Chapter 4

Water Resources

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Introduction

This ClimAID chapter covers climate change vulnerabilities and possible adaptation strategies for four major water resource themes: 1) flooding in non-coastal regions, 2) drinking water supply, 3) water availability for non-potable uses (primarily agriculture and hydropower), and 4) water quality. Ensuring reliable water supplies, minimizing the disruptive and destructive impacts of flooding, and maintaining the recreational and aesthetic value of water bodies are fundamental needs, critical to the well-being of communities and businesses throughout New York State.

4.1 Sector Description

New York State has an abundance of water resources. Despite having only 0.3 percent of the world's population, the state is bordered by lakes containing almost 2 percent of the world's fresh surface water: Lake Erie, Lake Ontario, and Lake Champlain. It is home to the Finger Lakes in central New York, which are the largest of the state's 8,000 lakes as well as some of the largest inland water bodies in the United States. The state has several high-yielding groundwater aquifers, particularly those underlying Long Island. It has an average annual rainfall of almost 40 inches, readily supplying numerous small municipal reservoirs as well as the extensive New York City water supply system with surface water impoundments in the Catskill Mountains and the Croton watershed east of the Hudson River. The state contains the headwaters of three major river systems in the Northeast: the Hudson River, the Delaware River, and the Susquehanna River.

In 2000, New York State's 19 million residents consumed approximately 2,200 million gallons per day of fresh surface water and 890 million gallons per day of fresh groundwater for public water supply, irrigation, and industrial uses (Lumia and Linsey, 2005). Of this nearly 3,100 million gallons per day of consumption, only about 10 percent was for industrial and agricultural use.

4.1.1 Economic Value

There is no direct way to describe the economic value of water resources in the state. One could attempt to place an approximate market value on the water consumed. Treated water costs approximately $3 per 1,000 gallons; given that New Yorkers consume around 3,100 million gallons per day, this works out to more than $3 billion in revenue per year. Another way to look at economic value is in terms of infrastructure. An estimated value of this part of the sector can be gathered by considering that the New York City Department of Environmental Protection's capital program for 2010 through 2019 is just over $14 billion (NYCMWFA, 2009, p. 24). Conversely, it is important to consider negative economic consequences associated with water. For instance, disaster assistance for a large flood event in the Susquehanna Basin in 2006 topped $225 million; such a flood event typically occurs every few decades. Overall, a clean, reliable source of potable water is an essential underpinning of community stability and a necessity for numerous other economic activities.

4.1.2 Non-climate Stressors

There are several non-climate factors that will interact with possible changes in climate. First, much of the water resource infrastructure in New York is old and requires updating and rebuilding. Failing infrastructure can contribute to water pollution and reduce the reliability of treatment and distribution systems. Recent estimates suggest that over $36 billion is needed to update wastewater treatment infrastructure in the next 20 years (NYSDEC, 2008a). Second, even without any possible changes in water supply with climate change, rapidly developing regions face increasing water demands. Continued increases in population are projected, particularly in the New York City metropolitan area. New York City alone anticipates an increase of about 0.7 million people by 2030 (NYCDEP, 2006). Newly developing suburban and exurban regions can face unique challenges. In many cases, older cities that built water infrastructure more than 100 years ago were able to develop water sources in undeveloped regions outside their immediate borders (e.g., New York City reservoirs, City of Troy Reservoir, Albany Reservoir). Newly developing communities face more extensive regulations, few undeveloped areas to claim for their use, and competition from other neighboring communities that may also have rapid growth.

4.2 Climate Hazards

This section focuses on the temperature, precipitation, sea level rise, and extreme event hazards of particular concern to the water resources sector.

4.2.1 Temperature

Increases in air temperature will lead to increases in water temperature. Up to a water temperature of approximately 77°F, water temperature directly increases with air temperature, with a proportionality constant of 0.6–0.8. For instance, an air temperature increase of 9°F would result in a water temperature increase of 5–7°F. Thus, increases in water temperature will be slightly less than increases in air temperature. Higher water temperatures will have direct impacts on certain elements of water quality such as oxygen content.

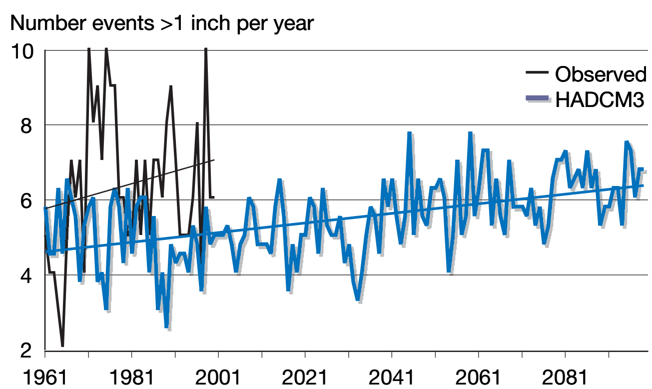
Additionally, increases in temperature are likely to decrease the fraction of precipitation falling as snow. This will lead to shifts in seasonal stream flows. Many observational and modeling studies suggest that late winter and early spring flows will increase and that spring snowmelt will occur earlier in the year (Hayhoe et al., 2007; Burns et al., 2007; Hodgkins et al., 2003; Neff et al., 2000). Thus, even if there is more annual streamflow, it may be distributed unevenly over the year, with lower flows in the late summer and autumn and higher flows in the late winter and spring. This shift in timing of flow magnitudes has already been observed in stream records.

Temperature will also have some impact on evaporation rates, either by extending growing seasons or by increasing the potential rate of water vapor transfer to the atmosphere from soils, vegetation, or open water. Although evaporation has some dependency on air temperature, the primary driver of evaporation in humid temperate regions such as New York State is the net amount of energy from sunlight plus the net amount of energy emitted from the Earth's own atmosphere (as demonstrated, for example by Brutsaert, 2006). Some models used to estimate evaporation (such as the Thornthwaite Equation) only consider temperature; we suggest that these temperature-based models may overestimate changes in future evaporation. Studies have long indicated the greater sensitivity of temperature-based evaporation equations to changes in temperature relative to more physically based equations for estimating evaporation (McKenney and Rosenberg, 1993). More accurate estimate of changes in evaporation will come from equations that consider the complete energy balance at the land surface (such as in the work by Hayhoe et al., 2007).

4.2.2 Precipitation

Precipitation feeds the hydrologic cycle. Changes in precipitation amounts and frequency can cause changes in stream and river discharges, lake levels, and groundwater levels. However, as discussed further in 4.2.4, hydrology is dependent on a number of interacting factors; changes in precipitation alone rarely explain likely changes to water resources. Based on historical observations, precipitation in New York State has been increasing both in total annual amount and in intensity. As noted in Chapter 1 ("Climate Risks"), annual average precipitation has been increasing by 0.37 inches per decade since 1900. In terms of intensity, increases in the frequency of heavy rainfall have been observed across much of the United States, with such upward trends strongest in the Northeast (DeGaetano, 2009; USGRCP, 2009). For instance, in New York State, the number of rainfall events each year with greater than 1 inch of precipitation in 24 hours has increased over time (**Figure 4.1**, black line).

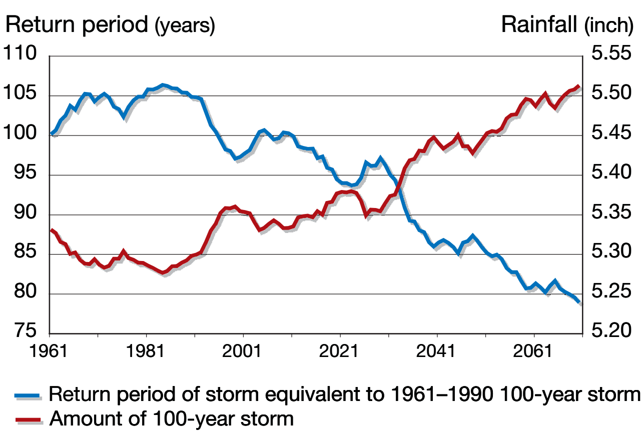
As discussed in Chapter 1, climate models indicate that annual average precipitation in New York State will



Note: UK Meteorological Office Hadley Centre Climate Model version 3 (HADCM3) projections adjusted to reflect regional climatology are shown in blue and observations are shown in black. These results are broadly consistent with those of the other 15 GCMs used by ClimAID.
Source: Tryhorn and DeGaetano, 2010

Figure 4.1 The observed and projected (by one global climate model) number of rainfall events exceeding one inch from 1960 to 2100, averaged over four stations in New York State increase by 5 to 10 percent by 2080. Based on climate modeling, the frequency of heavy rainfall events is projected to increase as well. Applying a model (the Statistical Downscaling Model, or SDSM, Version 4.2) that relates large-scale circulation patterns and atmospheric moisture to local weather conditions, Tryhorn and DeGaetano (2010) simulated daily rainfalls from 1961 to 2100. By the end of this century, precipitation from storms that now occur on average every 100 years is projected to increase by 0.2 inch (**Figure 4.2**). With these increased event rainfall amounts, storms that now occur on average every 100 years are likely to become more frequent, recurring on average every 80 years by the end of the century. These trends, however, likely underestimate the future changes, given that the model upon which these predictions are based is underestimating current trends.

It is important to note that only recently have researchers started to investigate changes in the intensity of sub-daily precipitation events (Berg et al., 2009; Lenderink and Van Meijgarrd, 2008). The intensity of sub-daily rainfall (particularly in periods of less than an hour) is of particular relevance. It is usually these intense short events that exceed a landscape's ability to allow water to infiltrate. Particularly in urban areas or steep basins, these intense rainfall events can result in flooding. For example, 1 inch of steady rainfall spread evenly over a day would likely produce less surface runoff than 0.5 inch of rain in an intense 15-minute event. There is evidence from historical data and regional climate modeling to suggest that the intensity of sub-daily rainfall events will increase in a warming climate. For example, one study found that 1-hour rainfall amounts increased 7 percent for every degree Fahrenheit that the air temperature increased in the Netherlands (Lenderink and Van Meijgarrd, 2008). Similar analyses of sub-daily rainfall intensities have not yet been carried out for New York State.



Note: The rainfall amount of the 100-year storm computed for each 30-year period beginning at the date in the graph (red) and the change in the return period associated with the amount of the 1961–1990 100-year storm (blue). The return period is the average interval of time between storm events of a given magnitude; a decreasing return period indicates that a given storm event occurs more often. These results from the HadCM3 model are broadly consistent with those of the other 15 GCMs used by ClimAID.
Source: Tryhorn and DeGaetano, 2010.

Figure 4.2 Projected rainfall and return period of the 100-year storm

If storm rainfall amounts increase in the future, the frequency of storm events could decrease (Trenberth et al., 2003; Hennessy et al., 1997), leading to longer periods with no rainfall. However, to date, an analysis of the time interval between historical storm events indicated no change in the Northeast despite increasing dry periods in other regions (Groisman and Knight, 2007).

4.2.3 Sea Level Rise

By the 2080s, sea levels could rise under rapid ice-melt as much as 55 inches (see Chapter 1, "Climate Risks"), with important implications for coastal storm flooding potential. With the additional water under the high-end scenario, the current 1-in-100-year flood could occur approximately an order of magnitude more frequently along the New York State coast (see Chapter 5, "Coastal Zones"). This shift will have ramifications for a broad set of coastal management processes including those for coastal water resources, groundwater protection from saltwater intrusion, and operation of wastewater treatment facilities.

4.2.4 Other Climate Factors

Changes in water resources rarely have a one-to-one link with a single climate factor. Numerous processes combine to determine the level of discharge seen in a stream or the amount of water available to a well. This can be illustrated by comparing typical monthly rainfall and stream discharge amounts for a stream in New York (see **Figure 4.3**). Rainfall is relatively even over most of the year, with the exception of lower amounts in the winter months. However, most evaporation and transpiration (water loss from plants) occurs between May and October when plants are active, making streamflows lower and soils dryer during summer and early fall. In addition, winter and spring streamflows may be further increased by the contribution of melting snow, causing streamflow to peak in the spring despite lower precipitation amounts. Thus, streamflows combine the effects of many interacting climate factors, as well as the water catchment's capacity for infiltration and storage.

A study of streamflows at 400 U.S. sites from 1941 to 1999 documented an increase in annual minimum and median daily streamflow beginning around 1970, particularly in the East. Notably, peak streamflow (i.e., floods) did not show a consistent increase in the studied streams (McCabe and Wolock, 2002). This is consistent with findings specific to New York. In the Catskill Mountain region, runoff increased from the 1950s to 2000s with an increase in annual warm-season streamflow (June to October) (Burns et al., 2007). Also, a study in Monroe County noted an increase in seven-day low-flows in rural streams from 1965 to 2005 (Coon, 2005).

There have also been efforts to project future streamflows in the northeastern United States. The basic approach in these studies is the same: 1) global climate models project future temperature and precipitation amounts for large-scale regions of the globe, 2) a downscaling procedure is used to adjust these projections for the climate conditions of the areas of interest, and 3) the downscaled climate data are incorporated into a hydrologic model that predicts streamflows and groundwater levels. Within each study, several scenarios comprising different emission levels, global climate models, downscaling techniques, and model parameterizations may be chosen, resulting in an

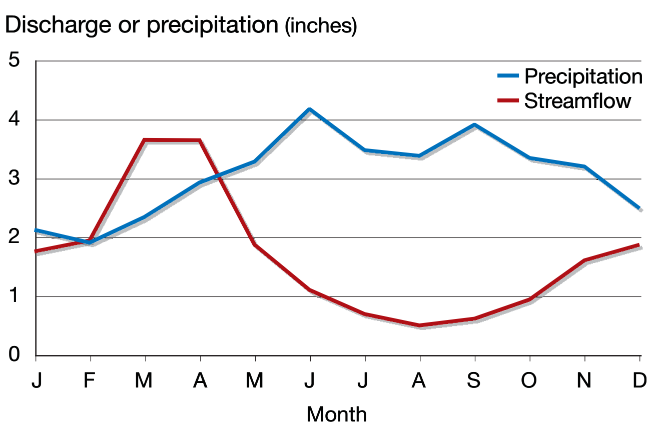


Figure 4.3 Average monthly streamflow discharge and precipitation for the Fall Creek watershed in Central New York

average and range of possible outcomes. However, there is a growing recognition that a large number (on the order of thousands) of equally plausible scenarios could be used. For example, one study in the United Kingdom demonstrated that streamflow projections are most dependent on the choice of global climate model, but that each global climate model and hydrologic model can also be parameterized slightly differently to result in additional variation in possible outcomes (New et al., 2007). In brief, no one outcome based on a single scenario should be granted much weight. Instead, multiple models can be used, as in the ClimAID study, to suggest the direction and relative magnitude of possible changes in hydrology.

In general, nearly all modeling studies that have assessed water bodies in the northeastern United States have estimated that, on average, annual streamflow should change little. However, studies do differ in their estimates of the largest and smallest possible amounts of change, as would be expected given the widely different choices of modeling approaches. One study using nine different global climate models predicted an increase in annual streamflow of 9 to 18 percent for 2070–2099 in the New York State/Pennsylvania region (Hayhoe et al., 2007). Another study that used projections from the United Kingdom Meteorological Office Hadley Centre Climate Model version 2 (HADCM2) and the Canadian Centre for Climate Modeling and Analysis Coupled Global Climate Model (CGCM1) estimated a -4 to +24 percent change in annual streamflow in the Susquehanna River by 2099 (Neff et al., 2000). Using four different scenarios from the same models, a different study estimated changes in annual streamflow of -28 to +12 percent for the 2080s for the Cannonsville Basin in Delaware County (Frei, 2002). More recently, another study estimated little annual streamflow change for Moodna Creek in Orange County when using high-end and low-end estimates of climate change from 16 different climate models (Frei et al., 2009).

4.3 Vulnerabilities and Opportunities

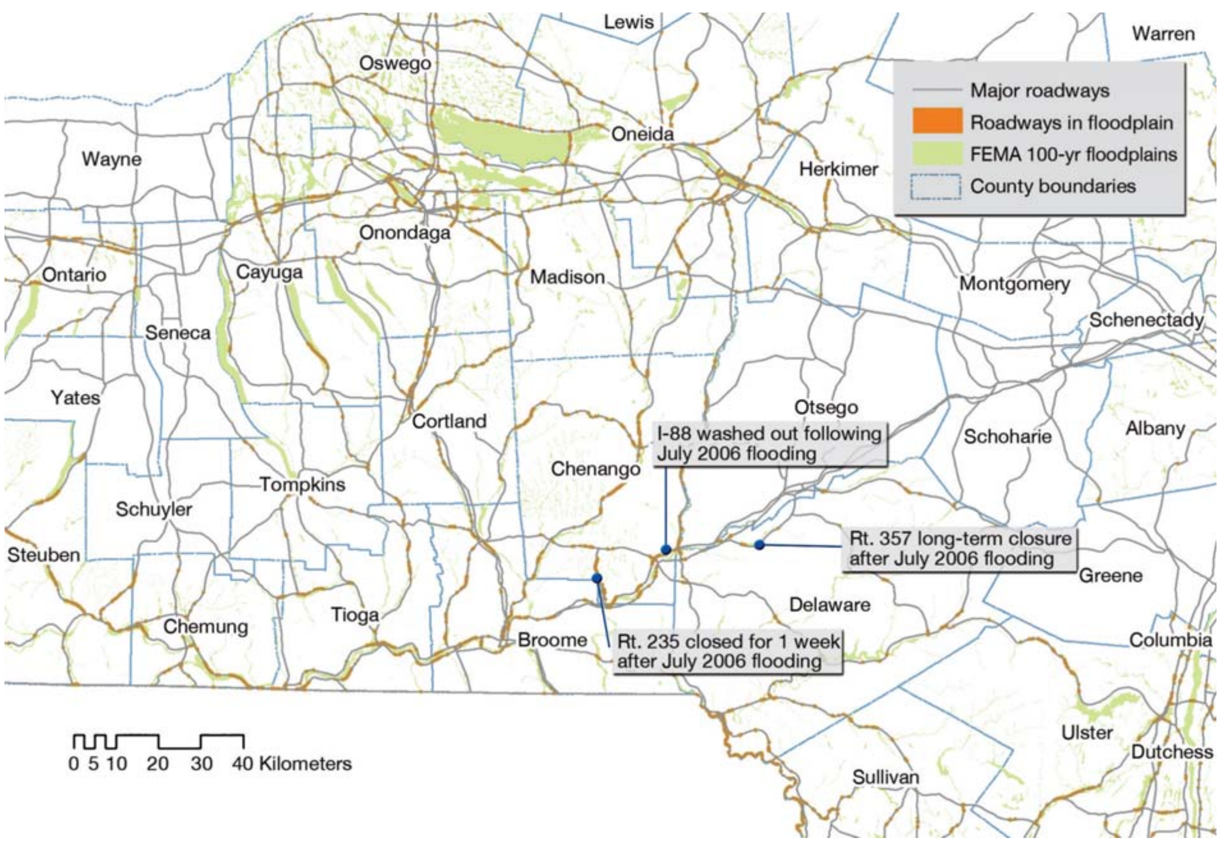
This section gives an overview of the likely consequences of climate change on flooding, water supply, and water quality. It discusses the certainty of different outcomes and speculates on possible favorable opportunities that could arise with a changing climate.

