Climate Change Effects on Forests, Water Resources, and Communities of the Delaware River Basin

Will Price

Director of Conservation Programs, Pinchot Institute for Conservation, Washington, DC

Susan Beecher

Research Fellow, Pinchot Institute for Conservation, Washington, DC

Abstract: *The Delaware River provides drinking water to 5 percent of the United States, or approximately 16.2 million people living in 4 states, 42 counties, and over 800 municipalities. The more than 1.5 billion gallons withdrawn or diverted daily for drinking water is delivered by more than 140 purveyors, yet constitutes less than 20 percent of the average daily withdrawals. Approximately 64 percent of the water withdrawal is used for thermoelectric cooling, a primarily non-consumptive use. The main stem of the Delaware River is free-flowing, such that permitted water withdrawal and discharge depends on weather-related flow conditions. Low flows can limit power generation based on in-stream temperature limits, and can also result in the salt line reaching water intakes in the 133 mile tidally-influenced portion of the river. High flows can damage facilities and cause exceedance of drinking water standards. Source water areas of the Delaware River Basin (DRB) are primarily forested (>75 percent), accounting for the relatively high existing water quality, and contributing to attenuation and reduction of flows. These areas are predominantly in private ownership, and in recent years have been among the areas of the Basin experiencing the fastest population growth. Development of private lands and associated changes in forest cover, impervious surface and floodplain encroachment are of concern. Modeled climate-related changes in timing, type, and intensity of precipitation are also concerns. The diversity in types of water use within the DRB corresponds with a variety of types of risk imposed by changes in climate and land cover. Common Waters, a partnership of close to fifty organizations is piloting strategies to avoid and adapt to changes affecting forests and water resources that are predicted to occur with climate change. This paper discusses predicted climate changes for the Delaware River Basin and what they imply for the importance of forests and water resources, and presents two case studies: a source water protection program for landowners and a climate adaptation plan for the Upper Delaware River Basin. These efforts in the Delaware River Basin could be models for watersheds with highly diverse types of use and complex regulatory systems.*

INTRODUCTION

The mainstem Delaware is the longest undammed river east of the Mississippi, flowing freely for 330 miles from southern New York (2,362 square miles or 18.5 percent of the basin's total land area), through eastern Pennsylvania (6,422 square miles or 50.3 percent), New Jersey (2,969 square miles, or 23.3 percent), and Delaware (1,004 square miles, or 7.9 percent) to the Atlantic Ocean. The Delaware River's 13,539 square mile watershed drains only about 0.4 percent percent of the United States land area yet supplies drinking water to 5 percent of the U.S. population—some 16 million people in four states. The Basin also supports the largest freshwater port in the world within the 782 square mile Delaware Bay. Three reaches of the Delaware River, about three-quarters of the non-tidal River, are included in the National Wild and Scenic Rivers System (Kauffman 2011).

In 2010, over 8.2 million residents lived in the basin including 654,000 people in Delaware, 2,300 in Maryland, 1,964,000 in New Jersey, 131,000 in New York, and 5,469,000 in Pennsylvania. An additional 8 million people in New York City and northern New Jersey receive their drinking water through interbasin transfers from Upper Delaware River reservoirs. Between 2000 and 2010, the population in the Delaware Basin increased by 6.1 percent. Over the last decade, a number of counties in the basin showed double-digit population increases and Philadelphia gained population for the first time in centuries (Kauffman 2011).

WATER USE AND MANAGEMENT IN THE DELAWARE RIVER BASIN

In the Delaware River Basin, as in many river systems around the world, water is put to an astounding number of uses. In some ways the mainstem Delaware River is unique for its size in that it is the longest free-flowing river east of the Mississippi. Flows from upper tributaries are partially controlled by dams, holding back 238 billion gallons in two reservoirs supplying the city of New York, for an average daily detention and diversion of 665 million gallons. The remaining 90 percent (land area) of the watershed downstream of the NYC reservoirs is controlled by the weather, and serves the needs of another 7 million people.

Approximately 64 percent of the 8.6 billion gallons withdrawn daily from the Delaware River is used for thermoelectric cooling. Typically Less than 5 percent of cooling water is actually consumed; the rest is discharged back into the basin. Less than 20 percent is used for drinking water—an average approximately 665 million gallons allowed for diversions to the city of New York and New Jersey and the rest (860 million gallons per day) for residents throughout the region, many of whom live outside the basin's boundaries.

In recent years per capita water consumption has declined with increased efficiency in all sectors, and declining productivity associated with the economic downturn. Declines in water consumption are offset to some extent by increased deployment of closed-cycle cooling (CCC) for electricity generation. This type of cooling reduces total water withdrawn, but increases water consumption as more water is lost from closed cycle systems. Despite improved efficiency, a projected increase in population within the Delaware River Basin is predicted to result in a gradual increase in total water consumption for drinking water, industrial processes, and energy generation (DRBC 2012).

