Assessing Infrastructure Decisions to Manage Water Resources in the Valle de México

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Abstract

Groundwater supplies nearly seventy percent of the regional water supply in Mexico City. Past groundwater extraction in the central city caused subsidence of up to 40 feet in some areas. Today, while pumping in the center city has ceased, groundwater supplies come from areas surrounding Mexico City, which are themselves experiencing effects of groundwater exploitation. Managing groundwater resources to preserve aquifer quality and quantity in the Mexico City Basin must incorporate a variety of strategies, such as promoting infiltration, altering extraction rates, managing demand, and developing wastewater treatment and reuse options. Further, aquifer management decisions have both long-term and short-term planning components. This paper describes a framework for characterizing infrastructure decisions to meet both long-term planning needs and short-term requirements. Long-term decisions include capital-intensive options such as construction of infiltration basins and wastewater treatment facilities, while short-term actions manage demands based on unexpected hydrologic and use parameters. Both short-term and long-term decisions have inherent uncertainty. Such a framework can be used to assess groundwater management and water supply options in Mexico City given infrastructure decisions, water demand forecasts, climate variability, and urban sustainability initiatives. The framework informs planning and management models for the basin.

Keywords

Groundwater; water, management; Mexico City; infrastructure

INTRODUCTION: GROUNDWATER AND CITIES

Groundwater is an important resource for urban regions. Cities in diverse geographies and climates have utilized groundwater at various stages of development to supply potable water needs (Howard & Gelo, 2002). Clarke, Lawrence, and Foster (1995) noted that fifty percent of all urban water use "has been attributed to well, spring, and borehole sources, and more than [1 billion] urban dwellers in Asia and 150 million in Latin America depend upon such sources." Groundwater is connected to many parts of the urban hydrologic cycle, making it a critical resource for sufficient and clean water in cities.

Groundwater fulfills many water supply functions. Young cities often tap groundwater supplies to meet growing demands. Established cities rely on groundwater for potable use (Howard, 1997). Groundwater provides important supplies during droughts and peak use. Overextraction of groundwater can also lead to numerous problems, including subsidence, saltwater intrusion, and aquifer contamination. Available water in an aquifer is governed by the balance between extraction and recharge rates. Groundwater pumping supplies demands, while leaking distribution and sewage systems, as well as surface irrigation, all provide recharge.

Given the numerous relationships between water demand, supply, and available resources in a given city, approaches that consider the interaction of multiple strategies may be more effective than singular actions. For instance, a strategy that incorporates both reduced groundwater extraction and increased recharge would facilitate comparisons between multiple decision options. Another potential approach for decisions would consider tradeoffs in centrally-managed strategies, including infrastructure expansion or infiltration basins, with distributed management strategies, such as promoting household rainwater capture and storage. This paper describes a probabilistic decision model for managing groundwater in the Mexico City Basin. The model seeks to understand optimal groundwater recharge strategies that use both centrally-managed and distributed approaches to preserve aquifer levels and improve water quality in the region.

URBAN GROUNDWATER USE IN MEXICO CITY

Aquifer management is a critical component to water management challenges in Mexico (Scott & Shah, 2004). Mexico is a hydrologically diverse country, with arid parts in the north and central regions, while rainy in the south. Many of the arid regions in Mexico rely heavily on water transports and groundwater to support agriculture, residential use, and industry. In the capital of Mexico City, a combination of geologic, historical, social, and technological factors converge to create a city with one of the world's most significant aquifer management problems, including both water quality and quantity. While groundwater extraction has helped the city to expand and industrialize, its exploitation also presents significant challenges for sustainable future development (Tortajada, 2006).

Geography, Hydrology, Culture, and Institutions

Mexico City (Ciuded de México or México D.F.) lies in the Valley of Mexico. The Mexico City Metropolitan Area (MCMA) consists of the Federal District and the State of Mexico. The city proper covers nearly 1,500 square kilometers and the metropolitan area is considered to have a population of 21.2 million (CONAGUA, 2010). While at an altitude of over 7,000 ft., the city lies in a basin that was formerly Lake Texcoco and was filled with runoff from the surrounding mountains. It was built on an island by the Aztecs and later taken over by the Spanish in 1521 during the siege of Tenochtitlan. Below the central city, a 300-meter thick aquitard of porous, fine-grained deposits overlays Quaternary lacustrine clays and Quaternary clasitics that comprise the underlying aquifer (Ortega-Guerrero, Cherry, & Rudolph, 1993). The aquifer strata consist of gravel, sands, and silts that vary in thickness from 0 to 50 meters, resulting in high compressibility. This soil strata composition poses complications for the built environment. Slab building foundations are only possible for buildings up to 4 or 5 stories, beyond which pilings must be used to assure stability. Average monthly precipitation in the metropolitan area ranges from approximately 5 mm to 160 mm (CONAGUA, 2007). Seasonally intense rainfall patterns in May through October combine with the lack of natural soil drainage to create periodic flood management issues (NRC, 1995).

