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Climate change, water, and wastewater in cities

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5.1 Introduction

While many previous studies have looked at the worldwide changes and impacts of climate change and related variability on water resources, few have focused on an assessment of the specific effects and needed adaptation and mitigation for water systems in cities across the globe. The Intergovernmental Panel on Climate Change (IPCC) report on the water sector (IPCC, 2008) summarizes links between climate change and water through all of the physical elements of the terrestrial hydrologic cycle, ocean components, linkages to water supply, and global effects, but does not focus specifically on urban water systems. Similarly, the ADAPT Project (Aerts and Droogers, 2004) looked at adaptation for regional water management in seven typical watersheds across the world. However, most of this study was focused on surface water resources and their impacts on agriculture, food supply, energy production, and flood hazards, or on other impacts including groundwater resources, but did not focus on cities. There is thus an urgent need for a focused overview of the water supply and wastewater treatment sector in urban areas.

The range of challenges related to climate change and cities in regard to the water supply and wastewater treatment sector is very great, depending on geography, economics, administrative capacity, and demography. Many of the challenges are general, and some are more specific to particular cities. Accordingly, this chapter includes capsule descriptions of water supply and wastewater treatment in four cities that illustrate a variety of situations in which adaptation to climate change will be needed. These include a developed city with advanced climate adaptation planning (New York); a city with a formal water supply sector that will be under increasing pressure from climate change, with little wastewater treatment (Mexico City); a city with a very limited formal water supply system, and essentially no wastewater treatment (Lagos); and a city facing potentially serious water deficits from climate change as well as urban growth (Santiago de Chile). The situations of these four cities are representative of many other cities around the globe. In addition, there are two cross-cutting case studies of urban vulnerability in less developed countries that illustrates the centrality of water issues.

The chapter has five sections in addition to this Introduction: (5.2) Description of the water supply and wastewater treatment sector in cities, including sections on formal and informal water supply and wastewater treatment systems; (5.3) Vulnerabilities and impacts of climate change in urban areas; (5.4) Adaptation to climate change for urban water and wastewater systems; (5.5) Mitigation of climate change related to the water sector in cities; and (5.6) Policy considerations for urban water management, including gaps in knowledge. The policy considerations in Section 5.6 provide a range of focused approaches for urban policymakers with respect to the water and wastewater treatment sector, supplementing and extending the key messages of the chapter. Within the chapter, the kinds of issues and options facing cities are illustrated in the descriptions of conditions in New York, Mexico, Lagos, and Santiago de Chile described above.

5.2 Description of sector

Water and wastewater systems can be divided into two basic categories, those that are established formally in a city's governance and management structure and those that are established and that function informally. The informal systems typically have developed with little central planning or organization and often with only scattered and limited resources supporting them. The informal systems are operated and expanded in largely unregulated ways, often in slums, favelas, and other essentially impromptu settlements and extensions of the more organized city structures. Formal and informal systems have very different capacities to respond to the stresses that climate change is likely to impose on them. Both systems provide for delivery of water supplies to urban populations and the removal of wastewater. While formal systems may have more capital and knowledge to bring to bear on adaptation to climate change, they may not be able to respond to climate change because of inflexible governance structures. Given the limited monetary and planning resources supporting them, informal systems may be even less able to cope with the changes in both the supply and demand for water that climate change is projected to bring.

5.2.1 Formal water supply and wastewater sector

The functions of the formal urban water supply and wastewater sector include storage, supply, distribution, and wastewater treatment and disposal systems that provide organized water services to established urban areas. The infrastructure generally includes water and wastewater utility systems with large raw-water storage facilities, storm-water collection systems, trans-basin diversion structures, potable and wastewater treatment plant equipment, pipelines, local distribution systems, and finished-water storage facilities (Figure 5.1; California Department of Water Resources, 2008a). Urban supplies come from mixtures of surface water and groundwater as well as contributions from reuse of treated wastewater and desalination of seawater. Urban water infrastructures are large plumbing systems that tap and distribute water from these sources, and that commonly extend beyond the cities themselves to organize and draw from regional resources and services (Figure 5.2). Thus, for many cities, pipelines and other conveyances for the importation of distant waters provide access to major supplies. A city's internal distribution system can sometimes include sub-regions that are separately regulated.

Many of these facilities, structures, supply sources, and wastewater disposal mechanisms are vulnerable to adverse effects from climate variability and change (Case, 2008). Urban supplies can be affected by changes in water availability due to increases or decreases in precipitation, increases or decreases in temperature, sea level rise, and increases in climatic variability.

An important goal of urban water suppliers is to assure reliable supplies of high-quality potable drinking water in quantities

Typical water-use cycle for cities

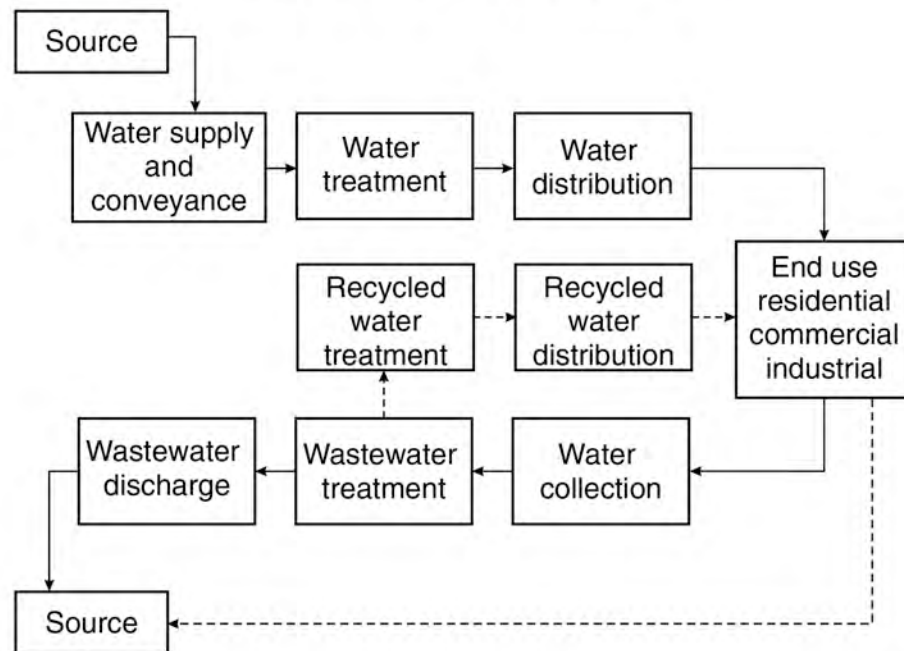


Figure 5.1: Typical water-use cycle for cities and other developed supplies; dashed arrows indicate pathways that sometimes occur.

Source: Modified from Klein et al. (2005a).

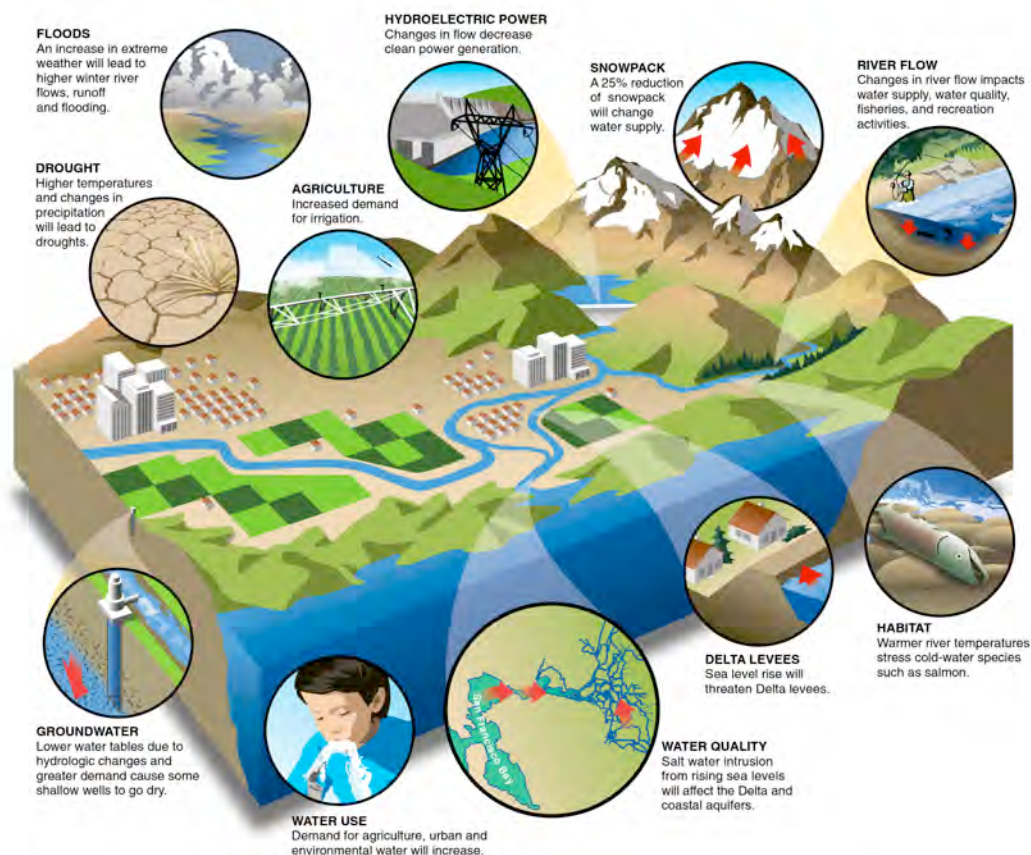


Figure 5.2: Diagram showing the typical components of a coastal urban water sector as impacted by climate change.

Source: Modified from CADWR (2008a).

that meet demands for municipal, commercial, and industrial uses. This most basic of tasks may not always be fully met, even in the absence of climate change. Demand has been estimated to exceed supply seasonally by as much as 25 percent (Queensland Department of Natural Resources, 2000) for some Australian cities to as much as 50 percent for a city like Calgary, Canada (Canadian Natural Resources, 2008), and, during droughts, by as much as 20 percent for urban coastal regions of California (Hanson *et al.*, 2003). Thus, many urban water systems that are already challenged by unreliable supplies face additional challenges from growing demands driven by population growth and climate change.

The supply infrastructure of many cities has evolved, as demands driven by urbanization have grown, from systems that initially were supported mostly by streamflow and storage, to systems that now rely also on groundwater and imported water. Streamflow diversions are one of the primary sources of water for many urban centers throughout the world. The principal structures related to streamflow diversion are pipelines for direct distribution and storage in surface reservoirs. Such storage lessens the difference between supply and demand during seasonal and multi-year periods. As streamflow resources have been increasingly exploited and depleted, additional storage has been required to offset the growing demand. Groundwater resources have been exploited to fill demands and provide additional storage. In at least some settings where this exploitation has adversely impacted groundwater supplies and services, recharge has been augmented to partially replenish aquifers that are actively pumped or are subject to adverse conditions from overdraft such as seawater intrusion or land subsidence. As environmental constraints, increased competition among various land uses, and risks associated with surface reservoirs (e.g., dam failures and seismicity) limit options for additional surface storage in many urban systems, storage underground may emerge as one of the largest contributors to new storage.

Groundwater pumpage can be a primary source of water if surface water and its treatment are very expensive or unavailable, or if economic and regulatory conditions make this the preferred resource. Some urban centers, such as Shanghai, China (Zhang and Wei, 2005), Venice, Italy (Carbognin and Tosi, 2005; Gambolati *et al.*, 1974), and Hanoi, Vietnam (Jusseret *et al.*, 2009), are located on major river systems yet still rely predominantly on groundwater as a primary source of potable water and industrial supply. Many other intermediate and large cities such as Fresno, California, and Mexico City, Mexico, have relied on groundwater for many decades.

Where demand has exceeded supply from surface water and groundwater supplies within many urban areas, imported water has become a substantial source of supply in cities large and small. These sources are commonly constrained by transboundary agreements and competition that limit the amount or impacts of importation between multiple counties, provinces, states, or countries. The systems can also be limited by the physical capacity of conveyance systems. For instance, Kahrl

and Roland-Holst (2008) note that in 2003 the Metropolitan Water District of Southern California (Los Angeles, Orange, San Diego, Riverside, San Bernardino, and Ventura Counties) purchased water from agricultural growers in Sacramento but was unable to obtain the water because conveyance systems in the Sacramento–San Joaquin Delta were already operating at full capacity (CADWR, 2005).

In some cities, imported water has become the primary supply (e.g., San Diego, California; San Diego Foundation, 2008). The supply of water resources for many major metropolitan areas extends far beyond the city's watershed. For example, water has been imported to Los Angeles, California, from rural areas several hundred kilometers away in Owens Valley since 1913 and from the Colorado River since 1941. Large urban areas that rely on such regional-scale supply and distribution systems include several large metropolitan areas in southern and northern California, Tucson and Phoenix, Arizona, Denver, Colorado, and New York City. Generally the infrastructure and maintenance costs of establishing such long-distance supply systems, as well as political considerations, tend to restrict this strategy to use by large and prosperous urban centers.

Some urban distribution systems also include secondary distribution systems for reuse of treated wastewater, advanced treatment systems such as reverse osmosis or filtration, and multiple types of storage systems. Treated wastewaters may be distributed to meet irrigation and other non-potable needs, and with adequate treatment can be used to augment some drinking water supplies provided that communities are willing (Hurliman, 2007). Some cities such as Avalon on Santa Catalina Island, California, have implemented double plumbing systems with seawater used for the wastewater stream. In other cities, the notion of universal water-based sewage systems and sewage-treatment facilities that use water to transport waste streams is being questioned as impractical and potentially unhealthy (Brown, 2006). For example, Narain (2002) of the Centre for Science and Environment in India indicates that a water-based disposal system with sewage-treatment facilities is neither environmentally nor economically viable for India when an Indian family of five, producing 250 liters of excrement and using a water flush toilet, requires 150,000 liters of water a year to wash away its wastes.