A recent study estimates the annual regional economic value of water supply at $25 billion (Kauffman 2011). Estimates in this study do not include the embodied water content and energy in and goods and services exported to the world from the New York, Philadelphia, and

Wilmington corridor—a region containing the 1st and 6th most populous metropolitan areas in the United States.

That the entire main stem of the river is free-flowing and is principally managed by the storage and release of water in the very upper reaches of the watershed, with implications for the annual water availability to New York, makes the system vulnerable to weather extremes. Periods of low flow can have several interrelated effects. Drought conditions became the first test of the federal compact between New York, New Jersey, Delaware, and Pennsylvania and resulted in a 1978 "Good Faith Agreement" developed and implemented by the Delaware River Basin Commission, and designed to protect aquatic life by maintaining minimum flows through reservoir releases (DRBC 2013; Albert 1987). Drought conditions and extended periods of low flow pose many other problems for water use in the basin, not the least of which is allocation for drinking water and energy generation. Energy generation—the largest category of water withdrawal—is limited by temperature requirements set for the river downstream of facilities. The Schyukill Restoration Fund in the Schyukill River watershed (a major river flowing into the Delaware River) was created through an agreement that also includes augmentation of "pass-by flows" for a nuclear generation station, which had at times exceeded temperature limits.

Perhaps one of the biggest problems posed by low flows is the upstream movement of the "salt-line." The Delaware River has the largest freshwater tidal prism in the world, as the Delaware Bay's depth and "cone-shaped geometry" allows for more than 100 miles of tidal exchange upriver. Freshwater flows normally impede tidal advance. However, low flows can allow high chloride levels (>250 ppm) to reach drinking water and cooling intakes within the tidally influenced portion. Floods are also a concern in the Delaware River Basin, especially the potential for lower basin flooding resulting from a combination of coastal storm surge and floodwaters from upstream—a scenario that was narrowly missed during Hurricane Sandy in 2012, which still devastated lower portions of the basin. Prior serious flooding in 2004 and 2006 led to the development of a Flexible Flow Management Program (FFMP) which balances drinking water needs for New York and the rest of the basin, energy generation, ecological requirements, and upstream movement of the salt-line (Gong 2010).

Climate changes affecting water quality and quantity in the Delaware River Basin

Changing climatic conditions are already being felt in the Upper Delaware region. Both annual mean temperature and annual mean precipitation in the upper basin have increased significantly over the past 100 years. The trend over the past 30 years for temperature and precipitation is more than 3 and 5 times the 100-year trend, respectively. The number of days per year with heavy precipitation shows a significant upward trend. Future projections generally show the basin getting progressively warmer and wetter throughout the 21st century (Najjar and others 2012). Higher average temperatures, increased magnitude and frequency of heavy precipitation events, a longer growing season, warmer winters with more precipitation falling as rain, and changing hydrologic conditions all put multiple sectors at risk, including forests, water resources, agriculture and human health.

Information on how these projected trends could affect *water quality* and *quantity* of the Delaware River is only beginning to emerge as global climate change models are downscaled to the region, and interpreted for the watershed. As described above global models predict that the region encompassing the DRB will experience more precipitation, and greater variability and intensity of events (Najjar and others 2012; McCabe and Ayers 1989). The magnitude of changes in streamflow is less clear. Milly and others (2005) have modeled the relative change in runoff over the next century under a number of scenarios, generating an "ensemble mean" of percentage increase in streamflow, which for portions of the northern Mid-Atlantic and New England constituting the DRB is projected to increase between 5 and 10 percent above 1900-1970 levels (Milly and others 2005). Considering storage capacity in the upper basin this alone may not be a problem were it predictable from season to season and year to year. However, increased unpredictability of seasonal storms and the difficulty of predicting the pathway of large single events can cause problems. Some models also suggest that the net increase could be accompanied by more severe droughts, earlier snowmelt, and more intense precipitation events in late fall through spring—an increase in droughts and floods (Najjar and others 2012). Similarly, the differences in projections for streamflow generated by the Hadley and CCC scenarios for the neighboring Susquehanna River Basin illustrate the challenges in understanding just how to prepare for climate change. Both show increasing and earlier streamflow in the late fall and early winter, but differ in their predictions for the spring (24 percent increase for Hadley, and 4 percent decrease for CCC) (Neff and others 2000).

