Connecticut River Flow Restoration Study

STUDY REPORT

A watershed-scale assessment of the potential for flow restoration through dam re-operation

THE NATURE CONSERVANCY, U.S. ARMY CORPS OF ENGINEERS,
UNIVERSITY OF MASSACHUSETTS AMHERST

The Nature Conservancy
Protecting nature. Preserving life.

UMass Amherst

US Army Corps of Engineers®

The Connecticut River Flow Restoration Study

A watershed-scale assessment of the potential for flow restoration through dam re-operation

Katie Kennedy, The Nature Conservancy
Kim Lutz, The Nature Conservancy
Christopher Hatfield, U.S. Army Corps of Engineers
Leanna Martin, U.S. Army Corps of Engineers
Townsend Barker, U.S. Army Corps of Engineers
Richard Palmer, University of Massachusetts Amherst
Luke Detwiler, University of Massachusetts Amherst
Jocelyn Anleitner, University of Massachusetts Amherst
John Hickey, U.S. Army Corps of Engineers

Kennedy, K., K. Lutz, C. Hatfield, L. Martin, T. Barker, R. Palmer, L. Detwiler, J. Anleitner, J. Hickey. 2018. The Connecticut River Flow Restoration Study: A watershed-scale assessment of the potential for flow restoration through dam re-operation. The Nature Conservancy, U.S. Army Corps of Engineers, and University of Massachusetts Amherst. Northampton, MA. Available: http://nature.org/ctriverwatershed

For a quick, easy-to-read overview of the Connecticut River Watershed Study, see our companion "Study Overview" document, available at: http://nature.org/ctriverwatershed

June 2018

Table of Contents

List of Appendices

List of Figures and Tables

FIGURES

TABLES

Executive Summary

More than 3,000 dams are present on the rivers and streams of the Connecticut River watershed. The ecological impacts of dams are widely documented and include blocking fish migration routes, severing connections between habitats and populations, changing water temperatures, and altering flow regimes. The flow regime is a primary driver of river ecosystem function; alterations to the flow regime can result in interrupted life history cycles, reduced habitat, and diminished nutrient availability, with consequent effects on natural community structure. Flow regime restoration through modification of dam operations can be a viable and important component of river restoration efforts. The Connecticut River Flow Restoration Study was established to examine the feasibility of re-operating the largest dams in the watershed for the benefit of ecological health and function while also maintaining the important services provided by these dams, such as flood risk management, hydropower generation, water supply, and recreation.

To evaluate current operations and develop operational alternatives, three model frameworks were used. The Connecticut River Unimpaired Streamflow Estimator (CRUISE) is a model developed by the U.S. Geological Survey to estimate unimpaired streamflow at any perennial stream location within the watershed. The U.S. Army Corps of Engineers (USACE) Hydrologic Engineering Center's Reservoir Simulation Model (HEC-ResSim) is a rule-based operations model that was used to simulate the operations of 73 major reservoirs throughout the watershed. The Connecticut River Optimization Modeling Environment (CROME) is a goal-based linear programming optimization model developed by the University of Massachusetts Amherst. The CROME model searches all potentially optimal combinations of flow release strategies among 54 dams in the watershed to find the one that best matches a desired system state given an objective function, such as provision of prescribed streamflows, maintenance of reservoir storage targets, generation of revenue from hydroelectric production, or allowance of water for municipal supply. The objective function used to represent ecological value in the CROME model was related to minimizing the deviations between operational flow and estimated natural flow, given "acceptable deviations" that were developed from expert-elicited ecological flow recommendations.

Simulated regulated flows were compared to estimated natural flows by evaluating 67 ecologically-relevant flow statistics at 30 locations throughout the watershed. Results suggested that the primary impact to the flow regime across the watershed is a loss of high flow events, with large floods impacted at more locations than any other ecologically-relevant flow component. Based on the locations and distribution of impacts to high flows, results indicated that these impacts are largely attributable to flood risk management facilities. Results also demonstrated that low flows are widely-impacted across the watershed; impacts included reduced frequency of low flows and low flow magnitudes that were either lower or higher than estimated natural magnitudes. Model results indicated that impacts to low flow events are generally attributable to water supply, flood risk management, and hydropower storage facilities. Lastly, although the impacts analysis focused exclusively on the daily hydrograph, some results also indicated potential for sub-daily flow impacts due to hydropower operations.

Development of operational alternatives began with a focus on the coordinated operations of 14 USACE dams to meet flood risk management and ecological flow objectives. However, results suggested that ecological benefit could not be achieved without a potential increase in flood risk or in flow alteration. Results also indicated opportunity for ecological gain through independent tributary management; further analyses therefore focused on operational alternatives in four tributary basins: the Ashuelot, Farmington, West, and Westfield rivers. To determine the degree of improvement to the natural hydrology in each watershed, the resulting hydrology of each alternative was compared to estimated natural flows and current simulated flows using flow metrics that were identified as impacted during the impact analysis. Two primary alternatives were evaluated. The first simulated the elimination of "pinch points", specific locations downstream of flood risk management dams where rising flows first start to cause damages. Removing the pinch points from simulated operations resulted in some improvements to the flow regime on the Ashuelot River, with increases to the annual maxima in some years, but did not substantially improve natural flow metrics on the West, Westfield, or Farmington rivers. Another scenario utilized the results of the optimization model, where operations aimed to achieve a more natural hydrology while meeting flood risk management goals. This alternative resulted in minimal changes to operations, and thus no improvement to the evaluated flow metrics, in all four tributary systems. For the West and Ashuelot rivers, one additional scenario was evaluated for each system. For the Ashuelot River, a second optimized scenario evaluated the impact of the downstream city of Keene, New Hampshire on the flow regime. Under this scenario, substantial benefits were demonstrated, such that the magnitude of small floods was restored, indicating the strong effect of the city of Keene on the natural flow regime in this tributary. For the West River, an optimized scenario evaluated the removal of a 25-foot pool rule that provided adequate flows for downstream salmon smolt passage. This scenario also resulted in some improvement to the flow regime, specifically with regard to low flows.

The model of estimated natural flows and the model of current operations at 73 dams in the watershed proved useful for evaluating the potential for flow restoration through dam re-operation in the Connecticut River watershed by demonstrating 1) where the greatest impacts to hydrology were estimated to occur, and 2) how potential management alternatives performed in terms of identified ecological flow parameters at these locations. However, because USACE dams are operated to pass all but the highest flows, and have limited to no permanent pools to provide flows when the river is not flooding, results suggest that there is little operational flexibility of these facilities given current operations and constraints. Effective flow management in the Connecticut River watershed may therefore require expanding the scope of management alternatives beyond dam re-operation to include additional creative alternatives such as bypass flows, structural changes to dams, sediment management actions, hydropower turbine installation, purchase of conservation and flood easements, and riparian and floodplain restoration. Since some of these alternatives may be associated with significant capital costs, we recommend the development of specific, measurable conservation objectives, and careful cost-benefit analyses to determine whether the benefits to restoring habitat and maintaining services for people are commensurate to the costs of large infrastructure or other high-investment alternatives.

Acknowledgements

We would like to express our gratitude to the many individuals who contributed their time and talents toward the completion of the Connecticut River Flow Restoration Study.

We especially thank Stacey Archfield of the U.S. Geological Survey, who developed the Connecticut River Unimpacted Streamflow Estimator (CRUISE) model, a critical component in the development, implementation, and results of this study.

Our thanks also go out to the faculty and students in the Civil and Environmental Engineering Department at the University of Massachusetts, Amherst. Faculty members Dr. David Ahlfeld and Dr. Casey Brown contributed to the formulation of the flow models and guided several students working on the Study. We are also grateful to the many graduated students who contributed to the optimization flow models that are central to this Study including Kelcy Adamec, Alec Bernstein, Kyle O'Neil, Brian Pita, Austin Polebitski, Scott Steinschneider, William Billa, and Sarah Whateley.

We also acknowledge the contribution of Rhonda Anderson and Adam Howes at the U.S. Army Corps of Engineers, New England District who developed the hydrologic simulation and hydraulic models used in the Study. Modelers at the U.S. Army Corps' Hydrologic Engineering Center were also instrumental in formulation of the Study, and testing the limits of the simulation modeling tools including Woodrow Fields, Leila Ostadrahimi, David Julien and Katherine Maher.

Our thanks also go out to the nearly 70 natural resource professionals from state agencies, academic institutions and private companies in New Hampshire, Vermont, Massachusetts and Connecticut who attended workshops and provided guidance on incorporating ecological values into the optimization model.

