practices in Mexico City, the Aztecs implemented non-structural measures to regulate water quality and water-consumption habits. For instance, to preserve the quality of water from the lakes and reduce health risks, city authorities prohibited the disposal of waste into the lakes or the channels that surrounded the city. The transgression of this rule was severely punished (Tortolero, 2000).

In contrast to the minor changes to the hydrology of this Basin during the Pre-Colombian period, the Basin was significantly modified after colonization by the Spanish. The new conquerors associated the water from surrounding lakes with an unhealthy environment and the outbreak of diseases (Tortolero, 2000). It was believed that to guarantee the health and well-being of the citizens it was necessary to extract excess water from the Basin—just as a physician might extract 'bad blood' from an unhealthy patient. Moreover, catastrophic floods repeatedly destroyed the new city, built on the ruins of Tenochtitlan and known as the capital of New Spain. The Spanish believed that the cause of this flooding was the overflow of surrounding lakes, rivers and dams. This belief, on the part of the Spanish, justified the destruction of Tenochtitlan's hydraulic infrastructure (Lombardo de Ruiz, 2000). In addition to destroying the Aztec's hydraulic infrastructure, colonial authorities failed to maintain the remaining infrastructure because of their lack of knowledge of water-related threats in the Basin of Mexico. Therefore, New Spain was frequently devastated by floods—which were not caused only by intense rains—since the city was not prepared to face these events.

More destruction and rebuilding were to follow. After the flood of 1555 destroyed the city once again, authorities ordered the reconstruction of the Nezahualcoyotl dyke. Ironically, although the Nezahualcoyotl dyke was repaired, the capital of New Spain continued to be devastated by more flooding in 1580, 1604, 1606 and 1607. However, the flood that followed, in 1629, proved to be the most catastrophic. Desperate, city authorities considered that the best—and only—solution was to dry out the lakes and rivers which fed the Basin of Mexico. Due to financial constraints, the construction of the required infrastructure was not undertaken until the 17th century.

The first tunnel designed to prevent floods in the capital of New Spain was built in 1607 by Enrico Martinez. Later, this tunnel became known as the Huehuetoca Channel. Through it, water from the Cuautitlan River—one of the most dangerous rivers of that period—was extracted (Perló, 1999). Contrary to expected, the Huehuetoca Channel did not end the flooding, and these destructive events continued affecting the city for several more centuries. For example, high levels of precipitation flooded the entire city in 1629, and the water did not abate for more than five years (Musset, 1992). Moreover, the extraction of water from the Cuautitlan River accelerated the sinking of the city, causing further concern. Today, this phenomenon—the sinking of Mexico City—has become one of the main threats faced by its inhabitants.

The repeated destruction of Mexico City, associated with catastrophic flooding, caused authorities to consider, on several occasions, the relocation of the city (Musset, 2003). Relocating Mexico City would have increased its sustainability. Nevertheless, for cultural and institutional reasons, this idea was not carried out; to the Spanish, the capital of New Spain had to be located on the ruins of the Aztec Empire as a symbol of conquest. The city's location and the transformation of the Basin's environment has been one of the main causes of its inhabitants' exposure to several risks, including water threats.

Water provided to the citizens of New Spain was of low quality because aqueducts used to transport and distribute it were not closed (Tortolero, 2000). Even more disturbing, wastewater generated in the city was discharged into the springs where drinking water was extracted. Indeed, the majority of citizens lacked access to safe sanitation services to dispose of personal waste, causing them constantly to face health risks. Levels of exposure to unsafe water were even higher; not only the governing authorities, but also the general population focused little attention on the maintenance of the lakes and channels that surrounded the city. Subsequently, these lakes and channels accumulated a great variety of waste products, and became a source of infectious diseases.