Other model results more explicitly include the effect of increasing temperatures on forests, which shifts the story to some extent, and perhaps adds to the "dampening effect" that forests can have on floods. Huntington (2003) shows that for 38 forested watersheds in the east, forests are an important determinant of predicted streamflow based on temperature-related changes in evapotranspiration (ET). For every 1°C increase in mean annual temperature (MAT), ET increased 2.85cm, suggesting that with a predicted 3°C increase in MAT over this century; the annual *reduction* in streamflow in a New England forested watershed could reach 11-13 percent (Huntington 2003). Their results are annual averages, reflecting longer growing seasons, less snowmelt during spring green-up, and other seasonal dynamics. In the Western United States vegetative water demand is also predicted to further decrease water availability (Westerling and others 2002).

A suite of water quality changes will also likely occur due to climate change, and will vary depending on conditions. Predicted increases in precipitation could expand stream networks and the volume of shallow subsurface flow in forested areas of the watershed, mobilizing more nutrients, and delivering them along with increased sediment to stream channels (Murdoch and others 2000). In urban and exurban areas the increase in volume would mean more non-point source pollutants. At the same time warming temperatures would increase microbial processing of nitrogen in forest soils, and accelerate metabolic processes in-stream, resulting in reduced nitrate loading in source water, and dilution and increased assimilative capacity of inputs from all sources (Murdoch and others 2000; Murdoch 1991). The other possibilities for potential water quality impacts are too numerous to describe, and many are speculative and depend on what happens in forests, along streams, and in developed parts of the watershed.

How modeled trends balance out in the DRB has not been determined. Longer growing seasons extending into later months with more rain could result in more, less, or similar amounts of runoff depending on the role of ET. Less forest cover would increase the runoff—the combined result of less ET and infiltration—increasing the possibility of flooding, especially during hurricane season. Warmer summers with less rain and increased vegetative water stress in upper portions of the basin surely seem a recipe for more severe droughts. Water quality will be tightly correlated with the flow regime—how, when, and where nutrients and sediments are delivered to the system. The magnitude of all of these changes is uncertain.

Calling these "….amplified water-related extremes," Kundewicz and others (2002) reviewed the causes of major floods and droughts around the world stating that ". . .Mechanisms of climate change and variability are intimately interwoven with more direct anthropogenic pressures." They go on to emphasize that global increases in the intensity of flood events are confounded, and often exacerbated, by changes that have already occurred in river basins.

Considering combined climatic and anthropogenic effects on forests

What happens to forests will influence how a changing climate affects water quality and quantity. Coined the "forest water controversy" scientists and politicians have debated how forests influence water quantity and quality since the emergence of hydrology and forestry as fields of study (Andriessen 2004). The debate is not entirely settled in that studies still reveal conditions in which different forest types, physiographic characteristics, and weather patterns produce unexpected outcomes. To some extent much of what has been learned in particular watersheds now changes, especially for watersheds managed on models using historical conditions.

Across the country changes in temperature and precipitation will variously affect forest ecosystems. For example, forests of the Southwestern United States are predicted to be increasingly subject to water stress due to decreases in precipitation, leading to extensive mortality and a wholesale change in vegetation types (Grant 2013; Westerling 2002). Increased drought is also expected in some parts of the U.S. Southeast—and similar to the West, introduces the possibility of changes in forest ecosystems that are driven by water stress (Sun and others 2008). In the DRB region the effect of longer growing seasons, warmer temperatures, and seasonal changes in precipitation must be considered along with concurrent anthropogenic forces that will also affect forest ecosystems. For example will streamside hemlocks that shade headwater streams throughout the basin be overcome by drought stress during the summer, and finally succumb to the forest pest hemlock wooly adelgid now undeterred by winter? How soon will more southern forest types come to dominate the landscape? What other changes and shifts in species may occur, and will the process take decades during which greater senescence and decay mobilizes more nutrients in the system (Murdoch and others 2007)? How will the inexorable loss and fragmentation of forests to development—and associated increases in impervious cover—exacerbate changes in water quality and quantity?

Along with climactic changes, forests of the DRB are being lost at a rate of 100 acres (40 ha) each week. Forests of the region were largely denuded for agricultural and industrial uses during the 1700s and 1800s, leading to extreme floods. With regrowth through the second half of the 20th century, small watersheds (HUC12) in the upper portions of the DRB were more than 75 percent forested in 2006, but this is predicted to change. There are also indicators of long-term forest unsustainability; forests are generally even-aged, maturing, dominated by larger, saw timber-sized trees, lacking in diversity, not fully stocked and predominantly privately owned by an aging demographic. Additional non-climate forest stressors include parcelization and fragmentation driven by population increases and changes in land ownership and land use. An array of diseases, insects and invasive species are present in forests throughout the region. Regeneration is negatively impacted by white-tailed deer populations and harvesting practices such as "high-grading" and diameter-limit cuts (PA DCNR 2010; NY DEC 2010; NJ DEP 2010).