4.3.1 Flooding

Non-coastal floods occur when rivers or streams overflow their channels, flooding the adjacent land or floodplain (coastal flood issues are discussed in Chapter 5, "Coastal Zones"). In areas prone to river and stream flooding, damage is contingent on the presence of humans and infrastructure. In New York State many original settlements were concentrated within the most viable transportation corridors, typically along rivers and their valleys, and much of the state's infrastructure reflects these early patterns of development. Many major roadways in Central New York lie within the Federal Emergency Management Agency's (FEMA) 100-year floodplain (**Figure 4.4**). Wastewater treatment plants are also at risk during floods (**Figure 4.5**). These plants are typically located at the lowest point in a landscape so that sewage can be conveyed by gravity.

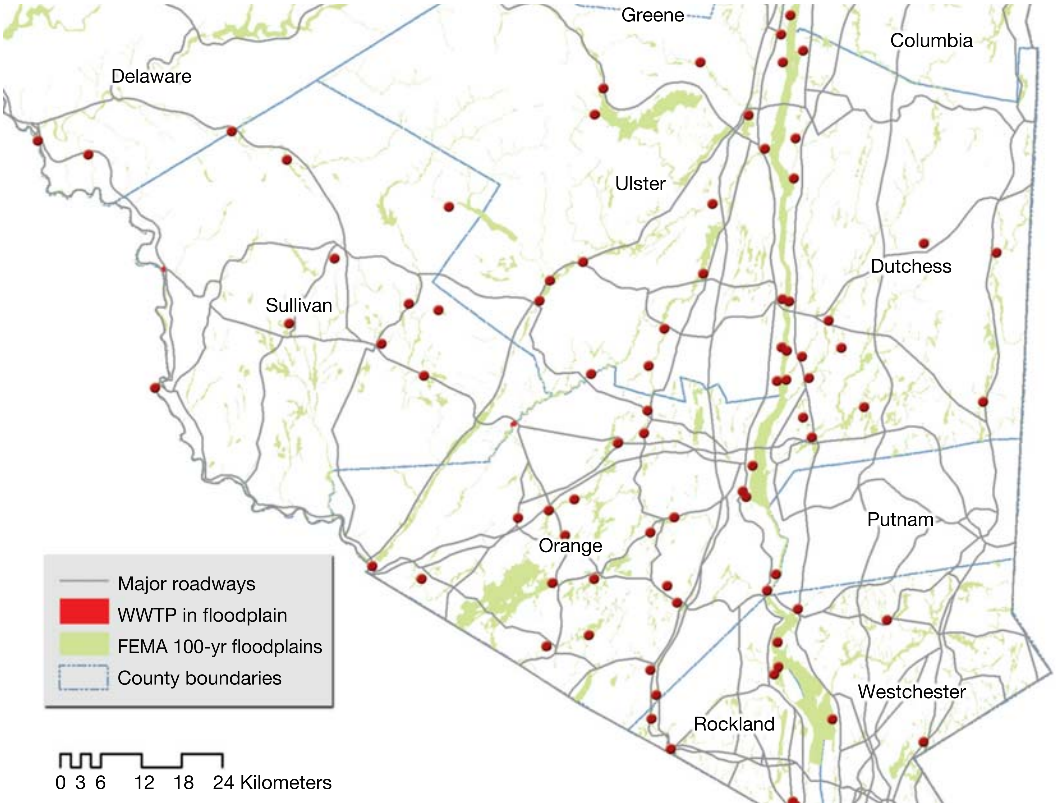
Across the state, flooding continues to be an expensive and disruptive phenomenon. Record flooding in the Susquehanna Basin in 2006 required more than $225 million in disaster assistance, as reported by FEMA. Over a recent 12-year period, nine New York counties in the Southern Tier and Catskill regions experienced more than four FEMA-designated flood disasters; Delaware County had flood damage in 7 of the 12 years (**Figure 4.6**). However, the question of whether flooding will increase with climate change remains inconclusive.

Increases in total annual rainfall as well as higher rainfall intensities—both likely as a result of climate change—are often used as justification for predictions of an increased likelihood of flooding. For some parts of the country, this direct link between precipitation and flooding is likely to be the case. For example, a study looking at the relationship between precipitation and flooding at a national scale found that a 13.5-percent increase in overall annual precipitation could increase future flood damage by approximately 130 percent (Choi and Fisher, 2003). However, large-scale flood damage predominantly occurs in the Mississippi Basin and such a study at the national scale is probably more reflective of the central United States than New York.



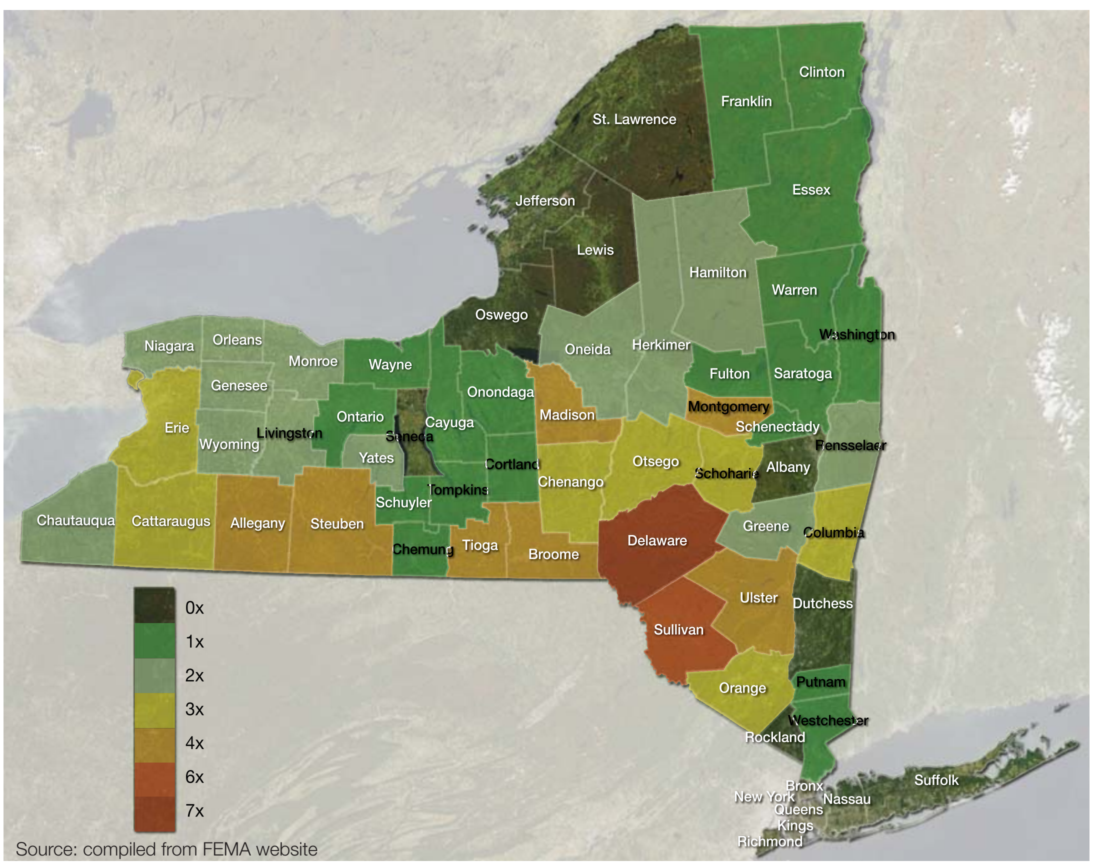
Note: Roads are highlighted that were temporarily closed after severe flooding along the Susquehanna River in July 2006. Sources: FEMA Q3 Flood Zone Data, Census 2000 Railroads, USGS NYS Transportation Coverage

Figure 4.4 Major roadways in proximity to FEMA-mapped 100-year floodplains



Sources: FEMA Q3 Flood Zone Data, Census 2000 Railroads, USGS NYS Transportation Coverage

Figure 4.5 Wastewater treatment plants (WWTP) in proximity to floodplains in the Hudson Valley and Catskill Region



Source: compiled from FEMA website

Figure 4.6 Number of FEMA-declared (Federal Emergency Management Agency) flood disasters in New York counties

To appropriately assess whether flooding in New York State may increase, it is important to focus on the dominant processes leading to large flows in streams and rivers in the New York region and to realize that studies carried out in other regions may not be applicable. For example, one study suggests that different flooding factors dominate in different regions: Damage in the Northeast is related to three-day heavy rainfalls, while damage in the central United States is related to the number of wet days across a season (Pielke and Downton, 2000).

To better understand flood processes in New York State, linkages among stream discharge, precipitation, and snowmelt were examined for three moderately sized watersheds in three different regions. The three watersheds generally reveal the same patterns in flooding. Most notably, less than 20 percent of the largest yearly stream flows correspond to the largest yearly rain events. Most large rainfall events occur between May and October when soils are dry and able to store rain. Instead of being associated with large rainfall amounts, many floods in New York State occur from snowmelt or moderate rainfall amounts on very wet soils. Given the number of interacting factors that affect flooding (snowmelt, precipitation, growing season length, soil wetness), it remains uncertain whether the magnitude of annual maximum flows will increase with climate change. Further details of this flood assessment are described in Appendix B.

There are some cases in which changes in flooding can be predicted with more certainty. More-frequent, larger-magnitude floods as a result of climate change are possible in areas in which flooding is directly linked to the intensity and amount of rainfall, such as in urban areas and steep basins. Urban areas tend to have impervious surfaces, reduced vegetative cover, and compacted soils that minimize the ability of soil to store water; thus, intense precipitation events can increase streamflows quickly. Similarly, small, steep basins, such as those found in the Southern Tier of New York State, rapidly collect water and have a limited capacity to lessen the impacts of rainfall, increasing the likelihood of flash floods following increases in rainfall intensity.

4.3.2 Drinking Water Supply

To assess the vulnerability of water supplies due to climate change, we assume that long-term average water supply will remain largely the same, but, consistent with the ClimAID climate projections, the duration and/or frequency of dry periods may increase. To compare vulnerability, water systems in the state have been classified based on the amount of time over which they can handle a temporary, but sizable, decrease in water supply.

For both surface water supplies and groundwater supplies, the systems are divided into three categories: 1) sensitive to short droughts (two months) and longer, 2) sensitive to moderate droughts (six months) and longer, and 3) relatively insensitive to any droughts. This provides a basic sense of the population and the characteristics of communities likely to be most vulnerable to the uncertain changes in water supply. This analysis was conducted for water systems that serve more than 3,000 people; thus, very small water systems are not directly represented.

Surface Water Supplies

Water supply systems that are relatively insensitive to droughts draw from a water source that greatly exceeds any potential demand. For instance, the City of Buffalo draws approximately 200 million gallons of water per day from Lake Erie. Lake Erie has a total volume of 128 trillion gallons, making Buffalo's daily withdrawal 1/10,000 of the total lake volume. Many other communities also fall into this category (**Table 4.1**). For instance, numerous small towns with demands less than 5 million gallons per day draw water from the Finger Lakes (containing nearly 1 trillion gallons). This analysis does not include possible emergency interconnections; the cities of Rochester and Syracuse as well as additional portions of the

Source	Population
Lake Erie & Niagara River	930,000
Lake Ontario	486,000
Hudson River*	122,000
Finger Lakes	115,000
Mohawk River	94,000
Susquehanna River	68,000
Chemung River	65,000
Other major rivers	53,000
Total	1,933,000

* Hudson River water withdrawn at Poughkeepsie could potentially be threatened by upstream movement of the salt front, as the division between saltwater and freshwater moves inland. Source: NYSDOH Public Water Supply Database

Table 4.1 Large New York water bodies and their dependent community populations

Onondaga County Water Authority's supply region could potentially use Lake Ontario water, adding upwards of 300,000 people within this category. Cumulative demands from communities outside New York State can also reduce Great Lakes' water availability. Nonetheless, on a relative basis, the water supplies within this category can generally be considered highly resilient to climate change. That is, although lake levels will likely be affected by climate change, lake volume is not expected to be altered enough to constitute a risk for these supplies.

Most water suppliers drawing from major river systems in New York State, such as the Niagara River, also fall under the category of relatively insensitive to any drought since the rivers' minimum flows greatly exceed the maximum likely demands given existing uses. Although municipalities drawing from large rivers, such as the Hudson, have been classified in this report as water supply systems with low sensitivity to drought, there could be circumstances in which this classification should change. On the Hudson, approximately 75,000 people rely on Hudson River withdrawals at Poughkeepsie. While this withdrawal of 10 million gallons per day is only a small fraction of total river flow, the intake is located far enough downriver that the saltwater/freshwater interface (salt front) could move above the City of Poughkeepsie's intake as a result of reduced freshwater inflows or sea level rise. Such a shift in the salt front would cause the supply to no longer meet regulatory standards for drinking water. Historical measurements during periods of low flow on the Hudson River give some indication of the possible movement of the salt front. During the 1960s drought, average freshwater flow as measured at Green Island was only 2,090 million gallons per day (the annual mean is 9,000 million gallons per day), and the salt front was observed at the Poughkeepsie intake (de Vries and Weiss, 2001).[1] See the "Coastal Zones" chapter in this report for additional information on salt fronts (Chapter 5).

Surface water supplies sensitive to short-drought periods are those served by what are called run-of-the-river systems (i.e., where water is pumped directly from the river) within a small drainage basin. A run-of-the-river system has either no storage reservoir or a very small storage reservoir. This design assumes that the minimum river flow always exceeds human demand, plus some required conservation flow necessary to sustain fish and other aquatic organisms and the needs of any downstream communities or other permitted users (e.g., industries) that rely on the same river.

Of primary concern are communities that use smaller rivers and streams. As a consequence of shifts in the timing of stream discharge (i.e., more discharge in winter time and less in summer time) and reduced frequency of summer rainfall, there may be new lows in streamflow. A brief period of very low water flows could greatly disrupt the habitability of a community relying on a small run-of-the-river supply. Only six water supplies in the state appear to rely solely on a single small stream, and the population served in most cases is below 5,000 people (Cornell University, Village of Warsaw, Village of Saugerties, Village of Herkimer, Village of Carthage, and the City of Hudson). The Cornell University supply is the largest such system and currently supplies about 20,000 people at an average demand of 2 cubic feet per second, with water being drawn from the 126-square-mile Fall Creek watershed in the Cayuga Lake basin. Based on the 84-year historical record for Fall Creek, the lowest recorded flow was 3.3 cubic feet per second in September 1999, slightly more than normal demand. It seems probable that a shift in streamflow timing could lead to periods when demand does exceed supply; however, the Cornell water system has proactively addressed this risk by recently completing an interconnection with a nearby municipality. Without secondary sources, these run-of-the-river systems with small drainage basins are considered to be at risk for occasionally running out of water under conditions of climate change.

Other surface-water systems in New York are those with a reservoir located on a stream or river and fall into the category of sensitive to moderate drought. A reservoir is constructed when the long-term average surface water supply is sufficient to meet long-term average demand but when short-term variations (from months to years, depending on the system) may lead to deficits between supply and demand. For example, runoff is generally much higher in the winter, while demand is much higher in the summer (for uses such as lawn watering, car washing, pools, commercial air chillers). Reservoirs are frequently constructed to store high winter and spring runoff for use in the summer and autumn. Inherently, reservoirs are only designed to extend supply over a dry period of a certain length. All reservoir systems will be stressed if there is a downward shift in their long-term average supply (although this appears unlikely based on the ClimAID and other climate projections for New York) or a large increase in demand associated with population influx, increased irrigation, or growth of water-dependent industries. Water systems with sufficient reservoir storage will face limited negative consequences even if short-term variations change, as long as the long-term mean inflows and demands remain similar to historical conditions.

There are approximately 40 reservoir systems in New York that each serve at least 3,300 people. These systems range in size from the New York City system, serving more than 9 million (NYCDEP, 2008; p. 34) and consisting of 580 billion gallons of storage, to a municipality such as the City of Mechanicville with a population of 5,000 and less than 100 million gallons of storage. An exact determination of each system's sensitivity to droughts of differing duration cannot be made without a thorough study of each system's infrastructure, demands, supplies, and operational procedures.