The storage systems required for wastewater reuse can include local reservoirs, infiltration ponds for inducing groundwater recharge, as well as aquifer storage-and-recovery systems (Hanson *et al.*, 2005, 2008). This type of replenishment is also used to prevent or reduce land subsidence and seawater intrusion owing to sustained groundwater pumpage as a primary source of water supply (Hanson *et al.*, 2005). Treated wastewaters have long been injected into some coastal aquifers, e.g., in southern California, to deter seawater intrusion (Gleick, 2000). Wastewater management is thus integrated into many formal water systems and sometimes includes at least some reuse of treated wastewater. The treatment, distribution, and disposal of wastewater as well as reuse of wastewater are subject to the effects of climate change through increased energy costs and through

increases in the volumes of wastewater and stormwater entering treatment facilities in areas where, and at times when, precipitation increases, and through increased needs for reuse where, and when, droughts become more prevalent.

Formal wastewater treatment systems in large cities are capital and operationally intensive. These systems receive wastewater from water supply systems and treat it to several levels, including primary, secondary, and tertiary treatment. In developed countries standards are set for these levels. Facilities related to the treatment of sewage include water pollution control plants, combined sewer overflow plants, wastewater pump stations, laboratories, sludge dewatering facilities, and transportation systems for sludge removal (New York City Municipal Finance Authority, 2004). A key issue for many cities, even in developed countries, is the existence of combined sewer and storm-water systems, which can result in combined sewer overflow events during heavy rains, and thus contribute to pollution in surrounding waterways. An example of a city with a developed formal water supply system but little wastewater treatment is given in the case study of Mexico City.

5.2.2 Informal urban water supply sector

For the most part, attention to the potential impacts of climate change on cities' water systems has been focused on formal water supply systems. However, there are increasing numbers of cities, especially in the developing world, where water supply systems for many or even most inhabitants and in most parts of the cities are informal. An example is given in the case study of Lagos. In these informal systems, water supply and treatment, and wastewater treatment and disposal, are not provided by large, centrally managed engineered systems under long-term plans, but rather are provided by a mixture of largely impromptu local supplies, informal water markets, and imports from outside an urban area through trucking and other means. The lack of large-scale central management leads to lack of planning and maintenance (United Nations Human Settlements Program, 2003). These limitations, in turn, suggest that the informal systems may be more vulnerable to climate change than the more carefully planned formal systems with their greater capital resources for infrastructure development and maintenance.



Figure 5.3: Urban informal water supply: a water vendor's cart in Lagos, Nigeria.

Photo by: Ademola Omojola

Even the formal water supplies in many of the developing world cities are inadequate or, at least, erratic due to high population growth rates not generally included in early planning, limited investments, and high operational costs of the regular systems. This situation has required finding alternative sources to supplement the original formal sector water supplies. In many cases, population growth in recent decades has been very rapid so that development of alternative supplies has lagged far behind demands.

Typical sources of water supply in the informal urban water system include water extraction from highly climate-sensitive shallow wells, deep groundwater extraction through boreholes, and the patronage of often-polluted urban fringe wetlands. Where even these sources are lacking or too limited, elaborate informal water markets develop to meet demands for drinking, cooking, and cleaning water with attendant high water prices, frequently poor quality and inadequate supplies (Lallana, 2003a; Davis, 2006; Gleick *et al.*, 2006). The distance to available water supplies is also an important factor in health and welfare (Howard and Bartram, 2003).

[ADAPTATION] Box 5.1 Lagos, Nigeria, megacity formal and informal water supply and wastewater treatment sectors

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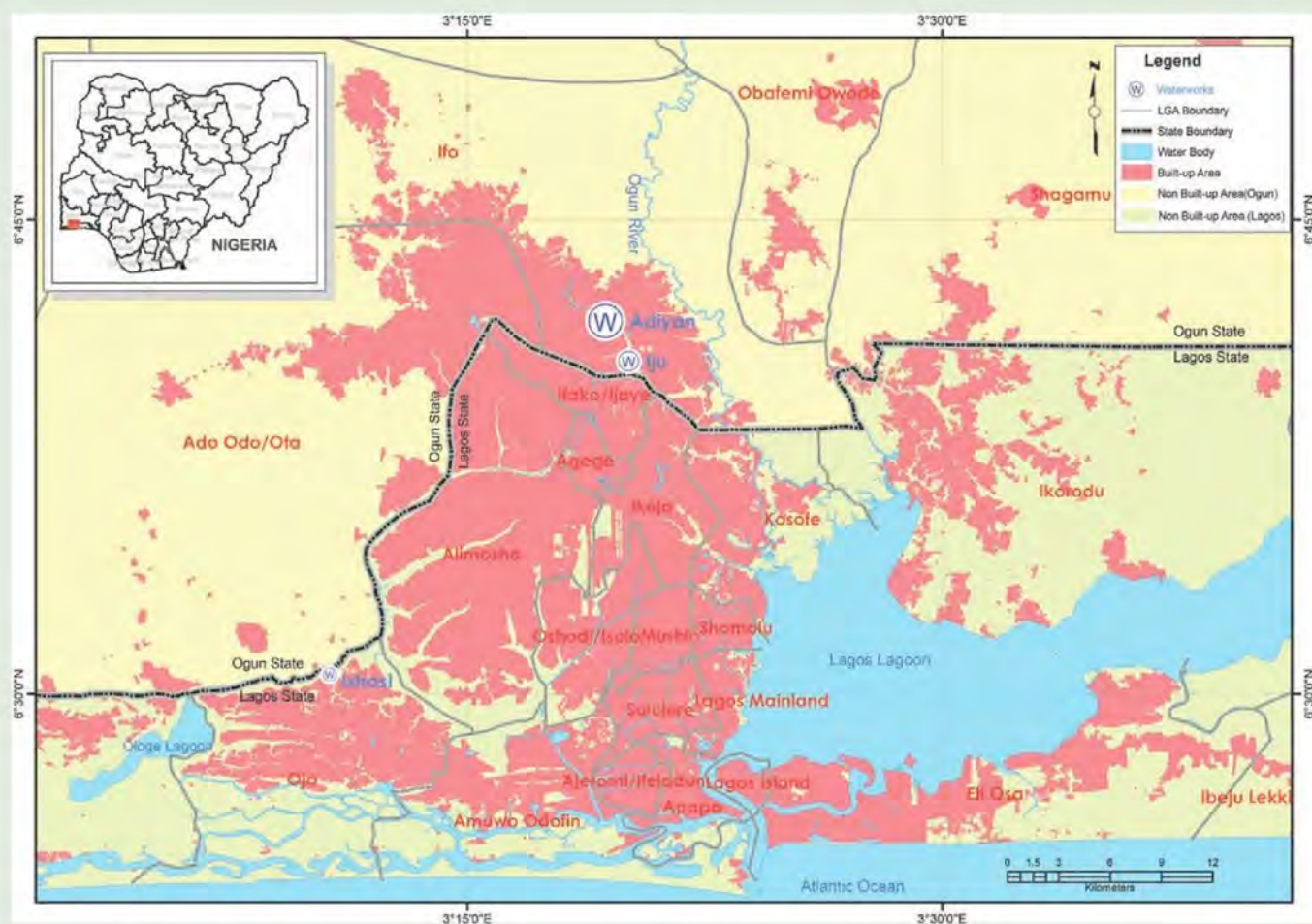
SYSTEMS DESCRIPTION

Lagos megacity in southwest Nigeria is one of the world's fastest growing urban centers. It covers an area of about 1,500 square kilometers of contiguously built-up area made up of twelve Local Government Areas (LGAs) in Lagos State and four LGAs in Ogun State. The total recorded population

of the LGAs of the trans-administration megacity in the 2006 census is over 10 million, which yields a population density of about 6,700 persons per square kilometer. There are indications and allegations that the figures are an underestimate. Lagos State for instance has been working with a population figure of about 17 million.

WATER SUPPLY

Urban water supply is the responsibility of the state government in Nigeria. The Lagos State side of the megacity



Box Figure 5.1: Location map, Lagos megacity.

is managed by the Lagos Water Corporation (LWC) and the Ogun State side by the Ogun State Water Corporation. Water supply to the megacity is both formal and informal. The formal sector is supplied mainly from three surface abstraction waterworks at Iju/Isheri (45 mgd) and Adiyin (70 mgd) on the Ogun River and Ishasi (4 mgd) on the Owo River. There are several mini-waterworks across the megacity mostly on the Lagos State side, relying on groundwater from boreholes. There are also some small non-water-corporation schemes of boreholes and overhead tanks built under different government programs in the megacity. These schemes usually supply consumers through localized public stand taps.

The LWC is basing the population to be served in the State on 17 million persons with an estimated demand of 600 mgd but currently with an installed capacity of 170 mgd out of which 119 mgd (66 percent) is from surface water and 51 mgd (34 percent) from groundwater. This translates into a 430 mgd (71 percent) supply gap. The water supply coverage in the Lagos State part of the megacity is about 40 percent through a pipeline network that runs north–south and mostly servicing the eastern part of the city and excluding a large sprawling population in the western part of the megacity. The water supply has significant capacity underutilization due to old

installations, erratic power supply, lack of maintenance, inadequacies in operational procedures, and poor funding among others. Also, water loss through leakage and poor service coverage due to limited pipeline network reticulation is very common. These problems are responsible for the inadequate supply in most of the areas serviced. The situation has forced many of the serviced residents to rely on redundant storage devices and on the informal sector to augment the current supply regime.

The informal water supply sector is very active in the megacity. This can be appreciated given that it serves about 60 percent of the residents in Lagos State and 67 percent in the Ogun State areas. This proportion may increase with the rapid sprawl and population growth of the megacity if proposed expansion programs are not promptly executed. The informal supply sources are mainly boreholes, shallow wells, and sometimes surface streams. The safe yield of the network of boreholes and their quality is yet to be adequately studied and monitored. This has grave implications on the sustainable use of the megacity's groundwater. For instance, there have been reported cases of groundwater contamination through seepages from the buried network of petroleum products in some parts of the megacity.

WASTEWATER MANAGEMENT

Wastewater management issues in the megacity are the responsibility of the Ministries of Environment and the Environmental Protection Agencies of Ogun and Lagos States. Pollution from wastewater is currently the greatest threat to the sustainable use of surface and groundwater in the megacity. Household, commercial, and industrial effluents and raw untreated sewage are often discharged into the open and fresh-water sources such as the Lagos and Ologe lagoons and the Ogun and Yewa Rivers.

There is no central sewage system in the megacity and less than 2 percent of the population is served with off-site sewage treatment plants that are currently in different states of neglect and disrepair. For example, the central sewage system in Festac Town – one of the few neighborhoods with such facilities – in the southwestern part of the megacity has collapsed for the past 15 years. Most of the sewer network has been connected directly to the storm-water lines. The direct spillage of sewage into the nearby rivers and roads from the sewage network and its consequent health hazard implications was published in the *Guardian* newspaper of December 22, 2008, page 73.

Besides the less than 2 percent with off-site sewage systems, only the toilet wastewater is connected to the septic tanks and soakaway systems, while the other household liquid wastes are discharged directly into the mostly open gutters in front of houses or on the streets in the high density areas. The wastewater eventually percolates or is washed into the water bodies by rainstorms. The stagnating pools of wastewater in the open gutters and on the roads often provide the breeding grounds for mosquitoes and habitat for several bacteria and viruses. In addition, wastewater pools contain hazardous contaminants such as oil and grease, pesticides, ammonia, and heavy metals (Saliu and Erutiya, 2006).

The water table in many parts of the megacity is very high. Consequently, the septic tanks and soakaway systems used in the collection of toilet wastewater readily contaminate and pollute the shallow groundwater that is a vital source of water supply to most low and middle income residents. Also, there is no septage treatment plant in the megacity and the evacuated untreated septage is mostly dumped in the Lagos Lagoon. The faecal contamination of the megacity's water system and the environment through the inadequate management of wastewater is a high health concern.

There is, however, a renewed awareness about the problem. For instance, the United Nations Environmental Programme (UNEP) has completed a training exercise with the environmental officers of Lagos State Environmental Protection Agency (LASEPA) on municipal waste management in coastal cities. Also, there is a renewed drive on storm drainage channel improvement and clearing to reduce incessant flooding in several parts of the megacity. Nonetheless, the 3rd Drainage Master Plan of the megacity, conceived in the 1990s, is yet to be implemented and flooding is still a common problem.



Box Figure 5.2: Wastewater in open gutter with water supply pipeline

Photo by: Ademola Omojola.

CLIMATE CHANGE INSTITUTIONS

Climate change awareness in the megacity is recent and can be associated with the Lagos State's participation in the C40 meetings. Lagos State has even gone ahead to establish a Climate Change Department in the Ministry of Environment. However, water and wastewater management in the megacity runs across administrations and agencies, which may be difficult to coordinate, most especially with respect to climate change mitigation and adaptation.

The assessment of climate change impact on water supply and wastewater treatment is currently not being given priority in the megacity. The issue of coping with the increasing water demands of the rapidly growing population in the megacity seems to be the topmost priority in water supply. Consequently, LWC has been reviewing its operational status within the framework of integrated urban water management such as reducing wastages due to leakages with the aim of increasing the resilience of the water supply. With respect to wastewater, the city has yet to fashion a coherent and comprehensive action of its management. This is, however, crucial for sustainable use of fresh water in the megacity.

METHODS AND IMPACTS

Climate change predictions for the coastal southwestern part of Nigeria suggest an increase in rainfall with increased intensity, sea level rise, flooding, coastal flooding from storm surge, and temperature increase and risk to coastal infrastructure (Ekanade *et al.*, 2008). It is therefore rational to accept that the strains on the supply and demand of Lagos megacity's water systems are likely to increase with such scenarios. However, unlike many cities that have been able to further provide background information and forecast data on the predicted impacts of climate change to local decision-makers, Lagos megacity does not currently have such background data for decision support.

Climate change scenario modeling for different emission levels and years for the megacity are yet to be carried out. To effectively plan for adaptation in a megacity such as Lagos, with low financial resources and adaptive capacity, there is the need to build scaled-down models of climate change to help in understanding the possible climate change scenarios and associated impacts and vulnerabilities in the city. This may eventually lead to an active input of climate change adaptation issues in managing this very vulnerable low-lying megacity.