Non-climate stressors on water resources include population growth and associated land use and impervious cover changes, competing demands for water and flow management practices that result in flow fluctuations, thermal stress to fish and other ecological impacts. Natural gas drilling, not currently a factor in the Upper Delaware region due to a moratorium on drilling while the Delaware River Basin Commission develops regulations to address potential risks, could become a stressor to both water quality and quantity in the near future.

As described by Kundewicz (2002), the effects of climate change are critically dependent on how anthropogenic pressures shape future conditions. In some cases, ongoing reductions in forest cover coupled with engineered storage (e.g., urbanized watersheds) may alleviate water scarcity in the face of increased droughtines. The tradeoff is that with fewer forests the quality of the water declines, timing is more episodic, and flows are more responsive to precipitation events. In other settings (e.g., moist temperate forests of the Pacific Northwest) forest loss would reduce fog interception by trees, which can account for up to 30 percent of the annual water budget (Harr 1982). For regions in which climate change poses risks related to the increasing intensity and frequency of storms, it is conceivable that the dampening effect provided by increased infiltration in forests soils and ET later into wet seasons are perhaps one of the greatest services of forests can offer. Forests in the Delaware River basin, as in many temperate systems, are the top consumptive use of water in the basin (Sloto and Buxton 2005), and therefore a major factor in managing flows. The impact of climate change on the Delaware River Basin's forests will regulate the change in evapotranspiration and rates of infiltration, and as a consequence the severity of floods and droughts.

Managing watersheds in the face of climate change

To date there has been no attempt to assess the combined influence of forest loss, ecosystem change, and climate change on water resources in the DRB. More troubling is that models developed for managing water allocation, determining permitted uses, and understanding flood probability have not yet accounted for significant land use and climate change effects. Additionally, most studies of climate change and water availability have not taken into account the effects of competition, response and adaptation to changes, factors which are critical in a basin like the DRB with its numerous and diverse forms of use. Hurd and others (2004) used Water Allocation and Impact Models (Water-AIM) to "simulate the effects of modeled runoff changes under various climate scenarios." Their models allow for analysis of changes in pricing, patterns of water use, and reservoir storage and associated economic welfare, based on changes in supply driven by different climate change scenarios. Overall, their modeling predicts that negative economic impacts are mostly borne by non-consumptive water uses that are dependent on instream flow (e.g., thermoelectric) and agricultural users. For the Delaware River Basin these types of uses would also include ski areas, golf courses, and other amenities that are critical to the economy of more rural portions of the basin.

Given the certainty of changes in climate and forest cover, but the uncertainty of the magnitude of the difference this will make for water quality and quantity, a pre-cautionary and conservative approach is perhaps the best watershed management strategy. Such a strategy should include conservation of forests that based on available data are most important for preserving water quality and affecting flows. A pre-cautionary approach should also include climate adaptation planning that promotes conservation of forests and ecosystem resiliency, while preparing communities that will be affected by changes in quality and quantity of water resources. Two cases studies illustrate efforts in the DRB to pursue these two strategies. One, the Common Waters Fund, seeks to engage downstream water users in the protection and maintenance of forests that are most important for water quality and regulating flows, before they are lost or degraded. Another case study is the development of a climate adaptation plan for the upper basin region, which provides a roadmap for taking multiple actions that reduce the impacts and vulnerability of upstream and downstream communities and the forests and the river on which they depend.

CASE STUDY ONE: THE COMMON WATERS FUND

The Common Waters Fund (CWF) is one of more than 70 source water protection funds or payment programs established around the country to maintain the quality and quantity of water resources on behalf of downstream beneficiaries (Bennett and others 2013). The programs differ by origin and structure, many of which were launched by cities such as New York, Denver, and Seattle—all of which are investing in forest conservation. For example the New York City program, which also involves the DRB, emerged as an alternative to installation of additional filtration capacity by instead investing in forestland acquisition, easements and *stewardship*—or the development and implementation of conservation-minded forest management plans (Pires 2004). Few of the models around the country have attempted to create a water fund/program in which the upstream protection priorities are predominately privately-owned and span multiple political jurisdictions (i.e., states, counties, and municipalities). Fewer still have attempted to engage as many different kinds of downstream beneficiaries. However, many of the large watersheds of the eastern United States face similar challenges.

