Climate Change and Urban Hydrology: Research Needs in the Developed and Developing Worlds

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Although opinion polls indicate the public continues to be uncertain about climate change, the scientific community generally has reached consensus that increasing anthropogenically-sourced greenhouse gases have contributed substantially to rising global temperature over the second half of the twentieth century. This chapter takes the position that global warming and attendant changes in the precipitation regime have started and likely will intensify over the next century and explores these issues in relation to urban hydrology research needs for both the developed and developing worlds. Most research on climate change and water resources has focused on river flooding and drought at the watershed scale, irrigation demands, and impacts due to sea level rise. Assessment of urban drainage and sanitation infrastructure impacts and resiliency under climate change scenarios have received much less attention. Urban hydrologic impacts are broadly defined in this chapter and are discussed under eight categories: i) system resiliency and adaptation; ii) storm frequency and runoff; iii) water and sediment quality; iv) health impacts; v) water use and reuse; vi) sea level rise; vii) greenhouse gas emissions; and viii) urban heat islands. Adaptation measures to improve urban hydrologic resiliency are explored, with a focus on low impact development (LID) technologies, water reuse, land use planning, green buildings, and political will. Research needs in hydrologic science and engineering include: continued improvement of General Circulation Models (GCMs), particularly in the area of spatial downscaling; the need to further link GCM outputs and stormwater/sewer modeling efforts (for both water quantity and quality); reconsideration

of design approaches under non-stationary rainfall time series; more extensive field verification (and modeling linkages) related to LID benefits; and opportunities and technologies for water reuse and green buildings. Scientists and engineers must increase their communication with politicians and policy-makers about the need to consider greater temperature and precipitation variability in community planning and include full-cost accounting of hydrologic services in these discussions. A more integrated approach to green community planning and management is required and the Singaporean model offers an interesting possibility. However, we also must recognize that a “one size fits all” solution to climate change resiliency and adaptation is not possible. Exchanges regarding water resource management technologies between the developed and developing world are occurring, but must be culturally appropriate and adapted to the specific environment.

11.1 Introduction

The theory of greenhouse-gas induced climate warming is not new, first being proposed in the 1800's (e.g. Arrhenius, 1896) and subsequently explored in the 1930's through 1950's (e.g. Callendar, 1938; Plass, 1956; Revelle and Suess, 1957). However, Leiserowitz (2005) suggested global climate change did not register with the U.S. public until 1988 when the hottest year since the middle 19th century coincided with Dr. James Hansen's testimony at a U.S. Senate Energy and Natural Resources Committee hearing that greenhouse gases were detectably changing climate. Although some scientists remain unconvinced regarding the evidence of anthropogenically-induced climate change (e.g. Khandekar et al., 2005), the general consensus of the scientific community is that anthropogenic greenhouse gases have been responsible for recent warming trends (e.g. Oreskes, 2004; IPCC, Intergovernmental Panel on Climate Change, 2007; Anderegg et al., 2010). However, at least in the U.S., there seems to be greater public uncertainty with respect to the reality and causes of global warming (Krosnick et al., 2006; Nisbet and Myers, 2007). An ABC poll conducted in 2005 found 59% of Americans were completely or mostly convinced that global warming was happening, but when the question was asked a different way (do you think world temperatures may have been going up slowly over the past 100 years) polls by Ohio State University and ABC in 1997, 1998, 2006 and 2007 reported 76%, 80%, 85% and 84% of the respondents agreed that it probably was happening (Nisbet and Meyers, 2007). Yet, Nisbet and Meyers (2007) also reported that Gallup surveys done each year between 2001 and 2005 found only 15-18% of Americans felt they understood the issue of global warming “very well”, with the percentage increasing to 22% in 2007. In their surveys conducted in 2006 and 2007 ABC

found only 11% of Americans felt they knew “a lot” about global warming (Nisbet and Meyers, 2007). Furthermore, 54% to 57% of Americans believed the greenhouse effect was caused by ozone depletion in surveys conducted in 1994 and 2000 (Nisbet and Meyers, 2007). Depending on how the question was asked, Nisbet and Meyers (2007) noted that between 33% and 60% of the American public thought scientists had reached a consensus on the issue of climate warming. Finally, of relevance to this chapter, Leiserowitz (2005) reported that few Americans associated global warming with extreme weather events.

A number of reasons have contributed to public uncertainty, including:

1. Conservative counter-claims: based on a content survey of conservative think-tank websites McCright and Dunlap (2000) concluded the conservative movement had mobilized through websites, promoting three counter-claims to global warming theory: i) evidence of global warming was weak, if not entirely wrong; ii) if it occurs, global warming could have substantial benefits; and iii) proposed action to ameliorate global warming would do more harm than good. Jacques et al. (2008) also noted conservative think-tanks have effectively utilized print media as well as television and radio. In addition, political lobbying has been a strategy employed by multinational corporations (van den Hove et al., 2002; Leiserowitz, 2005).
2. Politicization of science: Pielke (2004) suggested that “the use of science by scientists as a means of negotiating for desired political outcomes ... threatens the development of effective policies in contested issues.” In a linear model of the relation between politics and science, it is assumed that if the science is wrong then the politics will be wrong, or conversely, winning a scientific debate leads to a correct and appropriate political outcome. This is overly simplistic because the linear model fails to capture the complex relationship between science and politics. Pielke (2004) argued this linear model shortcoming plays out in the climate change arena because “both sides argue about science as a proxy for actually discussing the worth and practicality of possible alternative courses of action, of which the Kyoto Protocol is but one of many. On the climate debate many assume that victory in debate on scientific issues, as perceived by the public, ought to compel victory in political debate.” However, there also *appears* to be conflicting scientific evidence, with each side claiming victory; this may explain the low proportion of the American public who believe scientists

have reached a consensus on climate change and some of the confusion on the part of the public.

3. Balance as bias: in the public media a standard approach to reporting on a controversy is to present competing points of view, summarizing the most compelling arguments of both sides with equal weight. This balance thereby provides a check on bias. It has been argued that this approach to avoiding bias has allowed a small group of global warming skeptics to have a disproportional representation of their views in the public media (Boykoff and Boykoff, 2004; Kellstedt et al., 2008).
4. Confusion over the severity of risk: a number of studies noted that while Americans may be aware of the climate change concept, they do not rank it as a “serious” problem (Brechtin, 2003; Leiserowitz, 2005; Krosnick et al., 2006). There may be a number of reasons for this, including more recent concerns about the economy, labeling a problem as serious can be uncomfortable to people if they feel they cannot solve it, and Americans have a perception that the greatest dangers from climate change are geographically and temporally distant (i.e. few Americans have a major concern about impacts to their immediate family or local community).
5. The specific wording and order of questions in opinion polls, as well as when the poll is conducted, can produce very different results (Nisbet, 2004) and make interpretation of results difficult, at best.

The mass media clearly plays an important role in the public discussion of climate change and over the past year this has been well illustrated with reports of Environment Canada’s budget cuts that in part targeted research on climate change adaptation (<http://www2.macleans.ca/2011/06/15/720-million-of-programs-and-operations-to-be-cut-this-year/>) and more recently with Canada’s withdrawal from the Kyoto Protocol (<http://www.theglobeandmail.com/news/politics/canada-formally-abandons-kyoto-protocol-on-climate-change/article2268432/>). Burch (2010) suggested the “story of climate change mitigation and adaptation in Canada is one of innumerable false starts, often piecemeal policies and great potential.”