We are grateful for the many individuals who provided their thoughtful and substantive comments on the Study report including Mary Freeman, Frank Magilligan, Christian Marks, Tara Moberg, Keith Nislow, LeRoy Poff, Mark P. Smith, Kenneth Strzepek, Andrew Warner, and Julie Zimmerman.

Our thanks also go to Suki Casanave, who wrote the Study Overview, providing a easily read companion piece to the Study Report.

We would like to thank the Nature Conservancy volunteers Michelle Brooks, Amanda Smith, and Peter Severance, who contributed to development of maps, figures, and tables. Many thanks also to Kevin Ruddock who prepared the final maps for this publication.

Finally, we would like to acknowledge Bob Ackerman, and the Bingham and Eaglemere Foundations, who provided significant funding for critical aspects of this work.

1 | Introduction

The Connecticut River and its tributaries (Figure 1) have provided sustenance, transportation, and energy for the human and natural communities of New England for millennia. Over the past several centuries, as demands on the river increased, more than 3,000[1] dams were constructed throughout the watershed, making it one of the most dammed watersheds in North America (Dynesius and Nilsson 1994; Graf 1999). The majority of these dams are less than ten feet in height, and were built on tributaries to power small commercial and industrial facilities during the 18th and 19th centuries. Most of these small tributary dams no longer serve their original purpose (O'Connor et al. 2015), and as such, are the focus of concerted efforts to remove them[2].The remainder of the dams in the watershed continue to provide important services for people, such as flood risk management[3], hydropower generation, water supply, and recreation (Figure 2).

The impacts of dams on river ecosystems are widely documented; dams block fish migration routes, sever connections between habitats and populations, change water temperatures, reduce dissolved oxygen, disrupt sediment transport, and alter flow regimes (Bunn and Arthington 2002; Friedl and Wüest 2002; Magilligan and Nislow 2005; Graf 2006; Nilsson and Malm-Renöfält 2008). The flow regime is a primary driver of river ecosystem function, providing reproductive and dispersal cues for river-dependent species, defining habitat composition and availability, transferring nutrients longitudinally and laterally, and ultimately defining the natural community structure of rivers and their floodplains (Poff et al. 1997; Bunn and Arthington 2002; Naiman et al. 2008; Mims and Olden 2012; Rolls et al. 2012). Alterations to the flow regime impact these ecological functions, resulting in interrupted life history cycles, reduced habitat, and diminished food and nutrient availability, with consequent effects on the rates of reproduction, growth and survival of river-dependent species, and thus natural community structure (Poff et al. 1997, Bunn and Arthington 2002; Poff and Zimmerman 2010; Rolls et al. 2012; Mims and Olden 2013).

The most well-documented effects of dams in the Connecticut River watershed have been the blockage of migratory fish passage and consequent declines in abundance of species such as Atlantic salmon and American shad, which have been the focus of extensive research and conservation efforts (e.g., Gephard and McMenemy 2004; Castro-Santos and Letcher 2010; Brown et al. 2013). Empirical data describing the impacts of hydrologic alteration on river-dependent species and communities in the watershed are less common (Zimmerman 2006b). However, documentation of existing flow alteration throughout the basin, additional empirical studies from other systems, and observed declines in floodplain forest, riparian, and freshwater mussel communities, all provide support for hypotheses describing the ecological consequences of altered hydrology in the Connecticut River watershed (Zimmerman 2006b).

Effective watershed restoration strategies consider multiple stressors that influence and impair river function, including dam construction and operation, land use, point and non-point pollution, water withdrawals, and climate change. In the Connecticut River watershed, the density of dams, history of water management, and known and hypothesized effects of dams on river function support watershed restoration strategies that focus largely on dams and their impacts. Efforts to restore dam-impaired river function often employ dam removal, as this strategy immediately restores habitat and population connectivity, as well as the flow regime and its associated functions (Bednarek 2001; Vedachalam and Riha 2014). Although it may be an effective means to restore river function, dam removal is not always an appropriate near-term strategy, in particular for very large dams and those that currently provide important services for people, such as flood risk management, hydropower, water supply, and recreation. In these cases, flow regime restoration through modification of dam operations is a viable and important component of river restoration efforts.

1 The Northeast Aquatic Connectivity Assessment Tool (NEACAT; Martin and Apse 2011) includes 1,420 dams in the Connecticut River watershed. An additional 1,719 dams were not included in this analysis because they were outside of the project hydrography; that is, these additional dams were on smaller unmapped streams, farm ponds, etc. (E. Martin, TNC spatial analyst, personal communication).

2 The Nature Conservancy, American Rivers, Trout Unlimited, the Connecticut River Watershed Council, the U.S. Fish and Wildlife Service, and state natural resource agencies in Vermont, New Hampshire, Massachusetts, and Connecticut, are working together to prioritize dams and leverage funding to increase the rate of obsolete dam removal in the Connecticut River watershed.

3 Throughout this document the term "flood risk management" is used in place of "flood control" or "flood prevention" to reflect the current preferred terminology of the U.S. Army Corps of Engineers.

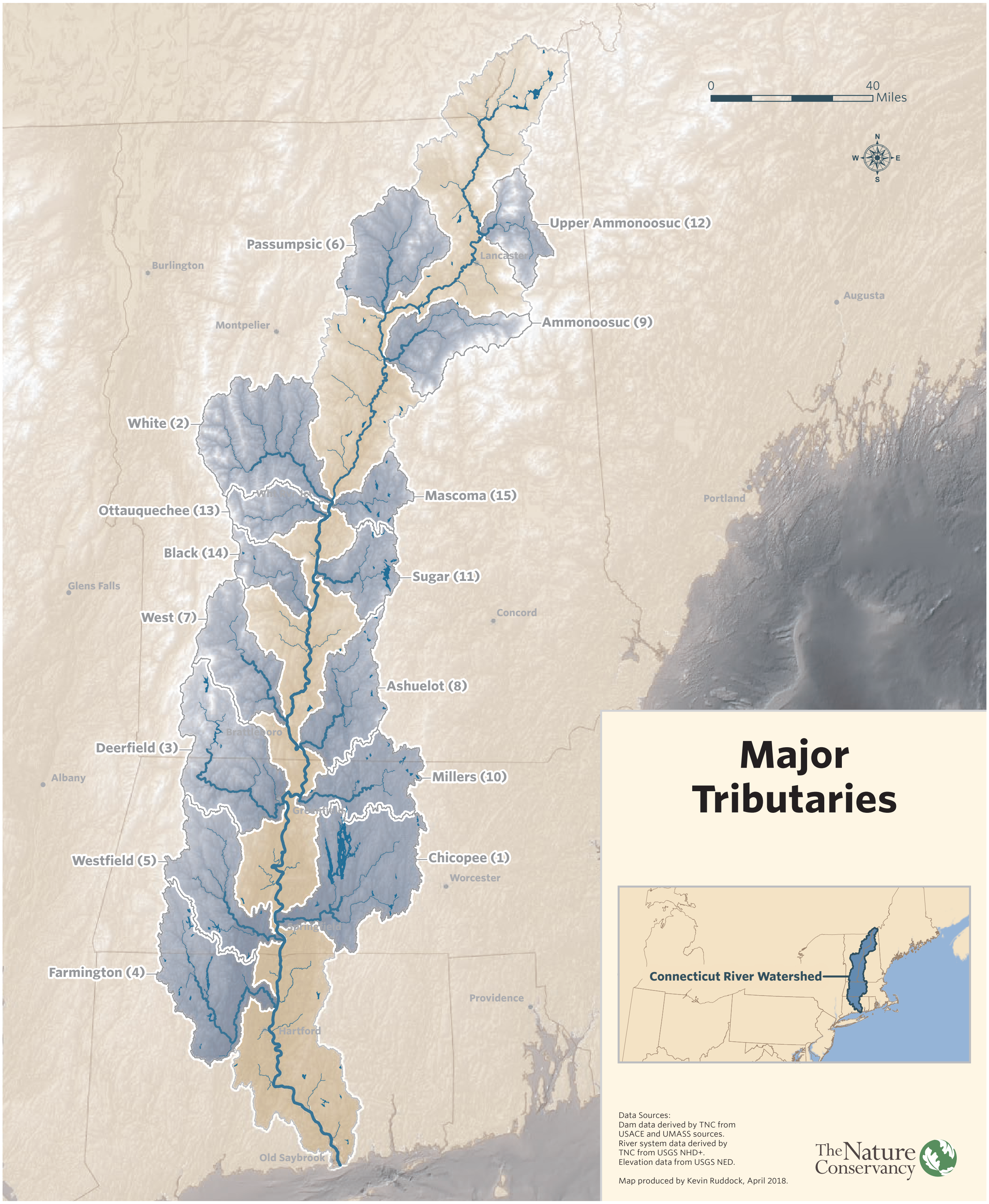


Figure 1. The Connecticut River watershed, with major tributaries and regional topography. The largest 15 tributaries are labeled in descending order by watershed size. At 724 square miles (1876 km^2), the Chicopee River watershed is the largest tributary watershed of the Connecticut River.