CLIMATE CHANGE ADAPTATIONS

Climate change adaptations to water supply in Lagos have not been officially incorporated into its supply and demand. This may be due to the focus on the huge water supply infrastructural gap that the megacity is still trying to fill. There are, however, some visible adaptation options being carried out in the formal sector in the megacity that cannot be associated directly with climate change, but seen as a spin-off from actions taken to address more mainstream concerns of water supply management. For instance, at the management level, LWC has embarked on greatly reducing water loss through leakages, proper billing, and reducing water theft (unpaid

usage) to increase the resilience of water supply. There are also paid advertisements to sensitize residents on water wastage on the demand side. On infrastructure, the corporation is embarking on several water schemes for development and rehabilitation, while on policy it enacted a law in 2004 to encourage public-private partnerships (PPPs).

The biggest climate change adaptation challenge to water supply and wastewater treatment in the megacity is, however, in the informal sector. The uncoordinated and unregulated extraction of water from borehole and shallow wells, and the pollution of surface and groundwater from poor wastewater and solid waste management can all be worsened by the megacity's increasing population and climate change. Attempts at the LGA or community levels that are best positioned to monitor and implement policies and programs in the informal sector are obviously lacking. Thus, there is the need for policy formulation that will ensure monitoring and fashion out appropriate adaptation strategies in the demand and supply of water in the megacity. A new national policy on water has been sent to the National Assembly, but how well the policy recognizes the burgeoning number of people serviced by the informal water supply sector and the administrative capacity to implement the policy is another challenge.

Some of the dangers associated with urban water supply from such sources include:

- Most of the shallow wells are in areas with virtually no septic or wastewater treatment, which exposes the urban population to dangerous health risks (e.g., Kimani-Murage and Ngindu, 2007);
- Ad hoc solid waste dump sites with heavy leachates quite often share the same water-level dynamics as shallow wells;
- Massive uncontrolled extractions have been reported from some coastal cities' aquifers that in turn cause saline intrusion of the aquifers.

5.2.3 Future urban growth and the informal water markets

UN-HABITAT and other international organizations expect that future urban growth will take place predominantly in poor countries in the coming decades. Rapid urban growth in those countries has long been characterized by incomplete urbanization and severe shortages in the supply of key infrastructure (water, sewage, drainage, and electricity). In view of the difficulties already faced with rapid expansion of urban areas and populations, it is all the more difficult to see how urban areas in those countries will be able to meet future demands and stresses for water and wastewater management caused by higher temperatures and increased evaporative demand projected under the IPCC climate change projections (IPCC, 2007a). If the past is any indication, the role of informal water markets, with their challenges of adaptability and responsiveness to stresses of all kinds (Neuwirth, 2006), will likely become even more important to meet future increases in the demand for water.

5.3 Urban climate risks: vulnerabilities and impacts

5.3.1 Vulnerabilities

Water and wastewater treatment services in urban areas are vulnerable to direct impacts of climate changes such as changes in the amount and intensity of precipitation, increased temperatures and related evapotranspiration rates, changes in the intensity and timing of storm runoff, changes in both indoor and outdoor water demands, and, in coastal cities, sea level rise and storm surges. Vulnerabilities of both quantity and quality apply both to highly developed supply and treatment infrastructure and to less engineered and informal water supply and treatment systems. Warmer temperatures can also indirectly cause more severe weather (Cotton and Pielke, 2006) exacerbated by urban heat islands that could, in turn, result in additional convective thunderstorms, hail, cyclonic events (i.e., tornadoes, cyclones, and hurricanes), and higher winds that may exceed the design capacity of infrastructure. The centrality of water issues to urban planning more generally is indicated in the cross-cutting case study in this chapter: Urban vulnerability in the least developed countries (see Box 5.2).

Urban water supplies and wastewater systems are also vulnerable to climate change through less direct lines of connection. For example, warming trends may lead to increased demands for power production that, in turn, require power-plant cooling waters in competition with other water uses. Increased water demands associated with warming trends and, in some areas, reduced precipitation and runoff may lead to reliance on overdrafts from

[VULNERABILITY] Box 5.2 Urban vulnerabilities in the least developed countries**David Dodman***International Institute for Environment and Development*

The effects of climate change will be felt especially strongly in the towns and cities of the least developed countries (LDCs). These urban areas often have high concentrations of people and economic activities located in vulnerable physical settings, with their physical vulnerability exacerbated by poverty, the lack of appropriate infrastructure, and weak or inefficient systems of urban management. Yet this dense concentration can also provide the potential for effective adaptation, improved resilience, and the opportunity to meet broader development needs.

The Capacity Strengthening in the LDCs for Adaptation to Climate Change (CLACC) project is a group of fellows and international experts working on adaptation to climate change in twelve countries in Africa and three countries in Asia. The aim of the project is to strengthen the capacity of organizations in low-income countries and support their initiatives in sustainable development. In 2008, these fellows and experts prepared review documents highlighting climate-related problems (current stressors and potential climate change impacts) and their impacts for 15 cities (Box Table 5.1). These were deliberately selected to incorporate cities in a variety of physical settings – from low-lying coastal cities, to inland water-scarce cities, to high-altitude cities – and to include secondary urban centers as well as major cities and capitals as a means of demonstrating key vulnerabilities of cities in different positions in the urban hierarchy. This process was intended to identify key threats and major institutional stakeholders, and to provide the necessary information for communities and local governments to begin the process of climate change adaptation planning.

The CLACC project identified several key climate-related issues affecting urban areas in low-income countries, many of which will be exacerbated by anthropogenic climate change. LDCs are among the countries most affected by recent droughts. Drought is predicted to become more frequent and severe as a result of climate change, and many LDC cities are already badly affected. Zimbabwe has seen a decline in average rainfall of nearly 5 percent since 1900, with Harare and Bulawayo both affected by water stress. The Kariba hydropower plant that serves Harare has also been impacted by water scarcity, resulting in load-shedding by electricity

providers. In Mali, Bamako is seeing widespread difficulties in accessing water throughout the city. Although 90 percent of families in the city have their own wells, the availability of water in these is declining as groundwater levels fall.

But even in towns and cities where overall rainfall totals are declining, precipitation is tending to occur in shorter, more intense bursts that can overwhelm urban drainage systems and lead to flooding. Frequent flooding has been affecting the congested slums of Kampala, particularly Kawempe, where almost half the houses are built on wetland. Heavy rainfall and flooding may also lead to landslides: in Kathmandu, Nepal, 207 mm of rainfall in a single day caused a landslide in nearby Matatirtha that killed 16 people.

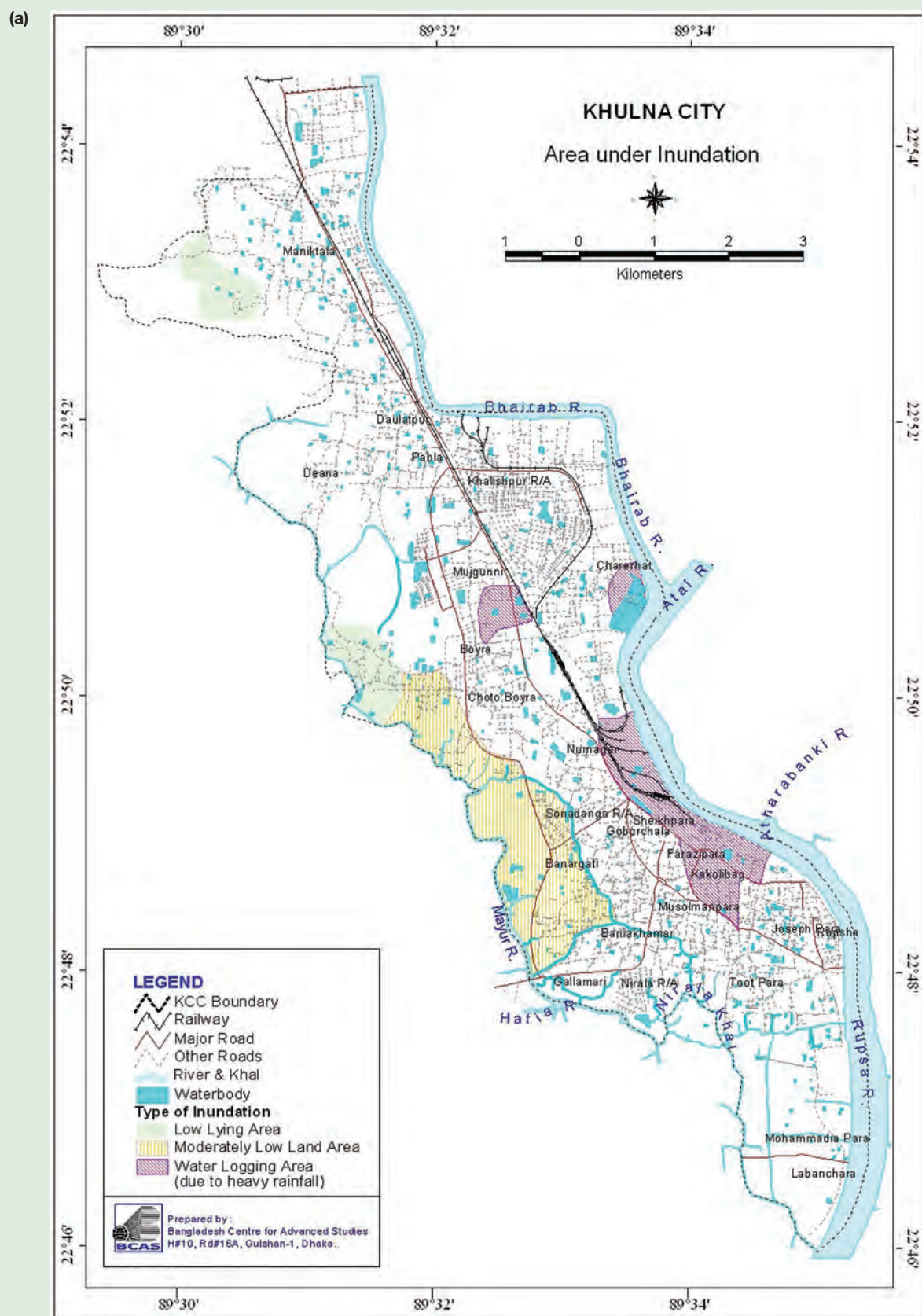
Sea level rise will affect towns and cities in the LDCs particularly severely because a relatively large proportion of their populations live in the Low Elevation Coastal Zone – the continuous area along the coast lying less than 10 meters above sea level. Already, coastal erosion has damaged infrastructure (including houses and roads) in Cotonou (Benin) and necessitated heavy investment in coastal protection in Dar es Salaam (Tanzania).

Yet even within these cities, exposure to risk is distributed unevenly. In Mombasa (Kenya), low-lying areas vulnerable to coastal flooding are inhabited by low-income groups, for example in the coastal settlement of Tudor. In Khulna (Bangladesh), a mapping exercise showed substantial overlaps between slum settlements and areas that frequently suffer from waterlogging (Box Figure 5.3). And these spatial distributions are compounded by a variety of social phenomena: low-income groups are less able to move away from vulnerable sites; whilst the very young and very old are at greater risk from heat stress, and vector-borne and water-spread diseases.

Building urban resilience in the LDCs is important because of the vulnerability of large and growing urban populations to the hazards described above. But it is also important because of the potential economic costs without effective adaptation strategies. Successful national economies depend on well-functioning and resilient urban centers. Building urban resilience will require not only improving urban infrastructure, but also creating more effective and pro-poor structures of governance and increasing the capacity of individuals and communities to address these new challenges.

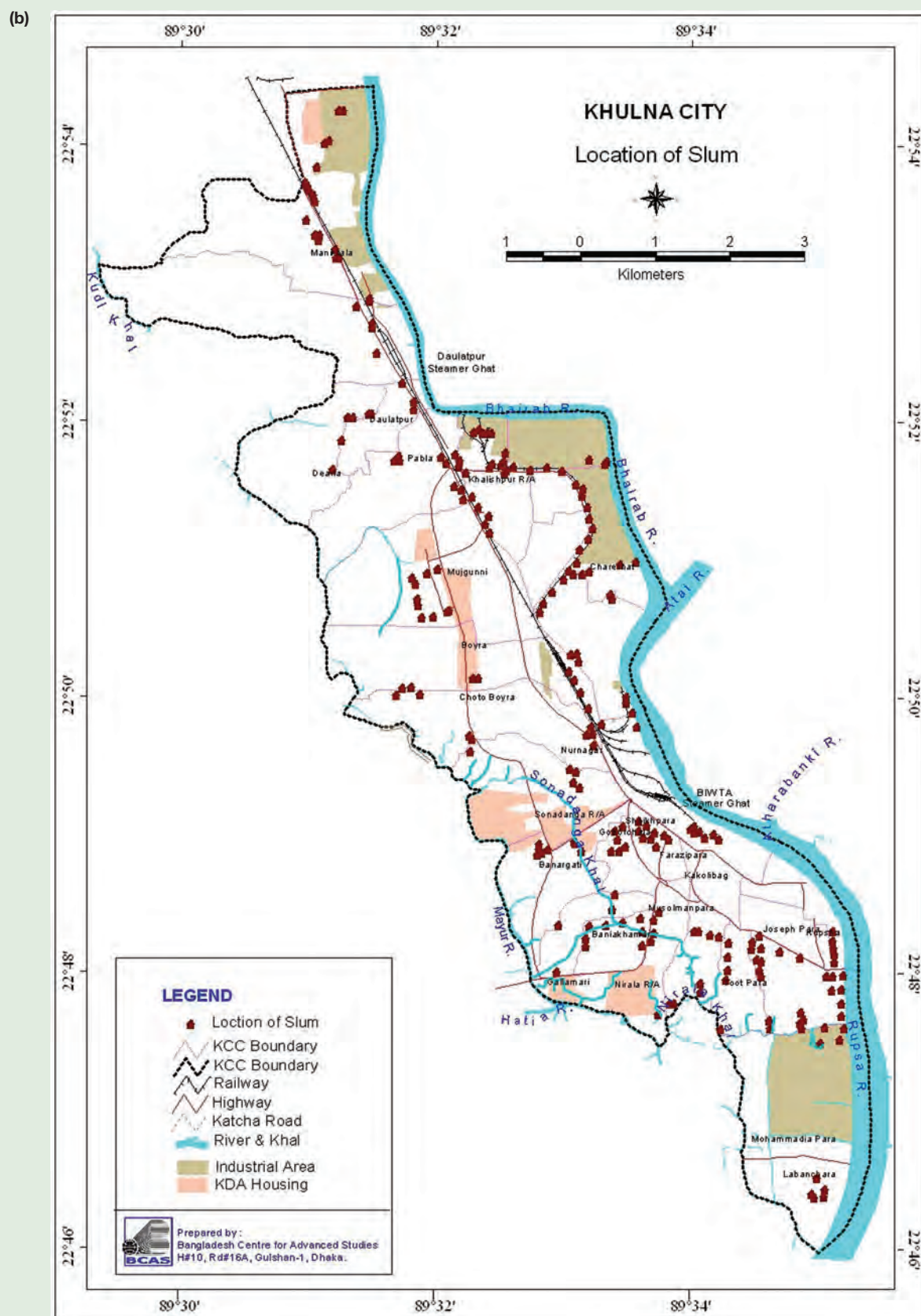
Box Table 5.1: *CLACC countries and cities.*

Asia	Eastern Africa	Southern Africa	West Africa
Bangladesh (Khulna)	Kenya (Mombasa)	Malawi (Blantyre)	Benin (Cotonou)
Bhutan (Thimphu)	Sudan (Khartoum)	Mozambique (Maputo)	Mali (Bamako)
Nepal (Kathmandu)	Tanzania (Dar es Salaam)	Zambia (Lusaka)	Mauritania (Nouakchott)
	Uganda (Kampala)	Zimbabwe (Harare)	Senegal (Diourbel)



Box Figure 5.3: Slums and waterlogging in Khulna, Bangladesh.