While public debate about the reality of climate change is interesting, and certainly public opinion can drive political will, this chapter takes the position that scientific consensus is strong enough to assume change is occurring and that the role of science and engineering is therefore to identify, assess and explain a wide range of possible outcomes. As such, I will provide a few, and certainly not exhaustive, thoughts about urban hydrology research

needs for both the developed and developing worlds. Most research on climate change and water resources has focused on river flooding and drought at the watershed scale, water supply, irrigation demands, and impacts due to sea level rise (e.g. Hatch et al., 1999; Asian Disaster Preparedness Center, 2003; Hurd et al., 2004; de Sherbinin et al., 2007; Nicholls et al., 2008; Asian Development Bank, 2009; Dany et al., 2010; Vastila et al., 2010; Shinker et al., 2010; Stroup, 2011; Arnell, 2011). Assessment of urban drainage and sanitation infrastructure impacts, and resiliency under climate change scenarios, has received considerably less attention and is not well understood (Rosenberg et al., 2010). Urban hydrologic impacts are broadly defined in this chapter and are discussed under eight categories: i) urban infrastructure resiliency and adaptation; ii) storm frequency and runoff; iii) water and sediment quality; iv) health impacts; v) water use and reuse; vi) sea level rise; vii) greenhouse gas emissions; and viii) urban heat islands.

11.2 A Quick Note on Climate Change Projections

The IPCC (2007) developed some greenhouse gas emission scenarios that explore alternative development pathways and give resulting differences in temperature and precipitation impacts. The A1B scenario (rapid economic growth, population increase to 2050 then decrease, quick spread of new and efficient technologies, income and way of life convergence between regions) is often used in different sectoral climate change impact assessments and under this scenario, mean global temperature is expected to increase 2.8 °C (range of 1.7 °C to 4.4 °C) by 2090–2099, relative to 1980–1999 (Figure 11.1).

Figure 11.1 Projected temperature change by 2090–2099 relative to 1980–1999 under the A1B scenario (from IPCC, 2007).

The possible global pattern of temperature increase and attendant shifts in elements of the hydrologic cycle under the A1B scenario are summarized in Figures 11.1 and 11.2. Figure 11.2 illustrates that some parts of the world are expected to get wetter while other areas may get drier. It is important to bear in mind that climate change projections encompass a large range of possible outcomes and the A1B scenario is only one of many possibilities, but it is useful to keep the A1B scenario as a touchstone for the discussions in this chapter.

Figure 11.2 Change in annual means, 2090–2099 relative to 1980–1999, A1B scenario (from IPCC, 2007).

11.3 System Resiliency, Sustainability and Adaptation

Burch (2010) distinguished between climate change mitigation strategies (actions that either reduce the emission of greenhouse gas or enhance carbon sinks) and adaptation strategies (efforts to reduce the severity of climate change impacts) for urban areas. This chapter focuses on adaptation strategies, although the most effective system management might integrate consideration of both. One important outcome of climate change adaptation strategies can be improvement of system resiliency. *Resiliency* refers to the ability of a system to respond to and recover from disasters and includes attributes that al-

low the system to absorb impacts (Klein et al., 2003; Fiksel, 2006). Many have noted that resiliency may be a key ingredient of sustainability as well as vulnerability reduction, such that resilient systems (including biological and socio-economic systems) are able to survive, adapt and grow in the face of uncertainty and unforeseen disruptions (e.g. Klein et al., 2003; Fiksel, 2006; Cutter et al., 2008).

Klein et al. (2003) concluded that while resiliency may be a useful concept, the challenge remains to transform the concept into an operational tool for policy and management purposes. This concern was more recently echoed by Cutter et al. (2008) who noted that although there are a number of conceptual and theoretical models for assessing resiliency, none have progressed to the point that they effectively measure or monitor resilience at the local level. Fiksel (2006) argued that a systems approach is necessary to better understand the linked behavior of complex social, economic, and biophysical systems so that we can improve our decision-making with respect to resilience and sustainability and provided a number of examples of complex, ongoing, modeling efforts, including thermodynamic life cycle analysis. While Sahely et al. (2005) also noted the possible use of life cycle assessment as a method to evaluate sustainability, specifically for urban infrastructure systems, ultimately they used an indicator approach in their case study for the City of Toronto. There seems to be a groundswell of support for using such indicator approaches in applications as diverse as water quality (House and Ellis, 1987; Bordalo et al., 2001; Cude, 2001); ecosystem health (Fausch et al., 1984; Barbour et al., 1999; Irvine and Murphy, 2009) and Millenium Development Goal assessment (Rajaratnam et al., 2010). Approaches to assess sustainability generally are more advanced than resiliency assessment, but because of similarities in concepts, it may be possible that assessment of resiliency could borrow from sustainability theory. As such, I include work on sustainability assessment in the remaining discussion of this section.

The indicator approach to resiliency and sustainability assessment provides a number of advantages: it can be easily understood by people from a variety of backgrounds; it can be quantified using a variety of tools, including raw data, mass and energy balances, cost-benefit analysis, life cycle costing, or even characterized qualitatively; in some cases indicators can aggregate data to simplify complex relations; and indicators have a theoretical basis that can lead to a greater understanding of system dynamics (Bossel, 1999; Sahely et al., 2005). Various guidelines have been developed to help select appropriate indicators (Reed et al., 2006; Eriksen and Kelly, 2007; Ciegies et al., 2009), but Niemeijer and de Groot (2008) provide a simple and clear set of considerations: universality (applicable to many areas, situations and scales of measurement); portability (repeatability and reproducibility); sensitive to change;

operationally simple; inexpensive to collect; already existing with historical comparative data; and having wide (international) use.

Most assessments using an indicator approach follow the *three pillar* or *triple bottom line* concept of sustainability that considers three types of capital: social, economic and environmental. In their review of five national scale indicator studies, Eriksen and Kelly (2007) found obvious differences, but also some similarities, specifically the common use of three variables (indicators): access to water and sanitation; per capita GDP; and infant mortality. The comparison also found that relatively few of the indicators reflected institutional conditions, even though Burch (2010) indicated that insitutional factors may produce important barriers to the implementation of adaptation and mitigation measures. In developing a conceptual model to assess community resiliency, Cutter et al. (2008) suggested a number of possible indicators and these are reproduced in Table 11.1. Sahely et al. (2005) examined sustainability criteria specifically for urban infrastructure systems and their framework for assesment is shown in Figure 11.3.

Figure 11.3 Framework for assessing urban water systems; solid lines represent water flows and dashed lines represent relevance to sustainability (from Sahely et al., 2005).

Table 11.1 Community resilience indicators (from Cutter et al., 2008).

Dimension	Candidate Indicators
Ecological	Wetlands acreage and loss Erosion rates % impervious surface Biodiversity Number of coastal defense structures
Social	Demographics (age, race, class, gender, occupation) Social networks and social embeddedness Community values-cohesion Faith based organizations
Economic	Employment Value of property Wealth generation Municipal finance and revenues
Institutional	Participation in hazard reduction programs Hazard mitigation plans Emergency services Zoning and building standards Emergency response plans Interoperable communications Continuity of operations plans
Infrastructure	Lifelines and critical infrastructure Transportation network Residential housing stock and age Commercial and manufacturing establishments
Community competence	Local understanding of risk Counseling services Absence of psychopathologies (alcohol, drug, spousal abuse) Health and wellness (low rates of mental illness, stress-related outcomes) Quality of life (high satisfaction)

Sahely et al. (2005) added a fourth pillar in their assessment, represented by engineering factors such as system performance (Table 11.2), although they were not able to fully quantify the social indicators within their paper.