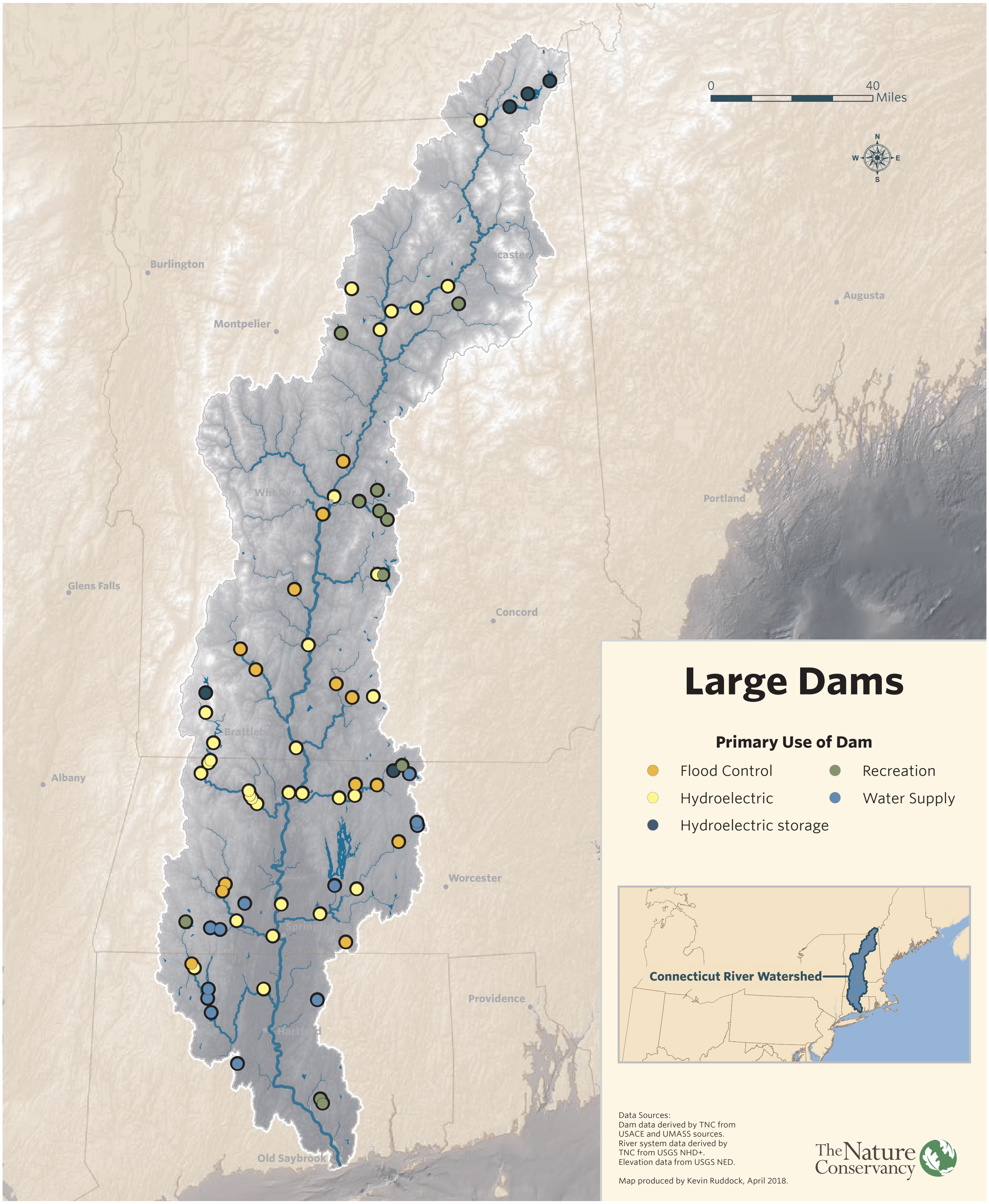


Figure 2. Large dams of the Connecticut River watershed and their uses. Dams include all those estimated to have a storage to annual discharge ratio of 10% or more (Zimmerman and Lester 2006), as well as all hydropower projects with a minimum capacity of 1 MW. See Appendix A for a descriptive list of the dams represented here.

Figure 3. Connecticut River Flow Restoration Study timeline of key actions, stakeholder engagement, and other milestones.

In 2000, the U.S. Army Corps of Engineers (USACE) and the Nature Conservancy (Conservancy) established a partnership to collaborate on the sustainable re-operation of dams across the United States through the Sustainable Rivers Program (SRP)[4], a nationwide effort to explore science-guided adjustments to dam operations that increase benefits to people and nature. In the Connecticut River watershed, the New England District of the USACE is one of the largest water managers, operating 14 flood risk management dams located on nine tributaries (Figure 2; Appendix A). Early collaborations to evaluate the potential for flow restoration through re-operation of these dams began in 2003, with a focus on four dams on the West and Ashuelot rivers. In 2005, a cost-sharing agreement between the Conservancy and the USACE established the Connecticut River Flow Restoration Study (Study), expanding early efforts to include the remaining ten USACE dams, as well as an additional 59 large dams in the watershed.

Authority to conduct the Study can be found in two resolutions (May 23, 2001 and June 23, 2004) adopted by the Committee on Environment and Public Works of the United States Senate. The 2004 resolution specifically states:

> *"That the Secretary of the Army is requested to review the report of the Chief of Engineers on the Connecticut River, New Hampshire, Vermont, Massachusetts, and Connecticut, published as House Document 412, 74th Congress, Second Session, and other pertinent reports, in the interest of identifying historic and current flow regimes, including the hydrodynamic and hydrologic characteristics of the Connecticut River basin, and based upon the review develop monitoring protocols for the Connecticut River Basin, New Hampshire, Vermont, Massachusetts, and Connecticut."*

The Study's goal was to examine the feasibility of changing operations of large dams in the Connecticut River watershed with the purpose of benefiting ecological health and function while maintaining the important services provided by these dams. This goal was to be achieved through 1) careful evaluation of current dam operations, including hydrological impacts; and 2) development of new operational alternatives aimed to meet both ecological goals and the intended purposes of these facilities. A study timeline including key actions, stakeholder engagement, and other milestones is provided in Figure 3.

This report provides the background and context for the Study, a description of the methods and models developed, results and findings of the Study, and suggestions for future use and applications. Specifically, **Section 2** discusses the pertinent physical, climatic, historical, and ecological characteristics of the Connecticut River watershed; **Section 3** describes preliminary analyses that drove the direction of the Study, including assessments of current flow alteration and ecological flow needs, and a demonstration of existing modeling frameworks; **Section 4** provides an overview of the modeling tools developed as part of the Study; **Section 5** offers an overview of the estimated hydrologic impacts of dam operations based on model outputs; **Section 6** provides an assessment of developed management alternatives; and **Section 7** discusses what was learned over the course of the Study with suggestions for application and implications for restoration of the Connecticut River watershed and beyond.

4 http://www.iwr.usace.army.mil/Missions/Environment/Sustainable-Rivers-Project/

2 | Study Area Description

2.1 Landscape

The Connecticut River flows 410 miles (660 km) from its source at the Fourth Connecticut Lake in the boreal forests of northern New Hampshire to its estuary on the shores of Long Island Sound in Connecticut (Figure 1). With a mean annual discharge of 19,200 cubic feet per second (cfs; 544 cubic meters per second, cms), the river and its 148 tributaries deliver 75% of the freshwater that enters Long Island Sound (Gay et al. 2004). Except for a sliver of Coastal Plain along the Connecticut shoreline, the watershed sits within the New England physiographic province of the Appalachian Highlands, which is characterized by hilly topography throughout, with higher elevations in the Green Mountains of Vermont and White Mountains of New Hampshire (Figure 1; Fenneman 1938; Fenneman and Johnson 1946).