Given this situation, the response by water-management authorities was based on the idea that to ensure the health and well-being of city inhabitants, it was essential to remove excess water from the Basin. To this end, infrastructure to drain the lakes and rivers from the Basin of Mexico was built. However, this caused unforeseen consequences, increasing the risks associated with devastating floods, the low quality of water and outbreaks of waterborne diseases. Since the majority of the aforementioned problems are still affecting Mexico City's inhabitants, it is relevant to consider whether institutional water-management decisions could have mitigated or prevented some of the previous water-related risks to which Mexico City has been exposed.

The Beginning of Great Transformations of the Basin

At the beginning of the 17th century, the existing hydraulic infrastructure demonstrated considerable deficiencies. The growing population put great stress on an already insufficient water supply provided by springs located further and further away from Mexico City. The volume of water provided for citizens' use was limited, and inequality and discrimination were evident in its distribution. The poorest, most vulnerable groups of the city were excluded from water access. Rich groups had access to water through an internal network of canals connected to their homes; in contrast, poor people needed to buy and store it in containers, or they could wash their head and armpits in public fountains (Tortolero, 2000).

Aqueducts often suffered failures in structural integrity and needed constant repair and maintenance. Thus, the water supply was suspended for long periods. Moreover, the water supplied by aqueducts was easily polluted because of the open design of the ducts. Further exacerbating an already difficult situation, wastewater became a prime source of infection for the inhabitants since it was not extracted from the city on a regular basis. The city environment itself became a health risk and water-management decisions taken by colonial city authorities were mainly focused on the implementation of temporary measures to address water-supply problems and untreated wastewater extraction.

How did later governments respond to this growing problem? By the end of the 19th century, advances in medicine and bacteriology to prevent cholera outbreaks proved that health was closely related to the quantity and quality of water that people had access to for cooking, drinking and cleaning. An insufficient and low-quality water supply was considered a direct factor promoting the rise and propagation of infectious disease. Consequently, during the presidency of Porfirio Díaz (1876–1911), the interest in preventing floods and spread of water-borne diseases was renewed. As 'the master builder of a great commonwealth', Díaz made it his goal to improve the water supply and ensure water quality in order to transform Mexico City into a modern city. City authorities pushed for the construction of numerous water and wastewater infrastructure projects, and several were developed to dry out the lakes and rivers of the Basin and to build water distribution and wastewater networks.

The construction of Mexico City's drainage system, known as the Great Channel, began after yet another catastrophic flood destroyed the city in 1878. The Great Channel project was completed in 1900. It consisted of an open channel, 50 km in length, which directed 27 m^3/s (second) of wastewater into the Tula and Panuco rivers for removal to the sea.

This drainage system was considered the most important infrastructure built in Mexico during the 19th century because city authorities believed it would prevent destructive flooding. Contrary to expectation, Mexico City continued to be affected by severe flood events, even though they were less frequent and less intense. Unfortunately, with the decision to extract water from lakes and rivers located in the Basin of Mexico, the sinking of the city was accelerated. Now, Mexico City sits in a depression below the current level of Lake Texcoco, making it more exposed to catastrophic floods.

The Great Channel did not resolve the problems associated with high mortality rates caused by waterborne diseases and a lack of an internal drainage system. For this reason, in 1898, the construction of an internal drainage system was initiated. With it, the risks associated with devastating floods and outbreaks of waterborne diseases were reduced. Nevertheless, a by-product of the decision to dispose of wastewater extracted from the city directly into several surrounding rivers and springs created terrible pollution, and the risks associated with it. For example, although water from these rivers and springs is severely contaminated with faecal bacteria and inorganic material, this water is still being used to irrigate grains and vegetables grown in the Mezquital and Tula valleys. The use of polluted water has increased the health risks for the farmers who plant and grow the crops, and for the consumers who later ingest these products. Environmental concerns continue to grow with the contamination of air, soil, fresh water and groundwater.