To provide a simplified picture of the vulnerability of reservoir systems across the state to droughts of varying durations, we calculated the number of days it would take for the maximum storage volume in a reservoir system to be depleted given historical rates of demand, adjusted down by 20 percent to account for conservation (**Table 4.2**). This approach notably ignores factors such as inflows during the dry period, required discharges to protect fisheries, and the fraction of the total storage volume that is not usable. The days of supply range from 99 to more than 1,000. Most systems with a supply of less than 200 days also have alternate sources that can provide at least a portion of daily demand. (Note: Days of supply is only intended as a simple metric to allow for comparison across systems of greatly varying size and should not be interpreted as a definitive measure of system resilience to drought.)

Municipality	Demand (million gallons/day)	Storage (million gallons)	Secondary Source	Days of Supply w/ No Inflow
Ithaca	3.3	261	Yes	99
Oneonta	1.5	140	Yes	117
Beacon	2.3	218	Yes	118
Ilion	1.97	225	Yes	143
Rome	9.5	1,419	No	187
Colonie	10.4	1,797	Yes	216
Plattsburg	2.3	457	Yes	248
Guilderland/Watervliet	7.3	1,700	Yes	291
Fredonia	1.4	335	No	299
Albany	18.5	13,500	No	912
Troy	14.4	12,912	No	1121

Note: Storage volume information was taken from a USGS inventory of large dams in New York and from a New York State Department of Health (1974) report

Table 4.2 Average daily demand, total storage, and approximate days of supply for a sample of reservoir systems in New York State

Reservoir systems provide a measurable quantity of stored water. With reasonable estimates on the timing of additional inflows, reservoirs can be conservatively operated by adjusting releases long before severe shortages occur. As an example, the Drought Management Plan for the New York City water supply system has three operational phases: drought watch, drought warning, and drought emergency. Different phases lead to different use restrictions. Phases are determined based on the probability that a major reservoir will fail to fill by the end of spring, which is typically when reservoirs reach their maximum water storage. For instance, a drought watch is declared when there is a 50-percent probability that a major reservoir will not be filled by June 1. However, while New York City has a formal protocol for monitoring supply sufficiency, most other water suppliers in New York State operate on an *ad hoc* basis. In conjunction with the New York State Department of Health, the New York State Department of Environmental Conservation tracks drought indicators across the state and issues drought declarations for regions outside of New York City. Individual water supplies may have more or less stored water per capita than suggested by these types of general drought declarations; in any case, it is up to individual water suppliers to decide how stressed their actual systems are and whether to implement appropriate management responses to these conditions. Water suppliers with limited technical resources or insufficient risk aversion in their operating procedures may fail to reduce releases to a point where an imminent shortage is unlikely.

New York City Water Supply System

The New York City water supply system supplies nearly half the state population with water. The system consists of 18 supply reservoirs located in three different drainage basins: the Delaware River, the Hudson River, and the Croton River. Located up to 125 miles north of New York City, the reservoirs are connected to the city by three aqueducts. In the last five decades (since the completion of the current upstate reservoir system in the early 1960s), drought emergencies have been declared for New York City in 1962–65, 1980–82, 1985, 1989, and 2002 (DeGaetano, 1999). The most severe was the 1962–65 drought. Based on the rain gauge in Walton (Delaware County), annual precipitation was at least 10 inches below normal for three consecutive years during the early 1960s. Paleoclimatological reconstructions in the region dating back several centuries (Leathers et al., 2008; Zhao et al., 2010) suggest that droughts similar to that of the 1960s have historically only occurred on average every 100 to 200 years and thus originate in very out-of-the-ordinary conditions likely related to changes in sea surface temperature patterns (Koster et al., 2009). Since it is not yet known whether the sea surface temperature patterns (and perhaps other factors) that likely underlie rare droughts will become more or less frequent in the coming century, it remains difficult to project changes in these drought events that occur once per 100+ years.

Even without considering changes in available surface water, other complicating factors in the New York City water supply systems could stress the available water supply in the coming decades. For instance, the New York City water supply system diverts water from the Delaware River Basin, which is also the drinking water source for the cities of Trenton and Philadelphia as well as many smaller communities in New Jersey. Operating rules that are responsive to water levels in the Delaware River require specific discharge rates from New York City's reservoirs into the river in order to maintain minimum river flows. Different declared drought phases allow for decreased releases downstream but also reduce the maximum diversion to New York City, requiring greater reliance on Catskill and Croton sources. The releases to the Delaware River during periods of dry weather are in large part intended to ensure that the Delaware River salt front remains below the Philadelphia water intakes and areas of recharge of New Jersey wells. Rising sea levels associated with climate change could result in a need to increase the minimum required discharge from New York City water supply reservoirs during droughts, in order to keep the salt front at a safe position relative to drinking water supplies (although such a change could require modification of a 1954 U.S. Supreme Court decree on water sharing in the Delaware River Basin). Thus, even if droughts per se do not become more severe, other factors such as sea level rise could put indirect pressures on the New York City water supply system.

New York City is currently undertaking an extensive modeling effort to better understand possible water supply (as well as water quality) challenges in a changing climate, including the implications of sea level rise. Also, as a preventative measure, the New York City Department of Environmental Protection has aggressively worked to reduce water demands—effectively enlarging the system storage—and is seeking other means (such as regional interconnections and groundwater storage) to increase system reliability (NYCDEP, 2008; Major and O'Grady, 2010).

Groundwater Supplies

Groundwater sources can be categorized in the same way as surface water: sensitive to short droughts (two months) and longer, sensitive to moderate droughts (six months) and longer, and relatively insensitive to any droughts. As with annual streamflow, average annual recharge (the amount of groundwater replenished from surface water sources) is considered to remain approximately the same with climate change, but there may be changes in yearly timing of recharge. Additionally, compared to studies of surface water, studies that assess groundwater recharge under a changing climate remain scarce, and there is a considerable amount of uncertainty surrounding the assumption of no change in recharge.

Municipal-scale groundwater systems generally only exist in areas overlying high-yielding glacial sediments, such as the Long Island aquifers. Coarse glacial sediments have a large capacity to transmit and store water, unlike bedrock or finer-textured silt and clay deposits that underlie other areas. These glacial sediments act as an underground reservoir, accumulating and storing water during periods of recharge. Drier soil moisture conditions during the summer and autumn, however, may reduce annual recharge. But decreases in recharge under a changing climate would likely be minimal since the majority of recharge to aquifers occurs during the late winter and early spring and not in the summer. A comparison of methods to estimate recharge in an upland watershed in central Pennsylvania (Risser et al., 2005) found that at most 10 percent of annual groundwater recharge traditionally occurred in July and August. Thus, a complete loss of this summer recharge under changing climate conditions would only reduce annual groundwater supplies by a limited amount, and wetter springs may be able to compensate for these summer declines, as suggested by a recent study in southern Ontario, Canada (Jyrkama and Sykes, 2007).

Long Island Aquifers

Nearly 3 million people in New York State rely on Long Island aquifers as a source of water. Long Island consists of deep, highly permeable (porous) glacial deposits. The high permeability leads to ready infiltration of precipitation, with a sizable portion of precipitation contributing to groundwater recharge (in comparison to less than 10 percent in many other areas that are representative of New York State [Risser et al., 2005]). Since infiltration and groundwater recharge occur over nearly all pervious surfaces, the entire surface area of a region can act to capture precipitation for human use in these systems. Furthermore, the deep deposits provide a large storage volume for water. In brief, the geology of Long Island makes it highly efficient at collecting and storing precipitation.

The Long Island groundwater system consists of a large pool of stored water plus a smaller fraction of water that cycles though the system and ends up as stream discharge, subsurface ocean outflow, or well water. This actively cycled water consists of the annual recharge and is equivalent to precipitation minus runoff and the loss of water from evaporation from the soil and transpiration from plants. As long as water users only draw from the annual recharge, the stored water amounts do not change and water use for drinking water remains sustainable.

Currently, approximately 400 million gallons of water per day are withdrawn from about 1,000 municipal and industrial wells in Nassau and Suffolk counties. Prior to extensive development on Long Island, groundwater was replenished at a rate of 1,100 million gallons of water per day each year—nearly three times greater than current annual demand. The addition of sewers to reduce pollutant loading to groundwater decreased recharge by nearly 240 million gallons per day between the 1960s and 1980s, lowering water table levels (Busciolano, 2005). Annual demand, however, still remains far below annual recharge (about half). This is in contrast to regions in the western United States where water is knowingly "mined" (with demand consistently exceeding recharge) and where groundwater levels continually decline each year.

Climate change has the potential to further reduce recharge rates. However, the primary impact of reduced recharge thus far has been to reduce streamflows. The 240-million-gallons-per-day reduction in groundwater recharge due to the addition of sewers led to a significant decrease in streamflow (reduced by 135 million gallons per day). According to long-term measurements, streamflows in Long Island streams and rivers have declined as levels of groundwater recharge in developed areas have decreased. Several streams in Kings and Queens Counties have all but dried up and others have just a fraction of their predevelopment flows. However, a decrease in streamflow has no direct impact on the reliability of water supplies, as long as wells are significantly deeper than the streambeds (Buxton and Smolensky, 1998).

The possibility of saltwater intrusion adds an additional complication to considering the resiliency of Long Island aquifers to climate change. Fresh water overlies salt water in the Long Island aquifers. When the water table elevation is greater than the ocean surface elevation, the fresh water can resist the inward and upward push of the more dense salt water. However, near the shoreline, where the land surface and water table elevations approach the ocean elevation, the denser salt water pushes into the freshwater aquifer at a relatively shallow depth. Thus, if water tables decline, near-shore wells that currently extend into fresh water may start to withdraw the intruding salt water. This impact would primarily be felt by shoreline communities. For example, a study of the North Fork of Long Island (a narrow peninsula that is representative of much of the shoreline area of Long Island) found that a 20-percent reduction in the historical groundwater recharge rate, combined with a 20-percent increase in the pumping of groundwater over a five-year drought period, could result in saltwater contamination of multiple well fields (Misut et al., 2004). Sea level rise will further increase the risk of saltwater contamination, especially under a worst-case scenario of approximately 2 meters of sea level rise by 2100 (see Chapter 1, "Climate Risks").

Other Primary Aquifers

Several cities in New York overlie large aquifers that provide the municipalities' primary water source. Many of these aquifers are located in valley bottoms with extensive glacial deposits. These include aquifers associated with the Susquehanna River (Johnson City and Endicott), the Chenango River (Elmira, Corning, and Bath), the Mohawk River (Schenectady), the Tioughnioga River (Cortland, Homer, and Preble), and Cassadaga Creek (Jamestown). These systems have been particularly well studied, since three of the five (all but the Cassadaga Creek and Chenango River aquifers) have been designated as sole source aquifers. The U.S. Environmental Protection Agency (USEPA) designates a sole source aquifer as one that supplies at least 50 percent of drinking water to a population, with no alternative source.

To provide a sense of the possible vulnerability, **Table 4.3** summarizes the ratio of storage to demand for four large aquifers in New York State. Aquifer systems with low daily demands relative to daily recharge rates and storage capacities are less vulnerable than those that have relatively high or near-equal daily demands. Jamestown, Endicott/Johnson City, and Cortland regions all have extensive storage relative to demand. However, in some cases, available storage does not entirely indicate the availability of water. Schenectady/Mohawk has limited storage, but much of the well water inflow is from induced infiltration of Mohawk River water. The average August flow (the lowest monthly discharge of the year) on the Mohawk River at Cohoes is 1,176 million gallons per day, so daily demand (26 million gallons per day) constitutes a small fraction of available water even during dry periods.

Numerous smaller aquifers serve many additional communities throughout the state, many of which are villages in rural areas. Well water has traditionally been preferable to many surface water sources, since it typically requires less treatment to be suitable for human consumption and it does not require construction of a reservoir. Rapidly developing areas outside of cities and towns also tend to rely on groundwater resources, since doing so avoids the political and regulatory complications of developing new surface water supplies. Approximately 79,000 people in Orange County and 200,000 in Rockland County rely on groundwater.

However, the groundwater supply is linked to, and limited by, the land area over which recharge occurs. As development intensifies, demand can exceed supply both due to the density of settlement and by an increase in runoff and associated reductions in recharge. This trend could be potentially exacerbated by climate change in smaller aquifers with limited recharge.

Homeowner Wells and Small Community Water Systems

Approximately 1.9 million people rely on household well water throughout New York State (Lumia and Linsey, 2005), and several hundred thousand others are connected to small public water systems that rely on wells. Residential wells range from low-yielding wells (such as those in glacial till or deep bedrock) to high-yielding wells (>5 gallons per minute) in sand and gravel fill. Wells also range in depth, from shallow dug wells to very deep bedrock wells.

Although recently drilled wells must be registered with the New York State Department of Environmental Conservation, well owners are ultimately responsible for ensuring that their wells can supply sufficient water. Most wells are tested for their average yield at the time of installation; however, this may not be representative of water availability during dry periods. Due to the large number of wells serving individuals or small populations and the unique hydrogeologic conditions at each well, it is difficult to make any predictions concerning the populations that are particularly sensitive to the types of drought periods that may increase with climate change.

As a simple illustration of existing well sensitivity to water depletion, we analyzed long-term records of several unpumped wells routinely monitored by the U.S. Geological Survey (USGS) in New York State.[3] Of the

System	Daily Demand (million gallons/day)	Daily Recharge (million gallons/day)	Well Field Storage (million gallons)	Days of Supply with No Inflow
Jamestown – Cassadaga Creek (Crain 1966)	4.8	30.1	3,000	625
Schenectady – Mohawk River (Winslow et al. 1965)	26	15 (plus Mohawk River infiltration)	500	19
Endicott/Johnson City – Susquehanna River (Randall 1977)	16	41	1,700	106
Cortland Homer Preble – Tioughnioga River (Miller 2004)	6.5	24	>1,000	~150

Table 4.3 Summary of major New York aquifer systems, including demand, recharge, and storage[2]

four wells, one would likely have gone dry sometime during the 18 years that observations were available. Thus, inter-annual variability within the current climate can already impact groundwater levels. In addition to individual homeowner wells, several small community well systems in New York (such as those associated with mobile home parks) have historically gone dry in years with severe summer droughts. However, temporary alternative supplies can typically be arranged (e.g., by trucking in water or drawing from a nearby surface water source). Groundwater levels can also be strongly influenced by excessive pumping in areas with continued development, resulting in the need to drill existing wells deeper. In these areas, climate change may exacerbate water supply shortfalls.

Summary of Water Supply Issues

This summary provides an inter-comparison of potential vulnerabilities in drinking water supplies across the state, giving perspective on how limited resources could potentially be targeted to build resilience to climate variability and change. **Table 4.4** lists each water source category discussed in the preceding section, identifies the categories' sensitivity to climate change, and highlights the population served by each source. Sensitivity to climate change is related to the length of drought that a water system could endure without being severely stressed, as estimated from system storage and demands. Systems with low sensitivity have sizable storage relative to demand while systems with high sensitivity have minimal storage relative to demand.

	Category	Sensitivity to Climate Change	Population Served
1	Withdrawal from large water bodies	Low	2,000,000
2	New York City system	Moderate	9,300,000
3	Other reservoir systems	Moderate	1,300,000
4	Run-of-the-river on small drainage	High	62,000
5	Long Island groundwater	Moderate	3,200,000
6	Other primary aquifers	Moderate	650,000
7	Homeowner well water	Moderate to high	1,900,000
8	Other small water supply systems (groundwater/surface water)	Moderate to High	600,000
	Total		19,012,000

Note: Water supply sensitivity is related to the length of drought that a water system could endure without being severely stressed, as estimated from system storage and demands. This analysis is only intended to provide a general assessment of vulnerability within broad categories. Ultimately, individual water supply systems would require system-specific analysis.

Table 4.4 Vulnerability of water supplies in New York State to climate change

The least vulnerable populations to climate change are those that draw from larger water bodies such as the Great Lakes, Finger Lakes, or large rivers (category 1). Most of the state's population has a water supply that falls into the category of moderate sensitivity to climate change. Reservoir systems (categories 2 and 3) and major aquifers (categories 5 and 6) are presumed to have moderate sensitivity because while most systems do have sizable stores, these stores are still finite. The determination of sensitivity to climate change for a wide array of systems in New York is a broad generalization; the actual sensitivity of individual systems will depend on many factors, including management.

Systems with little storage are likely to be the most sensitive to an increase in droughts that may be experienced in New York State. Run-of-the-river systems on small streams (category 4), shallow wells (a portion of category 7), wells in only moderately productive aquifers (a portion of category 8), and systems with small reservoirs relative to demand (a portion of category 8) will be the most affected by climate change.

4.3.3 Water Availability for Non-potable Uses

Hydroelectric generation is already a primary user of water resources in the state. However, agriculture may start to require a larger share, and there are other emerging uses of water, such as for natural gas well development and for supporting possible shifts in national population. This section primarily considers possible changes in demand for non-potable water brought on at least in part by climate-related factors.

Hydroelectric

Hydroelectric power plants in New York State supply about 15 percent of the state's electricity during a typical year, about twice the national average. Of the 5,800-megawatt capacity of the state's hydro facilities, 3,400 megawatts of the capacity comes from facilities on the Niagara and St. Lawrence rivers. The next-largest facility is the 1,000-megawatt Blenheim-Gilboa pumped-storage plant on Schoharie Creek used for generating power during peak demand periods. The remainder of the 1,400-megawatt generating capacity comes from approximately 150 small facilities spread across the state. Due to the unique facilities and operating conditions at these small plants and the minimal information available for them, this analysis only addresses the large facilities.

The Blenheim-Gilboa facility recycles much of its water by simply transferring water between an upper and lower reservoir. Since its water is reused, the plant is only minimally impacted by climate change. The three hydro facilities on the Niagara and St. Lawrence Rivers are unique in that they rely on discharge from the 29,000-square-mile Great Lakes Basin. Although Lake Ontario and its drainage basin comprise only 10 percent of the total Great Lakes Basin, Lake Ontario acts as a conduit, discharging the accumulated flow of the upper Great Lakes. Any changes in water supply throughout the entire Great Lakes Basin will, therefore, result in a change in water levels in Lake Ontario. As discussed more extensively in the case study in Chapter 8 ("Energy"), several studies suggest there is a likelihood for a future decrease in the Great Lakes' water levels and discharge. This would result in a decline in power production. However, a shifting of some water currently allocated for recreational use could buffer possible losses in hydropower production. Thus, changing water availability may require new discussion of a reasonable balance among competing uses of a water source.