The Connecticut River watershed is the largest in New England, covering 7.2 million acres (29,181 km2), nearly 74% of which are forested (Figure 4; CCRS et al. 2013). Interspersed among the forests are patches of agricultural (6%) and urban (9%) lands, with the highest-density population centers in the southern regions of the watershed, surrounding the cities of Springfield, Massachusetts and Hartford, Connecticut (Figure 4). Hartford, 48 river miles (77 km) upstream from Long Island Sound, is the most downstream city in the watershed, a unique feature for major river basins of the northeastern United States, which usually have port cities near their mouths. As a result, the Connecticut River estuary remains intact and is one of international significance, having been named a Wetland of International Importance in 1994 under the Ramsar Convention[5].

2.2 Climate and Hydrology

Precipitation across the Connecticut River watershed is evenly distributed throughout the year, with mean annual accumulations ranging from about 35 inches (90 cm) in the northern part of the watershed to about 47 inches (120 cm) near the coast (Garabedian et al. 1998; Magilligan and Nislow 2001). At higher elevations, especially in the Green and White Mountains, much of the annual precipitation accumulates in the winter months as snow. In most years, as air temperatures increase and snow melts in early spring, the accumulated snow pack results in a spring freshet. After the spring freshet recedes, summer months are typically characterized by low, stable flows interrupted by periodic storm events. As transpiration decreases in late fall and early winter, flows typically increase slightly, and then decrease again through winter as precipitation is locked up as snow. Figure 5 illustrates the annual hydrological pattern of the White River in Vermont, which is the largest unregulated tributary of the Connecticut River. The pattern illustrated by the White River is typical of natural annual streamflow patterns across the Connecticut River: high flows in the spring, followed by lower summer and early-fall flows, a slight increase in flows in late fall and early winter, and then a slight decrease through the winter months.

Flooding associated with the spring freshet can last for several weeks on the mainstem Connecticut River, especially in Connecticut where the waters initially rise from snowmelt in the southern reaches of the watershed, and are sustained by later snowmelt from the north. When combined with rain or ice jams, snowmelt-related flooding can become protracted, as occurred during the rain-on-snow flood event of March 1936 (Jahns 1947). Other significant flood events have been associated with late-summer or early-fall hurricanes, as in the 1938 and 1955 floods (Wolman and Eiler 1958), and most recently as a result of Tropical Storm Irene in August 2011 (Table 1). At the other hydrological extreme, all or parts of the watershed have also experienced several moderate to severe droughts (Table 2). The most severe drought on record for the region occurred from 1961 to 1969, when annual precipitation values were at a continuous deficit, resulting in agricultural losses and water supply restrictions and emergencies across the watershed (USGS 1991).

Over the past century, average temperatures in the Connecticut River watershed and across the Northeast have increased by almost 2°F (1.1°C; Horton et al. 2014). Precipitation has also increased (10% increase), with an increasing proportion falling in heavy events (70% increase; Horton et al. 2014), and a decreasing proportion falling as snow (Huntington et al. 2004). Corresponding trends in

5 The Ramsar Convention (www.ramsar.org) is the intergovernmental treaty that provides a framework for the conservation and wise use of wetlands and their resources, signed in the Iranian city of Ramsar in 1970.

Figure 4. Land use and land cover of the Connecticut River watershed. The watershed is 75% forested. About 10% of the watershed is developed, primarily around the cities of Springfield, Massachusetts and Hartford, Connecticut at the southern end of the watershed.

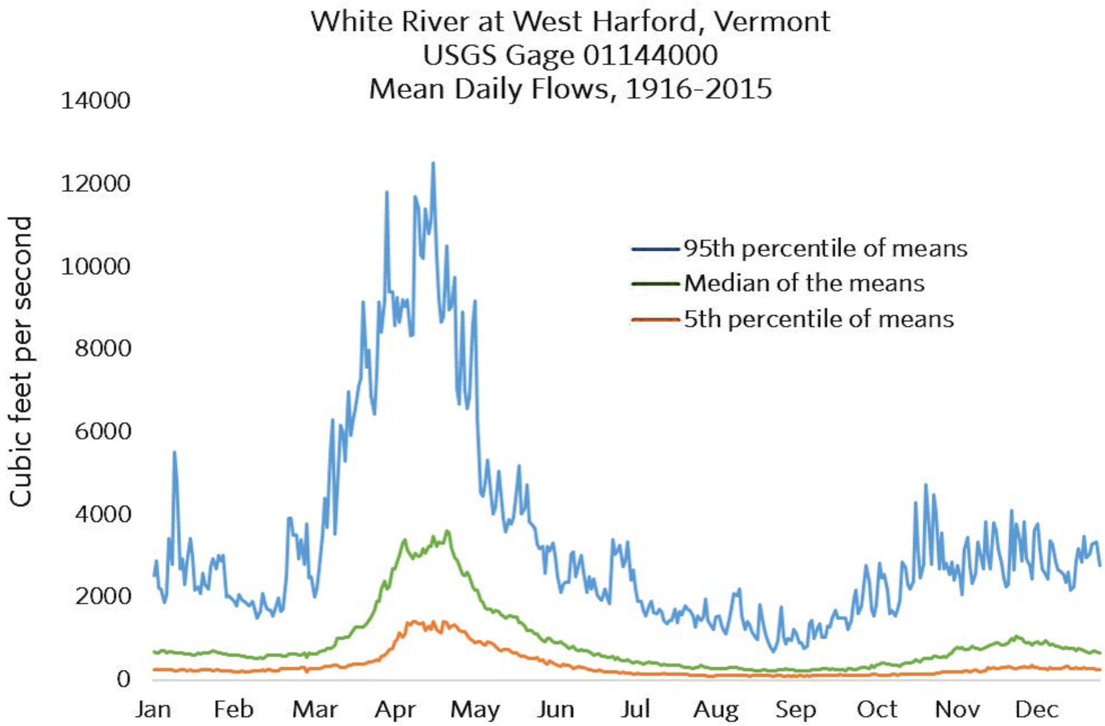


Figure 5. Annual hydrograph for the White River, Vermont. The White River is the largest unregulated tributary of the Connecticut River watershed. The annual pattern of flow is typical of the natural pattern of streamflow throughout the Connecticut River watershed: high flows in the spring, followed by lower summer and early-fall flows, a slight increase in flows in late fall and early winter, and then a slight decrease through the winter months. The median of mean daily flows foryears 1916-2015 is presented (green line), as well as the 95thpercentile of daily means (blue line) and the 5th percentile of daily means (orange line) to demonstrate the hydrological range of mean daily flows in this system. Data are from USGS stream gage 01144000.

hydrology have included an increase in the frequency of flood events per year (Armstrong et al. 2012; Archfield et al. 2016), and a shift toward earlier timing of the spring snowmelt peak as temperatures rise sooner in the spring (Hodgkins et al. 2003; Hodgkins and Dudley 2006). Regional projections are for continued increases in precipitation in winter and spring, and in the frequency of heavy precipitation events (Horton et al. 2014). Annual peak spring flows are also predicted to decrease by as much as 35% as snowfall contributes less to annual precipitation (Demaria et al. 2016).

2.3 History of Water Development

The construction of small mill dams on Connecticut River tributaries began with the first European settlements in the late 17th century. The first mainstem dam was completed in 1798 at "Great Falls" near present-day Turners Falls, Massachusetts. This dam and others on the mainstem Connecticut River were initially built to provide navigation for commercial traffic that supported the growing population and economy in the region. Through the 19th century, dams continued to be built throughout the watershed to support the Industrial Revolution, and then into the 20th century to capitalize on the introduction of hydroelectric power technology. The most recent hydropower facility constructed in the watershed was Northfield Mountain, a pumped-storage hydropower[6] project completed in 1972. With a capacity of 1,124 MW, Northfield Mountain has the largest generation capacity of any hydropower project in the Connecticut River watershed, and at the time of its construction, was the largest pumped-storage facility in the world (Northeast Utilities 1969).

At the turn of the 20th century, population centers throughout the Connecticut River watershed continued to increase, and communities like Hartford, Connecticut and Springfield,

6 Pumped-storage hydropower generates electricity by way of a two-reservoir system. When energy prices are low, water is pumped from a lower reservoir to an upper reservoir located at a higher elevation; when prices are high, energy is generated by releasing the water from the upper reservoir through turbines back into the lower reservoir.

Table 1. Major floods of record across the Connecticut River watershed; adapted from USGS (1991).