The Mexican authority for water management is the Comisión Nacional del Agua (CNA or CONAGUUA). Groundwater is managed throughout Mexico by Technical Groundwater Committees (Comités Técnicos de Aguas Subterráneas, or COTAS) after the CNA instituted a federal law to address groundwater resource management. The COTAS, whose boards are comprised of groundwater users, are charged with setting a common agenda within their jurisdictions to monitor and manage groundwater pumping; groundwater use is essentially self-regulated throughout the country. The federal district also has a water utility, Sistema de Aguas de la Ciudad de México (SACM), which is responsible for water supply and sanitation.

Traditionally, Mexico City residents viewed water as state property, entitling free and abundant use, similar to attitudes in the rest of the country. Water supply and drainage has been heavily subsidized by the federal government. Rapid urban growth has combined with limited financial resources to induce overexploitation and shortages of available, potable water in many areas of the country. Reforms in recent decades have sought to regulate water allocation and groundwater use, though monitoring and enforcement remains problematic (NRC, 1995).

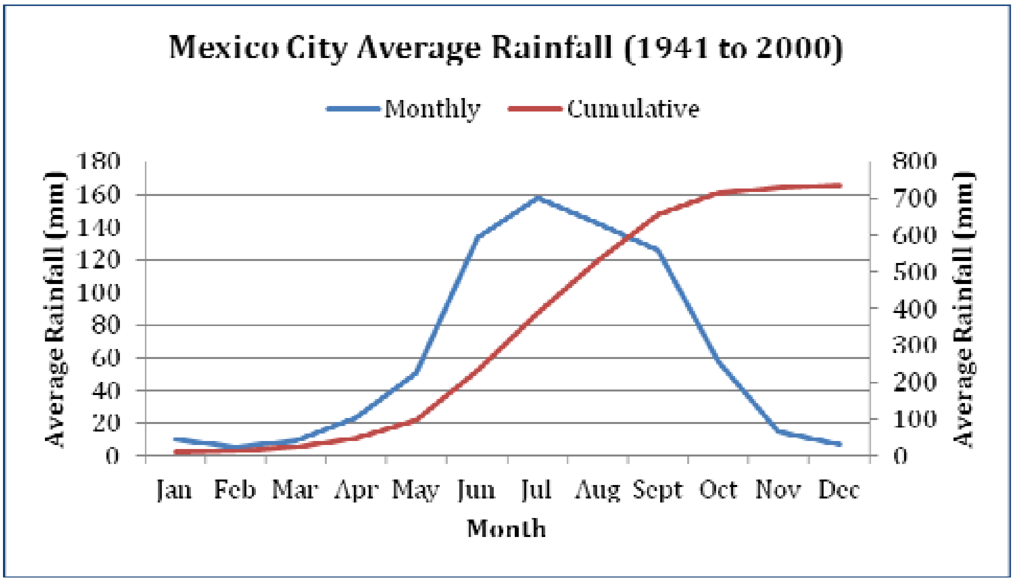

Figure 1: Average Monthly and Cumulative Rainfall in the Federal District (Mexico City) (source: CONAGUA *Statistics on Water in Mexico.* **2007)**

Groundwater Use and Subsidence

Throughout Mexico, 75 million urban users obtain over 70% of their water from groundwater, though agriculture uses 70% of the total volume of groundwater pumped. Groundwater extraction is less than infiltration nationally, but the central and northern areas overexploit groundwater resources for agricultural and urban needs (Arreguin-Corets & Lopez-Perez, 2007).