Source: Bangladesh Centre for Advanced Studies.



Box Figure 5.3: (continued)



Box Figure 5.4: Low-lying informal settlement in Mombasa, Kenya

Photo by David Dodman

Source: Reid, H. (2010). Building capacity to cope with climate change in the least developed countries. In J. Dodson (Ed.), *Changing Climates, Earth Systems and Society*, International Year of Planet Earth Series, Springer Science+Business Media.

Local and national governments have an important role to play, for they influence:

- the quality of provision of infrastructure for all areas within a city
- the quality of provision for disaster-preparedness and response
- the extent to which low-income groups can acquire safe housing in safe sites.

In addition, local governments strongly influence the environment within which local civil society action can take place. Community-based adaptation (CBA) is one such form of response. It is based on the premise that local communities have the skills, experience, local knowledge, and networks to undertake locally appropriate vulnerability reduction activities that increase resilience to a range of factors, including climate change. Facilitating and supporting this kind of response is likely to be key to building resilience in low-income urban centers.

For further information see Bicknell *et al.* (2009).

groundwater resources, land subsidence, and seawater intrusion. Increased overdraft and lower groundwater levels, in turn, can reduce or endanger the ability of wells to supply water without well retrofits such as lowering pumps and deepening wells. Finally, land subsidence can contribute to increased flooding as well as destruction of infrastructure resulting in additional leakage and reduced efficiency of distribution systems. These are examples of the complex connections and interdependencies that make essentially all water supplies and wastewater systems vulnerable to climate change at some level.

5.3.2 Impacts

These climate vulnerabilities lead to a wide range of potential climate impacts on urban water systems. Climate change and related increased climate variability threaten urban water infrastructures with disruption of service, reduced storage for potential emergencies, reduced water quality, and increased energy costs for operation and maintenance, at local and regional scales (see Chapter 4 on energy, and Chapter 7 on health).

5.3.2.1 Air temperature

Warmer temperatures, and especially more extreme temperature ranges, due to increasing greenhouse gas concentrations will accelerate the degradation of materials and structures in important urban water infrastructures. Warmer air temperatures can lead to biological and chemical degradation of water quality, e.g., by increased solubility and concentrations of contaminants in fresh water or enhanced growth of algae, microbes, parasites, and invasive species. Increased temperatures will result in higher evapotranspiration rates that will increase demands for

landscape irrigation and additional human consumption. Warmer temperatures will also result in additional demands for cooling water in arid and semi-arid regions. Warmer temperatures will result in greater summer peak demand and extended periods of increased demand during longer and drier summers, and may result in decreased reservoir or lake levels, which may require relocation of intake pipes that supply surface water from lakes or reservoirs (Thirlwell *et al.*, 2007).

5.3.2.2 Precipitation

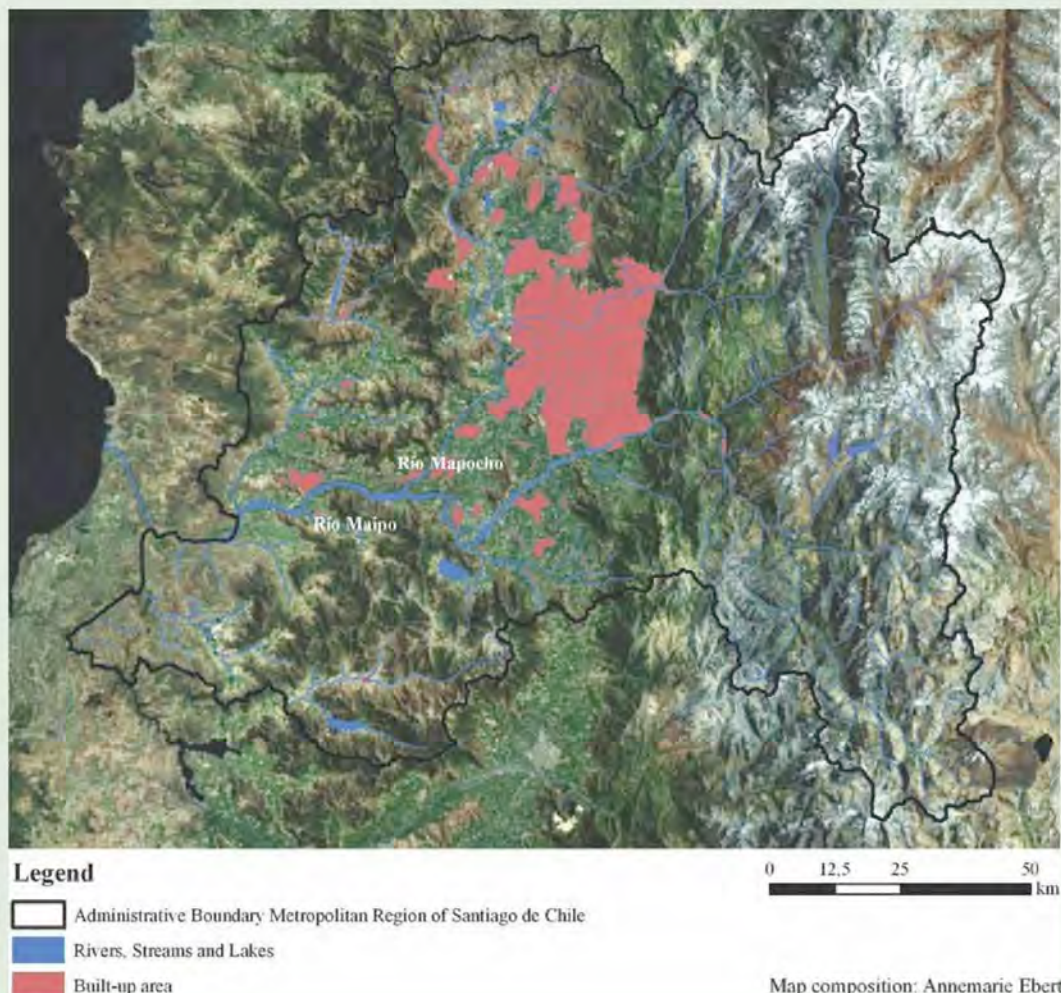
More frequent intense rainfall leads to more street, basement, and sewer flooding and stormwater runoff to various disposal systems. In most parts of the world, whether average precipitation totals increase or decrease with climate change, more intense rainstorms are expected (see Chapter 3 on Climate). More intense rainstorms will increase nutrient loads, eutrophication, taste and odor problems, and loading of pathogenic bacteria and parasites (*Cryptosporidium* and *Giardia*) in reservoirs. More intense precipitation will lead to more combined sewer overflow events that, depending on the city, pollute coastal waterways or other nearby bodies of water. More frequent intense rainstorms will also increase the sediment load in some rivers and reservoirs, and this may decrease the water quality of water diverted for water supply or further restrict periods of diversion. More intense and frequent rainstorms also can result in more flooding and erosion, which will lead to destruction of infrastructure such as bridges and approach embankments to bridges. The timing of rainfall may change, causing further disparities between supply and demand, e.g., with later rainfalls in places like the Seattle region (Chinn, 2005). An example of a city facing future climate stress from direct precipitation and loss of glacier mass is presented in the case study of Santiago de Chile (Box 5.3).

[ADAPTATION] Box 5.3 Santiago de Chile: Adaptation, water management, and the challenges for spatial planning**Jonathan Barton***Pontificia Universidad Católica de Chile***Dirk Heinrichs***German Aerospace Center*

Santiago de Chile, with its population of six million concentrated in the Maipo river basin on the western flanks of the Andes, is regarded as a Latin American city that compares well with others in terms of poverty, security, economic activity, and other urban indicators. Although the country contributes little in terms of global greenhouse gases, and is highly active in CDM projects, it faces considerable adaptation challenges, e.g., due to the vulnerability of its agro-business sector and its coastal cities (CONAMA, 2005, 2008). Santiago's future is linked to these changes, but faces more specific local adaptation challenges. Perhaps the most important of these is water management. The catchment is fed year-round from Andean glaciers

since localized precipitation is highly concentrated in the June–July winter period. The projections to 2070 under an A2 scenario suggest a potential 40 percent reduction in precipitation, compounded by reductions in glacial flows and rising evapotranspiration tied to higher temperatures of 2–4 °C (CONAMA, 1999; CONAMA, 2006). Pressures will grow to change the current water management system and meet the adaptation challenge as a consequence of increasing conflicts over water access. The expected population by 2030 exceeds eight million people (MINVU, 2008). This is likely to correspond to urbanization processes that displace agricultural interests in the region as the metropolitan area expands into productive land, also areas of increased risk and areas that provide important environmental services for the watershed.

The adaptation challenge to tackle this scenario lies in three fields: water markets, equitable distribution and water conflicts, and climate change governance within spatial planning. National and local government has only partially addressed these concerns to date.



Box Figure 5.5: *Maipo Basin, Santiago de Chile.*



Box Figure 5.6: *San Carlos channel (early nineteenth century) entry into the Mapocho River, an artificial channel that draws water from the Maipo River and takes it north into the Mapocho.*

THE WATER MARKET

The water market is based on water rights that are purchased and transacted (Water Code, 1981, modified 2005), based on a minimum streamflow condition and a total availability calculated by the national water authority (DGA). There is currently insufficient supply for new consumptive rights to be made available in the Maipo basin (DGA, 2003). Meantime, there is pressure from more powerful interests to buy out smaller rights holders, such as small-scale irrigation associations. The market is also unable to respond to fluctuations in the hydrological cycle, including the El Niño phenomenon for example, since rights are fixed and are awarded in perpetuity. In consequence, water availability decreases, existing rights will not be able to be extracted, and no new uses will be catered for.

EQUITABLE DISTRIBUTION AND WATER CONFLICTS

The limitations of the existing market, its weakness to respond to the natural cycles in the water basin, and the anticipated scarcity due to climate change, present a major adaptation challenge. Conflicts will increase particularly between residential, agricultural, and mining demands and environmental services. Assuming that the high residential value of land will lead to wine investments and horticulture moving to other regions, the question remains as to how a potential 40 percent reduction in water availability will be met by a population in the metropolitan area that is 30 percent larger than at present. The city's location is in a Mediterranean biodiversity hot spot, where current levels of "green" space per habitant ($3.2 \text{ m}^2/\text{cap}$; CONAMA, 2002) are well below the WHO recommendation of

$9 \text{ m}^2/\text{cap}$. This raises the issue of water use for maintaining the region's ecosystems, and for increasing public spaces to enhance urban quality of life (particularly in the lower income municipalities of the city) and reducing, for instance, the heat island effect. This will require a significant shift in water management in many areas with:

- reduced agricultural irrigation capacity
- watering of, and species selection in public spaces and domestic gardens
- a stormwater drainage system that seeks to shift water downstream of the city as swiftly as possible during peak events (rather than capture and storage)
- broad-based demand reductions.

CLIMATE CHANGE GOVERNANCE WITHIN SPATIAL PLANNING

The 2005 national climate change strategy concentrates on productive sectors, particularly mitigation and CDM commercial opportunities, but fails to put much weight on adaptation issues (CONAMA, 2005). It also fails to explicitly consider urban centers in spite of over 80 percent of Chileans living in urban areas, with over 40 percent of the national population living in the Santiago metropolitan region (RMS). This has changed slightly with the publication of the 2008 national action plan (CONAMA, 2008). The plan focuses on seven fields for action, water being one of them.

Although urban change, except coastal city risk, is not an explicit focus of the plan, all seven issues relate to urban transformations. Their incorporation into planning instruments is going to be a primary challenge for climate change adaptation: development strategy, metropolitan and local regulatory plans, and local development plans. To date, these documents have not included climate change considerations explicitly, largely because of the sectoral approach to public sector management.

Climate change adaptation will demand a coordinated response from government agencies, within the context of a regional adaptation plan. Although the DGA manages the water market, the water planning dimension must be brought within the administration of the territorial authority, the Regional Government, as part of a strategy able to engage with the priorities of the national plan (less fisheries) and the multiple public and private actors who are direct stakeholders, from rights holders (agriculturalists, mining firms and others), to the environment commission, the housing and urbanization ministry, the public works ministry, and municipal authorities. It would appear that the limitations of this natural resource market for the climate change challenge to be faced this century are already evident.