Thermoelectric Withdrawals

Cooling water at power generation facilities constitutes the largest water withdrawal in New York (but not consumptive use), withdrawing more than 4,000 million gallons per day (Lumia and Linsley, 2005). When considering the 20 largest thermoelectric power facilities in the state, much of this withdrawal is non-consumptive, and all of the large facilities draw from large water bodies in which the withdrawn water is a small fraction of the total flow or volume (DOE Energy Information Administration Report 869). These water bodies include Lake Ontario, Lake Erie, Long Island Sound, the Hudson River, and the East River. Most facilities use low-consumption, once-through cooling in which water is returned to the same water body at a higher temperature. This method consumes very little water, but the discharged water can be upwards of 95°F in the summer (based on DOE Energy Information Administration Report 767). Although the temperature of the discharged water will not be markedly affected by climate change, this additional heat load, in combination with higher ambient water temperatures in the receiving waters, may result in additional stress to aquatic organisms.

The Nine Mile Point and James A. Fitzpatrick nuclear plants located on Lake Ontario do use water consumptively with wet cooling towers that function through evaporation. Based on water consumption factors reported by Feeley et al. (2008), these plants consume around 30 million gallons per day, a negligible fraction of Lake Ontario water.

Agricultural Water Use

In most environments, rain-fed agriculture is inherently risky. Even on the best lands in the state, crop yields currently vary by as much as 60 percent from year to year, in part because of the damaging influence of mid-summer droughts. At present, only 2.5 percent of the cropped acreage in New York is irrigated (NASS-USDA, 2002). However, as discussed in Chapter 3 ("Equity and Economics") and Hayhoe et al. (2007), projected increases in the frequency of summer drought may increase the water requirements to obtain optimal crop production in some years. These issues are discussed more extensively in Chapter 7 ("Agriculture").

If economic factors in a changing climate favor expanding irrigation in New York State, key elements to enable or inhibit expansion in different regions of the state will be the proximity of arable land resources to stable water supplies and potential conflicts with other users. The types of water supplies used to feed irrigation dictate their reliability. Namely, unlike most drinking water supplies that have a source of storage (e.g., a reservoir), most irrigation currently draws directly from rivers and streams, and this approach would be unlikely to change given the costs and regulatory difficulties of constructing new reservoirs. As discussed in the water supply section above, these run-of-the-river type withdrawals that have no storage are sensitive to short-term variations in discharge. Other than on the largest water bodies, periods of agricultural drought would be likely to correspond to periods of low flow on streams and rivers that would be the most available sources of irrigation water.

Natural Gas Drilling in Deep Shales

An emerging consumptive water use in the region stretching from the Finger Lakes east to the Hudson River and south to the Pennsylvania border may be the drilling for natural gas in deep shale formations such as the Marcellus, which currently requires a hydraulic fracturing process. Hydraulic fracturing involves pumping water down the wells at high pressures to open up fractures through which trapped natural gas can be extracted. As much as 7 million gallons of water may be required to hydraulically fracture a well. The Susquehanna River Basin Commission, which in 2008 permitted the withdrawal for all consumptive uses of 563 million gallons per day of water from the Susquehanna, estimated that, at its peak, gas well drilling would consume 28 million gallons per day (5 percent of the total current allocation). While hydraulic fracturing is not likely to be a sizable use relative to the entire supply of basins in New York State overlying the Marcellus shale, withdrawals will not be spread uniformly across a basin and intensive withdrawals from smaller headwater streams may lead to localized low flows if not managed properly. It is important to ensure that these withdrawals do not affect established users (such as public water suppliers) and ecosystem services and that the potential impact of climate change on low flows is accounted for in the permitting process.

Other Competing Uses: A Shift from the West?

Severe water shortages in western states, which are likely to become worse with climate change, may shift populations to eastern states, including New York. If so, New York could experience new population and economic growth with an associated increased demand for water. There is a relatively strong likelihood that the Colorado River Basin will experience a decline in river flows in the future (Rajagopalan et al., 2009; Barnett and Pierce, 2009). The Colorado River provides water to more than 27 million people in seven states, including high-growth regions such as Nevada, Arizona, California, and Colorado. One study suggests that even if demand remains steady, there is a 58-percent chance of shortage by 2050 if the minimum expected decrease in runoff of 10 percent occurs as a result of climate change (it is likely that the decrease in runoff will be larger) (Barnett and Pierce, 2009).

Additionally, water rights conflicts and depletion of groundwater are already affecting agricultural production from California to the Corn Belt. The Ogallala Aquifer, which supplies irrigation water for 10 midwestern states, has been drawn down more than 100 feet in many places. The East is the only region of the United States that is likely to experience an increase in the summer rainfall that is vital to crop production (IPCC, 2007), potentially requiring less supplemental irrigation water than in other places to maintain maximum production. There are more than 1.5 million acres of idle or underused agricultural lands in New York State, and approximately 65 percent of the entire state is forested. Coupled with longer growing seasons, there is some possibility new agricultural land could be brought into production and that agricultural water demands could increase.

4.3.4 Water Quality

Climate could affect water quality, both directly and indirectly. Warmer temperatures tend to lower water quality directly. Changes in precipitation that result in more frequent low-flow periods in the summer may impact permitting for point discharges of pollutants that are discharged into surface water. Climate change also could lead to changes in non-point-source pollution associated with changes in land use, including a possible increase in the amount of land used for agriculture if yields in western U.S. states decrease due to water shortages (see section 4.3.3).

Combined Sewer Overflow and Non-point Source Pollution

In many older cities, a single sewer line is used to convey both sanitary sewage and stormwater to a wastewater treatment plant. During periods when there is little rain, the sewer and treatment plant have the capacity to handle incoming flows. However, when there is sizable rainfall, the capacity of the sewer and treatment plant is frequently exceeded, and the mixture of sewage and storm runoff is released into nearby waterways to keep the sewer from backing up and flooding basements or streets. These discharge events are referred to as combined sewer overflows. As would be expected, this sewage contains pathogens (disease-causing agents), excess nutrients (nitrogen and phosphorous), metals, and large debris that can harm aquatic organisms as well as curtail recreational use of waterways. In New York State, more than 60 municipalities have sewage systems that generate combined sewer overflows, and most are located in major cities (NYSDEC, 2008). The City of Rochester has greatly reduced these events; the cities of Buffalo and Syracuse are in the process of implementing mitigation plans. Cities on the upper

Hudson (Albany, Cohoes, Green Island, Troy, and Rensselaer) and New York City are still in the process of developing mitigation plans. **Figure 4.7** indicates communities in New York with combined sewer systems.

The degree to which combined sewer overflows may increase in frequency in a changing climate is dependent on the rainfall threshold at which a combined sewer overflow is initiated in a given sewage system. For instance, the City of Rochester reduced combined sewer overflows by constructing 34 miles of 12-to-16-foot diameter tunnels that can store sewage until it can be treated. While these tunnels will store the combined sewage generated by most rainfall events, Environmental Protection Agency regulations allow up to four combined sewer overflow events per year. An EPA study of the upgraded systems concluded that daily combined sewer overflow discharges could increase by 50 percent with climate change due to two additional large storm events (USEPA, 2008). However, as is often not clearly noted, this 50-percent increase assumes that only four combined sewer overflows currently occur each year.

In contrast, in combined sewage systems that have had no upgrades, a combined sewer overflow can be initiated with little rainfall, and upwards of 50 combined sewer overflows may already occur per year in certain locations. We reviewed design reports assessing sewer systems in the Harbor Brook watershed in Syracuse and in a portion of the Gowanus Canal watershed in Brooklyn. For the Gowanus Canal watershed, simulations predicted 50 combined sewer overflow events each year (Montalto et al., 2007). For the Harbor Brook watershed, modeling predicted 58 combined sewer overflow events each year. In these cases, two additional large rainfall events each year due to climate change would only slightly increase the total number of combined sewer overflow events.

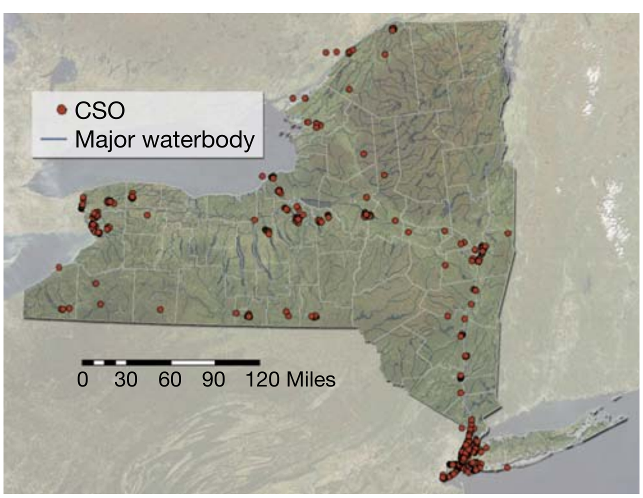


Figure 4.7 Communities with combined sewer overflow (CSO) systems in New York State

Besides sewer overflows, pollutants enter waterways from other sources. In particular, precipitation falling onto urban or agricultural land can pick up pollutants and transfer them to surface waters. However, with climate change, changes in discharge are not likely to be dramatic enough to greatly alter existing pollutant loads. In watersheds with little impervious surface, such as on agricultural land, the largest increase in intense rainfall events could occur during the warm season, when soils would be relatively dry and runoff would be limited. Additionally, as discussed previously in terms of water supply, annual average discharges are projected to only increase slightly.

Even in urban areas with impervious surfaces where runoff is more directly linked to precipitation, increases in pollutant loading would likely be limited because pollutant loads mainly depend on total runoff volume and only weakly on the intensity of runoff or precipitation (Sartor, 1974; Alley, 1981; Shaw et al., 2010). Furthermore, as mentioned earlier, more high intensity rainfall events would reduce the number of moderate events, likely leading to fewer total rainfall events. While speculative, if the interval between storms did increase in the future, this could result in a decreased summer frequency of acute pollution events, such as those that cause beaches near urban areas to close due to high pathogen levels. A Natural Resource Defense Council report on beach water quality notes that year-to-year decreases in beach closings are often associated with a shift from a wetter to a dryer year (Dorfman and Rosselot, 2009).

Impacts of Increased Water Temperatures

Increased water temperature can directly stress aquatic biota, in particular coldwater fish species such as trout. Warmer water also holds less dissolved oxygen (DO). Water bodies that are near the threshold for being DO limited, even for non-trout species, may drop below a critical point more often with climate change. For a water body with a mean summer stream temperature of 68°F, a 9°F increase in mean summer temperature could result in a 7-degree increase in temperature and a change from 9.1 milligrams per liter DO saturation to 8.4 milligrams per liter DO saturation (USGS TWRI Book 9). Streams that already experience oxygen depletion (the potential for DO depletion is measured as biological oxygen demand, or BOD) will start from a lower saturation point and may more frequently reach DO levels that are detrimental to aquatic organisms.

Increasing temperatures may also have both direct and indirect effects on nutrient export from watersheds. Indirectly, as mentioned earlier, factors such as changing water availability in western farming regions may lead to increased agricultural land use in New York State. In a study of Lake Michigan basins, Han et al. (2009) predicted that the presence of nitrogen in rivers could increase by up to 24 percent with climate change and expansion of corn acreage. In terms of direct impacts of temperature increases, Schaefer and Alber (2007) found that 25 percent of anthropogenic nitrogen inputs in northeastern U.S. watersheds reached coastal waters but only 9 percent of inputs in southeastern watersheds reached the coast. They hypothesize that higher temperatures in southeastern watersheds encourage gaseous loss of nitrogen to the air and decrease nitrogen loss to water bodies, and therefore reduce water pollution. Other studies have indicated that wetter conditions over the long term may increase nitrogen loss from watersheds to water bodies (Howarth et al., 2006). Thus the degree of change in nutrient loss from watersheds remains uncertain, since the outcome is dependent on several processes (land use change, temperature change, and soil moisture change) that may counteract each other.

Increased water temperatures are also sometimes associated with greater pathogen survivability in water. However, there does not appear to be a single general conclusion that can be drawn about the potential impact of climate change, since pathogen viability varies widely among organisms and is also influenced by other environmental conditions. Brookes et al. (2004) note that *Cryptosporidium parvum* (*C. parvum*) viability decreases with increasing temperature and that while freezing can kill *C. parvum*, ice cover formation on lakes only affects a small fraction of the stored water volume. A study of *E. coli* concentrations at 23 Chicago beaches noted that *E. coli* increased as temperature increased, but found that other factors, such as wave intensity, were also important in explaining variations (Whitman and Nevers, 2008). From a study of the occurrence of *Vibrio cholerae* (the cause of cholera) in the Chesapeake Bay, *V. cholerae* was found up to 10 times more frequently when water temperature was greater than 66ºF than when below 66ºF, but this also depended on salinity levels (Louis et al., 2003).

Finally, increased temperatures may also lead to increased algal growth in water bodies (French and Petticrew, 2007) as well as increased dissolved organic matter transported from soils and wetlands (Futter and Wit, 2008). Besides impairing recreational use and normal ecosystem function, this increased organic matter may result in increases in the concentration of disinfection byproducts (DBP) in drinking water (potentially harmful chemicals that form when chlorine added to kill pathogens reacts with organic matter). However, DBP formation is dependent on a number of variables (Chowdhury et al., 2009), and there is still limited definitive evidence whether DBP would significantly increase in a changing climate.

Wastewater treatment plants remove the vast majority of, but not all, pollutants in sewage. Federal regulations for sewage treatment balance water-quality objectives against what can be achieved with cost-effective technology. Most wastewater treatment plants (WWTPs) in New York receive a "general" State Pollutant Discharge Elimination System (SPDES) permit that allows them to discharge effluent with a biological oxygen demand (BOD) of up to 30 milligrams per liter (background in-stream BOD is around 1 milligram per liter). High BOD in a water body depletes dissolved oxygen levels, stressing fish and other aquatic organisms. The addition of BOD in a water body results in a decrease in stream-dissolved oxygen near the effluent point and an eventual recovery in stream-dissolved oxygen farther downstream from the discharge point as stream water mixes with air (reaeration). Increased temperatures could increase the rate at which BOD (and, consequently, dissolved oxygen) is consumed (Huber, 1993). But increased temperatures could also increase the rate of reaeration, the rate at which dissolved oxygen is reintegrated into the water from the air (Huber, 1993). While BOD consumption and reaeration push dissolved oxygen levels in opposite directions, BOD consumption is generally assumed to be more sensitive to temperature than rates of reaeration. Therefore, with the same amount of BOD released to a river at a higher temperature under a changing climate, more rapid BOD (and dissolved oxygen) consumption could decrease dissolved oxygen concentrations below current levels, although dissolved oxygen depletion would be limited to a shorter section of river.

Among the 100 water bodies in New York listed as having "impaired" water quality, 26 were noted as being impaired due to low dissolved oxygen (NYSDEC, 2008). Many were in the lower Hudson region or in urban areas of central New York. Most of the impaired water bodies were not associated with WWTP discharge but with non-point source loads, suggesting most of the thousands of WWTPs throughout New York do not currently have a strong impact on stream-dissolved oxygen under normal stream flow conditions. Presumably, an increase in temperature by only several degrees would not result in a dramatic increase in point-source-related dissolved oxygen depletion in waterways.

Impacts of Decreased Flows

Climate change will not only increase stream water temperatures but also potentially result in decreased stream flows, particularly during the summer when stream flow is already at its lowest for the year. At low-flow levels there is less dilution and the pollutant concentration is effectively higher. For water-quality-based SPDES effluent permits (issued in place of a general permit when the water body has an obvious impairment related to the pollutant for which a release permit is being sought), the in-stream concentration of the emitted pollutant is determined from the dilution capacity of the seven-day, ten-year return period of low-flow (which are based on data from the 1940s to 1975). Thus, decreases in low-flows may require reconsideration of these water-quality-based permits as well as a reconsideration of which facilities should still receive general SPDES permits. There are no direct means for estimating low-flows in streams across New York State under a changing climate. Existing regression models for predicting low-flows do include mean annual rainfall as a predictor (Ehlke and Reed, 1999), but the relationships behind these regression models were established from historical records (Eissler, 1979) and do not reflect possible changes in the frequency and size of summer storm events likely with climate change. More accurate predictions of low-flows will only be possible with a better understanding of how the temporal distribution of rainfall will likely change in the future.

4.4 Adaptation Strategies

A variety of adaptation strategies is possible for the water resources sector. Potential strategies span a range of temporal and spatial scales and system-level adjustments.

4.4.1 Flood Adaptation Strategies

As part of an ongoing effort to improve water quality, federal stormwater management regulations under the National Pollutant Discharge Elimination System stormwater program—applicable to both large and small communities—are in the process of being implemented. When retrofitting existing developments and designing new developments, a continued emphasis should be placed on encouraging cost-effective stormwater-management infrastructure that enhances natural hydrologic processes (infiltration into soils, recharging groundwater, evaporation) and slows the movement of stormwater instead of rapidly conveying it to water bodies.

Due to multiple interacting factors (snowmelt, rainfall amount, ability of soil to store moisture, evaporation rates), changes in flooding in large, rural-to-forested basins is uncertain. However, because of the steep slopes, convergent topography, and narrow valley bottoms, the Chemung, Susquehanna, and Delaware River basins have historically been subject to damaging floods. Consideration could be given to moving development out of floodplains as buildings, infrastructure, and flood-protection structures age and it becomes time to rebuild. This strategy of phased withdrawal from the highest-risk, flood-prone areas is currently recommended by the National Association of Floodplain and Stormwater Managers and was publicly endorsed by the New York State Department of Environmental Conservation commissioner at the 2008 Flood Summit.