Date	River	Location	State	Flow (cfs)	Stage (ft)	Notes
August 2011	Connecticut River	North Walpole	NH	99,700	31.3	Hurricane Irene
	White River	West Hartford	VT	90,100	28.2	
	Connecticut River	Montague	MA	127,000	35.9	
	Deerfield River	West Deerfield	MA	89,800	23.7*	
April 1987	Connecticut River	Montague	MA	126,000	35.8	4-7 in. of rain; uncontrolled spillway flood at 6 USACE dams
	Deerfield River	West Deerfield	MA	61,700	17.7	
May 1984	Connecticut River	Montague	MA	143,000	38.2	6-day storm; 5-9 in of rain
August 1955	Westfield River	Westfield	MA	70,300	34.2*	Hurricanes Connie and Dianne; $350+ million in damages in Connecticut; 200 dams failed across New England
	Farmington River	Collinsville	CT	140,000	35.6*	
	Connecticut River	Hartford	CT	198,000	30.6	
September 1938	Connecticut River	Montague	MA	195,000	44.7	6 in. of rain followed by the Great Hurricane; $400+ million in damages
	Connecticut River	Hartford	CT	232,000	35.4	
	Deerfield	Charlemont	MA	56,300	20.2*	
	Millers	Erving	MA	29,000	13.4*	
	Farmington River	Tarriffville	CT	29,900	14	
March 1936	Connecticut	Montague	MA	236,000	49.2*	9 days of multiple heavy rain events on melting snowpack
	Connecticut	Thompsonville	CT	282,000	16.6*	
	Connecticut	Hartford	CT	313,000	37.6*	
November 1927	White River	West Hartford	VT	120,000	29.3*	Late-season hurricane
	Connecticut River	Hartford	CT	180,000	27	

**Flood of record at this location*

Table 2. Major droughts of record across the Connecticut River watershed; adapted from USGS (1991).

State	Duration	Scope	Notes
Connecticut	1929-1932	Statewide	Regional, serious water shortages
	1957	Statewide	Rainfalls at 55% of normal
	1961-1971	Regional	Severe water shortages and crop damage
	1987	Central and Western Connecticut	Groundwater at record lows
Massachusetts	1929-1932	Statewide	Regional, serious water shortages
	1939-1944	Statewide	
	1957-1959	Statewide	Record low well levels
	1961-1969	Regional	Water supply shortages common
Vermont	1947-1951	Central and Northern Vermont	
	1960-1969	Regional	Most severe drought on record
	1929-1936	Statewide	
New Hampshire	1939-1944	Statewide	Severe in Southeastern New Hampshire
	1960-1969	Regional	Most severe drought on record

Massachusetts began to seek ways to secure their water supplies. Reservoirs such as Borden Brook in the Westfield River watershed, and Nepaug and McDonough in the Farmington River watershed were constructed in the early 1900s to support these growing cities. Even cities as far as Boston eventually looked to the rich water supply of the Connecticut River to meet their needs. In 1939, the Swift River, a tributary of the Chicopee River, was dammed to create the Quabbin Reservoir, by far the largest water supply reservoir in the Connecticut River watershed, and one of the largest public water supply reservoirs in the United States. It covers 39 square miles (101 km^2), when full holds 412 billion gallons (1.26 million acre-feet) of water, and includes 117 miles (188 km) of pipeline and aqueducts that convey water to the 2.3 million people of metropolitan Boston (MWRA 2016).

As the population density along the Connecticut River continued to increase in the 20th century, so did the vulnerability of population centers to extreme water conditions. In 1927, 1936 and 1938, New England experienced a series of historic floods that were catastrophic to the communities along the Connecticut River. In response to the first of these floods, the Flood Control Act of 1936 established a comprehensive flood risk management program for the New England region. In the Connecticut River watershed, the USACE constructed five flood risk management projects by 1950, as well as several dikes, flood walls, and pumping stations, to manage flood risk for the cities of Springfield and Hartford, and nearby communities along the river. A second wave of development began following President Eisenhower's 1953 authorization of the Connecticut River Basin Commission, which was tasked with assessing needs for additional flood risk management in the watershed; nine additional dams were constructed between 1957 and 1969 (Figure 2; Appendix A).

Although most early mills and dams are no longer being operated, many of the hydropower, water supply, and flood risk management dams constructed throughout the Connecticut River watershed in the 19th and 20th centuries continue to serve their original purposes today. Many of these dams now serve multiple purposes; for example, recreation is an additional purpose of many reservoirs, several water supply reservoirs also offer flood risk management benefits, and some USACE dams have been retrofitted for hydropower production. Although there has been a recent nationwide surge in efforts to increase hydropower capacity as a source of low-carbon energy (USDOE 2016), it is unlikely that additional dams will be built within the Connecticut River watershed[7]. Beyond the limitations of a system that is already heavily-dammed, one reason for the lack of new dam construction is an increase of our collective scientific understanding of the consequences of dams and reservoirs on the ecological health and integrity of river systems.

2.4 Ecological Impacts of Water Development

While many species—plants, amphibians, reptiles, birds, and mammals included—depend on the Connecticut River and its tributaries for sustenance and survival, in this section we focus on four groups of taxa: migratory fishes, resident fishes, freshwater mussels, and riparian tiger beetles; and one ecological community: floodplain forests. These taxa groups and communities represent those currently considered most-impacted and most in-need of restoration by the Conservancy and other organizations and agencies working in the watershed (Zimmerman 2006b; Appendix B).

2.4.1 ▸ Migratory Fishes

The Connecticut River supports 13 species of migratory fish, many of which are associated with documented declines (e.g., Atlantic salmon, American eel, alewife, blueback herring, shortnose sturgeon, sea lamprey, and American eel; Gephard and McMenemy 2004). Dams and other barriers often prevent migratory fishes from reaching their spawning grounds or increase the effort necessary to do so. As a result, dams are often correlated to declines in reproduction and population size of these species (Limburg and Waldman 2009; Castro-Santos and Letcher 2010; Cooney and Kwak 2013; Lawrence et al. 2016). In the case of Atlantic salmon, fragmentation together with overfishing resulted in the complete extirpation of this species from the Connecticut River by the early 1800s, only a few years after the first dam was constructed across the river's mainstem (CRASC 1998). Barriers can also divide populations, as in the case of the federally-endangered shortnose sturgeon, which presently has two distinct populations in the Connecticut River: one upstream of Holyoke Dam (Holyoke, MA) and one downstream (Kynard 1997; Kynard et al. 2012). Fragmentation can potentially weaken populations by causing declines in genetic diversity, making it difficult for populations to persist and be resilient to changes in their environment (Jager et al. 2001; Hanfling and Weetman 2006; Yamamoto et al. 2004; Junker et al. 2012). Furthermore, to ensure persistence into the future, migratory species not only require habitat and population connectivity, but also specific habitat conditions for migration, spawning, foraging, and juvenile development and rearing. The river's flow regime is a key driver of these habitat conditions, and is necessary for provision of adequate substrate, temperature, depth, velocity, biological cues, and other conditions required for migratory fish species to survive (e.g., shortnose sturgeon: Kynard 1997; Kieffer and Kynard 2012; American shad: Greene et al. 2009).

2.4.2 ▸ Resident Fishes

Native resident fish species in the Connecticut River watershed include longnose dace, fallfish, white sucker, brook trout, slimy sculpin, tessellated darter, and yellow perch, among many others. In addition, at least three river-dependent resident fish species in the watershed are listed by state resource agencies as endangered, vulnerable, or species of concern: eastern silvery minnow, northern redbelly dace, and longnose sucker. Riverine species have evolved life history strategies that enable them to live in a dynamic system with a particular natural pattern of flow. When dams disrupt this pattern, the life cycles of the organisms that depend on the natural flow regime are also disrupted (Poff et al. 1997; Bunn and Arthington 2002). For example, dams change the proportional availability of habitat by changing the river from a system dominated by lotic habitat (moving water) to one dominated by lentic habitat (still water). Modified flows may decrease connectivity of the river with its floodplain, reducing the creation and replenishment of backwaters used by some species for spawning and juvenile rearing (Junk et al. 1989; Bowen et al. 2003). Altered flows may also result in changes to the sediment regime, thereby limiting the formation of important sandbar habitats or increasing sedimentation that may smother newly-fertilized eggs (Wood and Armitage 1997; Petts and Gurnell 2005). Lastly, modified flows may directly interrupt spawning behavior by interspersing required periods of calm, steady flows with intermittent high flow pulses (Freeman et al. 2001; Young et al. 2011).