Table 11.2 Indicators for urban water systems (Sahely et al., 2005).

Environmental Pillar	Economic Pillar	Engineering Pillar	Social Pillar
Construction material usage	Capital, operation and maintenance costs	Flow rate – pressure Service interruptions	Access to potable water and sanitation services
Energy usage	Service fees	Fire flow	Water quality
Land use	Expenditures in research and development and technology change	Storage	Public participation
Chemical use		Leakage	
Contaminants	Reserve funds		
Nutrients			
Sludge			
GHG emissions			

Ravetz (2000) took an interesting approach in grouping his indicators under the ISCAM (Integrated Sustainable Cities Assessment Method) spreadsheet model to look at urban environmental metabolism, (or input and output of flows) that was an extension of the pressure–state–response framework. The indicators were compared using a trend–target index that considered current values, business as usual (BAU) trends into the future, and sustainable development (SD) targets. Conceptually, this approach is summarized in Figure 11.4 and the trend–target index was calculated as:

$$\text{trend – target index} = \frac{\text{current} - \text{BAU trend}}{\text{current} - \text{SD target}} \quad (11.1)$$

Figure 11.4 Representation of the ISCAM trend-target index (after Ravetz, 2000).

Negative values (Equation 11.1) represent unsustainable conditions, while small positive values indicate gradual progress towards selected targets. It could be interesting to adapt this type of approach in assessing resiliency. As different adaptation strategies are considered, such an assessment tool could help examine the different possible scenarios with respect to increasing system resiliency.

11.3.1 Research Needs

1. Identification of a suite of robust resiliency and sustainability indicators. The greatest challenge appears to be quantification of meaningful social and institutional indicators.

2. Currently there is a large gap between resiliency theory and application. Case study application of resiliency assessment that compares systems at the city, regional and international scales should be done.
3. Better consideration of full cost accounting is needed, including the monetizing of hydrologic and ecological services within the sustainability and resiliency assessment framework.

11.4 Storm Frequency and Runoff

A January, 2010 workshop sponsored by key United States federal water agencies, as well as the International Center for Integrated Water Resources Management, and Colorado State University, was held to examine the issue of non-stationarity in hydrologic frequency analysis and water management. In part, the workshop was prompted by Milly et al.'s (2008) article on non-stationarity in hydrological sciences. The workshop discussed non-stationarity in the context of changing land use, direct anthropogenic impacts (e.g. ground-water drawdown) and also, importantly, in the context of climate change and impacts on the definition and design for floods and drought. Fifteen papers from the workshop were published in two of the 2011 volumes of the *Journal of the American Water Resources Association*. In summarizing the workshop, Galloway (2011) made three important observations:

1. After 2.5 d of discussion, it is clear that the assembled hydrology community has yet to reach an agreement on replacing the assumption of stationarity with an assumption of non-stationarity.
2. Climatologists, especially those deeply involved in climate change speak in a convincing manner about the changes that are taking place. On the other hand, hydrologists are skeptical that, after reviewing the data they have gathered, there is sufficient evidence of change in river flow characteristics. The gap between these two opinions does not seem to be narrowing.
3. Much of what I heard during the workshop was directed at how we are going to manage activities within the water sector, and very little was expressed about how we influence those groups that may ultimately drive our actions.

Although none of the papers from this workshop focused specifically on urban hydrology (with the exception of some discussion related to anthropogenic impacts on river flow at a watershed scale; Vogel et al., 2011), the issue of non-stationarity clearly has relevance to research needs in urban

hydrology and climate change. While some studies (e.g. Hirsch, 2011) suggested there may be signals of change in long term (85 y to 127 y) annual U.S. peak discharge trends, the direction of change (increase or decrease) varied spatially, and other studies suggested either there is no indication of increasing peak flood or that the significance of the trend identified may depend on the statistical technique used for analysis (e.g. Villarini et al., 2011; Lins and Cohn, 2011). Some (e.g. Lins and Cohn, 2011) suggested that at this juncture, due to high uncertainty, there is no reason to abandon concepts of non-stationarity, while others (e.g. Stedinger and Griffis, 2011) suggested extensions or correction factors to existing flood probability approaches that potentially would provide more reliable forecasts. A similar correction factor approach was developed by Dormuth (2010) to update intensity–duration–frequency (IDF) curves for design work, rather than entirely updating the IDF curves. In an analysis of 162 hydrometric stations throughout Canada, for the period 1974–2003, Cunderlik and Ouarda (2009) found weak trends in the timing of the seasonal maximum flood, with these mostly being associated with an earlier occurrence of snowmelt generated floods. Snowmelt floods also exhibited a trend towards increasing magnitude. This work illustrates the importance of examining mixed-process floods for rivers in cold climates.

Hirsch (2011) recommended that research related to climate change and water resources should follow two paths simultaneously, with one path using climate change models to drive hydrologic models (i.e. a linked model approach, which is frequently used; cf. Cunderlik and Simonovic, 2005) and the other path being more extensive analysis of long term hydrologic records (i.e. an empirical approach). In the developed world, some long term hydrologic records exist, but such is not the case for most developing countries. Time series reconstruction through proxy data is possible (e.g. Meko et al., 1995; Tarboton, 1995; Rivard et al., 2006; Buytaert et al., 2010). Urban areas in the developing world will continue to depend on the linked model approach, despite some views that information currently available from climate models is inadequate for most planning and design aspects of water decisions (e.g. Kundzewicz and Stakhiv, 2010; Stakhiv, 2011). A further challenge for the developing world is that there is relatively little experience in applying dynamic runoff models for drainage assessment (e.g. Rivard et al., 2006; Chaosakul et al., 2009; Sothea et al., 2010). In fact, to my knowledge there is no specific modeling effort to assess urban stormwater issues under climate change scenarios for the developing world.

Most of the urban runoff studies that have examined climate change issues in the developed world, to date, take some form of the linked model approach. Because of the coarse spatial scale that general circulation models (GCMs) represent, frequently watershed studies downscale GCM output

using a regional climate model (RCM) approach for input to a hydrological model (Rosenberg et al., 2010; Buytaert et al., 2010). Semadeni-Davies et al. (2008) used the DHI MOUSE model driven by the Swedish Meteorological and Hydrological Institute's (SMHI) RCAO RCM to conclude that without further urban development in Helsingborg, Sweden climate change scenarios could produce a greater number of combined sewer overflows (CSOs). Nie et al. (2009) came to a similar conclusion (although the impacts were relatively smaller) for a study of Fredrikstad, Norway, using DHI MOUSE driving the the HIRHAM RCM. Berggren et al. (2007) also used DHI MOUSE and the RCM from SMHI to show that surcharging of the sewer system in an area of Kalmar, Sweden could double from current conditions, under some climate change scenarios. Rather than using an RCM approach, Waters et al. (2003) assumed that a two year, one hour design rainfall depth in southern Ontario would increase 15% by 2090, based on a literature review. They used this design scenario with PCSWMM to show that climate change potentially could increase runoff volume by 19%, peak, flow by 13% and surcharging by 24% within a southern Ontario test urban area. In a screening level assessment of 317 communities in the United States northeast, the USEPA (2008a) down-scaled GCM output using a stochastic weather generator (WGEN) and then estimated runoff with simple scaling factors. It was concluded that particularly in the Great Lakes region CSO frequency likely would increase under climate change scenarios. USEPA (2008a) recommended that a small scale case study approach using SWMM was needed to further evaluate the impact of climate change. Tait et al. (2008) looked at how a variety of drivers, including land use change, environmental legislation, energy and resource stress, and climate change might influence sewer system design and operation in the U.K. between 2020 and 2080. Using an example sewershed and increasing currently used synthetic design storms by a factor of between 1.2 and 1.4, modelled CSO volumes and surcharging were expected to increase by 2020. Hirschman et al. (2011) did not undertake modeling exercises but provided practical examples of how existing *hard* stormwater management designs (e.g. bioretention cells, rainwater harvesting practices) and *soft* adaptive management strategies can be implemented to accommodate the uncertainties of climate change. Perhaps not surprisingly, all of the studies discussed in this section were carried out in areas expecting increasing rainfall volumes and intensities. It is important to recall, however, that there are areas throughout the world that are expected to become drier by 2080 (Food and Agriculture Organization, FAO, 2008:Figure 11.2).