In particular, wastewater treatment plants within floodplains may require a more thorough examination, even with a limited degree of change in flood risk. A brief interruption of operations during infrequent floods may be acceptable (high floodwater would dilute and rapidly transport discharge from the plant), but floods that routinely interrupt operations for an extended time pose a risk to public health as well as water body health. Many wastewater treatment plants are located in floodplains, since this often coincides with a topographic low point in a municipality and sewage can be conveyed to the plant by gravity. Relatively simple siting modifications or the raising of the facility by several feet may prevent severe inundation and entail little additional cost if incorporated at the time of construction. Since many aging wastewater treatment plants are in need of replacement, the possibility of moving a plant out of the floodplain should be considered when new facilities are designed.

4.4.2 Drinking Water Supply Adaptation Strategies

Many reservoir systems lack the type of formal operating rules that are useful for mitigating the risk of shortages. Accordingly, one adaptation strategy that would be useful for managing current and future climate risks would be to require public water suppliers to establish "rule curves" for water supply reservoirs and aquifers (e.g., a rule curve sets specific guidelines for reservoir releases given the amount of stored water at different times of the year). Currently, New York City is one of the few entities in the state that has a drought-response plan triggered by set water-related thresholds. For the rest of the state, the New York State Department of Environmental Conservation, in conjunction with the New York State Department of Health, determines when to make regional drought declarations. Ultimately, local municipalities are responsible for avoiding shortages based on their own judgment and operational practices. The development of rule curves would provide a systematic, unbiased protocol for managing water supplies under current and future drought.

Additionally, while there are numerous stream gauging stations throughout New York, there are few routine measurements of reservoir, aquifer, or lake levels. Consideration should be given to developing an automated gauging network or, at a minimum, a formal reporting network (e.g., routine manual measurements submitted to a central online clearinghouse) of water levels in public water supply reservoirs and aquifers. This would provide the basis for an improved, statewide early-warning system for recognizing supply shortages, while also establishing a long-term record for better understanding the link between the hydrology of specific watersheds and climate.

Nearly 4 million people in the state rely on homeowner or small public water systems. These individual homeowners or small water utilities may lack the expertise or resources to make proactive decisions prior to running out of water. However, due to the dependence of such small systems on localized conditions, it is unlikely these systems will fail simultaneously or that all systems in a given geographic region will run dry. Given that failures are likely to be small and localized, there should be sufficient resources to assist in developing temporary alternate water sources, either by trucking in water or by tapping a nearby store of surface water. The New York State Department of Health currently maintains a stockpile of equipment (mobile pumps, water tanks, filters, etc.) that can be used by municipalities to assist in supplementing critically low water supplies. Given the potential vulnerability of small water supply systems to climate change, the New York State Department of Health should consider updating and possibly enlarging its stockpile of drought emergency equipment.

In regions with large or growing populations, a possible adaptation could involve creating new water management commissions to oversee water allocations among multiple competing users. The Delaware and Susquehanna River basins already have such commissions. Basin-level commissions could be established for other major rivers in the state, in particular the Hudson and Mohawk Rivers, where population density and growth are the greatest. Other major rivers (the Genesee River, Black River, and Oswego River/Finger Lakes Region) have fewer users and already fall into the Great Lakes Basin, and so will be subject to some oversight due to the Great Lakes Compact (an agreement among eight U.S. states and two Canadian provinces that will ultimately require more extensive reporting of water use in regions of New York located in the basin). There is already an existing Hudson/Black River Regulating District, although it is tasked with an important, but relatively narrow, set of responsibilities. In the upper Hudson River basin, the Regulating District manages discharge from the Great Sacandaga Lake and Indian Lake (two tributaries of the upper Hudson) in order to reduce flood risks and increase summertime low-flows. This regulation only has a moderate impact on the lower Hudson, since the portion of the Hudson below Troy is dominated by tidal flows rather than freshwater inflows. A Hudson and Mohawk River commission could more broadly consider water allocations as well as potential water quality impacts within the entire basin.

Finally, across the state the threat posed by less certain water supplies can be most readily addressed by reducing consumption. In addition, measures to reduce consumption can help control possible increases in water demand due to higher temperatures that arise from increased landscape irrigation, opening of fire hydrants, and water use in commercial air conditioning. Comprehensive water conservation plans have already been developed for certain regions of the state (e.g., New York City) as well as other parts of the country; measures often include the use of low-flow showerheads, toilets, and washing machines; limited car washing and lawn watering; and increased use of rain barrels for gardens. New York City's efforts during the 1980s probably served to avoid drought emergencies during the 1990s. From a review of water use data for 40 larger municipalities in the state, per capita water consumption varies between 89 and 237 gallons per day with a median value of 148 gallons per day. In many cases, a large portion of water usage is related to nonessential uses such as landscape irrigation, swimming pools, and car washing. For example, in Rockland County, water demand rises to upwards of 37 million gallons per day in the summer from around 27 million gallons per day during the winter (Haverstraw Water Supply Project, 2009; DEIS, United Water NYS). Thus, if demands must be cut, water usage could be greatly reduced in some locales without directly affecting basic activities related to hygiene and sanitation.

Western states that experience frequent water shortages have experimented with pricing schemes to modify consumptive behavior. An important consideration is the sensitivity of water demand to the price of water. Studies consistently find that increasing the price of water leads to only small declines in consumption (Kenney et al., 2008). This has been attributed to people's general lack of knowledge of water rates, presumably because water bills are such a small percentage of their total annual expenses. A new technology that is currently being evaluated for its ability to raise awareness of water rates and to modify consumer behavior is the smart water meter. These meters allow different rates to be charged when overall system demand is higher. Dubuque, Iowa, will be one of the first cities in the United States with widespread implementation of these meters (*New York Times*, October 11, 2009, "To do more with less, governments go digital"). A pilot study of smart-meter users in Colorado found that homes with smart meters increased consumption, but they did so by using more water during less expensive periods (Kenney et al., 2008). This suggests that water consumers' behavior is malleable and that with the right pricing structure, overall water use could be reduced.

4.4.3 Non-potable Water Supply Adaptation Strategies

While average annual water supplies are likely to remain at current levels, there may be greater variability in flows throughout the year. Water users with sizable storage capacity (such as most public water supplies) are not likely to be significantly affected by temporary low-flow periods, but water users that depend on run-of-the-river withdrawals (agriculture, power plants, commercial users such as golf courses) may face periods of critical shortages. Thus, it may be important to implement measures to better coordinate water use on shared water bodies. Starting in 2010, the New York State Environmental Conservation Law Article 15 Title 33 will require all water withdrawals that exceed 0.1 million gallons per day to be reported to the New York Department of Environmental Conservation. This will result in more complete information on water usage, in part to comply with elements of the Great Lakes Compact. Consideration could be given to developing a publicly accessible, online system for tracking water usage of all users across the entire state. A complete inventory of water usage across the state will be critical to planning and conflict resolution if competing demands for water usage for drinking water supply, agriculture, energy, industry, export for bottled water, or other uses intensify with climate change. Allocation records are currently maintained by the Department of Environmental Conservation, the Susquehanna River Basin Commission, and the Delaware River Basin Commission; however, a more open system would enhance accountability and potentially allow for more input from additional stakeholders groups (e.g., for recreation and/or ecosystem conservation).

Currently, agricultural, industrial, and commercial users do not need permits to withdraw water in New York State outside the Delaware and Susquehanna River basins. Therefore, water withdrawals from rivers and streams throughout much of the state are not subject to minimum flow requirements. Given that droughts and, consequently, low-flow periods may become more frequent, establishing minimum flow requirements using biological criteria could help to better determine and permit the maximum amount of water that can be withdrawn from a water body during different times of the year. As mentioned in the drinking water supply subsection, basin-level commissions could be established in areas of the state outside of the Delaware River Basin Commission and Susquehanna River Basin Commission boundaries to implement water allocations. The commissions already have guidelines for determining acceptable withdrawals during low-flow periods, and other possible guidelines have recently been proposed in the generic environmental impact statement related to shale gas drilling in New York State.

Finally, more severe climate changes in other parts of the United States (relative to the Northeast) could shift population growth and water-intensive economic activities from western and southern states to eastern states, including New York. Despite relatively plentiful water resources in the state as a whole, the state's most densely populated regions have few additional water sources with which to meet increased demand. A statewide water plan could provide an overview of which areas of the state have excess existing capacity or, at a minimum, have the potential for the development of additional water resources. Specifically, a statewide water plan could provide guidance to commercial and industrial entities, as well as homebuilders and home buyers, on which communities are most likely and least likely to face water shortages, particularly with the additional stress of climate change.

4.4.4 Water Quality Adaptation Strategies

Nearly all major cities in the state have or are developing plans to address impacts from combined sewer overflows. However, overflows are difficult and expensive to eliminate. For example, the City of Rochester began planning its tunnel system in the early 1970s; implementation took more than 20 years and half a billion dollars (75 percent of the funds were provided by the federal government). Due to the cost and complexity of such infrastructure, recent plans for handling combined sewer overflows have often emphasized the removal or elimination of pollutants instead of the attenuation of runoff volumes. For instance, Buffalo has implemented systems to capture large, floatable debris and to disinfect the discharges to kill pathogens (Di Mascio et al., 2007). Syracuse is in the process of constructing facilities that store volume from smaller combined sewer overflow events and that disinfect and remove solids from larger-volume events (see Onondaga County Department of Water Environment Protection Documents: www.ongov.net/lake/index.htm).

In terms of meeting regulatory requirements, communities designing to allow only four overflow events per year may need to consider design modifications to ensure this standard can be met in the future, as indicated above (see section 4.3.4) by the USEPA study (2008). Communities planning on using mitigation measures that remove the majority of the pollutant load in the combined sewer overflow likely have systems that can be scaled up without great difficulty, because these systems treat flows, not volumes. Disinfection and primary filtering facilities would have to operate longer or more often during high-flow events, but would not necessarily have to increase in size.

Gaps remain in the scientific and regulatory communities' understanding of certain basic water quality issues related to climate change. There is a clear need to better understand the impact of low-flows and higher temperatures on the pollutant assimilative capacity of streams and rivers in the State. This entails better understanding of the in-stream chemistry at higher water temperatures (the fundamentals are well established but should be evaluated on actual streams) as well as improving means to predict low-flows on streams so that the most-vulnerable streams can be identified. Improving low-flow estimates would require better accounting of the changes in the temporal distribution of rainfall, and in understanding fundamental subsurface geologic characteristics that create differences in low-flows among streams. There has been recent work to develop methods to estimate low-flows on streams with a minimum of two measurements during periods of stream recession (Eng and Milly, 2007) that could be employed on streams in New York.

An additional potential source of deteriorating water quality in the future will is shift in land use motivated by climate-related factors (e.g., addition of new farm land for biofuels production, unconventional gas well drilling to replace coal). Some of this new development will likely be on marginal land with steep slopes or wet soils, traits that may increase the potential for pollutant generation. Thus there is a need for additional applied research to identify areas that create a disproportionate amount of pollution relative to their size. This research would also allow for more targeted implementation of management measures directed to the critical areas and processes rather than intervening with multiple management options across entire watersheds without regard to the primary pollution source (Garbrecht et al., 2007). For instance, farm-scale research in the Catskills has demonstrated that fencing streams to keep cows out can be as effective at managing water quality as more extensive and costly changes to soil and manure management (Easton et al., 2008).

Potential changes to nutrient, sediment, and pathogen pollution in a changing climate are difficult to predict due to multiple interacting processes and other drivers of change, including urbanization and agricultural intensification. Currently, there is sparse and infrequent pollutant sampling, which limits our ability to separate the impact of the climate and changing land use on water quality. As a starting point, frequent monitoring of primary nutrients, turbidity, and pathogen indicators on major rivers (Chemung, upper Susquehanna, and Delaware) would enable a clearer picture to emerge of the associations among climate factors, land use, and water quality in New York State at a large spatial scale. This effort could integrate with ongoing work to manage nutrient loads in the Chesapeake Bay Region.

4.5 Equity and Environmental Justice Considerations

The anticipated impacts of climate change on livelihoods and ecosystems will be distributed unevenly, depending both upon changes in physical parameters and institutional and socioeconomic conditions that influence local capacity to adapt. Efforts to manage the effects of climate change may create new patterns of winners and losers, further emphasizing the need to consider social equity in adaptation planning.

Equity and environmental justice issues are likely to arise with regard to local management capacity, adaptive flood management, and water supply and quality. Because water resources are closely coupled to other sectors, particularly coasts and agriculture, a number of equity issues overlap and are addressed in more depth elsewhere (see Chapters 3, 5, and 7).

4.5.1 Local Management Capacity

The capacity of local municipalities to manage water resources is a critical indicator of ability to adapt to climate change. This capacity varies widely across local governments (Gross, 2003), and whether new policies that consider climate change are enacted depends largely upon the importance placed on water resource management by local governments, access to technology and information, and the willingness of water resource managers. The demographics and other characteristics of the community also play a role, including income levels, social capital, level of education, and institutional and political contexts, such as relative power and influence in policy-making. In the Great Lakes Basin, local governments taking the most action to manage water resources were in suburban areas around urban centers and in the Finger Lakes region (Gross, 2003). They tended to have larger populations that were more educated and economically healthier. Thus certain populations will be more prepared than others for climate impacts, and strategies to build adaptive capacity need to be locally tailored.

4.5.2 Equity and Flooding

Adaptation to flooding is another key challenge for local and regional governments. There are a variety of adaptations available, ranging from developing or expanding levees and other flood-control structures, to moving homeowners and public infrastructure out of high-risk, flood-prone areas. (See Case Study A for a more detailed discussion.) Each of these options is associated with varying levels of risk exposure and expense burdens, which have strong equity implications. For example, land-use controls that would modify property rights or values, such as remapping a floodplain, enacting new zoning and building codes, relocating infrastructure, or limiting developments, need to be weighed carefully against the burden on property owners and whether compensations are being distributed fairly, relative to market value. Among local governments in the Great Lakes Basin, 28 percent control floodplain development on a case-by-case basis

(Gross, 2003). Case-by-case decision-making that is not informed by established plans, policies, or regulations may increase the probability that the process is co-opted by those with greater power or elites or biased against ill-informed owners or low-income residents. In addition, cost-sharing responsibilities and cascading effects at the local and regional levels need to be considered prior to making these modifications. Ensuring an open and fair process is essential.

4.5.3 Equity and Water Supply

Communities that have limited water storage will be more vulnerable to periods of reduced water availability as the frequency and duration of summer droughts increases. Specifically, some of the 1.9 million people who rely on domestic well water and several hundred thousand others connected to small public water systems may experience periods of scarce or no water. Many of these people, including farmers, are located in more rural areas and may be economically more vulnerable. Conversely, rapidly developing, higher-income exurban communities (those that are located outside the city and suburbs) may also experience water scarcity as increasing demands overwhelm local supplies. Management options to address water supply limitations include conservation programs, water-pricing schedules, or infrastructure development. Policy choices should carefully consider the costs associated with each option relative to economic capacity of the specific community.

4.5.4 Equity and Water Quality

Water quality is already a serious concern for most regions of New York State. Problems associated with pollutant and nutrient loading, toxic and waste runoff, and disease-causing pathogens affect water quality in the state's rivers and lakes. Water-quality vulnerabilities include a number of equity-related issues. For example, nitrogen loading from New York City wastewater treatment plants has impacts on fishing and ecosystem management in places such as Jamaica Bay, Queens. In addition to geographic differences (e.g., upstream versus downstream), poor water quality can be associated with socioeconomic and racial status (Calderon, 1993). Lower socioeconomic groups are more likely to access contaminated waterways for swimming and fishing (Evans and Kantrowitz, 2002). Lower-income or non-English-speaking populations may be particularly vulnerable to increasing levels of pathogens in water or contaminants in groundwater wells, both from lack of insurance and lack of awareness about government programs and warnings. Recreational fishing, particularly among Latinos, is common from the piers and shores of Brooklyn (Corburn, 2002). The Water Working Group of the New York State Environmental Justice Interagency Taskforce unanimously rated combined sewage overflow (CSO) improvement as an urgent priority (NYS Department of Environmental Conservation, 2008). The confluence of these water quality vulnerabilities within specific water bodies in New York State, including Newtown Creek, the Gowanus Canal, and the Bronx River, is, in the current climate, a noteworthy environmental justice concern.

The specific impacts that climate change will have on water quality across the state are less certain. The degree to which increasing rainfall amounts will translate to increased pollutant loads remains unknown. Existing research documenting temperature controls on pathogen survival is also ambiguous. More research on the impacts of climate change on water quality is seriously needed. However, any climate change policies regarding water quality management will need to take into account education, literacy, ethnicity, and income characteristics of the relevant communities, as these factors will drive the success of the programs. One example of a successful water quality management strategy is the adoption of "Green Infrastructure" approaches designed to divert or slow storm water. Such approaches, which fall under a broad spectrum of low-impact development strategies and practices (LIDs), have gained increasing attention and support of environmental justice communities in New York State. Environmental justice communities are supportive of green infrastructure measures because of the ancillary benefits they can provide, including beautification, open space, air quality improvements, and shade, as well as the mitigation of CSOs.

4.6 Conclusions

This section highlights the key points from this ClimAID chapter, summarizing them under key existing and future climate risks, vulnerabilities and opportunities, adaptation options, and knowledge gaps.

4.6.1 Key Existing and Future Climate Risks

Although there are several water-quality issues directly linked to higher average air temperatures, in general, hydrologic processes are dependent on multiple interacting climate factors. In addition to temperature, possible future changes in timing and quantity of snow, rainfall, and evaporation will all have impacts on the state's water resources.