More frequent and intense droughts may affect reservoir and groundwater storage, as well as rainwater capture systems. Reduced precipitation may also result in less groundwater recharge and lower summer streamflows (Pitre, 2005; Earman *et al.*, 2006). Reduced precipitation will also contribute to increased pumping costs due to deeper groundwater levels and will also contribute

to increased conflicts over water related to baseflow in streams, maintenance of water rights, and restriction of new water users (Pitre, 2005). Reduced snowfall results in less water stored in snowpack reservoirs that provide water to some cities, and thus will change the temporal patterns of flow to reservoirs and supply systems. Reduced snowfall can also challenge many water

systems that implicitly or explicitly depend on seasonal storage in snow form, ultimately requiring the development of even more constructed storage to provide supply reliability. Reduced snow-fall and warmer water temperatures may aggravate demands for various instream and non-consumptive water uses, such as maintenance of fisheries, ecosystems, river amenities, and recreation, as well as various industrial and cooling needs. Increased precipitation and related peak flows may affect coastal and inland shipping by seasonally reducing water depths in channels, reducing passage heights under bridges, and limiting passage through weirs and locks (Klein *et al.*, 2005b), which can impact the shipping of wastewater treatment system outputs.

5.3.2.3 *Sea level rise and storm surges*

Salt water will encroach on coastal surface water sources, groundwater, and ecosystems. For example, increased sea levels will result in higher pressures of the ocean on submarine and coastal outcrops of coastal aquifers that will result in additional seawater intrusion. An increase in sea level will lead to an increased probability of flooding of sewers and wastewater pollution control plants (WPCP) and a reduced ability to discharge combined sewer overflows (CSO) and WPCP effluent by gravity. High storm surge levels lead to more street, basement, and sewer flooding. Higher sea levels, when inundating polluted areas (brownfields), can cause harmful release of pollutants. Higher sea levels can inundate fresh and saline wetlands and threaten the stability of canals and levee systems, which can have impacts on water supplies, water quality, and flooding. For example, a projected sea level rise of about 1.5 m along coastal California by 2100 with related levee failures and obstruction of fresh water flow in the Sacramento Bay–Delta system would jeopardize the fresh water currently passed through the delta for irrigation and drinking water supply to the cities and farms south of the delta (CADWR, 2008a). Higher sea levels will also increase the probability of water and wastewater damage due to surge action. Rise in sea level will result in reduced sediment transport, and may require increased dredging of sluices, weirs, groynes, locks, and canals, filling of wetland areas and raising and reinforcing levees and embankments (Klein *et al.*, 2005b).

5.3.2.4 *Surface-water impacts*

These threats, in turn, may lead to further hydrological challenges, such as: loss of reservoir storage owing to competition for reservoir space for flood control, ecological flows, recreation, or agricultural supplies; reduced natural storage of water supplies on seasonal to decadal time scales due to declining ice and snowpack reserves; loss of inflow into the reservoirs owing to increased droughts; loss of storage owing to unscheduled releases from increased precipitation, runoff, or transition of runoff from snow to rainfall; reduction of diversion flows owing to competition with ecological flows during dry periods or droughts; and increased runoff (including urban runoff) preventing adequate water quality of streamflow diversions for water-supply needs through entrainment of increased total dissolved solids or agricultural and urban contaminants.

5.3.2.5 *Degradation of groundwater aquifer systems used for urban supply*

Climate change may eventually affect groundwater aquifers that supply water for cities through seawater intrusion, land subsidence, lateral and vertical migration, and capture of contaminants. Flow of degraded waters between different parts of aquifers, or different aquifers, tapped by boreholes and wells may compromise aquifers used for water supply, even where not all the aquifers are directly impacted by climate change. Climate change may also increase the need for injection systems and surface water delivery pipeline systems in lieu of coastal pumpage to prevent seawater intrusion (Hanson *et al.*, 2008).

5.3.2.6 *Regional-scale changes*

Because many urban systems are part of larger regional water systems, the effects of climate change will also yield regional-scale challenges, such as reduction in snow-melt in watersheds that provide crucial supplies or storage mechanisms for urban supplies; loss of groundwater storage in supply basins owing to urbanization or legal constraints as regional competition for water supplies and wastewater disposal options increase; and disruption of delivery or competition for imported water.

5.3.2.7 *Impacts on informal urban water systems*

Given the meager capital resources and lack of centralized planning associated with development and maintenance of most informal water systems, climate change will have additional impacts on urban informal water systems. Even small perturbations of water sources, informal conveyances, and wastewater disposal options by climate change are likely to challenge these informal systems, and larger disturbances by extreme climatic events such as storms and heat waves typically will not have been accommodated in informal system designs. Such climate change stresses will bring management challenges, since informal water supply systems are complex structurally and institutionally, and since decision-making tends to focus on the short-term. The biggest impacts of climate change on the informal water supply sector have to do with the maintenance of sources in terms of both quantity and quality. Here, adaptations go beyond the management of particular systems to larger issues faced by cities and regional institutions. For example, increasing temperatures may adversely affect the health of populations not served by organized sanitary systems.

5.3.3 *Interactions of climate change, urban water, and other sectors*

Water is a cross-cutting theme in urban life and function and, as such, it is at the nexus of many issues regarding how climate change will challenge cities. The effects of climate change on urban water will impact other urban sectors; equally, climate change effects on other sectors will, in many cases, impact the urban water systems.

[ADAPTATION] Box 5.4 Mexico City's formal and informal water supply**Roberto Sanchez-Rodriguez***University of California Riverside*

The importance and complexity of water problems in Mexico City make it particularly vulnerable to the negative impacts of climate change. Water management has been a critical factor in the evolution of Mexico City. This megacity of more than 18 million inhabitants grew in a hydrological basin composed of five shallow lakes. Historical urban growth was on the lower part of the basin on top of the lakes and it has extended to the slopes of the surrounding piedmonts. The city has overtaken most of the former lakebeds and it has suffered major floods throughout its history. Despite numerous efforts to control this problem, flooding continues to be a major hazard in Mexico City and its solution requires an integrated approach together with other water problems.

Water supply is a multidimensional problem in Mexico City. The city has gone from a high level of self-sufficiency to a high level of dependence on two external watersheds. Current water use in Mexico City is approximately 63 m³/s. Close to 66 percent (43.5 m³/s) is extracted from aquifers and the remainder is imported from the Lerma basin (6.0 m³/s) and the Cutzamala basin (13.5 m³/s) (Ezcurra *et al.*, 1999). Importing water to Mexico City from those two basins has had a significant impact on them. The mean annual input of rainwater into the basin in Mexico City is 23 m³/s. It is estimated that only 50 percent of that water recharges the aquifers. Deficiencies in the operation of the distribution system cause leaks estimated to be about 30 percent of the water managed by the city. Considering that some of that water makes it to the aquifers, the estimated total recharge of the aquifers is 28 m³/s, equivalent to approximately only 50 percent of the water extracted every year. Water extraction from aquifers has caused a subsidence problem since the early 1900s. The city has sunk at different rates in different parts, but it reaches its extreme in the old historical center, where some parts have sunk up to 9 m during the past century. Subsidence has caused severe maintenance problems with the urban infrastructure, building, and transport systems. It has also aggravated pollution problems of the aquifers, particularly in critical areas for their recharge. Monitoring of the water in the aquifers has shown deterioration in its quality due to overexploitation of groundwater, and high bacteria counts have been observed in some wells (Mazari *et al.*, 2000). The protection of critical recharge areas of the aquifers is also a critical problem in Mexico City. The rapid expansion of illegal settlements in those areas jeopardizes the recharge of the aquifers.

The last component of water problems in Mexico City is wastewater. The city has a complex sewage collection system where wastewater and rainstorm water are mixed. The capacity of the system is 57 m³/s, 42.8 m³/s for sewage and 14.2 m³/s for rainstorm water. The effluent is shipped to the Tula basin about 50 km north of the city. Twenty-seven treatment plants treat only 7 percent of the total sewage generated in Mexico City.

**Box Figure 5.7:** *Subsidence in Mexico City.**Source: USGS.*

The increasing volume of sewage generated by Mexico City during the last decades has compromised the capacity of the system to evacuate rainstorm water, increasing the risk of flooding. The subsidence of Mexico City has also created problems for the operation of the system. The slope of some of the major drains has been reversed, requiring the construction and operation of pumps to evacuate wastewater. The Mexican federal government and the local government in Mexico City initiated significant maintenance and repairs to the wastewater system to prevent floods during the rainy seasons in 2007 and 2008. Major additional works are still being considered for the near future.

Water problems in Mexico City represent a major challenge for present and future urban growth. Climate change will aggravate those problems. Some of the studies of potential climate change scenarios show an increase in precipitation

**Box Figure 5.8:** *Alfalfa, a fodder crop grown with wastewater from Mexico City in the State of Hidalgo. Health problems can arise from the use of untreated wastewater for crop production.**Source: Flagstaffotos.*

and temperatures in the city by 2025 and 2050 (Gay *et al.*, 2007). The challenge to secure water supply will increase in light of the expected increase in the demand, particularly during the dry season when temperatures are expected to increase. The risk of flooding, a chronic problem in the city, will also increase under a climate change scenario. Those impacts will not only create significant consequences for the water sector, but also for the energy sector and the health of

the population. Mexico City needs a new strategy to address those problems. It will be critical to create integrated and multidimensional strategies recognizing the interactions among the different components of water in the city, as mentioned above. The federal and local governments have addressed each of those elements in isolation from the other, creating fragmented actions that have had limited success in solving a complex problem.

5.3.3.1 Energy

With warming, urban water demands and uses are likely to increase in many (perhaps most) cities. Future increases in the demand and use of water expected under climate change are likely to result in increased demands for energy (see Chapter 4 on Energy). The supply, treatment, and distribution of water supplies in urban areas require operation of pumps and other mechanical devices with attendant heavy energy use. Most sewage treatment plants operating in urban areas are mechanically operated and the collection, recycling, and outflow of sewage also frequently require the operation of pumps. If sewage flow is projected to increase under a given climate change scenario, an increase in the demand for energy must also be anticipated for both operation and capacity expansions.

5.3.3.2 Health

Urban water systems have close ties to many of the public health challenges associated with climate change (see Chapter 7 on Health). Water-borne diseases are a major health hazard in poor countries and emerging economies due to deficiencies in the supply of drinking water in their urban areas. Climate change can exacerbate those hazards by increasing gaps between drinking-water demands and supplies, and can stress sewage disposal systems and options beyond current conditions. Climate change may also aggravate public health challenges in urban settings by increasing the geographic ranges of some diseases and disease vectors (so that water facilities that did not sustain disease and vectors in the past may do so in the future); by increasing the opportunities for their propagation and development (e.g., by increasing reservoirs of standing water or promoting longer vector lives or more vector generations); and by generally reducing overall public hygiene and resistance to disease (as water supplies are challenged or limited).

5.3.3.3 Governance

The governance of a vital natural resource such as water is challenging in both poor and rich countries (see Chapter 9 on Governance). Climate change will stress further the political negotiations regulating access to water in formal and informal urban water markets even beyond often acrimonious historical levels. Whether privately or publicly owned, the governing structures of ownership, use, and sale of water resources may require redefinition if they are to be adaptable enough to accom-

modate growing and interacting pressures from rapid urbanization and climate change.

5.3.3.4 Land use

Urban demands for water often encourage or require land use changes in other areas that provide water supplies, storage, and conveyance corridors with the potential for severe negative social, economic, and environmental consequences. Increased urban water demands under climate change may create additional pressures to import water and to introduce land use changes in areas beyond the city. Water availability can dictate or limit land uses within urban areas, and consequently climate changes may redefine acceptable land uses within urban areas. Perhaps even more importantly in view of the rapid growth of cities expected in the twenty-first century, the forms, extensions, and types (particularly density) of future growth in and around cities will similarly depend on available options for provision of water and wastewater treatment and disposal, and how those options will be impacted by climate change.

5.3.3.5 Transportation

Water-borne transportation systems that are vital in many cities may be affected by changing climates, sea level rise, and changing streamflow timing and amounts (see Chapter 6 on Transportation).

5.4 Adaptation

Water supply and wastewater treatment infrastructures are typically long-lived, are ubiquitous elements in developed urban centers, and are subject to critical stresses from climate change, including sea level rise, higher temperatures, changes in precipitation patterns, and potentially more intense storms. In less-developed urban centers, water supply is more informal, and wastewater treatment may not be developed; yet these informal systems are also subject to climate change stresses. An orderly adaptation assessment process is needed to ensure the efficient use of scarce capital and operating funds over long time periods to meet these challenges in both formal and informal urban water systems. An example of a city with highly developed water supply and wastewater treatment systems, with an advanced adaptation planning process, is given in the case study of New York City (Box 5.6).

Climate change adaptations cover a wide range of actions in regard to urban water system operations and management, infrastructure, and policies. These will need to be developed for surface water, groundwater and rainfall-capture systems, and for wastewater treatment facilities for coastal and inland cities. Urban water adaptations will be needed for both highly developed supply and wastewater treatment infrastructure and for low-tech and informal water supply and treatment. They need to take into account rising populations, potentially rising and/or falling incomes, and changes in technology, and should be linked to co-benefits with investments for other purposes. Planning to address long-term needs for urban water system adaptation to climate change needs to be rigorous enough to justify major water-system investments but, given continuing uncertainties about the magnitudes and rates of the climate change challenges, will need to be flexible and ongoing (e.g., climate change scenarios for cities usefully could be updated on the order of every 5 years).

Some of the major urban areas that have aggressively begun to plan for, and adapt water systems and other infrastructure to, climate change are: Boston, USA (Kirshen *et al.*, 2004); Halifax, Canada (Halifax Regional Municipality, 2007); London, UK (Greater London Authority, London Climate Change Partnership, 2005); New York City, USA (New York City Department of Environmental Protection, 2008; see Box 5.6); Seattle, USA (University of Washington Climate Impacts Group and Washington Department of Ecology, 2008); and Toronto, Canada. Many adaptations for urban water systems have already been identified through the work of these “early adopters,” but research is still required to develop and evaluate available

options and capacities for adaptation. An example of needed work is the development of simulation tools for modeling climate change effects on reservoir system operations in order to evaluate changes in operating rules and storage capacity, as well as delivery and storage periods (New York City Panel on Climate Change, 2010). Much research on adaptation is needed for urban water systems in cities in the developing world. This need is illustrated by many local case studies such as that of Esmeraldas, Ecuador (see Box 5.5). There, urban areas are at risk from flooding and unstable hillsides, both problems that could become more serious with climate change.