In Mexico City, groundwater has been used for water supply needs for more than a century. Groundwater extraction began in 1847 (Farvolden & Adrian Ortega, 1989). Pumping expanded rapidly and by the mid-20th century, city authorities realized that extraction was causing land subsidence of up to 40 cm per year (Cabral-Cano et al., 2008; Gayrol, 1928; NRC, 1995; Strozzi, Wegmuller, Werner, Wiesmann, & Spreckels, 2003). This led the government to close pumping wells in the city center in 1952. From the early 1960's to 1982, groundwater extraction moved to peri-urban sites at the periphery of the aquitard (Oretga-Guerrero, Cherry, & Rudolph, 1993). Subsidence in different eras of the city's history has been estimated at: 4.6 cm/yr from 1900-1938; 16 cm/yr from 1938-1948; and 35 cm/yr from 1948-1956. After well closures in the city center in 1952, subsidence slowed to about 7.5 cm/yr and by 1990, the rate was estimated to be 4.5 cm/yr (Mazari & Alberro, 1990). Beginning in 1983, a piezoelectric network was installed to monitor the groundwater table, allowing for more accurate measurements (Lesser-Illades, Sanchez-Diaz, & Gonzalez-Posadas, 1990). Since then, the average annual decline ranged from 10 cm per year to 150 cm per year in different zones of the city. Subsidence in the central city has decreased to approximately 5 cm per year. In total, subsidence in the central city has been over 7 meters in the last century (NRC, 1995). The subsidence has damaged landmarks, impacted infrastructure development, and increased flood risks. For instance, the main combined sewer outflow that runs under the city center, called the *Emisor Central* (part of the *Drenaje profundo*), was designed as a gravity-fed canal but had its capacity reduced by nearly half since it opened in 1973 due to subsidence. This canal replaced an earlier *Gran Canal* that had to be shut down due to subsidence. The *Emisor Central* functions today through the use of pumping, which moves effluent upwards to reach the city boundaries. Moreover, wastewater from the drainage infiltrates and later emerges in springs in the Tula Valley to the north.

Despite challenges, the aquifer continues to provide nearly 70% of the region's water supply, with well depths reaching 300 meters (Cabral-Cano et al., 2008; Santoyo, Ovando-Shelley, Mooser, & y Leon, 2005; Tortajada, 2006). Most groundwater supplies come from the areas surrounding Mexico City, including Sierra Nevada (Chalco Basin), Sierra del Chichinautzin and Sierra de las Cruces (Ortega-Guerrero et al., 1993). Tortajada (2006) reported in 2002 that the total volume of water supplied to the Mexico City Metropolitan area was estimated to be 66 cubic meters per second (cms), with 68% (45.2

cms) coming from groundwater wells and springs, 22.6% (14.9 cms) coming from the Cutzmala watershed, and 8.9% coming from the Lerma watershed, as shown in Figure 2.

Water Supply Sources		*Water Supply by Jurisdiction (mcm/s)*			
		Federal District	**State of Mexico**	**Total**	**Percentage**
Internal Sources	*Wells*	19	24.8	43.8	66.4
	Springs and Rivers	1	0.4	1.4	2.1
	Sub-Total	***20***	***25.2***	***45.2***	***68.5***
External Sources	*Cutzamala*	9.9	5	14.9	22.6
	Lerma	4.9	1	5.9	8.9
	Sub-Total	***14.8***	***6***	***20.8***	***31.5***
Total		**34.8**	**31.2**	**66**	**1000**
Percentage		52.7	47.3	100	

Figure 2: Mexico City Water Supply (adapted from Tortajada 2006)

While 95% of the residents of Mexico City and 84% of the residents of the State of Mexico had access to centralized water deliveries in 2000, many residents must find alternative sources (Tortajada, 2006). Even in areas with water access, the water is often polluted and residents must purchase more expensive bottled water. This problem is especially acute in the informal settlements of the region, which are areas where squatters build structures without official land rights and often without municipal infrastructure improvements. The dichotomy between wealthy and poor residents is stark, with wealthy residents using up to 600 liters per capital per day and poor residents using approximately 20 liters per capita daily (Tortajada, 2006).

Current and Future Strategies

The water supply of Mexico City benefits from large aquifer reserves. While the reserves are plentiful, continued exploitation to meet urban demands creates significant problems of localized depletion, subsidence, and pollution. At the same time, crumbling water distribution and sewage infrastructure throughout the city complicates needed investments. To increase sustainable use of available resources, several recent and future strategies can be explored to slow peri-urban subsidence, improve system efficiency, and perhaps maintain groundwater quality.