- Rising air temperatures intensify the water cycle by driving increased evaporation and precipitation. The resulting altered patterns of precipitation include more rain falling in heavy events, often with longer dry periods in between. Such changes can have a variety of effects on water resources.
- Heavy downpours have increased over the past 50 years, and this trend is projected to continue, causing an increase in localized flash flooding in urban areas and hilly regions.
- Flooding has the potential to increase pollutants in the water supply and inundate wastewater treatment plants and other vulnerable development within floodplains.
- Less-frequent summer rainfall is expected to result in additional, and possibly longer, summer dry periods, potentially impacting the ability of water supply systems to meet demands.
- Reduced summer flows on large rivers and lowered groundwater tables could lead to conflicts among competing water users.
- Increasing water temperatures in rivers and streams will affect aquatic heath and reduce the capacity of streams to assimilate effluent from wastewater treatment plants.

Water resources in New York State are already subject to numerous human-induced stresses, and these pressures are likely to increase over the next several decades. For instance, water supplies are more likely to be stressed by increasing demands and insufficient coordination of supplies rather than by a dramatic downward shift in the availability of water. Water quality is more likely to be harmed by aging wastewater treatment plants, continued combined sewer overflow events, and excess polluting nutrient loading in agricultural regions. Therefore, nearly all the suggested adaptation strategies are intended to address these non-climate-change factors in tandem with the challenges posed by climate change.

4.6.2 Main Findings on Vulnerabilities and Opportunities

In **Table 4.5**, vulnerabilities have been divided into categories that parallel the major sections in this chapter: flooding, drinking water supply, commercial and agricultural water availability, and water quality. No single vulnerability takes precedence, since no vulnerability can be identified at this time as having a disproportionate societal or economic impact on the state. Additionally, some items listed are only potential vulnerabilities that require additional time and information before a more definitive determination of their importance can be made.

The New York City water supply stands as a special case when considering potential climate change impacts. Neither current hydrologic trends nor climate model projections suggest that a dramatic decline in water availability is likely (particularly since the system has a large storage capacity that provides resilience to increased intra-annual variability in stream flows to its reservoirs). However, since this single system serves such a large number of people and since it is also strongly impacted by several factors external to climate (population growth, interstate agreements on discharges to the Delaware River, aging infrastructure), even slight decreases in water availability could couple with other factors to constrain available water supplies to a large amount of the state's population.

Notably, the New York City Department of Environmental Protection has already been highly proactive in assessing its system reliability and is in the process of conducting additional in-depth studies of impacts on water quantity and quality at a level of detail far beyond the scope of this chapter. The Department of Environmental Protection will presumably maintain this proactive stance in dealing with the uncertainties of climate change. Some vulnerabilities and adaptation strategies in **Table 4.5** loosely encompass the New York City supply (i.e., increased frequency of deficits in systems with moderate-to-large storage volumes).

4.6.3 Adaptation Options

In this section, adaptation strategy options for the State are summarized and potential recommendations put forward. To make it easier for stakeholders and

Section	Vulnerability	Adaptation
Flooding	1. Uncertain changes in flooding in large basins	Consideration of moving development from flood-prone areas when infrastructure reaches end of life span
	2. Increased flooding in smaller, urbanized watersheds	Implementation of infrastructure that replicates natural hydrologic processes
	3. Uncertain potential for increased flooding of wastewater treatment plants	Design modification of new WWTPs
Drinking water supply	1. Likely increased frequency of deficits in homeowner wells, small community well systems, and run-of-the-river systems	i. Enhanced monitoring of groundwater levels; ii. Stockpiling of equipment for emergency withdrawals; iii. Water conservation
	2. Possible increased frequency of deficits in systems with moderate-to-large storage volumes	i. Enhanced monitoring of reservoir and aquifer levels; ii. Use of rule curves in reservoir or aquifer operation; iii. New basin commissions; iv. Water conservation
Commercial & agricultural water availability	1. Increased demand from additional agricultural irrigation	i. Establish minimum streamflow requirements; ii. Statewide inventory of water withdrawals
	2. Competition for water among human consumption, commercial uses, and ecological needs	i. New basin commissions; ii. Establish minimum streamflow requirements; iii. Statewide inventory of water withdrawals
Water quality	1. Decreased stream low-flows and higher water temperatures decrease assimilative capacity of waterbodies receiving waste	i. Modify waste discharge permits (given further study of likely changes); ii. Further study of low-flow characteristics of streams
	2. Uncertain changes in pathogen levels	Long-term monitoring and data analysis
	3. Uncertain changes in nutrient loading with no land use change	Long-term monitoring and data analysis
	4. Possible changes in CSO frequency (particularly in systems with high thresholds for CSO initiation)	Monitoring of possible changes in CSO frequency and implementation of scalable CSO mitigation plans
	5. Increased sediment and nutrient loads due to expanded agricultural production in water-rich region	Better targeted water and soil conservation measures

Table 4.5 Summary of vulnerabilities and adaptation options

decision-makers to evaluate, the strategies are grouped according to robustness.

Resources and Current Status of Implementation

There is considerable natural variability in hydrologic systems even without climate change. Water resource managers have long dealt with this innate climate variability, as well as changes in other factors such as land use and population. Nearly all suggested adaptation options are an extension or expansion of existing strategies for managing this variability. While most adaptation options are not yet being formally implemented, many are related to ongoing water-resource-related projects at the federal, State, and local levels.

Several adaptation options are extensions of existing State and interstate institutions and policies. For instance, a Hudson River Commission could be developed modeling the format and successful strategies of the existing Delaware and Susquehanna River Basin commissions and expanding on the powers of the Hudson River/Black River Regulating District to control releases from the upper Hudson Basin. Minimum streamflow requirements already exist in the Susquehanna and Delaware River basins, and guidelines could similarly be established throughout the rest of the state if the Generic Environmental Impact Statement for shale gas extraction is accepted (although State laws would need to be changed for them to apply to all water users). Water use reporting by industrial and commercial users (although not permitting) is required as of February 1, 2010, under a new State law. The National Weather Service already operates an effective flood-warning system, and the U.S. Geological Survey already measures numerous water bodies throughout the state.

Other possible adaptation options follow from existing operating protocols at the municipal level. In terms of water supply, most water utilities already make some attempt to encourage water conservation, although many appear to have only an *ad hoc* approach to reducing demands in time of drought. In terms of urban flooding and water-quality issues, many municipalities have long had laws restricting heightened peak runoff following new development, and nearly all have had to comply recently with federal stormwater management regulations.

Potential adaptation options

There are many adaptation pathways that can reduce the potential detrimental consequences of climate change for water resources. A challenge to building resilience, however, is the lack of certainty in the degree, pace, and even direction of water-related climate changes anticipated for New York State. Water resource managers will need to make decisions based on climate projections that reflect this uncertainty, which is very different from current approaches that rely on the historic record and the assumption of a stationary climate. One approach to making such decisions under uncertain conditions is to apply the concept of robustness. In the context of decision-making science, the term robustness is defined as a strategy that is effective (in terms of cost, societal impact, and risk reduction) under a range of possible future outcomes (Lempert et al., 2006). Recent research has identified several robust decision-making strategies (Hallegatte, 2009), and we supplement them with several categories of our own; although the adaptations are placed in distinct groups for organizational purposes, many have relevance in more than one category:

Strategic expenditures on adaptation options with co-benefits that result in a net public benefit with or without climate change.

1) Continue to encourage the development of cost-effective stormwater management infrastructure for use in urban and suburban landscapes that enhances natural hydrologic processes (infiltration, recharge, evaporation), instead of rapidly conveying stormwater to receiving water bodies.
2) The New York State Department of Health currently maintains a supply of equipment (mobile pumps, water tanks, filters, etc.) that can be used by municipalities to assist in temporarily supplementing critically low water supplies. The New York State Department of Health should assess and augment the adequacy of its inventory of emergency equipment if needed.
3) Encourage water conservation strategies that guarantee water sufficiency without increasing supplies through building reservoirs or other new infrastructure. Ultimately, increased water availability may provide economic benefits to New York State by increasing the viability and sustainability of water export or virtual trade through agricultural and industrial products.
4) Establish minimum flow requirements using biology-based criteria to determine and permit the maximum amount of water that can be withdrawn from a water body during different times of the year. Such minimum-flow criteria will also be important to make water allocation decisions for water bodies.

Taking advantage of low-cost margins of safety in new construction to avoid more expensive retrofits and modifications in the future.

1) Devise wastewater treatment plant upgrades and combined sewer overflow mitigation strategies (for communities that do not have one in place) to address possible changes in flood risk, sea level rise, and increases in large rainfall events. Modest water infrastructure design changes at the planning stage will avoid more costly modifications to constructed infrastructure later.
2) Consider moving development out of floodplains as buildings, infrastructure, and flood-protection structures age and it becomes time to rebuild.

Soft strategies (in contrast to hard infrastructure solutions) that seek to build new institutional or organizational frameworks.

1) Basin-level commissions could be established for major rivers in the state without them. The Hudson and Mohawk Rivers would likely be high-priority areas, as other major rivers (the Genesee River, Black River, Alleghany River, Oswego River/Finger Lakes region) have fewer users, already fall into the Great Lakes Basin, and will be subject to some oversight due to the Great Lakes Compact. Such basin commissions could provide oversight of supplies as well as water quality and fisheries issues.
2) Many adaptations to climate variability are implemented and coordinated at a local scale. The presence of a lead town or other entity can play a key role in mobilizing efforts in the surrounding region by providing leadership in education, best management practices, and fundraising. State-level recognition as well as funding support to leading local entities could enhance adaptation activities at

the local scale, which will build adaptation capacity that will help address future climate change.

3) Water demand data could be more widely reported even during non-drought periods through mass communication, but also through innovative technologies, such as smart water metering. Such efforts might help break the entrenched mentality that water supply systems should supply 100 percent of demand at all times (Rayner et al., 2005) and shift public behavior to recognize variations in demand and appreciate years when water is plentiful and conserve it in years when it is scarce. This also falls under the more general adaptation option of increasing water conservation.
4) Public water suppliers could establish formal rule curves for water supply reservoirs and aquifers. This involves no new infrastructure but entails establishing a new framework for system operation (likely to include the enactment of well-defined conservation measures at certain drought levels) understood by water managers, other municipal decision-makers, and residential and commercial water users.

Extensive monitoring efforts that expand the collection of environmental data, which are critical for making informed management decisions.

1) Starting in 2010, New York State Environmental Conservation Law Article 15 Title 33 will require all water withdrawals that exceed 0.1 million gallons per day to be reported to the New York Department of Environmental Conservation. Consider developing a publicly accessible online system for tracking water allocations to all users (water supply, industrial, thermoelectric, agricultural) across the entire state. A more open system would enhance accountability and potentially allow for more input from additional stakeholders groups (e.g., recreational, habitat).
2) Consider developing an automated gauging network or, at a minimum, a formal reporting network (e.g., routine manual measurements submitted to a central online clearinghouse) of water levels in public water supply reservoirs and aquifers. This would assist the New York State Department of Environmental Conservation and Department of Health in making drought declarations. More importantly, it would encourage water suppliers to more systematically track water storage and would complement the suggestion for suppliers to develop rule curves to regulate reservoir and aquifer operations.
3) Expand the extent and types of monitoring by the U.S. Geological Survey or other entities to provide additional data for decision-making. This could include additional measurements of groundwater levels, low streamflows, temperatures, and dissolved oxygen.
4) Additionally, there may be the possibility of leveraging widespread Internet connectivity and inexpensive data storage in order to enlarge informal data collection networks. The GLOBE data project (www.globe.gov) set a precedent for students collecting assorted weather data. With nominal funding, a water-quality program could be developed among community colleges, colleges, universities, public-interest groups, and watershed organizations to collect and analyze water data for specific water bodies, feeding it into a central clearinghouse. Such efforts would help engage the public, which is essential for building resilience.

4.6.4 Knowledge Gaps

There are several areas that require additional fundamental research to make educated policy and management decisions. These research areas are discussed below.

There are several fundamental hydrologic processes that need more in-depth assessment. In particular, groundwater recharge, stream low-flows, evaporation, and flooding need to be better understood in light of a changing climate. Such studies need to be process based, instead of simply drawing conclusions from historic data. Additionally, they need to specifically look at processes within the region and avoid making generalizations from other areas, a typical limitation of many existing studies. Such region-specific studies would benefit from additional data, much of which could come from a refinement of existing monitoring networks. The existing rain-gauge network could be expanded to ensure there is a satisfactory density of rain gauges in each basin with a stream gauge, providing a better understanding of the hydrologic response in gauged basins. Potential evapotranspiration as well as soil moisture could also be measured at several sites across the state to better understand how evaporation is affected by changing climate factors. Finally, snow depth measurements could start to include snow-water equivalents (which report snow as a depth of liquid water to account for snow compaction and differences in density) in order to provide a more objective measure of how snowfall and snowpacks are changing over time.

To protect water quality, research that identifies additional critical pollutant-contributing areas and processes is needed. Adaptation measures for water-quality protection in a changing climate should be targeted to the critical areas and processes rather than intervening with multiple management options across entire watersheds without regard to the primary pollution source (Garbrecht et al., 2007). At small scales, a critical field-based assessment of the effectiveness of best-management practices is needed. At larger scales, improved monitoring of primary polluting nutrients, turbidity (cloudiness of water caused by suspended sediment), and pathogen indicators on major rivers (Chemung, upper Susquehanna, and Delaware) would enable a clearer picture to emerge of the relationships among climate factors, land use, and water quality in New York State.

Many pollutant discharge permits for wastewater treatment plants are based on streamflow and temperature data from decades ago. An assessment is needed to estimate future streamflow and water temperature scenarios and to model what impact these changes will have on the quality of water bodies receiving treatment plant effluent.

There is often a desire for actionable future climate information for making decisions on infrastructure needs or policy changes. Results could be provided by downscaling global climate model projections and using these as inputs to a hydrologic or ecology model, but the reality is that this model estimate would be far from certain. Therefore, there is a need for a fundamental shift in the way engineers, planners, and policymakers make decisions. Instead of devising a strategy optimized for one outcome, the strategy should instead perform effectively (in terms of cost, societal impact, and risk reduction) across many outcomes (robustness). There needs to be both basic research as well as educational outreach to decision-makers to expand the concept of robust decision-making.

More severe climate changes in other parts of the United States (relative to the Northeast) could shift population growth and water-intensive economic activities to New York. A statewide water plan could provide guidance to commercial and industrial entities as well as homebuilders and homebuyers. The plan could detail which communities in the state have the most excess water supplies, even with the additional stress of climate change. Additionally, a state water plan could initiate thinking into potential economic opportunities, and the private sector would presumably have an incentive to further investigate these possibilities.

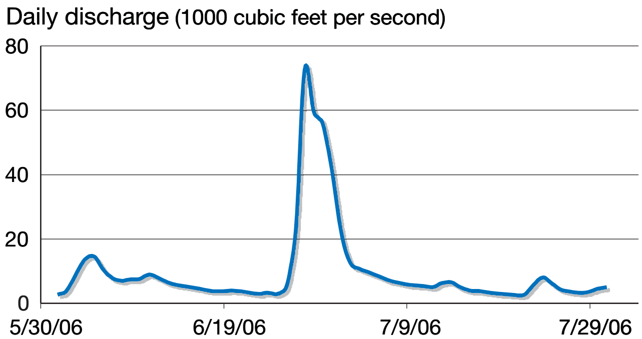
Case Study A. Susquehanna River Flooding, June 2006

Flooding is already a major problem across New York State and it may be exacerbated by climate change. Currently flood damage costs an average of $50 million a year in the state (Downton et al., 2005). The majority of the flood events consistently occur in the ten Southern Tier counties. The June 2006 Susquehanna River flood provides insights into the pros and cons associated with different strategies that can be used to reduce future flooding risks and impacts. Record precipitation during June 2006 culminated in significant flooding throughout the Susquehanna and Delaware River basins in New York and in northeastern Pennsylvania. Twelve counties in New York and thirty in Pennsylvania were declared disaster areas. This ClimAID analysis and summary focuses on Broome County, New York, which incurred the largest portion of damages throughout the entire flooded area.

Climatological and Hydrologic Drivers

The flood resulted from significant, intense precipitation falling on already-saturated soils throughout the 4,000-square-mile Upper Susquehanna basin. A total of 4.29 inches of rain fell in the 25 days before the most intense rain began, with varying amounts of rainfall almost daily, which prevented the soils from drying out. A stalled low-pressure system began contributing intense rainfall on June 25, and from June 25 to 28 total rainfall ranged from 3 to 11 inches throughout the basin (Suro et al., 2009).

Runoff from the steep hillslopes led to a record rise in river water levels. On the Susquehanna River at Conklin, river levels were less than 5 feet in elevation on June 26 (**Figure 4.8**). Flood stage was reached at 2:15 p.m. on June 27. Nine hours later, it reached the



Note the rapid rate of rising limb on June 27.

Figure 4.8 Water level of the Susquehanna River at Conklin, New York, during the June 2006 flood

previous high-water record of 20.83 feet. Rainfall stopped early in the morning Wednesday, June 28, but the river level continued to rise as a result of the water already in the basin, reaching its peak of 25 feet by 11:30 a.m. This flood is the largest recorded on the Susquehanna River at Conklin since gauging began in 1912. However, Broome County had experienced only slightly smaller floods in 2004, associated with Hurricane Ivan, and again in April 2005 when a combination of extreme rainfall and snowmelt very quickly flooded parts of the upper Susquehanna River.

Social and Economic Impacts

The city of Binghamton and a number of smaller rural towns in Broome County were flooded during the June 2006 event. This area included the majority of the FEMA-designated 100-year floodplain and portions of the 500-year floodplain (**Figure 4.10**).

Source: E. Aswald, used with permission.