The footprint of the average new home in the United States has progressively increased and is now more than double the 1950s average (Wilson and Boehland, 2005). This trend is seen in other parts of the world as well,

and together with the popularity of big box retail centers we have witnessed increasing imperviousness within the urban mosaic. As a counter measure to these residential and commercial construction trends, low impact development (LID) technologies are becoming part of the mainstream urban planning consciousness and Garrison and Hobbs (2011) presented case studies of fourteen cities in North America that have implemented green infrastructure to help manage stormwater runoff. Technologies including rain gardens, bioretention cells, permeable pavement, rain barrels or cisterns, and grassed swales all seem to have a place in the LID philosophy (Chang, 2010; Shamsi, 2010; Lawson et al., 2011; Wong, 2011) and many have been shown to reduce runoff and thermal exchange at a demonstration scale (e.g. James and Verspagen, 1997; Zhang et al., 2010; Stovin, 2010). Modeling efforts that assess the effects of these technologies are increasingly available, and are now explicitly included as an option in the stormwater management model SWMM5 (Rossman, 2010). Some important gaps in our understanding remain, as, for example, there seems to be very little empirical data at a large sewershed scale, across multiple storms and seasons, to confirm performance of the technologies and models. Hopefully this is starting to change with projects such as those described by Pitt and Voorhees (2011). Furthermore, modeling efforts (e.g. Holman-Dodds et al., 2003) suggest that LID technologies become less effective at higher rainfall amounts, which is critical for two reasons. First, climate warming scenarios suggest that rainfall events may become increasingly severe, which could reduce the efficacy of LID technologies, without some modification; and second, it is not clear that LID technologies developed in temperate climates can be directly transferred to tropical climates. For example, communities in the United States often seek to capture the 5 y rain event with rain barrels (Hager, 2003) and design storm frequency for storm sewers is 5 y to 10 y for residential areas and 10 y for commercial and industrial areas. The 10 y 24 h design storm for Buffalo, New York is approximately 86 mm and the 100 y 24 h design storm is approximately 122 mm. The 2 y storm for Thailand (92 mm depth and peak intensity of 113.2 mm/h) is between the 10 y and 100 y storm in Buffalo. The greater rainfall in tropical climates may not be well managed by existing LID technologies.

Green roof technology can potentially have a positive influence on stormwater runoff quantity, quality, and increase energy efficiency of a building, thereby attenuating the urban heat island effect (Solecki et al., 2006) and increasingly it is being included in management option strategies (Foster et al., 2011; Garrison and Hobbs, 2011; Chen and Li, 2011). In a 2 y study of five standard and eighteen test green roof constructions in Germany, Uhl and Schiedt (2008) found the green roofs effectively reduced annual runoff, with runoff coefficients in the range of 23% to 38%, depending on the soil layer

depth. Stovin (2010) reported an average volume retention of 34% and average peak reduction of 57% for a test green roof plot in the United Kingdom. At a larger scale, Li (2008) modeled stormwater and CSO benefits resulting from green roof implementation in Toronto and concluded that with full potential green roof implementation the city could accrue \$42m to \$118m in stormwater benefits due to BMP infrastructure savings, pollutant reduction, and savings from erosion control measures. Assuming 5% and 15% of potential green roof building, Li (2008) concluded that existing CSO volumetric control could be improved by 17.8% and 18.8% respectively. In a review of the literature, Rowe (2011) concluded that green roofs can reduce runoff by 50% to 100%, depending on the type of green roof system, substrate composition and depth, roof slope, plant species, antecedent moisture conditions, intensity and duration of rainfall. Rowe (2011) also concluded that green roofs generally have a positive effect on water quality, although this can depend on the age of the roof, the materials used in construction, and maintenance (e.g. fertilizers used).

11.4.1 Research Needs

1. Approaches to consider non-stationarity of rainfall in sewer design and effective transfer of these approaches to municipal engineers and consultants for application.
2. Improvements in spatial scaling of GCMs and methods of downscaling from GCMs to RCMs to runoff models.
3. Comparative hydrology in which we focus on larger scale watersheds that are embedded along temporal and spatial (e.g. human imprint) gradients.
4. Empirical evidence and monitoring of LID performance at a neighborhood and larger scale.
5. Long term performance, costs and benefits of LID (including energy savings and plant selection and dynamics related to green roofs).
6. Dynamic model development for developing countries, especially in tropical areas.
7. Performance of LID technologies in tropical areas—are temperate climate approaches transferrable?

11.5 Water and Sediment Quality

The most obvious impact of climate change on water quality in urban areas is related to the potential for an increased number of combined sewer overflows

and greater stormwater runoff for many areas around the world, as described in the previous section. Murdoch et al. (2000) noted that it is difficult to isolate the impacts on water quality due to climate from those generated by land use change, but they qualitatively separated impacts into those generated by increasing temperature only, those generated by increasing temperature and increasing rainfall, and those generated by increasing temperature and decreasing rainfall. More recently, both Depla et al. (2009) and Whitehead et al. (2009) concluded that the potential climate change impacts on water supply (quantity) had received considerable attention but little was known about changes in water quality, indicating relatively little progress had been made since the work of Murdoch et al. (2000). Both of these papers, however, identified some common concerns:

1. Dissolved oxygen dynamics: with increasing temperatures, dissolved oxygen levels in rivers and lakes may decline as the result of a number of interacting factors. First, the warmer temperatures decrease the oxygen holding capacity of the water (Figure 11.5 below) and this could stress fisheries, particularly in regions with temperate climates. For example, Irvine et al. (2005) reported that the majority of days not meeting state guidelines for dissolved oxygen occurred during the warm, summer, low flow periods for the urban impacted Buffalo River, New York. This condition could be exacerbated by warmer temperatures and lower flows in the summer. It also is thought that warmer air temperatures and greater CO₂ levels will lead to increased algae growth and associated eutrophication problems. Urban rivers around the Laurentian Great Lakes already have borderline stress on trophic status and problem algae (e.g. Irvine and Murphy, 2009). Delpla et al. (2009) suggested that warmer temperatures may favor the growth of cyanobacteria over phytoplankton, which may lead to a northward spread of traditionally tropical algae such as *Cylindrospermopsis raciborskii* (a neurotoxin producing algae, recently identified in lakes in Indiana; Jones and Sauter, 2005) as well as greater blooms of *Microcystis*, also a neurotoxin producing algae that has been documented in the Great Lakes (e.g. Murphy et al., 2003).
2. With drier conditions in urban impacted rivers there will be less dilution for point sources, but also less runoff and associated contaminant input from non-point sources. The opposite effect is expected for those areas experiencing greater rainfall. The relative severity of these impacts will vary from river to river, depending on the importance of the different source inputs, but

this has implications for source load allocation decisions made in association with total maximum daily load programs. If there are lower flows and less dilution in the summer months of temperate climates, levels of biochemical oxygen demand and phosphorus may increase, but ammonia levels may decrease due to higher nitrification rates.