Water provided to Mexico City by springs proved to be insufficient to satisfy water demands due to its growing population. To increase the volume of water available, city authorities started to look for water sources further and further away. This volume was complemented with groundwater extracted from several wells. In 1847, the first city well was dug, and by the end of the 19th century, the number of wells increased to over 1000—there was a well-drilling enthusiasm, when the city's population found out they could extract groundwater under artesian pressure (García-Acosta, 2007; Tortolero, 2000). Because of the decision to use wells as a source of water, the city's dependence on external water sources was curtailed, likewise the costs related to water transfer and distribution from far-away springs. However, the more intensive use of groundwater augmented risks associated with land subsidence.

Since colonization by the Spanish, water and land-use management have been at odds. Their contradictions were magnified during the government of Díaz. During that time, the paradigm of using the hydraulic infrastructure to ameliorate previous and new water-related problems was created. Through the construction of complex infrastructure projects, great volumes of water are transported from distant sources; at the same time, great volumes of water are extracted from the city to reduce excess. This paradigm brings into question the city's sustainability because it has increased Mexico City's dependence on more distant natural resources. Additionally, groundwater has become the most important water source for the city, providing more than 40% of the total volume consumed and increasing the city's rate of subsidence dangerously. These structural solutions can no longer be the main approach followed by city authorities to guarantee sustainable water management. Moreover, authorities believed that people's health was closely related to the quantity of the water they received, but neglected the importance of water *quality* to guarantee safe human consumption. Therefore, just as previous—and subsequent—city authorities had done, water-source pollution, pre-disposal wastewater treatment and water-related risk transference barely received any attention.

The End of the Metamorphosis

Over time, city authorities have been able to reduce the intensity and frequency of some risks to which the population has been exposed—as both a direct and an indirect result of their water-management decisions and practices. Regrettably, it has taken more than three centuries of attempting to control and transform the environment of the Basin of Mexico. Despite efforts, and constructed hydraulic infrastructure, *new* risks have been created, and certain *existing* risks have been intensified. Relevant examples can be used to analyse how water-management decisions and practices have influenced the exposure of Mexico City's population to water-related risks.

At the beginning of the 1930s, the infrastructure built to supply water to the city was no longer sufficient to meet the water demands of a growing population. Therefore, groundwater extraction was intensified. Water from more distant basins began to be transported to Mexico City. Because of this water-management decision, between 1950 and 1951 the city's sinking fluctuated between 35 and 46 cm/year. This situation urged authorities to suspend water extraction from several wells in 1954. With this measure, the rate of subsidence has decreased to approximately 6 cm/year, but the drilling of new wells in the city is still underway and the centre of Mexico City has sunk approximately 10 m (Academia de la Investigación Científica *et al.*, 1995).

Despite considerable efforts by city authorities to reduce groundwater extraction, if intensive aquifer exploitation remains a water-management practice—even though it has been proven to accelerate the sinking of the city—no measure to prevent land subsidence will be successful. Presently, the reduction of groundwater extraction from the aquifer of Mexico will be hard to accomplish since the volume extracted from this source is insufficient to meet the population's water demand. Moreover, the rate of groundwater extraction exceeds the rate of the aquifer's ability to recharge naturally.

The city's accelerated and disorganized urban growth has resulted in illegal and legal settlement of the population on land set aside for conservation, affecting many areas where groundwater is recharged. Although Mexico City has urban land-use programmes, for several decades land has been reclassified from protected to urban areas, increasing the demand of water supply and sanitation services. This situation has challenged city authorities not only in terms of management, but also regarding investment requirements and energy consumption (Tortajada, 2006).

The second most important water sources for Mexico City are the Lerma and Cutzamala basins. The volume brought in from the Lerma Basin is 5 m^3/s, and from the Cutzamala Basin, 10 m^3/s. These sources were selected from several alternatives, including the Papaloapan Basin, the Tepalcatepec Springs, and the Mezquital, Oriental, Tecolutla and Alto Balsas rivers. Although transferring water from these basins was considered the best option by city authorities, this decision had some disadvantages. For example, the Cutzamala Basin is located approximately 126 km from the city, and over 1200 m below it (Conagua & Semarnat, 2006).