CWF was developed by public agencies, conservation groups, and individuals that had formed a partnership called "Common Waters," with the support of private foundations, the U.S. Department of Agriculture (USDA) Forest Service, USDA Natural Resource Conservation Service (NRCS), and the U.S. National Park Service. As a pilot the CWF initiative seeks to protect source water through investments by downstream users (e.g., water purveyors, electricity generators, and water-intensive manufacturing) to manage future water resource risks. As an alternative, investments could also be mobilized through policies enacted on behalf of all stakeholders. The CWF demonstrates approaches that can help meet the challenge of managing risks and protecting water resources at the watershed scale: (1) developing an integrated program with the buy-in and capacity to work across a large geography with multiple political jurisdictions; (2) incorporating all readily available peer-reviewed scientific information to set consensus watershed protection priorities; (3) engaging a diversity of water users who share a common resource.

The partnership that created the CWF formed as a collaborative for sharing information and pursuing joint initiatives that would help protect the Delaware River and forests of the region, which are considered essential to the economy and quality of life for a three million acre area encompassing portions of New Jersey, New York, and Pennsylvania. It was modeled after the *Chicago Wilderness*, and eventually developed a formal mission and voluntary self-governance structure that permitted the active engagement of a broad spectrum of interests (Helford 2000). Members included public land management agencies at the state and federal level, whose participation in the development in the CWF program for landowners helped ensure it would meet federal and state requirements (i.e., state stewardship and tax incentive programs for NJ, NY, and PA; and participation requirements for the USDA NRCS Environmental Quality Incentives Program). Meeting these requirements meant that watershed protection projects involving stewardship planning and conservation practices could be implemented anywhere in the watershed, and would be familiar to partners working with landowners. Members also included land trusts engaged in working with landowners on the donation and sale of conservation easements. These organizations helped design CWF program requirements for permanent protection projects in priority areas, for which CWF paid transaction expenses. The collective capacity and expertise represented by the partnership was essential to the pace and scale of implementation of CWF, which at the end of the pilot period had enrolled approximately 50,000 acres (20,200 ha).

A pre-cautionary approach implies that areas most important for maintenance of water quality and quantity are protected using the best information and means possible. For the CWF, this meant: (a) offering protection options amenable to private landowners at the time of enrollment (e.g. permanent easements, ten-year watershed stewardship plans, and/or conservation practices), and (b) establishing priorities throughout the upper portion of the DRB based on the best available peer-reviewed science. Priorities were established by creating water resource *priority tiers* (0 to 4) that combined several datasets developed by Common Waters partners. These included the Natural Land Trust's *SmartConservation™* dataset (Cheetham and others 2003); The Nature Conservancy's *priority conservation blocks*; the USDA Forest Service's *Index of Forest Importance to Surface Drinking Water* (Weidner and Todd 2011); and datasets associated with the *Delaware River Basin Conservation Areas and Recommended Strategies report* (2012). In some cases CWF represented the first attempt to use these priorities for land protection. The use of combined datasets not only ensured that the highest priorities were targeted, but that there was broader agreement that CWF projects addressed goals held by participating organizations.

Concurrent with creating the CWF program and initial investment in protection projects, Common Waters engaged different types of water users, mostly located in the lower portion of the basin where the majority of the electricity and drinking water demand is located. Delaware River surface water is delivered to more than 16 million people by more than 100 water purveyors, whose water withdrawal is regulated by the Delaware River Basin Commission (DRBC). As described above, more than one-half (65 percent) of the average daily withdrawal (8,650MGD) is non-consumptive use for cooling in energy generation—whose withdrawal and discharge is also regulated by the DRBC. Drinking water purveyors include public (municipal) utilities, and publicly and privately-held corporations. Electricity generators are mainly publicly-held corporations. There are also major beverage producers and bottling facilities, pharmaceutical companies, and manufacturers with headquarters and/or facilities located in the DRB. All are dependent on DRB surface waters, or in some way face risks posed by changes in quality, floods, and droughts. Of these different kinds of water users Common Waters met with the largest consumptive users and representatives of each kind of use/industry, for a total of 26 organizations. The purpose of the meetings was to learn how users perceive their own business risks related to water resources, assess readiness to consider investing in source water protection, and determine the information that would be necessary to justify investments. As of 2013, two companies have made some investment in CWF, in support of science activities that would help better predict and assign economic value to changes in the water quality and water quantity. Better information linking climate change and forest loss with hydrology and chemical quality will be essential for identifying and valuing the proportional benefits of source water protection in the DRB.

CASE STUDY TWO—CLIMATE ADAPTATION STRATEGIES FOR THE UPPER DELAWARE RIVER BASIN

Common Waters joined with the Model Forest Policy Program (http://www.mfpp.org/) and a network of rural forested communities working collaboratively across the nation to develop a climate adaptation plan specific to the tri-state Upper Delaware region. The plan examines how environmental changes associated with climate could affect forests, waters, people and economies of the region, and recommends strategies for adapting to these changes. The planning area included portions of Monroe, Pike, and Wayne counties in Pennsylvania; Sussex and Warren counties in New Jersey; and Delaware and Sullivan counties in New York (Beecher 2013).