Reversing groundwater overdraft requires either reductions in extractions or increases in direct and indirect recharge. Research has suggested a number of potential solutions. Reducing urban demand through more effective water pricing or increased monitoring can help to curb extractions. Alternatively, many schemes have been proposed to increase recharge. The large canal that drains stormwater and wastewater outflows from the city is a potential source of infiltration. The hard clay upper soil layer in the area, though, means that infiltration must come through more-expensive well injection, as permeability is except in areas of basaltic rock where fractures exist that promote infiltration (Pyne, 1994). Various infiltration schemes have been considered in the past, with proposals seeking to inject raw river water and wastewater from rivers and the *Gran Canal* and treated water into the *Chichinautzin* sierra, which is the main area for infiltration (DGCOH, 1997). Green urban infrastructure techniques, including bioswales, rainwater gardens, and retention ponds, are growing in popularity throughout the world, but are less likely to induce infiltration without significant modifications to the substrate or underlying infrastructure to induce recharge. They may, however, alter the amount of water lost to evaporation. Vegetation and shading can create microclimates in urban environments that reduce heat and transpiration, though the vegetation itself requires water. The flashy hydrology of the region reduces the potential for infiltration from reconstituted first-order streams during small storms. Finally, the amount of water lost to evaporation in the region is significant. Nevertheless, landscape architecture and urban ecology approaches that model evapotranspiration and design landscapes with trees, shrubs, and other plants could provide solutions for reducing evaporation losses during the dry months of the year.

In Mexico City, governance structures such as the COTAS were formed by national initiative to increase management and oversight of groundwater use. Restrictions and monitoring programs for groundwater use have been more prevalent in Mexico City, especially the central area, than other rural communities in Mexico. Yet, groundwater overdraft has shifted from the central city to the surrounding suburbs, despite acute knowledge of the situation. More recently, the Mexico City government has recognized the long-term seriousness of this issue and incorporated mitigation strategies into a larger planning effort, even as utility-focused demand and supply actions are implemented. In 2008, the city introduced the *Plan Verde (Green Plan)*, calling for new water management approaches to preserve aquifer resources, including water conservation measures, soil preservation, promotion of green roofs, improved maintenance, and aquifer recharge through injection of treated wastewater (Secretaría del Medio Ambiente del Distrito Federal., 2008). Efficient and cost-effective combinations of such strategies have not been fully explored.

MATERIAL & METHODS

Decision Model for Aquifer Management Strategies

Water management decisions for the Basin of Mexico aquifer include a variety of complimentary long-term and short-term options. Long-term strategies typically require significant capital investments, such as infiltration basins, wastewater treatment enhancement, or large-scale landscape infiltration plans. Short-term options may be used to manage water availability or promote infiltration on smaller time scales in response to annual uncertainties in climate or demand. Such options might include private rainwater capture incentive programs or water conservation regulations. In reality, many planning and management decisions for all strategies in the Basin take place on short-term time frames of three to six years, but larger capital investments should be analyzed by employing long-term discounting of infrastructure.

While decision frameworks for flood management or drought measures often constitute long-term (permanent) options and immediate short-term measures in response to hourly or monthly changes in environmental conditions, for aquifer management, groundwater extraction is less evident and negative effects such as subsidence or contamination are less immediate. Thus, short-term option timelines must be elongated compared to many other problems in water management that employ two stages of decisions.

Infrastructure development decisions can also be framed as alternatives centralized or distributed approaches. For example, large infiltration basins represent centrally-managed infrastructure, while household rainwater capture incentive schemes promote distributed infiltration. In between, municipal programs might promote rainwater capture and infiltration on public lands redevelopment of parks or public buildings to promote green infrastructure. Tradeoffs between options can be formulated as a decision model, which can assist water managers in the Basin to assess future strategies. Further, uncertainties in water supply and demand in the arid basin, especially given a changing climate, can be incorporated to provide managers tools for future water planning decisions under uncertain future conditions.

Conceptual Model

A framework was formulated to identify the minimum cost for potential combinations of infrastructure and program management decisions. Sustainable aquifer management consists of a first stage of long-term decisions (5-30 year actions) and a second stage of short-term decisions (0-5 year actions). Long-term decisions include construction of infiltration basins in geologically-favorable areas, development of wastewater treatment infrastructure that enhances infiltration and reuse, watershed protection programs for sensitive recharge areas, large landscape development programs on public lands that increase localized infiltration, and regulatory or incentives to increase infiltration on private lands. Short-term options include incentive programs to promote rainwater capture and regional water demand restrictions for particular sectors. While many reuse programs such as promoting rainwater harvesting may have long-term benefits, these programs are considered short-term because many cities have promoted such programs only on a short-term basis due to policy changes and budget constraints. The available decisions will be refined through interviews and field work based on current decisions under consideration.