2.4.3 ▸ Freshwater Mussels

Freshwater mussels are relatively sedentary organisms that live buried in stable river bottom substrates, filtering food from the water column, and moving slowly through the river sediments—both vertically and horizontally—as temperatures and river flows change. They are unique in their reproductive

7 However, the addition of hydropower capacity at non-powered multiple-use dams may continue to increase.

strategy, depending on the gills of host fish species to support their parasitic larvae (glochidia). Twelve species of freshwater mussels are present in the Connecticut River watershed, nine of which are state-listed within the watershed as endangered, threatened, or a species of concern (e.g., brook floater and yellow lampmussel), and one that is listed as federally endangered under the Endangered Species Act (dwarf wedgemussel; Nedeau 2008). Like riverine fish species, freshwater mussels that occupy river habitats are adapted to the natural variability of these dynamic systems, and nearly all freshwater mussels that exist in rivers with dams have been impacted by river fragmentation and an altered flow regime (Vaughn and Taylor 1999; Nedeau 2008). While the precise reasons for the decline in freshwater mussels are not clear, there are several possible explanations, including changes in habitat related to flow alteration (Strayer et al. 2004; Bogan 2008). For example, increased flow variability and rates of change may impede the ability of mussels to find suitable habitat, leading to stranding and desiccation (Galbraith et al. 2015). Further, while some mussel species use a variety of host fish species, many others are more selective and compatible with only a few host fishes (Strayer et al. 2004). In these cases, population persistence requires not only adequate habitat and flow conditions for the mussel, but also for its host.

2.4.4 ▸ Riparian Tiger Beetles

Riparian tiger beetles are terrestrial insects that live exclusively on narrow bars of sand and cobble at the river's edge. Three species of riparian tiger beetles—puritan tiger beetle, cobblestone tiger beetle, and Appalachian tiger beetle (Pearson et al. 2006)—are found in the Connecticut River watershed, and one—the puritan tiger beetle—is listed as federally threatened under the Endangered Species Act. Riparian tiger beetles are habitat specialists, depending completely on the dynamic interaction of moving water and shifting sands and cobbles that maintain their habitat along the river. Regular high flows and winter ice scour are necessary to build new bars, maintain existing bars, and control vegetation growth, while lower, relatively stable flows (e.g., natural summer low flows) are required at other times to provide conditions necessary for foraging, reproduction, and larval development (USFWS 1993; Pearson et al. 2006; NatureServe 2014). Because rivers are naturally dynamic systems, with sand and cobble bars continually created and destroyed, tiger beetles are adapted to changing conditions in spite of their narrow habitat requirements. However, to persist they require a functioning river system with just as many sand bars formed as destroyed over time, and where the elimination of one bar does not mean local elimination of the species. Since dams and their impoundments have reduced the number of sand and cobble bar habitats in the watershed, especially in the mainstem river, provision of adequate flows and sediment delivery in the remaining lotic segments is essential to ensure the survival of these small but important members of the ecological community.

2.4.5 ▸ Floodplain Forests

Floodplain forests are highly productive and structurally complex riparian habitats that attract many species of wildlife including fishes (when flooded and connected to the river), amphibians, reptiles, riparian mammals, picivorous raptors, migrating songbirds, and waterfowl (Govatski, 2010). To maintain their distinct species assemblages and ecological processes, floodplain forests require periodic flooding (Junk et al. 1989; Tockner and Stanford 2002). Annual multi-day floods are necessary to prevent more competitive upland tree species and invasive non-native shrub species from displacing floodplain plant species (Marks et al. 2014). Unlike the seed of upland tree species, the seed of floodplain trees (e.g., silver maple, elm and cottonwood) ripen in late spring to coincide with the receding spring freshet, which provides new seedbeds with fresh sediment required for germination (Mahoney and Rood 1998). New bar formation and disturbance by major floods also creates habitat for pioneer species like willows and cottonwoods. Because of their dependence on high flow events and seasonally-varying flows, many floodplain forests have been depleted and degraded by reduced flooding caused by large dams (Burke et al. 2009; Stallins et al. 2010; Johnson et al. 2012; Dixon et al. 2015; Gope et al. 2015). Furthermore, because these habitats are rare in the Connecticut River watershed, with only 6,000 acres of the watershed's 5 million acres of forest classified as floodplain forest (Carpenter 2007; Anderson et al. 2010; C. Marks, TNC, personal communication), these habitats are particularly vulnerable to alteration of flooding flows.

3 | Preliminary Analyses

3.1 Assessment of Current Flow Alteration

To begin to determine the feasibility of making operational changes to dams throughout the Connecticut River watershed, the Conservancy conducted an assessment of the current extent of flow alteration throughout the watershed. Specifically, an analysis was conducted examining the ratio of dam storage to mean annual discharge throughout the basin (Zimmerman and Lester 2006). The ratio of storage capacity to annual discharge is a measure of the potential of a dam or series of dams to control downstream hydrology, with higher ratios indicating a greater potential for hydrological alteration (Graf 1999; Nilsson et al. 2005; Graf 2006; Lehner et al. 2011). Seventeen tributary systems in the watershed had moderate (10-30%), high (30-50% storage), or severe (>50% storage) potential for flow alteration based on the ratio of total tributary storage to mean annual flow (Figure 6). In general, dams in the watershed and in other basins throughout New England have relatively limited storage compared to other regions of the United States. For comparison, dams in the New England region have an average storage equal to 26% mean annual flow, while those in the western United States store up to 4 times the mean annual flow (Graf 1999). Results of the Conservancy's analysis indicated that most of the watershed's 3000+ dams store less than 10% mean annual flow; approximately 65 dams store at least 10% mean annual flow or greater (Zimmerman and Lester 2006). The dams in this latter category will be referred to as "large" dams throughout this report to distinguish them from the majority of smaller dams in the watershed.

The hydrological impacts of dams may often be described based on their designated purposes, whether hydropower, flood risk management, water supply or recreation (Richter and Thomas 2007). The hydrological alteration caused by hydropower dams in the Connecticut River watershed is generally related to peaking hydropower operations, in which dams hold and release water following the demand for energy: holding water when electricity prices are low and releasing water when prices are high. Because energy demand can rise and fall on an hourly basis each day, so can the flows below hydropower dams.

On some tributaries, most notably the Chicopee and Farmington rivers, water supply reservoirs are major contributors to flow alteration. The flow regimes below water supply dams are often characterized by extended low flows as reservoirs capture upstream inflows, resulting in the interception of all but the highest inflows during the driest part of the year (Richter and Thomas 2007). Large reservoirs constructed for recreation often function similarly, as they capture all upstream inflows until the reservoir is full, at which point outflows equal inflows.

The primary hydrological impacts of flood risk management facilities are increased flow stability and decreased high flow events; Zimmerman (2006a) also documented decreased frequency of low flow events on the West and Ashuelot rivers. Studies have demonstrated that small floods are currently more common on the mainstem Connecticut River than they are on tributaries with flood risk management projects, but that large floods are absent across the basin (Magilligan and Nislow 2001; Nislow et al. 2002; Zimmerman 2006a). This pattern is consistent with the intended operations of the 14 USACE dams located along the major tributaries of the Connecticut River. These dams serve as a comprehensive system of flood risk management for the watershed, each operated to provide protection to the communities directly downstream of the projects as well as to the major urban centers (Springfield, MA and Hartford, CT) along the mainstem river. Although the 14 dams together manage only about 13.9% of the total watershed drainage area (1,567 mi2 of 11,260 mi2; 4,054 km^2 of 29,163 km^2), the system is designed to hold back flood water long enough to desynchronize tributary flood peaks and prevent them from reaching downstream damage centers at the same time. When forecasts indicate the channel capacity of the tributaries or mainstem river will be exceeded, flows from the reservoirs are significantly reduced and operations are coordinated to obtain the maximum reduction in overall flood damages. These operations also often limit flooding in localized flood-prone areas, or "pinch points"; however, sometimes circumstances (e.g. releasing stored water to prepare for a coming storm event) require flooding of these "pinch point" areas, in spite of the overall mission to reduce flood risk.