To assess the potential impacts of climate change on the Upper Delaware Region and identify strategies by which communities might adapt and prepare, the planning group conducted an assessment and risk analysis for each sector—forests, water resources and economics. A master list of current and potential climate risks was developed and consequences associated with those risks were ranked. The probability of each risk occurring and the ability of communities to respond were also part of the overall risk value assigned.

The broad goals identified to address key risks are summarized below.

Education

Generating dialogue and information exchange about climate risks was identified as a top priority for the Upper Delaware region—both to reduce risks and build support for implementing solutions. While many of the region's residents have a general understanding of climate change as a future global problem, they might not make the connection with impacts happening in their communities now or, if they do, don't know what can be done about it. Raising the awareness level about climate risks in the region will have the added benefit of building understanding about what it will take to reduce greenhouse gas emissions (mitigation). This is important since the ability to adapt will likely be limited if the pace of climate change continues on its present course.

Local Government Policy and Planning

In considering the findings of the risk assessments, analysis and prioritization, it is clear that risks to the region could be reduced significantly through implementing land use policies that maintain existing forest cover, reduce forest fragmentation, maintain impervious cover at reasonable levels (e.g., < 10 percent), and take full advantage of the ecosystem services provided by floodplains and riparian corridors. Local governments have primary responsibility for the land use decisions that can ultimately make communities less vulnerable and more economically resilient to environmental changes. Although it is a challenge to coordinate land use policy in a region that includes three states, seven counties and hundreds of municipalities, it has great potential for far-reaching climate resiliency benefits.

Local governments also have responsibility for the health, safety and welfare of the people in their communities and for managing the impacts associated with flooding and heavy precipitation, extreme heat and drought and the municipal budgets that fund emergency response. To prepare for these changes, local governments can develop floodplain management policies that reduce flood risks and the substantial costs of emergency response, infrastructure damages and property losses. Local governments can also incorporate what they know about climate change into updates of emergency plans, hazard mitigation plans, transportation plans, stormwater management plans, comprehensive plans and other local planning efforts. Culvert sizing and bridge design standards should be examined and updated to account for changing precipitation patterns. Funding mechanisms should be identified to address the backlog of high hazard dam maintenance and repairs as these structures are vulnerable to increases in precipitation intensity and present a safety threat to downstream people and properties.

Forest Landowner Support

Management practices that improve the health and diversity of forests in the region are important to reducing forest and water stressors. With so many of the forests in the Upper Delaware region under private ownership, landowners and the professional foresters that work with them are essential to enhancing forest resilience during an expected long period of climate change. Land trusts and a network of hunting and fishing clubs are also key partners in forest health initiatives, such as managing insects and invasive plants or supporting science-based deer population management that balances populations with sustainable forests and quality timber management. Collaborating with these groups and identifying funding to support management practice implementation are key strategies. Tax assessment policies that incorporate the value of ecosystem services provided by forest lands are another important tool to help landowners keep forests as forests.

Financial Investment

Forests in the Upper Delaware River watershed are essential to maintaining the extraordinary water quality of the Delaware River. Forests that keep water clean for the residents of the New York City metropolitan area, who draw their water directly from reservoirs in the headwaters, are maintained by the NYC Department of Environmental Protection, a public, tax-dollar funded authority. But the millions of people who live downstream and also depend on Delaware River water (Philadelphia, Easton, Trenton) have no such centralized oversight of the forests on which their water quality depends. The Common Waters Fund discussed above aims to fill this gap, by funding stewardship and conservation by the private forest landowners in the Upper Delaware region on whose forests the water quality of all downstream users depends. A permanent funding stream would include contributions from downstream users who enjoy the extraordinary water quality of the Delaware River and are willing to invest in its protection.

Support and Mitigate Impacts to Businesses

Strategies that address climate change by conserving forest and water resources are also crucial to the region's economic vitality, quality of life, and natural and cultural heritage. Sustainable development does not represent a trade-off between business and the environment but rather an opportunity to strengthen the synergies between them. The Plan recognizes the significant economic importance to the region of entrepreneurism, agriculture, tourism and outdoor recreation and the risks to these sectors, and to small businesses in general, of climate-driven extreme weather, hydrologic changes and seasonal disruptions. Strategies that help manage impacts while identifying and capitalizing on new economic opportunities presented by a changing climate will be important to businesses in the region now and in the future.