In order to approach adaptation to urban water systems, a common assessment framework is needed to allow intercomparisons and coordination between and among cities and systems, in order to assist different jurisdictions to develop adaptations more efficiently. Such a framework is designed to encompass the full range of decision-making tools required to go from climate impacts and scenarios to adaptation project and program implementation, review, and monitoring (Table 5.1; Rosenzweig *et al.*, 2007). Potential climate change adaptations can be divided into operations/management, infrastructure, and policy categories, and assessed by their timeframes (immediate, medium, and long-term), the capital cycle, costs, and other impacts. The steps also need to adequately account for other changes that a city is likely to experience (such as population growth and changes in per capita water use), irrespective of climate change. Potential adaptations would ideally manage the combined risks of climate change and other predictable challenges to urban water supply and wastewater treatment facilities so as to provide an overall “coping strategy” (Ayers *et al.*, 2003).

[VULNERABILITY] Box 5.5 Urban expansion and vulnerability in the city of Esmeraldas, Ecuador

Christophe Lalande

UN-HABITAT

In 2001, Esmeraldas was the 12th largest municipality and its urban component the 15th largest city in Ecuador. It is a coastal city in the northwest of Ecuador. In most respects, the city is a typical Ecuadorian medium-sized city; its social and economic indicators are comparable to those of other cities in the same size group. However, unlike most cities in Ecuador, Esmeraldas experienced growth far below what was observed in most other cities in the group until the beginning of this decade.

The population estimate for the canton Esmeraldas for the year 2010 is 188,694, of which 66 percent is urban, up from 162,225 in 2001, an increase of 16 percent in nine years. As in most cities in Ecuador and Latin America, urban growth in Esmeraldas has largely been associated with illegal occupations of land in areas surrounding the consolidated city. Spatially the growth of the urban component of the canton in the past decade has concentrated in the south of the city, in

new neighborhoods such as La Tolita, Tiwintza, San Rafael, and Los Pinos.

Esmeraldas, like most cities in Ecuador, has increasingly incorporated areas at higher risk to natural disasters as it grew. The first settlement of what today is Esmeraldas stood above the flood zone of the Esmeraldas River; some accounts place an earlier settlement several kilometres upstream. Until 1975, the city grew by occupying the hillsides surrounding the original settlement (see Box Figure 5.9) and later occupying the flood zones of the Teaone and Esmeraldas Rivers to the south, and the Piedad and de Prado Islands in front of the city. The hillsides surrounding Esmeraldas have proven to be unstable throughout the city's development, with the latest significant emergencies occurring during the strong rains associated with the ENSO (El Niño) event of 1998.

After this period, the risks the new settlements faced were primarily related to floods, in part due to significant infrastructure improvements in the hillside settlements, but also because new settlement areas avoided such locations.



Box Figure 5.9: Overview of Esmeraldas, Ecuador.

By 2007, almost 60 percent of the population lived in areas with medium to high risks of floods or landslides. Sixty-six percent of the city showed medium to high exposure to climate-related risks.

Climate change scenarios for the city of Esmeraldas

The variability and uncertainties associated with the climate change projections available for the Esmeraldas River Basin are consistent with those observed for Ecuador as a whole.

Five models and nine emission scenarios have been identified and analyzed at the local level. Models and scenarios project increases in temperatures of approximately 2–3°C for the Esmeraldas River Basin. For the coastal region in and around Esmeraldas, precipitation projections vary from +30–50 percent to –30–50 percent (mm/day). There are several small, isolated watersheds in this area that would be affected severely by either extreme. Unlike large basins, and especially those with direct connections to the highlands, there is little room for compensating local increases or decreases in precipitation.

Exposure to climate change and tools for adaptation and mitigation in Esmeraldas

The impacts of climate change on the city of Esmeraldas identified by local stakeholders vary depending on the climate transition path guiding the analysis of potential adaptations and vulnerabilities. Current relatively high risk levels of landslides and floods (see Box Figure 5.10), both linked to current climate patterns, make Esmeraldas one of the riskier cities in which to live in Ecuador.

Under climate change scenarios predicting a path towards hotter and more humid climates, Esmeraldas would face even greater and more frequent disasters and more complex planning and management scenarios. Increased precipitation



Box Figure 5.10: Riverbank settlements in Esmeraldas, Ecuador.

would certainly cause additional life and property losses. In this respect, one of the key challenges the city faces is the ongoing expansion of informal settlements along flood zones of the Taeone and Esmeraldas Rivers and the low-lying Piedad and Prado Islands.

Under climate change scenarios predicting a path towards hotter and dryer climates, Esmeraldas could potentially experience lower risks of flooding, and lower stress on the water delivery systems. In contrast, stakeholders consider water shortages and price increases a major concern if the environment becomes dryer.

In both climate transition paths energy demands are expected to increase drastically, not only because of higher temperatures and larger populations, but also due to increased consumption levels throughout the city.

In this context, adaptation to climate change in and around the city of Esmeraldas requires a complex set of actions designed to compensate current vulnerabilities and to avoid expanding the range of risks associated with natural events.

Efforts to compensate for vulnerabilities or taking advantage of opportunities rely on actions and adaptations based on a combination of zoning, infrastructure modifications, energy shifts, capacity building, and improved governance.

According to stakeholder assessments, adaptations to climate change in Esmeraldas would consist of: structural adjustments, such as the constructions of upstream water storage and flood control systems (e.g., dams, reservoirs), and levees to protect flood-prone neighborhoods; the consolidation of the existing drinking water and sewage systems, and their expansion into new settlement areas; and institutional tools, such as zoning plans and cadastral capacity, that improve governance. Economic diversification would also reduce vulnerability by facilitating the consolidation of marginal urban areas.

Table 5.1: Steps in adaptation assessment for water supply and wastewater treatment facilities.

1. Conduct risk assessment inventory, including main potential climate change impacts
2. Apply future climate change scenarios
3. Characterize adaptation options:
Operations/management
Investments in infrastructure
Policy
4. Conduct initial feasibility screening
5. Link to capital and rehabilitation cycles
6. Evaluate options
Benefit/cost analysis
Environmental impact
Legal mandates
7. Develop implementation plans, including timeframe for implementation
8. Monitor and reassess

Source: Rosenzweig *et al.* (2007).

The adaptation assessment steps in Table 5.1 are based on standard water-resource planning procedures (Goodman *et al.*, 1984; Orth and Yoe, 1997), with the significant addition of climate change (Step 2) and an explicit link to agency capital cycles to provide for efficient incorporation of adaptations during rehabilitation and replacement (Step 5). While these steps are broadly comprehensive, climate adaptations for particular circumstances may require additional steps (as, for example, securing external funding for adaptations in developing countries). These steps are further elaborated here, with examples of potential adaptation measures for formal and informal systems. This approach provides a way of framing the range of challenges and opportunities for adaptation of urban water supply and wastewater treatment systems to climate change. An application in slightly modified form is in New York City Panel on Climate Change (2010), Appendix B.

5.4.1 Step 1: Conduct risk assessment inventories

The inventory is designed to highlight the most significant potential climate change impacts on urban water systems. Suitable inventories of water supply and wastewater treatment systems are not always available for several reasons; and such inventories are fundamental to good adaptation planning. Since climate change is a new consideration for most urban jurisdictions, integrating it into water infrastructure

planning and operation has not typically been considered. In addition, water supply and wastewater treatment systems infrastructure is sometimes managed by several agencies, even in quite small urban jurisdictions, and each agency may have different record-keeping procedures. As a result, water supply and wastewater treatment system elements are not always identified by potentially limiting physical parameters that connect them to their changing environment (e.g., height above mean sea level and storm surge records, distance from shore, expected lifetime, rehabilitation cycle) relevant to climate change. Further, infrastructure is now often subject to planning for replacement over time periods much shorter than those relevant to long-term climate change. Examples of questionnaires are in New York City Panel on Climate Change (2010), Appendix B.

In conducting inventories, due attention should be paid to operational, financial, or physical relationships with neighboring urban areas (e.g., to address competition for water supplies, and to promote shared wastewater treatment plants and transportation facilities).

The risk inventory provides both a basis for focusing subsequent steps of the assessment framework and a basis for identifying major thresholds and tipping points beyond which the urban water systems are most likely to fail (Pielke and Bravo de Guenni, 2004). These thresholds then can provide clear and important criteria for planning and monitoring to avoid the most critical tipping points within the urban water systems, allowing planning and adaptation to proceed with greater clarity of purpose.

5.4.2 Step 2: Apply future climate change scenarios

Climate change scenarios are now typically developed from downscaled IPCC GCM model simulation runs (Rosenzweig *et al.*, 2007; Lettenmaier *et al.*, 2008). In some cases RCM models driven by GCM boundary conditions are used for this downscaling; statistical downscaling methods are at present more common than RCM modeling. Several approaches are possible, including using mean values of a variety of simulations with different emission scenarios, or providing a range of values, for example in the form of histograms, with suggestions for critical protection levels. (An even simpler approach is to assume certain levels of, e.g., sea level rise, and plan for these, e.g., Franco *et al.* (2008), although this is generally less instructive.) Ensembles of climate model projections can be combined with the ensemble of potential responses that can yield probabilities of occurrence of sea levels that exceed certain thresholds such as unacceptable levels of sea level rise and storm surges in coastal regions or seawater intrusion into coastal aquifers. This may result in redefinition of certain common historically based criteria such as design standards for siting and constructing urban structures, which are governed, in part, by flood frequencies that were previously based on historical streamflow records.

[ADAPTATION] Box 5.6 Adapting New York City's water supply and wastewater treatment systems to climate change

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SYSTEM DESCRIPTION

Water is supplied from upland reservoir systems north of New York City (NYC) with a total area of almost 2,000 square miles. Annual precipitation on the city's watersheds averages about 44 inches. The total storage capacity of the reservoir system is 547.5 billion gallons, with a safe yield of 1,290 million gallons daily (mgd). (There is a small additional 33 mgd of safe yield from well fields in the southeastern part of NYC.) Safe yield compares to daily system demand of about 1.3 bgd in NYC and upstate. Water from the system supplies 8 million people in NYC and an additional 1 million people in upstate counties. The NYCDEP sewer and wastewater treatment system includes over 6,600 miles of sanitary, storm, and combined sewer pipes. This system processes 1,500 mgd of wastewater at 14 water pollution control plants (WPCPs) located on the coast to allow for treated water discharge (Rosenzweig *et al.*, 2007; New York City Department of Environmental Protection, 2008; Box Figure 5.11).

CLIMATE CHANGE INSTITUTIONS

The New York City Department of Environmental Protection (NYCDEP) is the municipal agency responsible for water supply and wastewater treatment. It has taken a leading role in assessing the impacts of climate change on water supply and treatment facilities. This work began with the creation of the NYCDEP Climate Change Task Force in 2004, a joint NYCDEP, university, and engineering firm effort (Rosenzweig *et al.*, 2007). The most recent report is *New York City Water Supply System* (New York City Department of Environmental Protection, 2008).

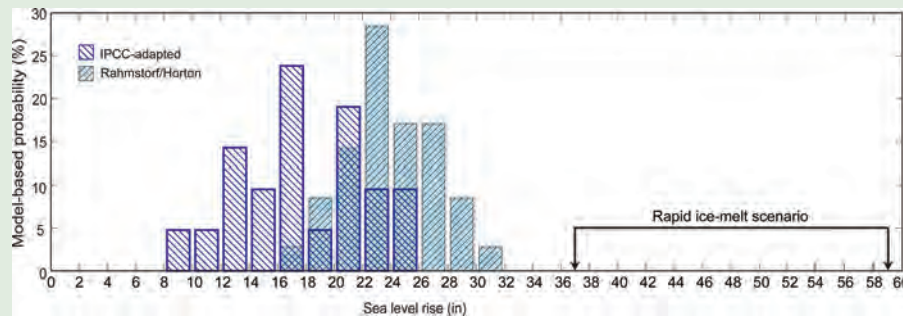
METHODS AND IMPACTS

Future climate scenarios for the 2020s, 2050s, and 2080s have been developed based on downscaled IPCC GCM simulations, using 16 models and 3 emissions scenarios in the most recent applications, and 7 models for sea level rise (SLR) (Box Figure 5.12) These methods are described in detail in New York City Panel on Climate Change (2010), Appendix A. Scenarios for the NYC region predict higher temperatures,



Box Figure 5.11: New York City water supply system.

Source: New York City Department of Environmental Protection.



Box Figure 5.12: Sea level rise scenarios, NYC 2050s.

Source: New York City Panel on Climate Change (2010).

more precipitation, and sea level rise, with impacts including more droughts, more frequent inland flooding, coastal flooding from SLR and storm surge, and water quality issues from higher temperatures and changing precipitation patterns (Box Figure 5.13). The most recent scenarios are in New York City Panel on Climate Change (2010), Appendix A.

CLIMATE CHANGE ADAPTATIONS

Using a multistep adaptation assessment process, wide-ranging adaptation studies are under way, including a study of the impacts of sea level rise on the system, and a study of reservoir operations using future climate scenarios in reservoir modeling. Potential adaptations include operating system changes (see the schematic in Box Figure 5.14), flood walls for WPCPs, relocation of facilities, improved drainage, and enhanced water quality treatment.