Decision Type	Characteristics	Examples
Long-term Decisions	• Often capital intensive, including initial costs and long-term maintenance • Regional scale of implementation • Requires coordination and potential financing • May use centralized or distributed approaches, but regulations and incentives from central authority are likely	• Infiltration basins • Wastewater treatment enhancement • Large-scale landscape infiltration plans • Landscape approaches on both public and private lands • Watershed protection programs for recharge areas
Short-term Decisions	• May incorporate behavior of water users • Consider highly elastic supply and demand options	• Private rainwater capture incentive programs • Water conservation regulations • Realignment of pumping locations

Table 1: Short- and Long-term Aquifer Management Options and Characteristics

Futhermore, available options can be characterized through a water balance model that includes water supply sources, uses and losses, and system outflows. Figure 3 graphically details these three categorizations.

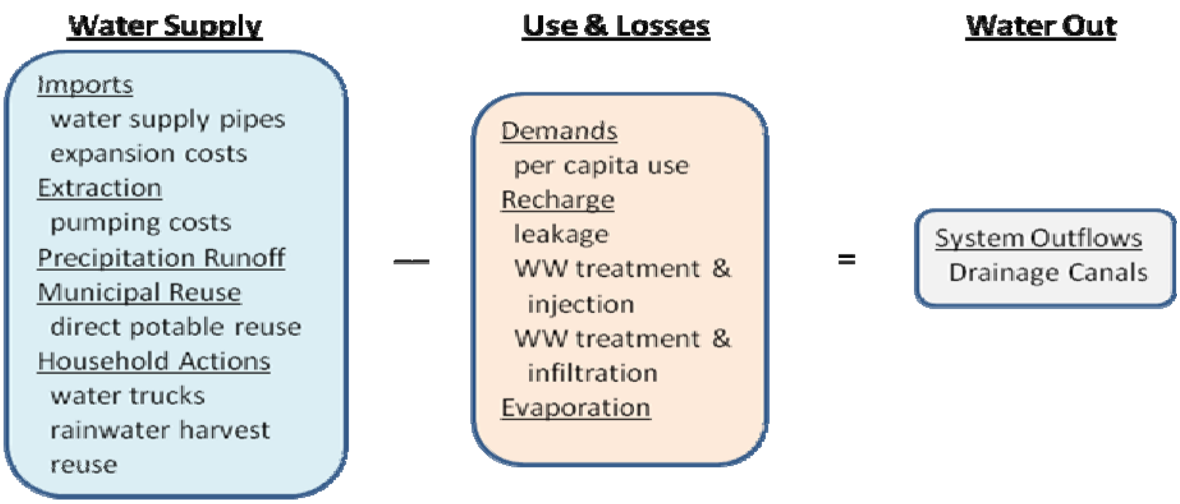

Figure 3: Water balance models for understanding inflows, uses, losses, and outflows for the water management system in the Basin of Mexico

Possible actions may be categorized based on similarity to current appraoches as well as the predominant management strategy. In this context, long-term decisions can promote typical importation and conveyance or landscape appraoches (green infrastructure and centralized infiltration) to meet demands and remove used water from the city. Similarly, short-term actions can meet demands or respond to shortages through importation via trucks or innovative capture and reuse capabilities that, while more expensive, are employed during times of water stress. Figure 4 outlines these potential options in relation to current strategies.

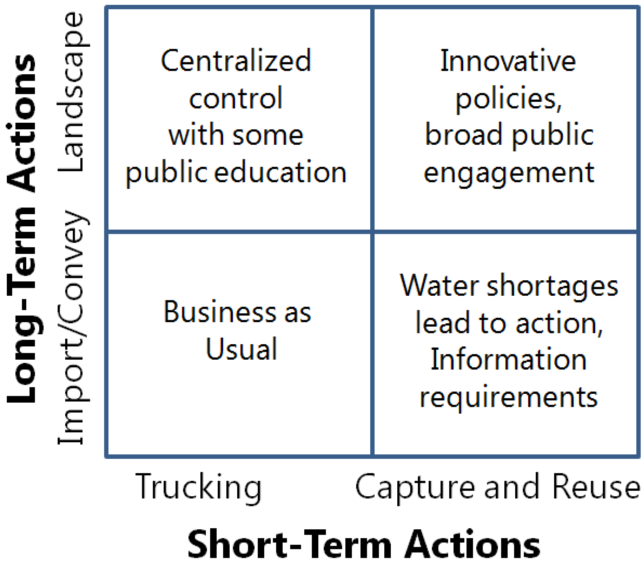

Figure 4: Long-term and Short-term water management optoins, characterized in relation to current policies