Flow Management

There are many entities vying for Upper Delaware region water resources and few regional stakeholders directly involved in decisions about how that water gets allocated and managed. Given the hydrologic changes associated with increasing temperatures and the finite storage capacity in upper basin reservoirs, it is essential that flow management policies factor in climate change to ensure sufficient water quantity for both human and ecological needs.

There is much at risk with both non-climate and climate-related stressors, but the Upper Delaware region has the natural assets that can help reduce those risks: a high percentage of forest cover; private landowners with a stewardship ethic; clean water and healthy ecosystems; and institutional and organizational frameworks in place that could facilitate regional adaptation strategies. Translating the Climate Adaptation Plan to action represents an opportunity for the people and governing bodies of the region to prepare for a "new normal" set of environmental conditions while maintaining the health of the natural systems that sustain the quality of life and support the region's economic base.

CONCLUSION

Predicted changes in climate combined with anthropogenic pressures have implications for forests, water resources and regional economies in the Delaware River Basin. Common Waters partnership has piloted approaches to avoid and adapt to these changes. The two case studies presented here—a source water protection program for landowners and a climate adaptation plan for the Upper Delaware River Basin—represent strategies that could be models for watersheds elsewhere with highly diverse types of use and complex regulatory systems.

REFERENCES

Albert, R.C. 1987. Damming the Delaware: The Rise and Fall of Tocks Island Dam. 2nd ed.

University Park, PA: Pennsylvania State. University Press.

Andreassian, V. 2004. Water and forests: from historical controversy to scientific debate. Journal of Hydrology. 291: 1-27.

Beecher, S.; Thaler, T.; Griffith, G. [and others]. eds. 2013. Adapting to a Changing Climate: Risks & Opportunities for the Upper Delaware River Region. Model Forest Policy Program in association with Common Waters Partnership, Pinchot Institute for Conservation the Cumberland River Compact and Headwaters Economics; Sagle, ID (in progress).

Bennett, G.; Carroll, N.; Hamilton, K. 2013. Charting New Waters: State of Watershed Payments 2012. Forest Trends. Washington, DC.

Bogardi, J.J.; Kundzewicz, Z.W., eds. 2002. Risk, reliability, uncertainty, and robustness of water resource systems. Cambridge, UK: Cambridge University Press.

Burns, D.A.; Klaus, J.; McHale, M.R. 2007. Recent climate trends and implications for water resources in the Catskill Mountain region, New York, USA. Journal of Hydrology. 336(1): 155-170.

Cheetham, R.; Billett, C.; Natural Lands Trust. 2003. SmartConservation™: Automating a Conservation Value Assessment Model.

Copeland, J.H.; Pielke, R.A.; Kittel, T.G.F. 1996. Potential climatic impacts of vegetation change: A regional modeling study. Journal of Geophysical Research: Atmospheres. 101.D3: 7409-7418.

Croke, J.C.; Hairsine, P.B. 2006. Sediment delivery in managed forests: a review. Environmental Reviews 14.1: 59-87.

Delaware River Basin Conservation Areas and Recommended Strategies. 2011. Final Report for the National Fish and Wildlife Foundation. Submitted by The Nature Conservancy, Partnership for the Delaware Estuary, and the Natural Lands Trust. September 2011.

Frederick, K.D.; Major, D.C. 1997. Climate change and water resources. Climatic Change. 37(1): 7-23.

Foley, J.A.; DeFries, R.; Asner, G.P. 2005. Global consequences of land use. Science. 309 (5734): 570-574.

Gong, G.; Wang, L.; Condon, L. [and others]. A simple framework for incorporating seasonal streamflow forecasts into existing water resource management practices. Journal of the American Water Resources Association. 46(3): 574-585.

Grant, G.E.; Tague, C.L.; Allen, C.D. 2013. Watering the forest for the trees: new priorities for managing water on forest landscapes. Frontiers in Ecology and Environment.11(6): 314-321.

Harr, R. D. 1982. Fog drip in the Bull Run municipal watershed, Oregon. Water Resources Bulletin. 18(5): 785-789.

Helford, R.M. 2000. Constructing nature as constructing science: expertise, activist science, and public conflict in the Chicago wilderness. Restoring Nature: Perspectives from the Social Sciences and Humanities. Washington DC: Island Press.

Huntington, T.G.; Richardson, A.D.; McGuire, K.J.; Hayhoe, K. 2009. Climate and hydrological changes in the northeastern United States: recent trends and implications for forested and aquatic ecosystems. Canadian Journal of Forest Research. 39(2): 199-212.

Huntington, T.G. 2003. Climate warming could reduce runoff significantly in New England, USA. Agricultural and Forest Meteorology. 117(3): 193-201.