Operating the Cutzamala System requires annual energy requirements of 1787 million kWh, at an estimated cost of US$62.54 million/year (Tortajada & Castelán, 2003). The high volume of water removed from these basins and transferred to Mexico City has severely damaged the hydrology of the area by reducing water availability, and consequently soil fertility, agriculture productivity and the population's overall quality of life. Thus, the fourth stage of the construction of the Cutzamala System—known as the Temascaltepec Project—has been suspended due to the refusal of the communities where the water is to be extracted to sell their water rights (Conagua & Semarnat, 2006).

The decision to dry out the surrounding lakes and rivers increased the rate of the city's sinking. Consequently, the first 20 km of the Great Channel lost their slope, requiring seven pumping stations to extract wastewater generated in the city for removal to the sea. The use of these pumping stations has also increased electrical power costs (Academia de la Investigación Científica *et al.*, 1995). The loss of the slope of the Great Channel, and an increase in wastewater generated by accelerated population growth, has saturated this infrastructure on several occasions, exposing Mexico City to wastewater flooding. To prevent this catastrophe, between 1937 and 1942 a parallel tunnel to this channel, known as the second tunnel of Tequixquiac, was built. However, in 1951 Mexico City was flooded with wastewater for nearly three months, which forced city authorities to consider other measures to prevent such events.

With this objective, in 1967 city authorities ordered the construction of the Deep Drainage System—the fourth artificial drainage system of the Basin. This drainage system was designed to avoid the effects of land subsidence, and to extract rainwater. Its tunnels are located over 200 m deep, and for several decades it used the force of gravity to extract rainwater from the city. Currently, the Deep Drainage System has an extraction capacity of 220 m^3/s, but contrary to expectation, subsidence did damage this infrastructure; today, its operation requires eleven pumping station (Conagua & Semarnat, 2006). This drainage system has been used to extract wastewater, although it was not built for this purpose. Presently, the East Drainage System is under construction, and it will constitute the fifth artificial drainage of the Basin of Mexico. This work will address the insufficient extraction capacity of the Deep Drainage System during the rainy season.

Since the Great Channel construction, the city's wastewater has been disposed of to surrounding rivers for removal to the sea. The water of these rivers, polluted with untreated wastewater, has also been used to irrigate vegetables and cereals, including alfalfa, sorghum, beans, wheat, corn and tomatoes in the Mezquital and Tula valleys. The irrigation has increased various districts' and irrigation units' productivity by nearly fourfold (Conagua & Semarnat, 2006). For example, post-irrigation, alfalfa productivity increased from 70 to 120 tons/ha; corn productivity from 2 to 5 tons/ha; and tomato productivity from 18 to 35 tons/ha (Esteller, 2002).

Although this practice has endangered people's and the environment's health with expected results, farmers refuse to stop using wastewater for crop irrigation because a high concentration of faecal coliform bacteria—from 4.9×10^8 to 1.3×10^9 MPN per 100 ml—is an effective fertilizer. However, the morbidity rate by *Ascaris lumbricoides*, an intestinal roundworm, has increased from 2.7 to 15.3 cases per 100 000 inhabitants in the 0–4-year age group. Health impacts are even greater for *Giardia lamblia*, a flagellated protozoan parasite; registered cases have climbed from 1.0 to 16.1 per 100 000 inhabitants in the 5–14-year age group (Esteller, 2000). Wastewater also has large concentrations of detergents, metals (such as boron, cadmium, chromium, nickel and lead), in addition to chemical compounds (as sulfates, sulfides and phenols), all of which are harmful to human health (Mazari-Hiriart & Mackay, 1993).