DISCUSSION: MANAGING WATER TO MANAGE SUBSIDENCE

In examining Mexico City water management practices, Tortajada (2003) concluded that, "[t]he current water supply and wastewater-management problems of the Mexico City metropolitan area can be directly linked to the lack of long-term regional economic development policies, poor and inappropriate management practices, and the absence of any serious attempt to formulate and implement a viable wastewater-management plan." This quote demonstrates a clear need for Integrated Urban Water Management (IUWM) strategies. While IUWM is often an endearing term in policy circles, for the MCMA, water supply, wastewater, and external effects such as subsidence are intimately linked to holistic management practices, urban growth patterns, policy development, corruption, and long-term planning processes.

Effective wastewater management in the city, such as installation of treatment plants, would increase the opportunity to reuse or infiltrate wastewater. At present, drainage canals move a combination of grey water and black water out of the Basin of Mexico through the *Drenaje profundo*, depleting the aquifer and transferring imported water out of the Basin. This drainage system, however, was installed to handle the unique hydrology of the region, with massive storms flooding the area during a few short months of rain. In addition, unlike many cities, industrial users in the region have little incentive to discharge wastewater into the aquifer because of slow infiltration capacity (Foster, 2001). While this may mitigate some contamination dangers, it means that the vast majority of extracted and imported water is quickly moved out of the city limits.

Natural ecology and hydrology of the region affected the development of the city water infrastructure, and they continue to influence the current water management challenges. Newer, more systematic approaches that recognize the connection between surface water and groundwater sources, such as landscape infiltration or artificial recharge, may help to simulate the ancient biophysical and hydrologic processes. Even more progressive options, such as utilizing increased tree cover to change evapotranspiration rates in the region, draw on increasing understanding of urban ecosystems, recognizing that cities are products of human ingenuity but still subject to constraints of the surrounding environment. While pilot projects have explored opportunities to increase infiltration and promote sustainable long-term policies, Mexico City has not undertaken a full commitment to these problems in the way that, for example, Los Angeles groundwater basins did in the middle of last century. To this extent, insights from modeling may assist managers to long-term decision processes. Household options such as rainwater harvesting are also possible, as increased economic incentives from either government programs or future water scarcity may prompt residents to augment central supplies. Innovations to address the challenges of water supply and flood management in the Basin may develop at localized scales within the larger MCMA, such as rainwater harvesting schemes or community-based pollution management. While poverty and crime issues continue to plague the city, the large infrastructure already built demonstrates that Mexico City is capable of tackling significant challenges, provided motivated leadership and a clear vision for the future. As future cities incorporate new approaches to water management such as reuse, localized contaminant removal, and natural treatment buffers, Mexico City can capitalize on growing knowledge to implement such practices that help to protect its aquifer resources.

CONCLUSIONS

In many cities, groundwater overdraft is precipitated by extraction for residential, commercial and industrial uses. Groundwater contamination is the most prevalent effect of urban development and aquifer exploitation. Given the right geologic conditions, however, subsidence can pose significant problems for urban infrastructure. In many cases, subsidence is reversible, meaning that if cities do overdraft groundwater resources, they can subsequently recharge them to halt and even reverse subsidence.

In Mexico City, groundwater depletion continues as the city draws on regional aquifer resources to meet supply needs. To maintain available resources, the city must explore a portfolio of approaches to promote infiltration, improve treatment, and manage demand. Aquifer recharge and urban greening offer possible strategies to increase recharge and reduce extraction. Importantly, the lack of wastewater treatment facilities in the city result in large effluent streams that, if treated, could reinstate natural hydrologic cycles. Instead, the wastewater presents a stark environmental and health hazard. In all likelihood, a balanced suite of alternatives will emerge to tackle water supply problems in Mexico City, including more efficient water imports, improved wastewater treatment, regulations on groundwater extraction, managed recharge, and landscape changes to promote infiltration and reduce evaporation. The city offers a hearty case study for the value of integrated water management strategies.

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