Figure 4.9 Aerial photograph of Endicott Sewage Treatment Plant during June 2006 flood

There are thousands of properties at risk from flooding in Broome County (**Table 4.6**). Though it is difficult to determine exactly which properties were damaged by the flood and to what degree, an estimate was made by overlaying the flood extent on parcel level data from Broome County's 2004 property tax register. Because of data restrictions, the City of Binghamton is excluded from this dataset and from all of the associated analysis. Also, since there is no way to judge how well individual properties fared during the 2006 flood, aggregate market values should be taken as a maximum estimate of risk. Actual flood damage was a fraction of these estimates. Approximately 3,350 properties were in the flood zone, distributed largely among commercial (10 percent) and residential (58 percent) uses (**Table 4.6**). Two sewage treatment plants, a public works facility, a hospital, and several hundred miles of roads were also in the flood zone (**Figure 4.9**). Approximately 8 percent of the aggregate value of property in the county was at risk, amounting to nearly $563 million.

Despite the rural nature of the county as whole, less than 1 percent of the flooded parcels was agricultural. The Susquehanna River has been a historic beacon for growth, with significant and disproportionate development occurring along its banks. A large amount of commercial property value was within the flood inundation zone, accounting for about 19 percent of the county's total (**Table 4.6**). This helps explain why a number of critical commercial classes were flooded in greater number than would be expected given the size of the county as a whole. For example, nearly 30 percent of the neighborhood shopping area in the county was within the flood zone, as was more than a quarter of the county's warehouse and storage facilities.

	Number of Parcels		Aggregate Market Value	
	Not flooded	Flooded	Not flooded	Flooded
Agricultural	675	12	$39,883,239	$933,359
Commercial	2,870	319	$876,156,504	$210,199,932
Community services	763	55	$1,405,660,897	$61,987,704
Industrial	197	44	$277,401,671	$34,041,765
Public services	353	69	$75,659,552	$110,578,336
Recreational	158	30	$52,536,817	$11,270,494
Residential	47,134	1,954	$3,929,664,223	$123,055,714
Vacant	13,392	804	$169,609,828	$9,748,270
Wild/forest	250	21	$16,173,424	$1,033,142
No data	488	40	$0	$0
Total	66,280	3,348	$6,842,746,155	$562,848,716

Table 4.6 Land use and value of properties in Broome County, broken out by flooded and non-flooded parcels in June 2006

Of all the towns that experienced flooding, Conklin was hit the hardest, with 30 percent of its properties flooded, followed by 13 percent in Kirkwood and 10 percent in Port Dickinson. Of the remaining eight towns, flooding ranged from 6.9 percent in Johnson City to 0.1 percent in Binghamton. The difference in flooding across localities is a reminder of the range of exposures that local governments face during a regional flood event and the importance of cost-sharing mechanisms in the aftermath.

Flood Insurance and FEMA Designation

The extent of the flood draws attention to the limitations of current flood insurance and the uncertainty of FEMA's modeled 100-year floodplain versus actual flooding. The FEMA boundaries are important, not just because they indicate areas where insurance is federally mandated, but also because these boundaries often become the definitive communication

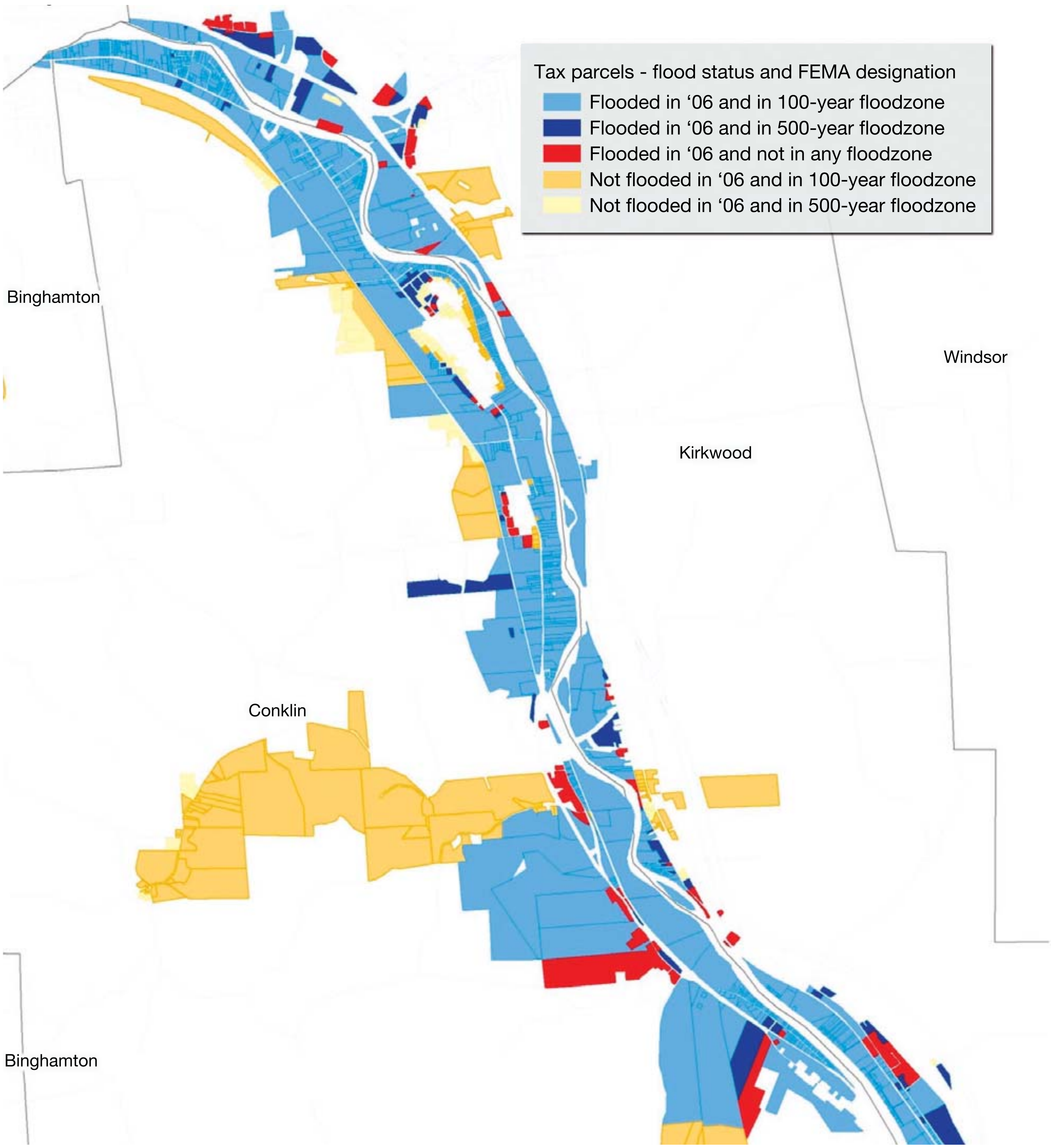


Figure 4.10 Distribution of flood risks in a select area in Broome County: Properties flooded in 2006 relative to FEMA designation

of perceived risk and thereby serve to define the range and limits of a homeowner's or community's response to potential flooding. In total, 1,020 properties were located within the 2006 flood extent but not included within FEMA's Special Flood Hazard Area (the 100-year floodplain) (**Table 4.7**). Of these, 723 were residential and comprised about $46,316,088 worth of property that was exempt from the federally mandated insurance requirements. Large numbers of homeowners outside of FEMA's Special Flood Hazard Area who were devastated by the flood did not have flood insurance (**Figure 4.10**).

Approximately 6,200 people were living within the extent of the flood. Across the entire flood extent, more than 30 percent of housing units were renter-occupied, amounting to more than 920 in total (**Table 4.8**). Conklin and Dickinson had especially high rates of renters in the area inundated, with blocks located on the western side of the river containing 50 to 100 percent renters. Displacement of renters had widespread impacts, including difficulty finding suitable affordable accommodations near places of work or their children's schools. Availability of rental units also decreased as displaced homeowners and renters competed for viable alternative housing.

Patterns of seniors at risk, defined as individuals 65 years or older, varied among communities. Seniors are considered particularly vulnerable due to higher rates of impaired mobility, difficulties with communication, and potential lack of awareness of warning and evacuation systems. More than 30 percent of households in the flood area had at least one member who was 65 years or older, but these households were not concentrated in any one area. The dispersed nature of this vulnerable population may complicate evacuation and response.

	Number of Parcels	Aggregate Market Value
Total		
Flooded and within 100-year flood zone	2,328	$373,050,159
Flooded but outside 100-year flood zone	1,020	$189,798,557
Not flooded but within 100-year flood zone	4,651	$499,763,169
Residential		
Flooded and within 100-year flood zone	1,231	$76,739,626
Flooded but outside 100-year flood zone	723	$46,316,088
Not flooded but within 100-year flood zone	2,717	$184,005,238

Table 4.7 Distribution of flooded and unflooded properties within FEMA's flood zones

	Population
Total population within flood extent	6234
Latino	87
African American or black	101
Non-white	317
Households	2650
Households with one or more members over 65 years of age	845
Housing units, renter-occupied	921

Table 4.8 Select demographic profile of population within the 100-year flood[4]

There was not a distinct relationship between the flooded area and where nonwhite residents lived. The highest densities of the nonwhite populations were located in Binghamton, but very few were located in the flooded area. In Conklin, there were several blocks composed of nonwhite communities, and more than 25 percent of that population resided within the flooded areas.

In order to gain some measure of systematic inequities between flooded tracts and concentrations of vulnerable populations, we compared block groups within the extent of the flood to those block groups in the rest of the county outside of the flood. Apart from slightly higher rates of renters in the floodplain (perhaps a reflection of the more urban housing context along some parts of the river), the profile of the two populations did not differ significantly in terms of demographics.

Adaptation Response Options

Various options are available to increase resilience and reduce risks from the flood-related impacts of climate change, each with its own benefits and disadvantages. A few options are presented here. A complete assessment should evaluate damages due to structural losses or costs of new construction, costs due to loss of work-related productivity, and offsets provided by insurance. However, there are impacts, such as from losses in human lives or subsequent short-term and long-term illness, as well as loss of ecosystem services, to which it is much more difficult to assign dollar values.

Option A: Maintain Status Quo

Despite the very rapid onset of the flood and the thousands of properties that were inundated, there were only four deaths (Suro et al., 2009), which is sometimes viewed as the real measure of a disaster. The success was due to the excellent warning-and-response system coordinated by NOAA's National Weather Service that is linked to local communities. This system depends on the availability of real-time data on streamflow for the Susquehanna River and several tributaries measured at USGS gauges. Notably, some of these gauge sites were recently at risk of being eliminated due to budget constraints, but currently most have been continued with other funding sources. The response included pre-flood community-wide warnings and evacuations, water pumping and sand bag efforts, and emergency evacuations and medical services during the flooding. Such flood-warning systems are not cheap. For example, it costs about $17,000 per year to operate and maintain a single USGS streamflow station in New York (Ward Freeman, personal communication, 2009). Additional costs for manpower, communications, computer resources, vehicles, and other emergency-response equipment total in the hundreds of thousands of dollars or more (Ward Freeman, personal communication, 2009).

If the status quo approach is taken, similar levels of damage are likely to occur when the next flood of similar magnitude occurs on the Susquehanna River. Properties that are within the 2006 flood area constitute an estimated 8 percent of the value of all property in the county. And while the rates of socially at-risk populations are not extremely high, the raw numbers suggest that thousands of people with potential vulnerabilities were located within the flood zone. A no-action scenario is likely to lead to similar or worsening impacts, especially if floods become more frequent or severe. Uncertainty about flood forecasting, due to climate change or inadequate emergency systems elsewhere in the state, will also raise the likelihood that people and their property will be caught off guard.

Option B: Increase Levees, Dams, and Other Barriers to Reduce the Flooding Risk

Extensive levees and dams were built in the 1950s. This system has been highly successful at preventing flooding for several decades along the Susquehanna River. However, in some locations the current system is no longer adequate to deal with potential higher-magnitude floods. Additionally, development within the floodplains behind these barriers has intensified, perhaps due to an artificial perception of safety, making communities more vulnerable and damages greater when floods do occur. Developing or upgrading existing levees to support floodplain development is extremely expensive. This is being demonstrated in parts of Broome County, where recent updates to FEMA flood mapping will soon require upgrades to existing levees. If levees are not updated, thousands of residents will have to purchase flood insurance policies for the first time. Costs for the planning stage and subsequent renovation of the levees by the U.S. Army Corps of Engineers are estimated to be in the tens of millions of dollars (William Nechamen, personal communication, 2009).

Both options A and B are strongly influenced by the availability of flood insurance to property owners as it offsets a significant portion of flood-damage expenses. Current FEMA regulations require some level of flood "proofing" (e.g., constructing elevated buildings to reduce damages within insured communities). However, the global insurance industry has recently recognized the potential risk increase given the impacts of climate change (Geneva Group, 2009). Future insurance options will have significant ramifications for homeowners' willingness to accept risks, housing values, and future land uses within high flood-risk areas.

Option C: Phased Withdrawal from the Highest Flood-risk Areas Over Time

Moving out of the highest flood-risk areas has been successfully accomplished by using homeowner buyouts following floods in multiple places nationwide, including Conklin in 2007. Payouts have been set at pre-flood fair market value or at pre-flood value minus the estimated costs of damage repairs. The local government takes over the land, which is deeded for recreation or open space. At a minimum, towns may consider moving infrastructure, such as wastewater treatment plants, out of floodplains. The withdrawal strategy reduces all subsequent flood risk, both to human lives and buildings. Monetary costs can be comparable to or less than costs to expand levees. It has the added benefit of expanding natural flood-control processes by increasing floodplain storage and not "bouncing" floodwaters downstream. It also improves water quality and aquatic ecosystem health. However, one of the strongest deterrents to greater adoption of a withdrawal policy has been the strong sense of place or "roots" that people feel for their locations (homes and communities); another is a desire to live near water.

Option D: Improve Watershed Management

Improving watershed management should be considered in conjunction with any of the options listed above and can play a significant role in reducing the amount of runoff that contributes to flooding. Best-management practices, including improving soil infiltration capacity, expanding vegetated surfaces, decreasing impervious cover, and uncoupling roadside ditch systems, have been documented to reduce downstream flooding.

In all of these options, the critical question is, How will decisions about new infrastructure, buyouts, or land management be made? The largest infrastructure projects are possible only with regional and national collaboration, while local and individual property protections can be cobbled together by local governments or individual property owners. Whichever path is pursued will determine who bears responsibility for the costs of these measures, including impacts on livelihoods, and who controls the safety nets in the event of system failure. Whichever option is chosen, the process must be inclusive of those living in affected neighborhoods and sensitive to underlying socioeconomic conditions and indirect economic impacts

Case Study B. Orange County Water Supply Planning

A portion of future population growth in New York State will occur in higher-income exurban regions. Unlike traditional suburbs, these areas are farther from established major city centers and in recent decades have grown mainly through low-density residential development. Much of the growth in Rockland, Orange, and Putnam counties, located 20 to 40 miles outside of New York City, has been in exurban areas. In terms of water resources, these areas frequently have higher per capita water usage due to greater landscaping demands. These areas may face major challenges in developing new larger-scale sources of water, particularly surface water reservoirs, in part due to regulatory constraints. In some parts of the state, exurban areas have emerging regional governmental entities that are just becoming established enough to plan and finance centralized water supplies. In contrast, Orange County has had a legally established and active water authority (Orange County Water Authority, or OCWA) for more than two decades. Orange County is in many ways representative of other areas of exurban growth in the state that face water-resource supply issues, many of which could be complicated or exacerbated by climate change. However, it is also one of the few locations to have proactively undertaken a recent study of water resources that has included the impacts of future climate change in addition to socioeconomic, geographic, and political constraints. Much of the following information in this ClimAID analysis is drawn from the proposed Orange County Water Master Plan Amendment of July 2009 (OCWA, 2010).

Water Supply Planning in the County

In 2007, Orange County's population was 377,000. It was partially concentrated within several small cities (Middletown, Newburgh, and Port Jervis) and in smaller villages, but also was widely dispersed throughout the county. By 2018, the population is projected to grow to 436,000 (OCWA, 2010). With this increase in population, water demand is expected to rise from 29.9 million gallons per day in 2008 to 34.1 million gallons per day in 2018 (OCWA, 2010). While there are no estimates of longer-term growth, given the projected rise in the U.S. population it would seem reasonable to assume that the county would continue at its current growth rate, adding about 45,000 additional people per decade and thereby increasing the demand for water by about 5 million gallons per day each decade. These projections and others in the OCWA Water Master Plan are based on an assumption that per capita demand will remain approximately constant over the next 10 years (OCWA, 2010).

As of 2007, approximately 101,000 people in the county (spread over 80 percent of the land area) were served by individual homeowner wells (OCWA, 2009). The remaining people were supplied from groundwater and surface-water sources by 63 municipally operated water districts and 89 community water suppliers. These groundwater and surface-water supplies are almost exclusively owned and operated by the individual entities, with limited sharing of water-supply infrastructure. Thus, there are more than 150 independent and decentralized water suppliers in Orange County alone.

The OCWA is the county's primary agency responsible for planning and development of drinking water supply resources and infrastructure. Other county and State agencies—notably the Department of Health and Department of Environmental Conservation—have key roles and authority over certain aspects of drinking water supplies as well. The OCWA was formed in 1987 to implement a county-wide wholesale water system that would be composed of new reservoirs, treatment plants, and a looped transmission pipeline throughout the central part of the county ("the water loop"). The water loop project was the culmination of several decades of planning for a centralized supply. As early as 1959, an engineering firm created plans for damming creeks and rivers to create reservoirs. Based on a 1977 water supply study, the county purchased three possible reservoir sites: Black Meadow, Dwaar Kill, and Indigot. Then, a 1987 study laid the foundation for the OCWA and loop project. In addition to the water loop centralized distribution system, this study called for construction of 1) the Dwaar Kill Reservoir with flood skimming from the Shawangunk Kill in order to provide an increased capacity of 18 million gallons per day, and 2) a siphon to the Catskill Aqueduct that could provide 21 million gallons per day. However, the water loop project was never implemented, largely due to the unwillingness of local municipalities to commit to long-term contracts to purchase water from the OCWA. These proposed contracts were the basis of the OCWA's plan to finance the project, which was estimated to cost $142 million in 1990 dollars ($236 million in 2010 dollars). Despite not having its own facilities, the OCWA has certain legal and financial powers not available to municipalities. The OCWA is still establishing its place in coordinating the water supply in the county, with the recent report an example of the evolving process of trying to provide centralized planning.