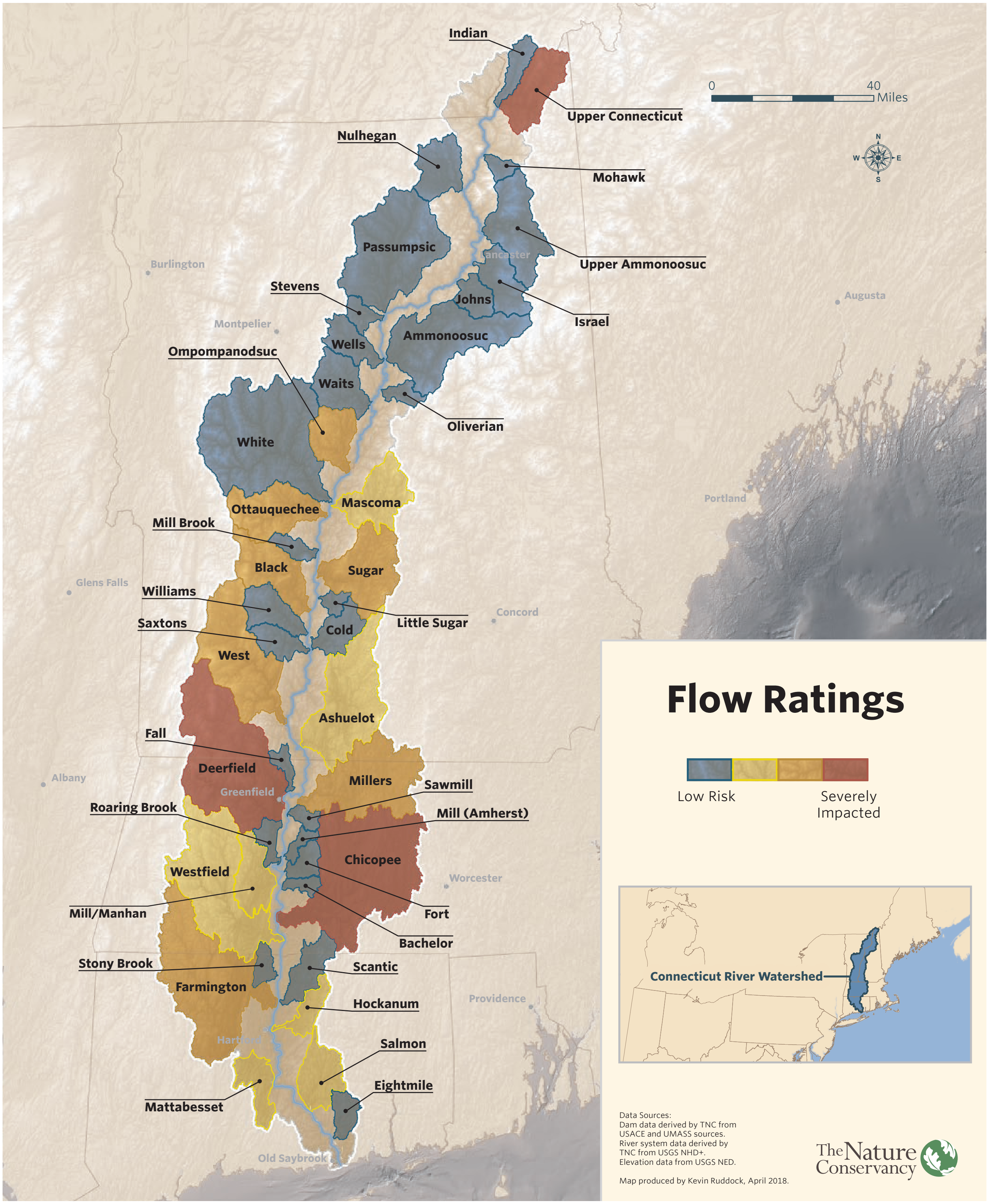


Figure 6. Potential for flow alteration in tributaries of the Connecticut River watershed based on total tributary dam storage (from Zimmerman and Lester 2006). Categories are based on the ratio of total dam storage capacity (per tributary watershed) to mean annual watershed discharge: "severely impacted" is >50%; "high risk" is 31-50%; "moderate risk" is 10-30%; "low risk" is <10%. Seven tributary systems in the watershed had moderate to severe (>10% storage).

3.2 Assessment of Ecological Flow Needs

Since its formal development in 1997, the natural flow regime paradigm (Poff et al. 1997) has played a central role in the fields of river flow ecology, management and restoration. Whereas early flow management for dams focused primarily on establishing minimum flow releases for ecological health, the natural flow paradigm introduced the concept of natural patterns of flow variability as a required component of a functioning river ecosystem. Natural patterns of flow include elements of magnitude and time, with temporal components described in terms of frequency, duration, timing, and rates of change. These patterns are in turn primary drivers of many other ecological parameters of river function, including water quality, temperature, nutrient cycling, sediment transport, physical habitat, and biotic interactions.

Having identified the largest dams contributing to flow alteration throughout the Connecticut River watershed, the Conservancy followed the flow alteration assessment with a literature review to begin to establish hypothesized flow needs for restoring and maintaining ecological health and function. Zimmerman (2006b) reviewed current literature from studies conducted within the Connecticut River watershed, supplemented as needed by studies in nearby basins and other regions of the eastern U.S. Based on this review, the Conservancy developed a list of hypothesized relationships among components of the natural flow regime and components of a functioning Connecticut River ecosystem (Table 3; Zimmerman 2006b).

In summary, large floods (>10 year recurrence interval[8]) enhance meander generation and the re-working and construction of channel bars and are also fundamental to the critical channel-floodplain exchange of sediment and nutrients. Small floods (2-10 year recurrence interval) are important for maintaining the structure of riparian and floodplain ecosystem communities, and may provide spawning cues and habitat for migrating fish species. Bank-full flows (1.1-2 year recurrence interval) maintain channel form and control vegetation growth. Finally, seasonal low flows (<Q70)[9] increase available habitat for some riparian and shallow water species (Table 3; Zimmerman 2006b).

Based on existing literature and the hypothesized ecological dependencies on components of the flow regime summarized above, Zimmerman (2006b) further described potential hypotheses of the consequent ecological impacts of altered flow regimes in the Connecticut River watershed (Table 5). For example, elimination of large floods could result in loss of meandering channels and areas of floodplain forest communities. Reduction or elimination of small floods could result in reduced nutrient inputs and access to floodplain habitats. Decreased frequency of bank-full flows could lead to vegetation encroachment and shifts in channel shape. Increased duration and/or reduced magnitude of low flows could increase stream temperature and decrease dissolved oxygen and favor generalist over fluvial species. Finally, increased short-term flow fluctuations could lead to loss of stable spawning, rearing, and riparian habitats for fishes and invertebrates (Table 5; Zimmerman 2006b).

Using this literature review and initial hypotheses of ecological flow dependencies and impacts of altered hydrology as a starting point, a two-day workshop was held in March 2011, to which natural resource experts from across the Connecticut River watershed and broader New England region were invited to further develop these hypotheses into flow management recommendations. The product of the workshop was a draft set of flow hypotheses and flow recommendations aimed at meeting the ecological requirements of floodplain, riparian, and instream riverine communities of the Connecticut River watershed (Table 6; See Appendix B for the full set of drafted flow hypotheses and recommendations).

3.3 Demonstration Project

To evaluate the potential for operational changes to support ecological benefits at large dams throughout the Connecticut River watershed, it was necessary to first have an understanding of current operational conditions. However, the USACE had not previously attempted to model operations for such a large number of dams. One of the early steps of the Study was therefore to test the effectiveness of existing model frameworks for application to this relatively large, highly-regulated watershed. A complete description of this demonstration project is provided in Appendix C.

Three modeling frameworks were evaluated as part of the model demonstration project: a model of unregulated flows, a rule-based operations model, and a goal-based optimization model. The demonstration project area was focused on the Connecticut River watershed between North Walpole, New

8 Note that the metrics used in this investigation are conventional metrics in the field of environmental flow ecology; however, we recognize that these metrics do not strictly follow Corps regulations (ER 1110-2-1450). As this Study is a collaborative effort between USACE and other entities, including The Nature Conservancy, and terminology is not standard from one organization to another, in Table 4 we have provided a comparison of values across several standard flow metrics as a courtesy to the reader.

9 Q refers to an exceedance value in the flow duration curve, where Q70 is the flow value that is exceeded by 70% of the flow values in a period of record. Seasonal low flows that are <Q70 refers to all flows that are lower than the Q70 flow value, or Q70-Q99.

Table 3. Hypothesized relationships among components of the natural flow regime and components of a functioning Connecticut River ecosystem; adapted from Zimmerman (2006b).