BROADER URBAN RELEVANCE

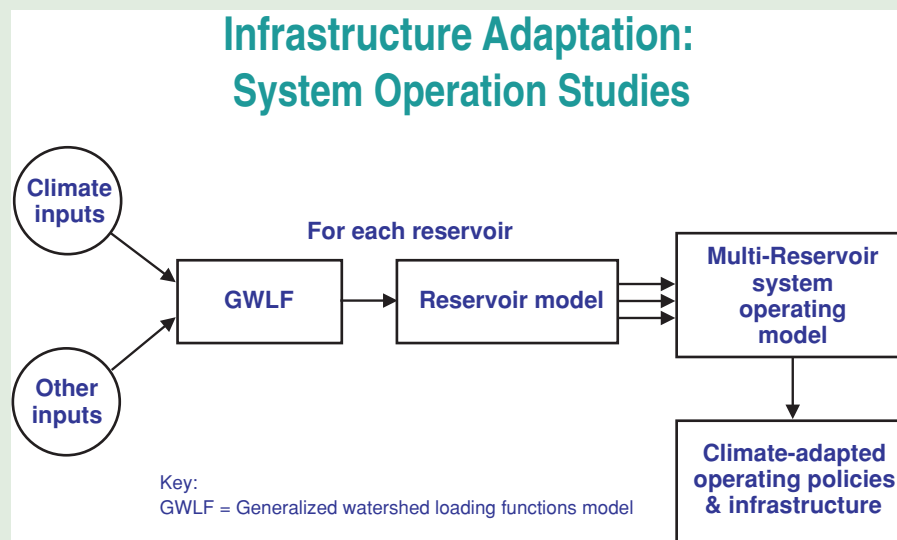
New York City initiated (2008) its Climate Change Adaptation Task Force, which is investigating climate change impacts on all of the City's critical infrastructure. The pioneering NYCDEP efforts are continuing within this broader



Box Figure 5.13: Flooding at a coastal water pollution control plant (WPCP) in New York City.

Source: New York City Department of Environmental Protection.

supportive framework (New York City Panel on Climate Change, 2010).



Box Figure 5.14: NYCDEP reservoir modeling with climate change. In the figure, note that future climate inputs are among the drivers of the system.

Source: New York City Panel on Climate Change (2010), Appendix B.

5.4.3 Step 3: Characterize adaptation options

Adaptation options may be usefully categorized as operations/management, investments in infrastructure, and policy. Many adaptations fall into more than one of these categories. A wide range of potential adaptations should be examined at the initial stage and evaluated and prioritized in later stages of the decision-making process.

5.4.3.1 Operations/management adaptations

These include a range of new criteria for system operations that reflect non-stationary hydrologic processes. As one example, scenario results can be incorporated into the design process for drainage structures by estimating new rainfall intensity–duration–frequency (IDF) curves based on projected precipitation patterns. This is a new challenge for planners and engineers (Frederick *et al.*, 1997). Studies are also needed of the operation of the sewer and wastewater treatment systems with rising sea levels and increases in storm intensity. As sea levels rise and storm surges increase, the operations of the systems will be increasingly compromised. Operational changes may be needed to deal with backsurge problems in the early stages of sea level rise, before infrastructure changes are required (Rosenzweig *et al.*, 2007).

Many operational adaptations may be suggested by the use of water system simulation models run with inputs from the climate scenarios, a process that has begun in NYC (see Box Figure 5.14 in Box 5.6 on New York City) (Moore *et al.*, 2004). This is especially important for both water supply and wastewater treatment systems, since in many urban regions of the world there are expected to be both more frequent floods and more frequent droughts, the result of increased precipitation, higher temperatures, and possibly more intense storms. Other operational changes may include further efforts to reduce consumption through changes in fixtures, pricing, and education. Demand reductions are themselves important adaptations to climate change because they can increase resiliency and margins-of-error in existing supplies. Examples of successful conservation programs can be found in Boston, USA (Massachusetts Water Resources Authority, 2001), and Melbourne, Australia. Another potential change is in drought rules: if droughts become more frequent, as is expected in many settings based on climate simulations, these rules may need to be adapted to provide, through regulation and pricing, more effective water restrictions. Finally, the incorporation of climate change considerations into a city's environmental review process is an important potential adaptation for planning growth or urban renewal.

Most of the operations/management adaptations described thus far are for developed (formal) systems. Evaluations of operation/management strategies to adapt informal systems to climate change are urgently needed, including strategies for entraining them into the formal water supply and wastewater treatment sectors so as to better adapt to dynamic climate conditions.

5.4.3.2 Investments in infrastructure

A wide range of potential adaptations is available for adapting water supply and wastewater treatment systems to climate change, and in some cases adaptations are under active consideration. These may entail substantial financial outlays, some of which may be included in future system expansions, while others may be required for actions undertaken specifically as climate change responses. There are also infrastructure changes undertaken for other reasons, such as the Thames (UK) (Aerts *et al.*, 2009) and Venice (Italy) tide surge barriers, which should prove useful in dealing with climate change stresses. Another such example is the New York City Department of Environmental Protection dependability study, designed to provide for continuing supplies of water for 9 million New York system customers if any element of the system goes off line (New York City Department of Environmental Protection, 2008). The redundancy measures contemplated in this study will also be helpful in future periods of increased droughts and floods.

Among infrastructure adaptations for sea level rise and storm surge, flood barriers for wastewater treatment plants and other coastal structures are possible, as is the construction or relocation of tide gates and the installation of pumping capacity. If more freshwater will need to be taken from estuaries or if less freshwater is expected to enter the estuaries, water intakes may have to be moved upriver to cope with encroaching salt fronts. New system interconnections will increase resiliency in both coastal and inland cities. Desalinization plants may become more attractive in changing climatic conditions, although capital and energy costs may be limiting. Artificial groundwater recharge by streamflow or imported water, aquifer storage and recovery (ASR), or seawater barrier injection systems to provide replenishment of subsurface stores of water may also be needed, and may expand options for more urban water banking and marketing.

5.4.3.3 Policy adaptations

Policy adaptations may be distinguished from operations and management decisions because they are made at higher levels of government. For example, policy decisions include those involving joint operation of systems run by different authorities, of which some examples exist already. These include a recent modification of operating rules at Lake Wallenpaupack, in the Delaware Basin (USA), to provide for changes in releases and more flexible joint operations involving a private utility, the Delaware River Basin, and New York City (DePalma, 2004). Further into the future, large potential adaptations involving joint operations and investments may include integrating New York City reservoir operations with Delaware River Basin facilities (Rosenzweig and Solecki, 2001). As policy focuses on water markets, and related distribution systems evolve near urban centers, a wider variety of water sources and applications of water reuse will become available. Conjunctive uses of groundwater and surface water supplies have economic benefits, or can be structured to create economic benefits (Reichard and Raucher, 2003) that

can be used to promote alternative adaptations through incentives, reduced costs, and greater supply availability.

Policy adaptations may be very important in dealing with climate change in the informal water supply and wastewater treatment systems, including decisions to bring such systems under more adequate supervision. In much of the developing world, a policy shift in allowing public–private partnership (PPP) through water concessions and vendor-based supply, among others, has the capability to increase access to safe water supply; however, there are important pricing and equity considerations in such partnerships, which have not always been successfully implemented. Particularly in developing countries, it may be important to develop a new culture of water value, use, and consumption based on balanced perspectives of its economic, physical, ecological, social, political, and technical dimensions.

5.4.4 Step 4: Conduct initial feasibility screening

This is an important step to ensure, as soon as possible, that potential and proposed adaptations are at least feasible, during the time frame in which they might be implemented. Feasibility must be evaluated from the engineering, economic, environmental, legal, and other perspectives. In this step, it is important to err on the side of inclusion rather than exclusion, because many adaptations that may seem unfeasible according to current standards and expectations may become feasible as climate change conditions (and challenges) unfold, or advances in engineering, budget, and organizational possibilities occur.

5.4.5 Step 5: Link to capital and rehabilitation cycles

Adaptation strategies should be integrated with expected rehabilitation and replacement schedules. This will provide for potentially significant cost savings in implementing adaptations. In addition, there may be planned maintenance/operations and policy changes that will provide opportunities for efficient scheduling of adaptations. Revenue streams generated from use and sale of water and wastewater services may be linked to climate changes and can partially constrain when rehabilitation, expansion or adaptation can occur and can be funded.

5.4.6 Step 6: Evaluate options – benefit/cost analysis, environmental impact, legal mandates

Benefit/cost analysis has a long history in water resources and other infrastructure planning (classic treatments include Eckstein, 1958; Gittinger, 1972; current applications are discussed in, among many recent texts, Freeman, 2003 and Tietenberg, 2006). With reference to climate change, the focus of economic studies has been on general economic costs and impacts of climate change (e.g., Nordhaus and Boyer, 2000) and high levels of anthropogenic climate impacts (e.g., Mastrandrea and Schneider, 2004), although there have been some locally detailed studies (e.g., Yohe and Neumann, 1997). Despite the widespread

awareness of the importance of climate change for sectors such as water utilities (Miller and Yates, 2005), there have been few attempts to integrate the technique precisely into the decision frameworks of agencies. New applications should include three elements not typically integrated into benefit/cost applications:

1. Changing climate risks over time as represented by model-based probabilities
2. Capital cycle and capital programming for long-lived infrastructure
3. Planning and regulatory time-lags typical of, and often decisive for, urban infrastructure.

Environmental laws and other legal mandates will vary widely among jurisdictions; a first level of adaptation assessment should be the analysis (and revision where required) of current mandates to include climate change adaptation (Sussman and Major, 2010). Particularly in cities, environmental impact analyses should include the human environment as a priority.

5.4.7 Step 7: Develop Climate Change Adaptation Action Plans, including timeframe for implementation

Water and wastewater treatment agencies' Climate Change Adaptation Action Plans should include the program of identified adaptation strategies, outlining the resources committed to implement the plans, the resources that are still needed, and next steps to be taken (including areas that need to be researched further). All plans should include specific dates for implementation and metrics to measure success. When climate risk management has been fully incorporated into agency procedures, implementation plans will be incorporated into capital and operating budgets over the long run, and revisited regularly as uncertainties and eventualities associated with climate change unfold. Time horizons may be at different levels for mitigation and for adaptation and have parallel but separate metrics.

This step should also include coordination with other agencies, such as transportation agencies whose decisions may affect urban water flows (e.g., by changing surfaces or slopes). In addition, opportunities to link adaptation to mitigation should be explored.

5.4.8 Step 8: Monitor and reassess

Adaptation plans should be reviewed and updated on a regular basis to reflect changes in environmental conditions and climate change science. Agencies should continue to monitor their infrastructure and use updated climate risk information to determine further vulnerabilities and the adequacy of plans and efforts to date. Monitoring and reassessment is a normal long-term part of climate risk management, because the science, and the ability to prepare climate scenarios, progresses each year. In addition, every year there is additional information on actual climate changes, which should be used to refine and readjust adaptation programs on a regular basis. This step is crucial to

the development of flexible adaptation pathways that are appropriate and realistic to the urban water systems of individual cities (New York City Panel on Climate Change, 2010). Using procedures similar to this Adaptation Assessment procedure (Rosenzweig *et al.*, 2007, Table 1), the state of California has since 1983 required every urban water supplier to develop and implement an Urban Water Management Plan (UWMP) (CADWR, 2008b) that includes urban water contingency analyses with six components to address drought, climate change, and other catastrophic shortfalls of supply:

1. A description of the stages of action an agency will take in response to water shortages
2. An estimate of supply availability under conditions of three consecutive dry years
3. A plan for dealing with catastrophic supply interruptions
4. A list of prohibitions, penalties, and demand reduction methods to be used
5. An analysis of expected revenue effects of reduced sales during shortages and proposed measures to mitigate those effects
6. A plan to monitor and document water cutbacks.

5.5 Mitigation

Under the IPCC definition (e.g., IPCC, 2007a), mitigation is action to reduce emissions of greenhouse gases in order to reduce overall climate change. Notably the IPCC Fourth Assessment Working Groups II and III conclude that “mitigation primarily involves the energy, transportation, forestry, and agricultural sectors, whereas actors involved in adaptation primarily represent a large variety of sectoral interests, including agriculture, tourism, and recreation, human health, water supply, coastal management, urban planning and nature conservation” (IPCC, 2007a). Most of the references in the Working Group III 2007 Assessment Report (IPCC, 2007c) to urban water and wastewater refer to improvements in wastewater management as an approach to mitigating emissions (primarily of methane). Nonetheless, in the urban-water sector, there are several important mitigation options that can be incorporated into planning and operations because, in urban areas, water and energy are inextricably linked.

5.5.1 Water conservation/demand reductions

Reductions in water use can have multiple benefits, including cost reductions, increased overall supply reliability, and mitigation of greenhouse gas emissions (e.g., Cohen *et al.*, 2004; Klein *et al.*, 2005a). Less water used can mean less water needing to be captured at, and drawn from, various reservoirs and aquifers, less water to be transported and lifted over obstacles, less water to be treated, less water to be heated, less wastewater to be treated, and less wastewater to be transported and disposed of (Figure 5.1). Each of these steps in the water system generally requires energy (e.g., Cohen *et al.*, 2004; Klein *et al.*, 2005a). For example, in California, the State Water Project,

which transports water from the wetter northern parts of the State to urban southern parts, is the largest single electrical energy user in the State (Cohen *et al.*, 2004). In many cities, the energy used for water supply, treatments, and disposal has come from burning fossil fuels that emit greenhouse gases into the atmosphere. In many – perhaps, most – urban systems and situations, water conservation and demand reductions can provide greenhouse gas emissions mitigation benefits.

Urban water-use demands for residential supplies are typically largest in cities where housing is most dispersed, because outdoor uses of water are frequently the largest demands (e.g., Mayer *et al.*, 1999). Thus, in many dense urban areas, achieving substantial demand reductions can be difficult. Nonetheless, one particularly important mechanism for controlling water waste in the cities of many developed and developing nations is reduction of large-scale leakage from the water-supply infrastructures. Lallana (2003b) compiled urban water-supply leakage estimates from 15 European nations, and found leakage rates ranging from about 4 percent of the total water supplies to 50 percent (Figure 5.4).

In informal urban settlements, planning and maintenance of water delivery systems are presumably less rigorous than in the formal areas, and leakage losses may be even larger. Leakage losses also represent opportunities for contamination of water supplies, so that efforts to reduce leakage will provide multiple benefits (Lallana, 2003b). Reduction of leakage is likely to depend on pressure in the water mains, soils, topography, and age of the water systems. Nonetheless, progress is possible and, indeed, being made in many urban water systems.

5.5.2 Water reclamation and recycling

Reclamation and recycling offer opportunities for reducing the energy used to provide water supplies (see e.g., Furumai, 2008). Recycled water generally still requires treatments that demand energy, but otherwise many of the initial extraction and transport energy demands can be reduced or eliminated because the reused water is already in the municipality (Figure 5.1).