Figure 11.5 Weekly mean dissolved oxygen (D.O., based on measurements made every 15 min by Hydrolab Datasonde 4a's) for the Buffalo River and Buffalo Harbor, New York; the river dissolved oxygen is lower, primarily because of the hydraulics of the river, while the harbor is more reflective of dissolved oxygen at the eastern end of Lake Erie.

3. Contaminant cycling between the water column and bed sediment may be impacted in a number of ways. Increased warming may result in increased dissolution of iron phosphates from sediments in anoxic bottom waters and the release of contaminants to the water column or, conversely, an increased transfer of contaminants from the water column to the sediments through enhanced biological activity may occur. These impacts therefore depend on the magnitude of temperature change and the initial conditions of the water. In areas experiencing more intense storms there may be greater disturbance and resuspension of contaminated bed sediment. Such considerations are important for areas, such as Great Lakes Areas of Concern, that

are undertaking contaminated sediment remediation programs, after more than 20 y of study (e.g. Irvine et al., 2003).

4. Under warmer, drier conditions, there may be greater dessication of wetlands. This may be of particular concern in locations relying on constructed (or natural) wetlands for stormwater or wastewater treatment (e.g. Scholes et al., 1998; Walker and Hurl, 2002; Nasser et al., 2006; Kengne et al., 2008; Brix et al., 2007; Kootatep and Panuvatvanich, 2010; Visoth et al., 2010) as it could impact the efficacy of treatment.

Much as Hirsch (2011) called for the need of continued long term monitoring of hydrologic variables to help sort out climatic signals, Murdoch et al. (2000) noted the importance of long term monitoring for water quality. Unfortunately, water quality monitoring records typically are even fewer than water flow records. Kundzewicz et al. (2008) observed that there was limited research on water quality and climate change, but also raised the issue that this work has focused on developed countries and does not address the differences in water quality problems between developed and developing countries. Whitehead et al. (2009) noted that to date most modeling studies have only addressed the water quantity effects of climate change, but they indicated that the Euro-limpacs project, a large, European, multidisciplinary effort, was starting to apply modeling approaches to examine the issue of eutrophication.

Over the past 15 y, some groups have examined the issue of thermal enrichment of urban runoff by paved surfaces. The negative impact of warm water discharges could be particularly important in areas supporting cold water fisheries through both direct (e.g. disruption of egg maturation and spawning) and indirect impacts (e.g. warmer stream temperatures leading to lower dissolved oxygen levels). Xie and James (1994) found that thermal enrichment in the Speed River, in southern Ontario, was related to percent imperviousness. The type of urban surface can impact the runoff temperature, as James and Verspagen (1997) reported temperatures from permeable pavers being cooler by a factor of 2 °C to 4 °C, compared to asphalt, while Thompson et al. (2008) found temperatures from sod plots on average were 9.5 °C cooler than asphalt plots.

Various types of statistical and physically based modeling approaches (and combinations thereof) have been used to assess thermal enrichment (Xie and James, 1994; James and Verspagen, 1997; Van Buren et al., 2000; Thompson et al., 2008). In one study Herb et al. (2008) extended their model results to consider impacts on the Vermillion River, Minnesota, a designated trout stream. The modeled runoff from a 100 m × 100 m asphalt plot indicated an increase in stream temperature of between 0.13 °C and 4.23 °C, depending on the timing and size of the storm event and the flow in the river (2 cfs to 20 cfs,

57 L/s to 566 L/s, was considered). Under climate warming scenarios, particularly for temperate areas, thermal enrichment from pavement could increase.

11.5.1 Research Needs

1. Consideration of different process rates and water quality conditions within the developed world associated with different climate zones (e.g. humid continental, subtropical).
2. Consideration of the potentially different water quality challenges facing the developed and developing world, together with technology-appropriate solutions to water quality management.
3. Biochemical, trophic, and ecosystem responses to warmer water temperatures and increased or decreased sediment perturbations due to changing storm dynamics.
4. Establish coordinated, long term water quality monitoring programs within urban impacted watersheds designed to explicitly consider water quality–human systems–biological systems linkages that also are able to provide baseline information for more specific, question-driven research.
5. Improve water quality modeling capabilities, particularly related to urban surfaces and LID performance in treating storm-water.

11.6 Health Impacts

Hunter (2003) concluded that despite considerable research during the previous decade, the impacts of climate change on public health were still far from clear while Charron et al. (2004) noted that the existing scientific information regarding most adverse health impacts related to global warming were insufficient to support informed decision making in Canada. Since the time of these publications, work has continued and progress has been made in understanding links between health, climate, socio-economic factors, and level of education, but it appears considerable research is still needed. As described in other sections, impacts can be anticipated in association with higher temperatures, increasing rainfall and river flow, or decreasing rainfall and river flow. Several papers provide case study evidence for increased mortality due to thermal stress from heat waves, suggesting that these problems will increase, particularly in urban areas that can generate large heat islands (e.g. Haines and Patz, 2004; McMichael et al., 2006; Kovats and Achta, 2008).

Flooding in urban areas, expected to increase in many areas of the world due to greater precipitation extremes, could cause greater hardship than

already is experienced. The October, 2011 flooding in Bangkok, Thailand, for example, was in part generated by cumulative extreme rainfalls in the north and central part of the country (Komori et al., 2012). Countrywide, the death toll from the flood was >800 people. It might be wondered whether more of the same can be expected. Coastal flooding due to sea level rise will be discussed in more detail in a later section. A number of studies have reported evidence that outbreaks of waterborne illness are preceded by heavy rainfalls (e.g. Rose et al., 2001; Hunter, 2003; Kovats and Akhtar, 2008). This may occur as both urban and rural sanitation systems are overcome, delivering bacterial and viral burdens to drinking water sources, as well as from dermal contact. The situation can arise in both developed and developing countries, but in developing countries conditions are exacerbated by urban poor who often do not understand the linkage between contaminated flood water and diarrhea which may be further compounded by an annual cycle of floods associated with monsoon rains (Mollah et al., 2010). Furthermore, because public health and sanitation systems in developing countries frequently are outdated, undersized, and poorly operated and maintained, when urban flooding events do occur the impacts to these systems and the time required to re-establish the systems often is prolonged.

As noted in the previous section, climatic warming may result in increased algal growth which may include outbreaks of neurotoxin producing cyanobacteria; this concern has been reiterated by Delpla (2009) in relation to drinking water production. Patz et al. (2005) outlined an ecologically based link between climate and increased incidence of cholera. With warmer climates it has been suggested that zooplankton will feed on the increasing amounts of algae, providing greater reservoirs for *Vibrio cholera*. A similar concept was offered by Hunter (2003). Of course, there are confounding factors, including the role of El Nino, flooding, intrinsic host immunity to the disease, and socio-economic considerations.