Untreated wastewater reuse is regulated by the national norm NOM-001-ECOL-1996: the maximum monthly limits of pollutants in wastewater used to irrigate vegetables and cereals eaten raw must not exceed a BOD_5 of 150 mg and one helminth egg/litre. Nevertheless, the wastewater used to irrigate Mezquital Valley's crops exceeds some of these limits: one wastewater sample taken by Esteller (2000) had $BOD_5 = 427$ mg and 27 helminth eggs/litre.

Clearly, water-management decisions and practices by city authorities—decisions meant to reduce the population's exposure to water-related risks—have profoundly transformed the environment of this Basin. These decisions have been based on a supply-oriented approach by city authorities. Thus, water supply has been a priority, as has avoiding catastrophic floods. Some of these decisions and practices have indeed reduced certain water-related risks, but others have generated *new* or intensified *previous* ones. Risks related to a low water quality, water source pollution, water conflict emergence and unequal water distribution are currently being addressed. Nevertheless, these topics are still not considered critical since their political relevance and benefits are not as noticeable as the need for more water—even though that water is not safe.

Conclusions

Water-management decisions and practices have been affected by authorities' and societies' perceptions of water's influence on their health, welfare and very survival, along with the views of interested parties and technical knowledge limitations. For instance, if water is considered a threat, governments generally try to control it through dams, ponds, wells, major canals, drains, collectors and pumping stations. Otherwise, if water is considered an essential resource for a city's social and economical development, authorities will supply the population with water, even if is necessary to transfer it from increasingly distant sources. Today, new approaches for more sustainable water management are needed because history has shown that water problems cannot be solved by implementing technological solutions alone. Technical solutions must be integrated with non-structural strategies to be effective. No strategy can successfully guarantee future safe water supply and wastewater disposal if water policy is not reinforced by proper land-use and effective urban planning.

Given the complexity of the current water-related situation, authorities have to consider the long-term impacts that their decisions and actions may have on a city's sustainability, in addition to the interactions among and within basins. Although history also shows that water-management decisions have had both positive and negative consequences, it is only reasonable to expect that the positive outcomes of these decisions—and subsequent actions—far exceed the water-related risks they create. If anything is learnt from the past, it should be to recognize the potential impacts on a city's sustainability from following certain courses of action, and to avoid them by identifying alternative solutions to water-related problems. Therefore, the sustainability of Mexico City's water management comes under question due to the increasing electrical power requirements to pump water and to extract untreated wastewater for removal to the sea, the greater dependence on more distant sources, the pollution of its water sources, the reduction of water quality and availability, the threat related to wastewater flood occurrence, and the transference of various water-related risks to surrounding areas, beyond its political boundaries.

Past and present water-management decisions, in response to limitations imposed by its location, have created an untenable future for Mexico City and its inhabitants. If the city continues its present physical, demographic and economic growth trends, the current infrastructure will not be sufficient to meet the demands for water and wastewater services. Future decisions and actions taken will have a major impact on surrounding watersheds as new water sources are sought to supply an ever-growing capital, but the vitality of distant water basins and cities will be, in consequence, also endangered.

Water management success depends on the recognition and integration of water policies, urban planning and land-use, whose strategies are frequently not compatible with one another. It is imperative to improve the city's planning process and to rethink the model of urbanization that has been followed during the past century; water-management decisions need to receive greater scrutiny—based on past mistakes. Those who make decisions must look to the past in order to make more accurate assessments to ensure water security and future sustainability. Mexico City's very survival may depend on it.

First, over-exploitation of the aquifer of Mexico has accelerated the city's sinking and has brought new risks associated with differential land subsidence, such as building deterioration, water and wastewater pipelines breakages, and wastewater flooding caused by failures in the pumping system. Additionally, the excessive extraction of groundwater has also reduced moisture in the subsoil, generating cracking in the clay layers of the aquifer and exposing it to direct pollution from wastewater infiltration (Mazari & Alberro, 1991). Although the artificial recharge of the city's aquifer with treated wastewater and rainwater was implemented in 1992 to reduce land subsidence, there were no norms for regulating this practice until 2007, when two environmental norms were designed (NOM-014-CONAGUA-2007 and NOM-015-CONAGUA-2007) to define specifications for treated wastewater and rainwater that must be achieved before release into aquifers.