5.5.3 Attention to energy efficiency of water supply expansion

More generally, most actions to expand or improve water supplies have ramifications in terms of overall energy use, which in turn need to be carefully assessed in terms of greenhouse gas emissions. Development of some urban water sources – such as groundwater pumpage or, more recently, desalination of brines or seawater – can require amounts of energy or conditions of energy development that may be problematic in terms of mitigating greenhouse gas emissions, especially if they are allowed to degrade (e.g., overdraft of aquifers with attendant increases in pumpage lift). Energy requirements for treatment of some water sources can also be decreased or increased depending on whether the water quality of the source is managed or mismanaged.

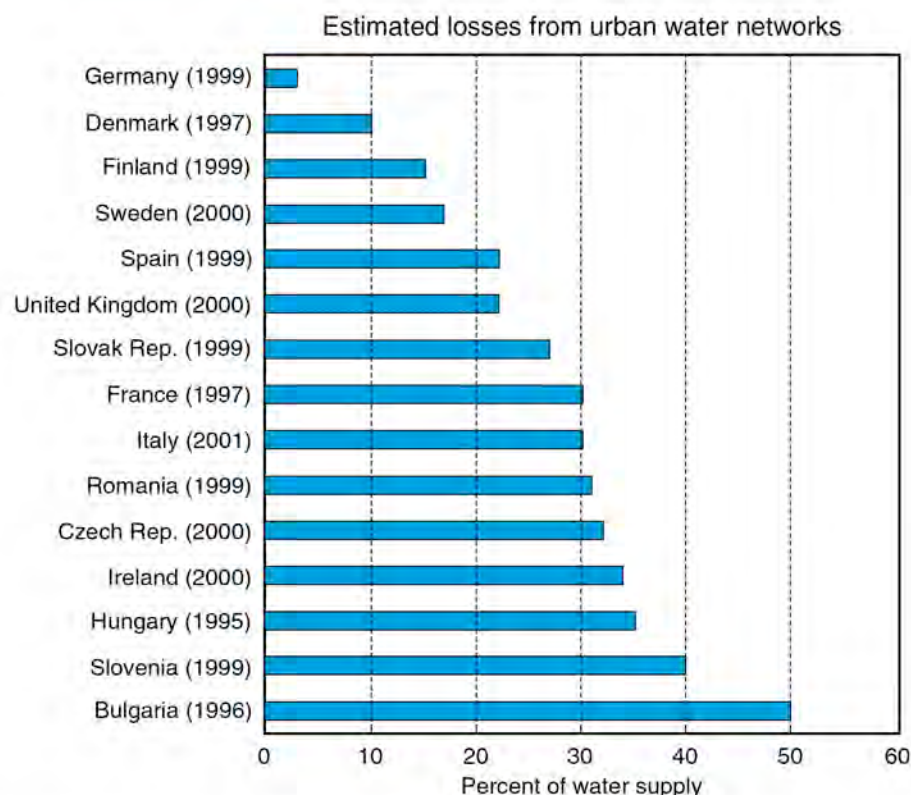


Figure 5.4: Urban water supply leakage losses from 15 European nations. Note that leakage rates will vary by city within countries.

Source: Lallana (2003b).

5.5.4 Hydropower and reservoirs

Hydropower and surface water reservoir-based water supplies can have implications for mitigation of greenhouse gas emissions, although those benefits remain difficult to specify. Most reservoirs emit varying amounts of greenhouse gases through processes involved in the natural carbon cycle (Battin *et al.*, 2008), although some reservoirs also absorb these gases. In particular, greenhouse gas emissions can be significant from shallow tropical reservoirs; e.g., Fearnside (1995) calculated emissions from two reservoirs in Brazil amounting to tens of millions of tons of CO₂ and tens of thousands of tons of CH₄ in a single year, three to six years after their initial inundation. It is believed that deeper, cooler reservoirs emit less gas (IPCC, 2008). However, wetlands and floodplains that were inundated in the establishment of reservoirs may also have been methane emitters, and those wetland emissions may have been substantially reduced by their inundation (Mata and Buhooram, 2007; IPCC, 2008). Thus, opportunities for greenhouse gas emissions mitigation may also be available in the planning, operations, and use of hydropower in general, hydropower as energy supplies for urban water and wastewater systems, and reservoir-based water supplies, but the extent of these opportunities generally needs more study.

5.5.5 Urban water heating

A significant amount of the energy associated with urban water supplies is dedicated to water heating for residential,

commercial, and some industrial purposes. For example, in California, over half of urban water uses are residential, and over half of those uses involve water heating (Cohen *et al.*, 2004, Figures 3 and 4, and p. 26). Actions and opportunities that favor the expansion of solar water heating have been identified as a useful part of urban mitigation programs (e.g., Razanajatavo, 1995; IPCC, 1996b; Nadel *et al.*, 1998) in both developed and developing nations. Localized small-scale wind power could also help minimize the centralized energy needed to pump, distribute, and heat water for urban and domestic uses. Even if solar heating is not deployed, it is often possible to reduce greenhouse gas emissions by heating with fuels (or electricity) that are less carbon intensive, or by using tankless water heating.

5.5.6 Watersheds and river basins

Many traditional urban water systems tap into water supplies derived from broad hinterland watersheds and river basins (Kissinger and Haim, 2008; Broekhuis *et al.*, 2004). Many cities, recognizing the vulnerabilities of these hinterlands to contamination and disruption, are moving to institute better land use and watershed management practices in these resource areas. Land use and watershed management impact overall land- and water-surface emissions or sequestrations of greenhouse gases, and thus need to be assessed in terms of their mitigation impacts or benefits, along with other costs and benefits.

5.5.7 Wastewater

Cities are large and concentrated producers of wastewater (Satterthwaite, 2008). Methane emitted during wastewater transport, treatment, and disposal, including from wastewater sludge, amounts to 3 to 19 percent of global anthropogenic methane emissions (IPCC, 1996a). Globally, the major sources of the greenhouse gas nitrous oxide (N_2O) are human sewage and wastewater treatment (IPCC, 2007b). Methane emissions from wastewater are expected to increase by about 50 percent in the next several decades, and N_2O emissions by 25 percent. Thus, one of the most direct ways to mitigate greenhouse gas emissions is through improvements in collection and management of urban wastewaters, using technologies most appropriate to the economies and settings involved (IPCC, 2007b). Technologies already exist for reducing, and perhaps reversing, these emissions growth rates.

In cities in developed nations, wastewater treatment facilities are sometimes major greenhouse gas emitters but those emissions have been identified as important avenues for overall greenhouse gas emissions reduction (e.g., Rosenzweig *et al.*, 2007). A large proportion of the greenhouse gas emission from urban wastewater, however, is expected to take place in developing countries (e.g., Al-Ghazawi and Abdulla, 2008) and from informal urban settlements. In many of those developing countries and informal urban settlements, rapid population growth and urbanization without concurrent development of sufficient wastewater collection, treatment, and disposal infrastructures results in very large and unmitigated greenhouse gas emissions. Non-existent sewer systems, open sewers, ponding, and unchecked releases of untreated wastewaters are a fact of life in the informal sectors of cities in both developed and developing countries (IPCC, 2007b; Foster, 2008). Improved sanitation facilities, infrastructures, treatment and disposal systems in these settings would not only mitigate emissions but would offer substantial public health benefits as well (e.g., Al-Ghazawi and Abdulla, 2008; IPCC, 2007b).

5.6 Policy considerations and knowledge gaps

5.6.1 Policy considerations

Some cities have implemented policies to encourage adaptation and mitigation in the face of the effects of increased urbanization combined with climate change and variability. These include, among others, Chicago, London, New York, Seattle, and Toronto (Parzen, 2008). A broad range of policies is available for implementation, including operational/management changes, infrastructure investments, and new policy including institutional changes. Diversity and redundancy promote the reliability of water supply and wastewater systems and allow for a broader platform of policies that promote the implementation of adaptation and mitigation.

Approaches to managing urban and regional water resources for long-term sustainability have become more complicated in recent years as our understanding of the interconnections within hydrologic systems has increased. The fact that surface water and groundwater resources are not separate resources, but instead are generally linked, is increasingly recognized as both constraint and opportunity in the development and management of urban water resources (Winter *et al.*, 1998). The concept of sustainable yields (Alley and Leake, 2004; Alley, 2006) has grown from capture of recharge to include capture of discharge, groundwater storage depletion, and capture of streamflow. With these and other linkages, achieving sustainability is becoming more complex as urban centers attempt to reconcile supplies and demands in the face of changing climates, runoff, and recharge.

Following are some important options for urban adaptation of water and wastewater systems to the impacts of climate change that emerge from this assessment. These options provide a range of focused approaches for urban policymakers with respect to the water and wastewater treatment sector, supplementing and extending the key messages of the chapter.

1. *Fix leaks.* In many urban areas, both in developed and emerging economies, water leakage from collection and distribution systems amounts to large fractions of the overall flows of water through the urban systems and, indeed, amounts to large absolute volumes of water wasted. Programs to control leakage, and thus to reduce demands and increase resilience to climate change, are among the first and most cost-effective adaptations that should be undertaken. Moreover, the control of leakage reduces pumping and thus energy costs, providing opportunities for both adaptation and mitigation.
2. *Integrate systems.* Innovative policies and strategies to ensure that new investments produce benefits across the integrated water systems (supply, access, quality, treatment, and recycle) are needed to help urban areas respond more effectively and efficiently to the new challenges created by climate change and to improve equity in the access and use of water. Integration of entire ranges of hydraulic components, such as artificial recharge/water banking with incentives for replenishment, reuse, and conservation, will produce efficiency and cross-cutting benefits.
3. *Improve institutions.* The roles of institutions managing formal and informal water resources in urban areas need to be analyzed and reassessed to insure that institutions are appropriate to changing challenges, including climate change impacts. Potential issues may include the investigation of the benefits of increased regionalization of systems to promote redundancy.
4. *Capture rainwater.* The capture of rainwater may be an important conservation adaptation to reduce pumped groundwater and related energy use as well as to reduce potential urban flooding and provide a supplemental source of water for irrigation of urban landscaping.
5. *Reduce demand.* Programs for the implementation of indoor demand reductions, such as low-flow toilets, shower heads,

and other efficiency measures, and outdoor demands such as landscaping, would increase the reach and resiliency of water supplies in both formal (and to the extent relevant) informal water supply systems.

6. *Reuse water.* Policies to increase water reuse would increase options for adaptation by reducing overall demand for original system water, thus making the system more robust, and they also can contribute to mitigation depending on the balance of energy required for reuse and original source.
7. *Establish water marketing.* Water marketing can provide mechanisms and opportunities to increase efficiency and improve system robustness. Water marketing also may facilitate integration of multisector use in situations where urban, agricultural, and environmental uses could be enhanced by combined management.
8. *Increase water banking.* Water banking may also provide important options for adaptation as a way of hedging against uncertainties and improving system robustness.
9. *Incorporate climate change into planning.* Optimal scheduling of adaptations for long-lived infrastructure, as a regular part of planning, can help to ensure that investments are made at the most efficient times in terms of climate change and other system drivers.
10. *Rationalize water rights.* Revisions of the structure and distribution of water rights to more fully encompass conjunctive use of groundwater and surface water may be needed. In the same context, “use-or-lose” policies that do not promote efficiency, conservation, and reuse are likely to become more and more problematic in the face of climate change induced growth of demands and stresses.
11. *Develop public-private partnerships.* In much of the developing world, a policy shift to allow public-private partnerships (PPP) through water concessions, vendor-based supply, and other measures may help to increase access to safe water supply as the impacts of climate change are felt. However, equity considerations and the urgent needs of the poor are also important considerations (e.g., Argo and Laquian, 2007), and there have been cases in which such arrangements have been problematic.

5.6.2 Gaps in needed understanding of urban water systems and climate change

Effective responses to the many challenges that climate change poses to urban water and wastewater systems require a strong understanding of the challenges themselves, of the workings and limits of the urban systems under stresses for which they may not have been designed, of the range of options that are feasible in engineering, economic, and political terms, and of the interactions between the water sector and other sectors also striving to accommodate climate change. Many gaps in our understanding currently limit our ability to develop those responses.

The largest gap in understanding the implications of climate change for urban water systems is the limited and short history

of monitoring, evaluation, and prediction of vulnerabilities of water supplies and wastewater management in informal settlements. Much more information is needed in order to manage these systems well and to encourage the incorporation of these systems into the formal sector. All “urban watersheds” need to have a data monitoring structure that will allow the computation and monitoring (of supply and demand as well as potential climate change) of the hydrologic budget (i.e., inflows and outflows).

In both formal and informal urban areas, a key knowledge gap is lack of intercomparability among measures of water and wastewater systems describing the systems from city to city. Regular, intercomparable data describing water uses, stormwater rates and the economics of water and wastewater are needed to prioritize urban water/climate issues at regional to international scales, and to identify early successful management responses in both formal and informal sectors.

The hydrologic cycle in urban settings is less well understood and quantified than those in many less intensely populated regions (e.g., Grimmond *et al.*, 1986; van de Ven, 1990; Gumbo, 2000; Marsalek *et al.*, 2007; Furumai, 2008). Better, more site-specific quantification and knowledge of the urban water cycle will provide baselines for interpreting the influences of climate change on urban waters and environments.

The impacts of untreated wastewaters (both residential and industrial) on ecosystems and downstream water supplies (Gleick *et al.*, 2006) are not well understood, and the interaction of climate change with such impacts is even less well characterized at present (Nelson *et al.*, 2009). Significant research is required on these subjects.

One set of specific data that needs to be compiled is information about which of the world’s coastal cities’ water and wastewater systems are threatened by different levels of sea level rise, accounting for local subsidence and ocean conditions. This is essential both at a city-by-city level, and at international and global levels to understand the magnitude and prioritization of required adaptation investments.

The role of water management in greenhouse gas emissions mitigation has not been well addressed to date. These mitigation issues are complex and interlinked (Satterthwaite, 2008); more research in the area of how water management interfaces with mitigation is needed.

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