McMichael et al. (2006) noted that modeling of the effects of climate change on vector borne diseases has focused mainly on malaria and dengue fever. Patz et al. (2005) indicated that while transmission of malaria may be related to climate and temperature, there are a number of spatially variable biological factors (including resistance) that make these relationships difficult to accurately establish. Modeling dengue fever spread (e.g. through tools such as geographic information systems, GIS) is somewhat simplified by the fact that the disease is spread by only one mosquito species while malaria has two pathogen variants distributed by several dozen mosquito species (McMichael et al., 2006). There seems to be a more general agreement that dengue fever movement can be driven by temperature (e.g. Haines and Patz, 2004; McMichael et al., 2006), but Cazelles et al. (2005) also noted that dengue is

a peri-urban disease and recent resurgence in the tropics has been associated with population growth and urbanization. Using wavelet theory, Cazelles et al. (2005) showed that dengue movement in Thailand operates in two modes: an annual mode associated with the monsoon cycle; and a 2 y to 3 y cycle associated with El Nino. McMichael et al. (2006) mapped model projections for the spread of dengue in northern Australia for different climate change scenarios but did not consider the impact of socioeconomic variables in this effort.

Frumkin et al. (2008) made several important observations with respect to climate change and public health preparedness. They likened preventative health care approaches to climate change mitigation and adaptation, noting that preparedness in public health often occurs in the face of scientific uncertainty. Frumkin et al. (2008) underscored the importance of appreciating *health justice* (i.e. the unequal vulnerability of poor populations and poor countries). They emphasized the importance of collecting socio-economic, health and environmental data in a coordinated way in order to identify climate change impacts on health (cf. Hirsch, 2011, and his plea for hydrologic data), and they explained that new planning partnerships must be forged between the health professions, engineers, architects, urban planners, and even the faith community to respond to the potential health challenges presented by climate change.

11.6.1 Research Needs

1. Better understand links between health, climate, socio-economic factors, and level of education through coordinated data collection.
2. Improve our understanding of at-risk populations to waterborne and vector borne diseases, particularly in the developing world, to produce more effective education and management strategies.
3. Increase efforts in linking health impacts with climate change scenarios to identify public health strategies for risk reduction. This will require increased multidisciplinary interactions and better application of decision making tools, such as GIS.

11.7 Water Use and Reuse

There is a relationship between temperature and water demand for urban and agriculture areas throughout the world, although the relationships (particularly in urban areas) may be complex (Arbues et al., 2003; Tsanis and Naoum,

2003; Sadiq and Karney, 2005; Domene and Sauri, 2006; Guhathakurta and Gober, 2007; Revi, 2008; Jorgensen et al., 2009; ADB, 2009). Certainly, in agricultural areas, increasing temperatures and evapotranspiration rates can lead to higher demands for irrigation. In the urban areas of developed countries greater water demand may be related to outdoor uses, while in tropical developing countries, increased demand may be related as much to indoor uses. Along with increasing temperature there will be attendant shifts in precipitation patterns, so that some areas will be wetter and some drier. Those areas that are warmer and dry may experience increases in water demand and decreases in water availability (e.g. Izaurrealde et al., 2003; Kundzewicz et al., 2008; ADB, 2009). In coastal areas, a lowering of the groundwater table due to increased demand and lower recharge may result in salinity intrusions.

Wastewater reclamation may be one option to provide greater resiliency to salinity intrusion and climatic change. The idea of water treatment and reuse is not new (Stander and Van Vuuren, 1969; Angelakis et al., 1999) and in many countries of the world reuse (or reclamation) is increasingly implemented (Miller, 2006; Bixio et al., 2006). In the United States recycled water use is growing volumetrically at an annual rate of about 15%, but this still only amounts to 7% of the total wastewater produced. Chu et al. (2004) concluded that reuse potential in China is only 6.3% of the total urban wastewater produced because of the high cost of reuse projects and low cost of raw water supply. Water reuse projects include industrial applications (e.g. cooling water and product processing), environmental applications (e.g. low flow maintenance in rivers), groundwater recharge to hold back the saline intrusion of coastal aquifers, agricultural irrigation, and indirect potable reuse (Angelakis et al., 1999; Bixio et al., 2006; Khai et al., 2007). Although guidelines have been developed by agencies such as the World Health Organization (WHO) for reclaimed water quality to be used in irrigation, and reclaimed water may be of potable quality, there still can be considerable psychological resistance to reuse projects. The quality of the reused water must match the intended use and this matching needs further research (Miller, 2006). Miller (2006) noted other barriers to widespread water reuse, in addition to public education for acceptance, including poor documentation of the economics of water reuse, as well as the need for additional research into cost effective technologies to provide chemical and microbiologically safe water. Globally, the agricultural sector represents the greatest demand for water. This demand will increase under a growing global population and shortages for irrigation may worsen as the result of climatic change (e.g. Doll, 2002; Fischer et al., 2007). Khai et al. (2007) concluded that with appropriate nutrient management, irrigation with wastewater in peri-urban areas could be beneficial and this may be a sustainable water source for other agricultural activities as well. A similar conclusion

was reached by Trinh Thi et al. (submitted) for the Mekong Delta region of Vietnam. Sowers et al. (2011) reported progress on water reuse for agriculture in Tunisia and, particularly, in Israel, but concluded that most countries of the Middle East and North Africa concentrate their efforts on large scale supply-side projects such as desalination, dam construction, inter-basin transfers and groundwater withdrawals. Although wastewater may provide sources for nutrients to crops, such as rice (e.g. Trinh Thi et al., submitted), others (e.g. Zou et al., 2009) suggest that such irrigation may increase the release of methane and nitrous oxides, thereby enhancing the greenhouse effect. Murphy et al. (in press) reviewed cropping methods for rice production that could be implemented to manage methane and nitrous oxide emissions. There is a need to better understand intervention approaches that could be implemented to reduce health risks for both the farmer and the consumer when wastewater is used in irrigation (e.g. Dreschel and Seidhu, 2011; Wichelns et al., 2011).

An excellent example of highly efficient urban water reuse comes from the NEWater program in Singapore. Luan (2010) noted that the Singapore government established legislation that goes hand-in-hand with a well coordinated institutional framework to provide an integrated whole government approach to land use planning, water management, a sound built environment and pollution control. The Public Utilities Board (PUB), the comprehensive National Water Agency, manages all stormwater and wastewater collection, treatment, distribution of potable water (including water importation from Malaysia, local reservoirs, and desalination), and water reuse schemes as a single, closed loop system, using principles of integrated water resources management (IWRM) (Luan, 2010). NEWater has become an important element of the closed system. When Singapore became independent from Malaysia in 1965, its main source of water was that imported from Malaysia. Since then, new reservoirs have been opened, a desalination plant came on line in 2005 to supply 10% of the country's demand, and five NEWater plants now meet 30% of the country's demands (Chew et al., 2011). The NEWater plants treat and recycle wastewater using a three stage process that includes micro-filtration, reverse osmosis and ultra-violet disinfection to produce water that meets USEPA and WHO drinking water standards (Benett, 2011). NEWater is used primarily as a replacement for potable water in industrial processing, including microelectronics and wafer fabrication, although a small percentage is also blended into reservoirs for indirect potable use. The NEWater plants are an outstanding example of innovative research and development that resulted from the combined efforts of government and the private sector (Chew et al., 2011).