Second, with the construction of the Lerma and Cutzamala Systems, city authorities reduced the aquifer's over-exploitation; however, dependence on distant water sources and the associated conflicts have increased. Most of these water conflicts arose because the communities where the water was to be extracted did not receive financial compensation for the exploitation of their resources. Moreover, several water-related risks faced by Mexico City were then transferred to other, more distant, basins and communities.

Third, even though Mexico City is still affected by flooding, with the construction of the Deep Drainage System these floods are not as devastating as previously. City authorities have managed to mitigate the occurrence of any floods. Nonetheless, wastewater and rainwater continue to be extracted from the city *together* in a common pipeline, and the recycling and reuse of rainwater (for activities that do not require high water quality) is still very limited. The use of one pipeline for the extraction of wastewater and rainwater has increased the costs associated with their treatment because larger volumes of wastewater require tertiary treatments. Moreover, the city is incurring high-opportunity costs for not taking advantage of this source, which has the potential to supplement water demands. Presently, only 7% of wastewater is treated in the city, and most treated water is used to irrigate green areas, to fill lakes and canals, to cool industrial processes, and to recharge the aquifer. If available alternative water sources were to be used, the aquifer's over-exploitation and water transportation from increasingly distant basins would be reduced. Conagua & Semarnat (2006) estimated that approximately 19 m^3/s of rainwater coming from mountains ends in the drainage system without being used.

Q2 Four, based on reports from Mexico City's Water System (SACM) (2008), 2% of the samples tested to monitor the quality of water supplied to the city's inhabitants did not meet the standards of residual chlorine concentration, whereas 12% of these samples had evidence of bacteria pollution. The areas most affected by poor-quality water are located south and south-east of the city. Water quality monitoring must be improved since the sampling used is not representative: over 80% of the samples tested are gathered from less-affected areas; thus, 20% or fewer samples are collected from the areas reported to be affected by poor water quality. Furthermore, since 1997, the number of samples taken to assess water quality has been reduced from 160 000 to fewer than 30 000 per year, and the number of neighbourhoods sampled has also been reduced (Sosa-Rodríguez, 2010). Improvements in the quality of water received by the city's inhabitants could be a misperception—a 'statistical illusion' as Guardiola *et al.* (2010) also identified in the case study of Yucatan—since the results of sampling are neither comparable nor reliable. As a result, the population's exposure to health risks caused by low water quality has increased because the city authorities cannot clearly locate areas of substandard water (Sosa-Rodríguez, 2010).

Finally, but not less important, the majority of wastewater generated in the city is extracted without being previously treated, thus polluting the rivers and lakes used for its removal to the sea and increasing health risks along the way, as the water is reused to irrigate crops in the Mezquital and Tula valleys. This practice has had a negative impact on the health of farmers and consumers of these crops, and on the surrounding environment. The continuous transfer of wastewater from Mexico City to the Mezquital Valley to irrigate crops has increased the groundwater recharge of local aquifers and has also generated several surrounding springs. Both local aquifers and springs have become important water sources for the Mezquital Valley. However, although its use and consumption may pose a threat the population's health, the quality of water obtained from these sources is still unknown (Tortajada, 2006).

Acknowledgements

This article was written with financial support from the Mexican National Council for Science and Technology (Conacyt). The supervision of Professor Manuel Perlo (IIS-UNAM) is greatly appreciated. The author also acknowledges the opportunity given by Dr Rob de Loë (ERS—University of Waterloo) to pursue postdoctoral research; and to Mary McPherson (ELPP—University of Waterloo) for invaluable assistance.

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