Hurd, B.H.; Callaway, M.; Smith, J.; Kirshen, P. 2004. Climatic Change and US Water Resources: From Modeled Watershed Impacts to National Estimates. Journal of the American Water Resources Association 40(1): 129-148.

Iverson, L.R.; Prasad, A.M. 1998. Predicting abundance of 80 tree species following climate change in the eastern United States. Ecological Monographs. 68(4): 465-485.

Kauffman, G.J. 2011. Socioeconomic Value of the Delaware River Basin in Delaware, New Jersey, New York, and Pennsylvania: The Delaware River Basin, an economic engine for over 400 years. Newark, DE: University of Delaware.

Kundzewicz, Z.W.; Budhakooncharoen, S.; Bronstert, A. [and others]. 2002. Coping with variability and change: floods and droughts. Natural Resources Forum. 26(4): 263-274.

McCabe, G.J.; Ayers, M.A. 1989. Hydrologic Effects of Climate Change in the Delaware River Basin. Journal of the American Water Resources Association. 25(6): 1231-1242.

McKenney-Easterling, M.; DeWalle, D.R.; Iverson, L.R. [and others]. 2000. The potential impacts of climate change and variability on forests and forestry in the Mid-Atlantic Region. Climate Research 14(3): 195-206.

Milly, P.C.D.; Dunne, K.A.; Vecchia, A.V. 2005. Global pattern of trends instream flow and water availability in a changing climate. Nature. 438(7066): 347-350.

Murdoch, P.S.; Bonitz, C.L.; Eakin, K.W. [and others]. 1991. Episodic acidification and associated fish and aquatic invertebrate responses in four Catskill Mountain streams: An interim report of the Episodic Response Project. U.S. Geological Survey, Albany, N.Y.

Murdoch, P.S.; Baron, J.S.; Miller, T.L. 2000. Potential Effects of Climate Change on Surface Water Quality in North America. Journal of the American Water Resources Association. 36(2): 347-366.

Murdoch, W.; Polasky, S.; Wilson, K.A. [and others]. 2007. Maximizing return on investment in conservation. Biological Conservation. 139: 375-388.

Najjar, R.; Ross, A.; Kreeger, D.; Kilham, S. 2012. Climate Change in the Technical Report for the Delaware Estuary & Basin. PDE Report No. 12-01. 225-241.

Neff, R.; Chang, H.; Knight, C.G. 2000. Impact of climate variation and change on Mid-Atlantic Region hydrology and water resources. Climate Research. 14(3): 207-218.

New Jersey Department of Environmental Protection. 2010. Statewide Forest Resource Assessment and Resource Strategies. 6 Aug. 2010.

New York State Department of Environmental Conservation. 2010. Forest Resource Assessment & Strategy 2010-2015: Keeping New York's Forests as Forests.

Pires, M. 2004. Watershed protection for a world city: the case of New York. Land Use Policy. 21(2): 161-175.

Pennsylvania Department of Conservation and Natural Resources, Bureau of Forestry. 2010. Pennsylvania Statewide Forest Resource Assessment.

Sloto, R.A.; Buxton, D.E. 2005. Water budgets for selected watersheds in the Delaware River Basin, eastern Pennsylvania and western New Jersey: U.S. Geological Survey Scientific Investigations Report 2005-5113. 37 p.

Sun, G.; McNulty, S.; Moore Myers, J.; Cohen, E. 2008. Impacts of multiple stresses on water demand and supply across the southeastern United States. Journal of the American Water Resources Association. 44: 1441-1457.

Stanton, T.; Echavarria, M.; Hamilton, K.; Ott, C. 2010. State of Watershed Payments: An Emerging Marketplace. Ecosystem Marketplace.

Available online: http://www.forest-trends.org/documents/files/doc_2438.pdf

Veblen, T.T.; Kitzberger, T.; Donnegan, J. 2000. Climatic and human influences on fire regimes in ponderosa pine forests in the Colorado Front Range. Ecological Applications. 10(4): 1178-1195.

Weidner, E.; Todd, A. 2011. From the Forest to the Faucet: Drinking Water and Forests in the US. Methods Paper. Ecosystem Services & Markets Program Area. State and Private Forestry, USFS.

Westerling, A.L.; Hidalgo, H.G.; Cayan, D.R. [and others]. 2006. Warming and earlier spring increase western US forest wildfire activity. Science. 313(5789): 940-943.

Wood, A.W.; Maurer, E.P.; Kumar, A.; Lettenmaier, D. 2002. Long-range experimental hydrologic forecasting for the eastern United States. Journal of Geophysical Research: Atmospheres. 107.D20 (2002): 4429.

This paper received peer technical review. The content of the paper reflects the views of the authors, who are responsible for the facts and accuracy of the information herein.