Constructed wetlands have been used for wastewater treatment in Denmark since 1983 (Brix et al., 2007) and are now used throughout Europe,

Asia, Africa, and the United States (Campbell and Ogden, 1999; USEPA, 2000; Koottatep et al., 2001; Nassar et al., 2006; Kengne et al., 2008). Constructed wetlands are regarded as a promising treatment option, since they are easy to operate (Koottatep et al., 2005; Paing and Voisin, 2005), cost effective, and are a technically feasible approach for the treatment of stormwater runoff; municipal, industrial and agricultural wastewater; landfill leachate; and fecal sludge (Brix et al., 2007; Nielsen, 2005; Kengne et al., 2008; Koottatep and Panuvatvanich, 2010). Constructed wetlands, in particular, seem to be an area where both the developed and developing worlds can have significant and equal exchanges of experience and ideas. Wastewater discharge from the wetlands certainly could be reused, and when innovatively designed, as was the case on the resort island of Phi Phi, Thailand, they can even provide a tourist or an education opportunity (Figures 11.6 and 11.7).

Figure 11.6 Plan of the constructed wetland on Phi Phi Island (see also Koottatep and Panuvatvanich, 2010).

Figure 11.7 The constructed wetland has now become a tourist attraction on Phi Phi Island.

11.7.1 Research Needs

1. Constructed wetland performance in cold climates, including relative differences in kinetics and reaction rate constants, hydraulic residence times, sustainability of different plant species, and insulation strategies to reduce heat losses (and prevent freezing).

2. Constructed wetland dynamics under warmer and drier conditions with specific evaluation of survival and performance of different plant species.
3. Identifying and more fully evaluating intervention approaches to reduce health risks from using wastewater for irrigation, including consideration of economic, social, policy, and education factors that would integrate with technical tools such as quantitative microbial risk assessment and disability-adjusted life years.
4. Methane and nitrous oxide release from rice paddies irrigated with wastewater should be quantified and methods to mitigate potential higher release rates should be investigated.
5. Overcoming social and economic barriers to water reuse, particularly in the area of domestic reuse.

11.8 Sea Level Rise

Rahmstorf (2007) noted that there are numerous physical unknowns (e.g. extent of thermal expansion of water, amount of increased ice stream flow after the removal of buttressing ice shelves, uncertainty in physically-based projections of ice loss from glaciers and ice caps on Greenland and the Antarctic) when trying to predict future sea level rise associated with climatic warming. In geologic time, sea level exhibited considerable range, being 120 m lower during glaciation, 20 000 years ago, when global temperatures were 4 °C to 7 °C less, and 25 m to 35 m higher during the Pliocene, 3 million years ago, when the mean global temperature was 2 °C to 3 °C warmer (Rahmstorf, 2007). Domingues et al. (2008) reported that GCMs do not handle dynamics of ocean heat content well, but by including bias correction factors, were able to accurately backcast the average rise in sea level between 1961 and 2003 at 1.5 ± 0.4 m/y. Using satellite altimetry data Cazenave and Nerem (2004) calculated global mean sea level rise to be 2.8 ± 0.4 mm/y for the period 1993–2003, which is higher than observed in previous decades. For example, in reconstructing global mean sea level to 1870, Church and White (2006) concluded the average mean sea level rise for the period 1870–2004 was 1.7 ± 0.3 mm/y, which is similar to the values determined by Domingues et al. (2008) for the 1961–2003 period. Church and White (2006) suggested that if sea level rise continued at the calculated average rate, it would increase between 0.28 m and 0.34 m for the period 1990–2100. The IPCC (2007) projected that sea level would rise between 0.22 m and 0.44 m during the period 1990–2090 using emission scenario A1B, consistent with the estimates of Church and White (2006). However, Rahmstorf (2007) analyzed the rela-

tionship between warming trends and sea level rise, and using the range of projected temperature increase to 2100 (1.4 °C to 5.8 °C), calculated sea level could rise between 0.5 m and 1.4 m by the end of this century. Tol et al. (2006) discussed the remote possibility that a collapse of the West Antarctic Ice Sheet (as alluded to by Rahmstorf, 2007) could cause a sea level rise of 5 m to 6 m within centuries.

McGranahan et al. (2007) reported that settlements in coastal lowlands are especially vulnerable to risks from sea level rise, yet despite the risks, these areas are increasing in population. Defining low elevation coastal zones as those areas that, conservatively, are <10 m in elevation, McGranahan et al. (2007) found that 2% of the world's land and 10% of the world's population (600 million in 2000, with 360 million or 60% being urban dwellers) live in the low elevation coastal zone. Asia accounts for two-thirds of the global urban population in this zone and eight of ten countries having the largest population in this zone are found in Asia.

Urban risk from sea level rise includes flooding from static water levels, flooding from storm surges, and saltwater intrusions into drinking water sources (both groundwater and surface water). Nicholls (2005) estimated that a total value of assets at risk to a 1 in 100 y surge induced flood event was \$3 000b (2005 U.S.) with the top ten at-risk cities (based on assets) being Miami, Greater New York, New Orleans, Osaka-Kobe, Tokyo, Amsterdam, Rotterdam, Nagoya, Tampa-St. Petersburg and Virginia Beach. De Sherbinin et al. (2007) conducted a case study of the vulnerabilities (using selected indicators) of three coastal cities, Mumbai, Rio de Janeiro and Shanghai, to climate hazards, including sea level rise. Sanitation and waste disposal was one indicator and potable water capacity was another. They concluded Mumbai's drainage system is already over-capacitated during the monsoon season and would be even more taxed as the result of sea level rise, although, because potable water was obtained from artificial rain fed lakes in the hills north of the city, drinking water was relatively safe. Waste disposal in Rio de Janeiro already generates pollution problems in local rivers and Guanabara Bay but drinking water, piped from a state to the north would not be susceptible to sea level rise. Shanghai experiences land subsidence from groundwater over-draught and greater flooding could be experienced as the result of sea level rise. Hallegatte et al. (2011) conducted a detailed economic study of the potential impact of sea level rise on Copenhagen and concluded that the city currently is quite well protected, but should levels increase to the upper end of those projected by the end of the century, the city may need to invest in additional dyking that would cost a few hundred million Euros.

Nicholls (2005) found that different cities around the world have varying levels of flood protection from the sea, with those in developed countries

having better protection than those in the developing world. Cities including London, Tokyo and Amsterdam are protected to better than the 1 in 1 000 y storm event, but as an anomaly, Greater New York is only protected to a 1 in 100 y event. The New York City Department of Environmental Protection (NYDEP) recently established a climate change program (http://www.nyc.gov/html/dep/html/news/climate_change_report_05-08.shtml) through \$1.5m in funding from the New York City Water Board and one of the first steps was a study to identify the potential impacts, adaptation strategies, and greenhouse gas emission issues (NYDEP, 2008). The city's main drinking water supply, sourced in reservoirs up to 200 km to the north, should be relatively safe, although climate change may present some watershed management challenges to maintain its Filtration Avoidance Determination permits. The city has an extensive combined sewer system and the NYDEP (2008) concluded that more intense storms will generate a greater number of CSO events while higher sea level will inhibit the CSO discharges, resulting in localized street and basement flooding. The city's wastewater treatment plants are located in floodplain areas and therefore could be subject to direct flooding under sea level rise scenarios and at least sea level rise could impact the hydraulic capacity of the treatment plant outfalls, as peak flows already are difficult to discharge during very high tides. Furthermore, increases in temporary inundation by saline water may lead to greater equipment corrosion and biological upset in the treatment plants.