Instead of a large centralized project, smaller-scale projects have been developed by local municipalities to provide additional supplies. These smaller projects have largely been based on groundwater sources, primarily because of their much lower capital costs and their ability to be phased in as demand increases. Orange County is currently evaluating the potential for additional groundwater supplies from two basins originally planned for reservoir development (Dwaar Kill and Indigot). It is estimated that each of these two basins could supply 600 to 800 gallons per minute, enough water for 2,000 homes. Additionally, interconnections have been suggested among several municipal systems to help better distribute supplies. The OCWA's water conservation programs, especially a leak detection program, have contributed to controlling demand.

County Vulnerability to Water Supply Shortages

The current drinking water supply capacity is 50 million gallons per day with a demand of 30 million gallons per day. In 2018, the projected supply capacity is 53 million gallons per day with a demand of 32 million gallons (OCWA, 2010; Table 2). Supply estimates are based on the so-called safe-yield projection, the amount of water available during the drought of record. In Orange County and other parts of the region, the drought of record is based on the 1960s drought. Thus, according to this supply estimate, in 2018 there will be a county-wide surplus of 20 million gallons per day.

However, since the water supply sources are localized, certain municipalities are projected to have deficits in supply. Some of these deficits would be eliminated if planned or existing back-up systems come online. But based on projections, the Village of Goshen, the City of Middletown, and the Village of Kiryas Joel would have a deficit in water supply by 2018 (OCWA, 2010; Table 2).

While there is a significant range of possible futures in current modeling projections, climate change projections that are within the most-likely range suggest that average annual surface-water supplies will stay near their current levels (Frei et al., 2009). But these projections also indicate reduced groundwater and soil moisture, and there is certainly the possibility of decreases in surface-water supplies as well. With certain systems in the county already approaching a threshold at which demand may exceed supply in the next decade, additional population growth, combined with even slight changes due to climate, could lead to deficits in these already-stressed systems. During the drought of 2001–2002, five municipal water systems had to activate emergency supplies (including using water from New York City's Catskill Aqueduct). And even if average annual supplies remain relatively constant, increased variability in summer precipitation and evaporation could temporarily stress small water systems (which largely serve small residential developments) that have little storage. During the drought of 2001–2002, four water districts (Walton Lakes Estates, Arcadia Hills, Hambletonian Park, and Pheasant Hill) serving residential developments (with a total population of only several hundred each) needed to truck in water from neighboring communities and empty it into district wells in order to replenish the supply.

Case Study Conclusions

The examination of drinking water planning in Orange County provides a glimpse at some of the bureaucratic, political, and financial challenges that are intertwined with any assessment of the impacts and possible adaptations to climate change in an exurban region.

Orange County as a whole probably has sufficient drinking water supplies to meet demand in the near future, but certain areas within the county do not. While the development of major centralized water sources now (such as new reservoirs) could reduce the risk of water shortages from a changing climate in the future, the economic costs and regulatory challenges involved suggest that this is not likely. The water loop plan of the late 1980s or other large-scale centralized supply and distribution plans may not be reinvigorated given the high overall cost and lack of demonstrated benefits to many of the numerous communities that would have to agree to participate.

Future strategies to ensure there is sufficient water in all communities would benefit from addressing population growth and potential climate change impacts. They will most likely be similar to past and current efforts of the OCWA. The proposed Water Master Plan recommends planning limited interconnections between nearby municipalities to address localized shortfalls, the ongoing use of water from New York City's aqueducts, and studying new small-scale sources, such as groundwater wells. The plan also recommends increased conservation programs, though it does not factor potential water-efficiency gains into projected water demand. This is a conservative approach that seems aimed at ensuring adequate supplies in case conservation programs have a limited impact. The county's ongoing ownership of several potential reservoir sites may become more important in the future if water availability becomes more limited and there is a heightened political willingness to fund reservoir development.

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Appendix A. Stakeholder Interactions

The major issues of vulnerability and associated potential adaptations were identified in conjunction with seven stakeholder workshops involving about 200 stakeholders held during the ClimAID project. These workshops included presentations and discussions with lake association leaders at the annual conference of the Federation of Lake Associations, with engineers and planners at the annual conference of the American Public Works Association, with forestry and wildlife professionals in a regional ForestConnect webinar, and with multiple workshops for Cornell Cooperative Extension educators and rural landowners. Given the breadth of professions and stakeholders that are involved with water resources across New York State, these efforts need to be viewed as the beginning of an ongoing and expanding engagement with all water stakeholders statewide as New York prepares to cope with the challenge of climate change.

List of Workshops

1) **Date:** 4 May 2009
Venue: New York State Lake Associations Annual Conference, Hamilton, NY
Lead: Rebecca Schneider, Cornell University, Dept. Natural Resources
Participants: 16 directors of lake associations across NY

2) **Date:** 27 March 2009
Venue: American Public Works Association – Ann. Conference, Canandaigua, NY
Lead: Rebecca Schneider, Cornell University, Dept. Natural Resources
Participants: 28 municipal engineers, town planners, watershed council program managers, private engineering consultants

3) **Date:** 10 March 2009
Venue: Cornell Cooperative Extension Advisory Council Workshop for Natural Resources and Environment
Lead: Rebecca Schneider, Cornell University, Dept. Natural Resources
Participants: 20 CCE directors, members – American Wildlife Conservation Foundation, member – Federation of NYS Solid Waste Assoc., biologist – Ontario Dune Coalition, assoc. director of state wetland managers and state floodplain managers; president – NY Forest Owners Assoc.

4) **Date:** 18 March 2009
Venue: ForestConnect Webinar
Lead: Kristi Sullivan, Cornell University, Dept. Natural Resources
Participants: 149 including 46 percent landowners, 29 percent foresters, 20 percent educators and 12 percent specialists responsible for ~11,000,000 acres of land in 21 states

5) **Date:** 12 November 2009
Venue: Rural Landowner Workshop on Climate Change, Arnot Forest, Newfield, NY
Lead: Rebecca Schneider, Kristi Sullivan, Cornell University, Dept. Natural Resources.
Participants: 12 private landowners

6) **Dates:** 11 November and 8 December 2009
Venues: Ecosystems Climate Change Workshop, Ithaca, NY Ag and Food Systems CALS In-service, Ithaca, NY
Lead: David Wolfe, Cornell University, Dept. of Horticulture

Stakeholders

Adirondack Mountain Club
Akwesasne Task Force on the Environment
Alley Pond Environmental Center
American Wildlife Conservation Foundation, Inc.
Association of State Wetland Managers
Au Sable River Association
Basha Kill Area Association Hudson Basin River Watch
Battenkill Conservancy
Beacon Sloop Club
Black Creek Watershed Coalition
Boquet River Association (BRASS)
Bronx River Working Group
Buffalo Niagara Riverkeeper
Building Watershed Bridges in the Mid-Hudson Valley
Butterfield Lake Association
Cornell Cooperative Extension
Canandaigua Lake Improvement Association
Canandaigua Lake Watershed Task Force
Catskill Center for Conservation and Development
Cayuga Lake Watershed Network
Cedar Eden Environmental

Central New York Watershed Consortium
Chautauqua Lake Conservancy
Chautauqua Watershed Conservancy, Inc.
Coalition to Save Hempstead Harbor
Coalition to Save the Yaphank Lakes
Columbia County Lakes Coalition
Community Water Watch Program
Cornell Cooperative Extension - all counties
Croton Watershed Clean Water Coalition
Dutchess County Soil and Water Conservation District
Esopus Creek Conservancy, Inc.
Executive Director of Catskill Watershed Corporation
Fed. of NY Solid Waste Associations
Finger Lakes Land Trust, Inc.
Friends of Jerome Park Reservoir
Friends of the Bay
Genesee Land Trust
Groundwork Yonkers/Saw Mill River Coalition
Honeyoe Valley Association
Horseshoe Pond/Deer River Flow Association
Hudson River Foundation
Hudson River Environmental Society
Hudson River Sloop Clearwater
Hudson River Watershed Alliance
Jamaica Bay Watershed Alliance
Java Lake Colony, Inc.
Keep Putnam Beautiful
Lake Colby Association
Lake Erie Alliance
Lake George Association
Lake George Land Conservancy
Land Trust of the Saratoga Region
Metropolitan Waterfront Alliance
Mirror Lake Watershed Association
Mohawk River Research Center
Mohegan Lake Improvement District
Monroe County Stormwater Coalition
Natural Resources Defense Council
Nature Conservancy Great Swamp Program
Nature Conservancy Neversink River Program
New York Agricultural Land Trust
New York Forest Owners Association
New York Rural Water Association
New York Rivers United
New York State Federation of Lake Associations, Inc.
New York State Lakes
North River Community Environmental Review
Oatka Creek Watershed Committee
Onesquethaw/Coeymans Watershed Council
Onondonaga Creek Revitalization Committee
Ontario Dune Coalition
Peconic Bay
Peconic Baykeeper
Peconic Estuary Program
Plymouth Reservoir Association
Protect the Plattekill Creek & Watershed
Quassaick Creek Coalition
Riverkeeper, Inc.
Saranac Lake River Corridor Commission
Saranac Waterkeeper/Upper Saranac Lake Foundation
Save Our Seashore
Sawkill Watershed Alliance Scenic Hudson, Inc.
Saw Mill River Coalition
Seneca County
Skaneateles Lake Watershed Agricultural Program
Snyder Lake Association
South Bronx River Watershed Alliance
Sparkill Watershed Conservancy
St. Regis Mohawk Tribe
The River Project
The Urban Divers Estuary Conservancy
Upper Delaware Council, Inc.
Upper Saranac Lake Association
Upper Susquehanna Coalition
Wallkill River Task Force
Westchester Land Trust
Western New York Land Conservancy

Appendix B. New York State Flood Analysis

To better understand flood processes in New York State, linkages between stream discharge and precipitation and snowmelt were examined for three moderately sized watersheds in three different regions of the state: Ten Mile River in the lower Hudson Valley, Fall Creek in the Finger Lakes Region, and the Poultney River in the Lake Champlain Valley. The three water bodies were selected because they have at least 50 years of stream gauge and precipitation records and do not have any major impoundments or diversions.

For each water body, the following indicators were examined: the annual maximum daily average flow, the daily average flow associated with the annual maximum two-day precipitation event, and the annual maximum daily flow associated with the maximum three-day snowmelt event. The intent was to investigate the relationship between maximum stream discharges and two of the most important causes of flooding, large precipitation events and melt of a sizable snowpack (**Table 4.9**).

The three watersheds generally reveal the same patterns in flooding. Most notably, less than 40 percent of annual maximum daily discharges correspond to either two-day maximum rainfalls or maximum snowmelts. To explain this outcome in terms of snowmelt, the largest snowpacks are usually only on the order of 20 inches in depth (it would be preferable to know the actual water content of the snowpack, but this is not routinely measured), and they typically melt over at least several days (the largest one-day melt in any of the watersheds was 13 inches but the median was only 6 inches). An inch of snow typically contains about 0.1 inch of water, so melting of a large snowpack is only equivalent to a moderate rainfall event and not sufficient to result in very large stream discharges.

To explain this outcome in terms of precipitation maximums, most two-day maximum rainfall events occurred between May and October. During this time of year, moisture-laden air from the south reaches New York State and causes two-day rainfall amounts that can exceed 5 inches. However, counteracting these larger rainfall amounts is an increase in available soil-water storage capacity due to the drier soil conditions and lowered water tables that are common in the same timeframe. Using data from the Fall Creek watershed in central New York State, **Figure 4.11** shows the correlation between the two-day storm precipitation amount and the resulting average daily discharge in the stream. Although there is a general upward trend (larger stream discharges occur with larger precipitation amounts), rainfall is clearly not the only factor related to peak discharge. For instance, there are three days with discharges around 6,000 cubic feet per second, but these correspond to medium-sized storm rainfall amounts ranging anywhere from 3 to 5 inches. Though the rainfall amounts of the largest storms will likely increase, impacts on peak flows are uncertain due to hydrologic buffering from possible increases in soil dryness.

Rather than snowmelt or large precipitation events, approximately 60 percent (**Table 4.9**) of the annual maximum discharges in these New York watersheds typically result from a combination of limited soil-moisture storage capacity (i.e., wet soils) and moderate rainfall events (1-to-3-inch two-day events). In all three watersheds only 15 percent of annual maximum daily discharges occur between May and October—at most—because the soils are relatively dry (**Table 4.9**, column 3). Ultimately, the degree of change in flooding will likely be dependent on the timing of projected increases in spring rainfall when soils tend to be saturated. If it entails moderate amounts of rainfall on more days, streamflows will be higher more often but will not necessarily reach new maxima. If, however, the number of spring rainfall events remains the same but their maximum potential size increases, flood magnitudes could increase. Such an increase could be partially offset by a lengthened growing season that narrows the window in which a large storm event on wet soils could occur. In brief, given the number of interacting factors, it remains uncertain whether the magnitude of annual maximum flows will increase with climate change. If it does, it would seem probable that wetter spring conditions would likely increase the number of moderate floods (10- to 25-year return periods).

The largest floods of record (50- to 100-year return periods) in the three watersheds can be attributed to distinct hydrometeorological conditions. In the

	% Annual Maximum Discharge Events Occurring When:		
Watershed	2-day annual max rainfall	3-day annual max snowmelt	May to October
Ten Mile River	15	10	14
Fall Creek	20	20	5
Poultney River	17	9	10

Table 4.9 Causative conditions of annual maximum discharges on three watersheds representative of conditions in New York State

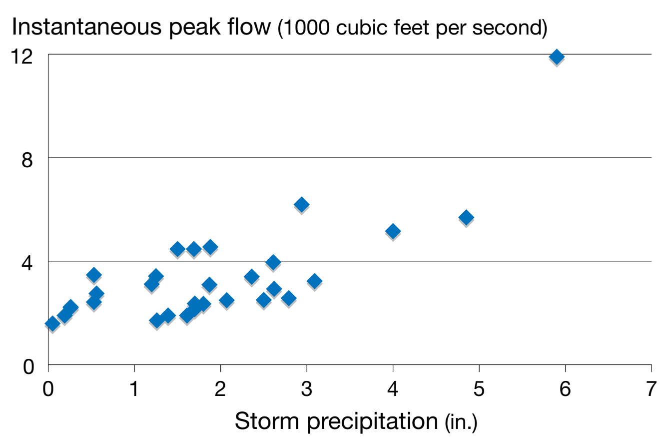

Figure 4.11 Storm rainfall amount and resulting instantaneous peak discharge on Fall Creek, Tompkins County, for the annual peak discharges from 1974 to 2007

Poultney River watershed—the watershed expected to have the most snow—the largest flood (7,010 cubic feet per second) was caused by a combination of snowmelt and rain on presumably still frozen soils (snow remains at the end of the flood event). Surprisingly, this is one of only five annual maximum discharges with rain on snow in this watershed. In Fall Creek, the largest discharge (7,060 cubic feet per second) was caused by a 5.9-inch rainfall event during a month with unusually wet antecedent conditions. In the Ten Mile River watershed, the two largest maximum discharges were associated with a hurricane (10,700 cubic feet per second) and several consecutive days of rainfall (9,930 cubic feet per second). In all these cases, the large flow events were caused by relatively rare conditions. The historical record is too short to observe a trend in the occurrence of these conditions, and projecting future trends is currently beyond the skill of coarse-scale climate models. Additional research is needed to determine the change in probability of these large floods.

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1 The salt front is not a sharp division between freshwater and ocean water; rather it is the point at which chloride concentration exceeds 100 mg/L. This concentration has been selected to minimize the negative impacts of high salt intake on human health, but it is far lower than a level where it would be entirely unfit to drink for temporary periods (ocean water is 200 times saltier). In extenuating circumstances, withdrawing water even if the salt front had moved upriver beyond the Poughkeepsie intake could still be done with minimal short-term consequences.

2 The vulnerability of reservoirs to drought was assessed by dividing storage volume by daily demand, and a similar analysis can be accomplished for aquifers by comparing subsurface storage to daily demand. Demand data were determined from the annual water quality reports mandated by the Safe Drinking Water Act. Days of supply with no recharge may be exaggerated because water will not be perfectly redistributed to well fields and the area around a well field may experience localized depletion. Since only the surface area of an aquifer is typically given, stored water is determined by assuming 30 percent of aquifer volume consists of recoverable water and by taking an average aquifer thickness (typically ~40 feet).

3 This assessment of wells includes the following: A 16-foot-deep sand and gravel well in Madison County (M-178 Valley Mills) had its water level drop to 11 feet below the surface in the summer of 1999, the lowest point reached in its 27-year history. A 31-foot well in sand and gravel in Oneida County (Oe-151 Woodgate) dropped to 30 feet below ground surface in late 2002, the lowest point in its 18-year history; if subject to pumping, it is presumed that this well would probably have run dry. A 79-foot sand and gravel well (Re-703 East Greenbush) dropped to 42 feet below ground surface in 1986, the lowest point in its 18-year history. A 126-foot bedrock well (364TRNN) (Du-321 Hyde Park) dropped to 72.5 feet below land surface in late 1981, the lowest point in its 24-year history.

4 Table 4.8 was constructed by comparing 2000 census block data to areas of inundation to determine the vulnerability of certain populations to flooding, specifically renters, seniors, and non-white populations. Demographic data were weighted by the area of the block that was inundated in 2006. The results provide some measure of the human profile of flooding and highlight the presence of a few populations with potential vulnerabilities.