The NYDEP (2008) qualitatively identified a number of adaptation strategies to address increased urban runoff and higher sea level: (i) increase the size of sewer pipes in selected areas; (ii) construct supplemental high level storm sewers; (iii) additional pumping of stormwater and combined sewage; (iv) more frequent sewer and catchbasin cleaning; (v) LID measures, including green roofs; (vi) exploration of using above ground water conveyance (e.g. selected street areas) during extreme events; and vii) storm surge barriers. Clearly, several of these adaptation measures involve high costs, a challenge also noted by de Sherbinin et al. (2007) and Nicholls (2005) for other cities of the world. Many urban adaptation plans include the construction of seawalls or other such structures (e.g. Mukheibir and Ziervogel, 2007; Hallegatte et al., 2011), with Singapore recently requiring (<http://uk.reuters.com/article/2012/01/27/us-climate-singapore-idUKTRE80Q05P20120127>) the height of all new land reclamation projects to be 2.25 m above the highest recorded tide level, an increase of 1 m over the previously mandated minimum height. To the other extreme, the Indonesian government has considered moving its capital from Jakarta because of its vulnerability to sea level rise (<http://uk.oneworld.net/article/view/166143/1/5795>). Nicholls (2005) advocated land use planning to reduce vulnerability to sea level rise.

11.8.1 Research Needs

1. Local investigation of potential impact of sea level rise on urban infrastructure. The NYDEP report provides a good template.
2. Local adaptation measures identified—including land use planning and policies to limit economic migration to coastal areas.

11.9 Greenhouse Gas Emissions

Methane is about 21 times more powerful at warming the atmosphere than carbon dioxide (CO₂) (<http://www.epa.gov/outreach/scientific.html>) and some estimates suggest that on a global scale, wastewater may account for 9% of methane emissions (www.globalmethane.org). For considerations of space, this section focuses only on methane emissions, but certainly carbon dioxide and nitrous oxide emissions are also important. Wastewater treatment ranks seventh as a source of methane in the United States, representing 3.6% of production in 2009. Methane produced by anaerobic digestion traditionally has been used as an onsite fuel source for treatment plants in developed countries (Angenent et al., 2004), but could also be used to produce electricity. In a study done for the state of Wisconsin, for example, Vik (2003) identified 85 municipal wastewater treatment plants that operated anaerobic digestion systems and concluded that 23 of these could use the digester gas for cogeneration, with a payback of <8 y and a capacity of 2 315 kW. The U.S. Federal Energy Management Program reported that in 2004, 3 500 facilities throughout the country had anaerobic digestion but only 2% used the gas to produce electricity.

Although moderate temperature developed countries generally have underground, covered sewer systems, this is not the case for many tropical countries. The open sewers in these countries (e.g. Figure 11.8) may be an important source of methane (USEPA, 2011), however, the IPCC (2006) noted the fraction of sewers that are open, as well as the degree to which open sewers are anaerobic and will emit methane is not well known. This will depend on retention time and temperature as well as on other factors including the presence of a facultative layer and possibly components that are toxic to anaerobic bacteria (e.g. certain industrial wastewater discharges). There are a number of complex feedback loops here, as climate change may influence urban runoff quantity and quality, but in turn, open sewers may influence climate through methane emissions. Very little work has been done to quantify these issues, as noted by the IPCC (2006), but a combination of hardware and software modeling and test sewershed sampling is ongoing at the Asian Institute of Technology, Thailand, to explore this topic (Chaosakul, ongoing).

Figure 11.8 Open sewer in Phnom Penh, Cambodia.

11.9.1 Research Needs

1. Improved methods to capture and reuse methane from treatment plants and constructed wetlands.
2. Improved modeling of sediment deposition, organic decay, and methane production to assist with better sewer design and global estimate of methane cycling back to the atmosphere.

11.10 Urban Heat Islands

The phenomenon of urban heat islands, whereby the temperature is greater than the surrounding rural areas, has been well documented globally for a long time (e.g. Oke, 1978; Kim and Baik, 2002; Arnfield, 2003; Offerle et al., 2005; Hung et al., 2006). Along with increasing temperatures, however, there seems to be evidence that urban areas can increase rainfall amounts through convective processes and possibly higher aerosol levels (Jauregui and Romales, 1996; Bornstein and Lin, 2000; Dixon and Mote, 2003; Shepherd, 2005). It seems possible that green roof (or even blue or white roof) construction can reduce thermal exchange to the atmosphere through lower energy

adsorption and re-radiation as well as providing a better insulation barrier (e.g. Wong et al., 2003; Solecki et al., 2006, USEPA, 2008b). Basu and Samet (2002) reviewed the relationship between elevated ambient temperature and mortality, and specifically noted the urban heat island effect and concerns about elevated temperatures in relation to climate change. Clearly, then, there may be some interest in mitigating the urban heat island effect, from both a hydrologic and an health perspective. Two obvious opportunities to effect such changes are LID technologies and green buildings through LEED certification.

11.10.1 Research Needs

1. Increased experience with plants and roofing materials to decrease installation and maintenance costs and improve options for roof retrofitting.
2. Better documentation of full cost accounting to better quantify the possible benefits of green roofs.
3. Improved documentation of urban impacts on precipitation and study of the mechanisms (such as aerosols) that may enhance precipitation impacts.
4. Improved accuracy of rainfall intensity representation by radar and incorporation of spatially explicit radar rainfall rates in localized urban runoff and global runoff studies.

11.11 Conclusion

Since the 1980s an enormous body of literature on climate change has been generated and this review has only scratched the surface. Although considerable progress has been made towards our understanding of the complexities of climate change, considerable uncertainty, as noted in each section of this chapter, remains. Marsalek and Schreier (2009) noted that while there has been research into various LID technologies, these have not been sufficiently promoted and have not been widely incorporated into new urban development. Montalto et al. (2007) advocated the need for life cycle cost analysis and promoted public-private partnerships to increase LID implementation. Such issues point to some broader questions explored by Burch (2010) regarding the barriers to implementing climate change mitigation and adaptation policies, particularly at the municipal level. In part, Burch (2010) noted that the establishment of effective climate change policies needs to be signaled from national and regional levels, but she also emphasized the importance of local leadership as being informed and promoting a culture of collaboration, mutual

respect, and innovation. Ultimately, climate change adaptation measures are most likely to be implemented if they are consistent with programs designed to cope with non-climatic stresses. Political and economic barriers to implementing adaptation measures as explored in this chapter are even greater in the developing world (Sajor and Ongsakul, 2007; Irvine et al., 2010; Lebel et al., 2011).

Wagener et al. (2010) concluded that hydrology has made great strides in understanding the behavior of small, relatively homogeneous and unchanging systems over short periods of time. They also emphasized that hydrology must embrace a paradigm shift which more fully recognizes the intrinsic coupling of hydrologic and human systems as a step towards sustainability and adaptation to climate change. As I write this, however, perhaps hydrology does not need a paradigm shift, but just a re-focusing, as Chorley (1971) insightfully commented: "The study of water provides a logical link between an understanding of physical and social environments." We face great challenges ahead that can only be successfully met through a systematic, multidisciplinary, but integrated path that effectively links engineers, scientists, policy-makers, and the public. Perhaps this path can be guided by the principles of integrated water resource management.

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