Flow Regime Component	Flow Metric	Hypothesized Ecological Function
Large floods	>10 year recurrence interval	Enhance meandering, scouring, and filling of channel
		Scour riparian vegetation and deposit alluvial soils; enhance re-working and construction of channel bars
		Fundamental to the critical channel-floodplain exchange of sediment and nutrients
		Supply a diverse seed bank to floodplains; enhance recruitment and diversity of riparian species (when timed with seed drop of riparian species)
		Develop young floodplain forest communities
Small floods	2-10 year recurrence interval	Maintain floodplain landforms (e.g., side channels, oxbows, wetlands, deposition bars, sandy and cobblestone beaches) and transport nutrients from the floodplain to the channel
		Regularly inundate riparian vegetation and maintain existing floodplain communities
		Provide habitat for spawning and rearing of river herring (alewife and blueback herring) on floodplains when timed with spawning (flood duration must be sufficient to allow for egg hatch and rearing of juveniles)
		Cue migration and dispersal of fish life history stages; delayed timing of spring floods outside of spawning window of shortnose sturgeon (defined by temperature and photoperiod) results in delay or cessation of spawning
		Increase invertebrate production by connecting floodplain habitat to the main channel
Bankfull flows	1.1-2 year recurrence interval	Define and maintain channel shape and prevent vegetation growth in the channel
		Effective discharge for sediment transport
		Provide maximum area of channel and riverbank (snags, undercut banks, overhanging vegetation) for fish and invertebrate habitat
		Increase invertebrate production by maximizing riverbank habitat
Seasonal low flows	<Q70[1]	Increase water temperature
		Decrease available deep water habitat
		Concentrate prey for fish predators
		Increase some available shallow water and riparian habitats

[1] *Q refers to an exceedance value in the flow duration curve, where Q70 is the flow value that is exceeded by 70% of the flow values in a period of record. Seasonal low flows that are <Q70 refers to all flows that are lower than the Q70 flow value, or Q70-Q99.*

Table 4. Comparison of various flooding flow metrics used by the USACE, The Nature Conservancy, and other entities. The metrics used in this investigation (primarily recurrence intervals, first column) are conventional metrics in the field of environmental flow ecology; however, we recognize that these metrics do not strictly follow Corps regulations (ER 1110-2-1450). This table is thus provided as a courtesy to the reader.

Return Period or Interval (x-year storm); 1:X Annual Chance Exceedance	Percent Chance Exceedance	Probability of Exceedance
2	50	0.50
5	20	0.20
10	10	0.10
20	5	0.05
50	2	0.02
100	1	0.01

Hampshire and Montague City, Massachusetts, including the mainstem river and four of its tributaries: the West, Ashuelot, Millers, and Deerfield rivers. Six dams were included: the Vernon and Turners Falls hydropower projects on the mainstem Connecticut River, the Ball Mountain and Townshend USACE dams on the West River, and the Surry Mountain and Otter Brook USACE dams on the Ashuelot River.

The first model evaluated was a model of unregulated flows for use as hydrological input into the operations and optimization models. Unregulated flows were calculated for the West and Ashuelot Rivers by subtracting the influence of the USACE reservoirs using a water-balance approach that incorporated historic reservoir levels, operations records, and available USGS streamgage data (waterwatch.usgs.gov). Although this method was manageable for the scope of the demonstration project, the time and cost projection for scaling the method to the whole watershed proved to be prohibitive. Because estimated unregulated flows were important inputs for modeling alternative dam operations, the USACE and the Conservancy sought a partnership with the U.S. Geological Survey to apply their regression-based sustainable yield estimator (SYE) methods for estimating unimpaired[10] flows to the Connecticut River watershed. The SYE methods had been applied to the state of Massachusetts (Archfield et al. 2010) and partially to the state of Connecticut, and would therefore only need to be expanded to the northern part of the watershed. See Section 4.2 for a more detailed description of this unimpaired flow model.

The demonstration project also evaluated a rule-based reservoir operations model, the USACE Hydrologic Engineering Center's Reservoir Simulation System (HEC-ResSim)[11]. A set of rules was developed to simulate operations of the four USACE dams in the demonstration project area, based on the policies and guidelines of the New England District. Results indicated that the HEC-ResSim model accurately simulated operating policies, and because these operations were representative of other USACE dams in the watershed, USACE had confidence that HEC-ResSim could successfully model operations at the larger Connecticut River watershed scale. See section 4.3 for a more detailed description of the HEC-ResSim simulation model.

The final model framework evaluated as part of the demonstration project was a goal-based optimization model, the USACE Hydrologic Engineering Center's Reservoir Flood Control Optimization Program (HEC-ResFloodOpt). The HEC-ResFloodOpt model is a linear programming model that simulates releases from reservoirs in order to minimize user-defined penalties that accrue when river flows violate operational guidelines. Flood risk management operations were simulated for the USACE dams on the West and Ashuelot rivers, and while HEC-ResFloodOpt did have some utility for simulating optimal operations, the software's input and output management proved to be antiquated and cumbersome, and would therefore not be applicable to a project of a larger scope and scale. Because optimization models are goal-based, and aim to optimize the net benefits of water management, they can be useful for developing alternative management scenarios. The USACE and the Conservancy therefore decided it was worthwhile to pursue an alternate optimization modeling platform, and sought the expertise and partnership of the Department of Civil and Environmental Engineering at the University of Massachusetts Amherst to fulfill this project need. The LINGO (LINDO Systems, Inc.; www.lindo.com) optimization modeling software was selected; a more detailed description of the resulting model is provided in Section 4.4.

10 Throughout this report, we use the term "unimpaired" to refer to river flows that are modeled with minimal influence of anthropogenic activities (e.g., land use, water withdrawals, or dams). We use the term "unregulated" to refer to river flows that are modeled without the influence of dam operations only.

11 http://www.hec.usace.army.mil/software/hec-ressim/downloads.aspx

Table 5. Hypothesized ecological impacts of altered flow regimes in the Connecticut River watershed; adapted from Zimmerman 2006b.

Flow Regime Impact	Hypothesized Ecological Response
Elimination of large floods	Vegetation encroachment on floodplains
	Decreased regeneration of floodplain forests
	Shifts in species composition at higher-elevation floodplain sites
	Decreased input of terrestrial nutrients and organic material to aquatic systems
	Shifts in sediment dynamics that may lead to degradation of floodplain landforms
	Shifts in species composition at lower floodplain sites; potential decrease in regeneration
	Loss of habitat for fishfishes that spawn on floodplains
	Potential loss of migratory or spawning cues for some fish species
Decreased frequency of bankfull flows	Vegetation encroachment in the channel
	Change in channel shape and sediment transport
	Loss of habitat (snags, undercut banks, overhanging vegetation) for fishfishes and invertebrates
Increased duration and/or lower magnitudes of low flows	Increased water temperature and decreased dissolved oxygen
	Decrease in available habitat
	Shifts in fish communities to species that prefer slower water velocities; conditions that favor habitat generalists over fluvial specialists
	Elimination of habitat for some fishfishes and invertebrates, resulting in reduced diversity and abundance of fishes and freshwater mussels
Increased short-term flow fluctuations	May result in bank erosion, loss of stable shallow water habitats, and increased water temperature at stream margins
	Stranding and displacement of fishfishes and aquatic invertebrates
	Reduced or eliminated fish and mussel species that depend on stream margin habitat, resulting in reduced diversity and abundance of fishes and freshwater mussels
	Loss of species diversity and total abundance of benthic invertebrates
	Reduced or eliminated stable beach habitat for puritan and cobblestone tiger beetles

Table 6. A draft set of flow hypotheses and recommendations aimed at meeting the ecological requirements of floodplain, riparian, and instream riverine communities of the Connecticut River watershed. See Appendix B for a full set of drafted flow hypotheses and recommendations.

Target Species/ Communities	Season	Environmental flow component	Flow Ecology Linkages	Preliminary flow recommendation
Floodplains	Mar to Apr	Annual spring floods	Time annual spring flood peaks to match seed dispersal and germination of floodplain trees	Maintain natural timing & magnitude of 1-2-year recurrence interval spring floods
Open bar and beach habitat	Mar to Apr	Bankfull and small floods	High flows in spring and ice scour in winter create and maintain habitat for rare insects and plants.	Maintain 2 -10-year floods at unregulated magnitude and duration, coinciding with ice break up during some years.
Tidal marshes	Year-round	All flows	Maintain salinity levels necessary to support existing tidal freshwater, brackish, and saltwater marsh communities	No change to monthly Q95; <10% change in monthly Q90, Q50, Q10
Freshwater mussels	Jul to Oct	Mid-range flows	Maintain habitat conditions needed for peak spawning and larval survival	<10% change to monthly Q90, and Q10; +/- 20% change to monthly Q50
Benthic macro-invertebrates	Year-round	High flows	High flows recruit organic matter; however, increased frequency of high flow events could increase displacement	<10% change to annual Q10; no change to magnitude, frequency, or timing of 2-yr RI; no increase in magnitude, frequency or timing of floods greater than 2-yr RI
Atlantic salmon	Jul to Oct	Low flows	Adequate low flows are needed to maintain habitat and (cold) water temperature conditions for parr	No allowable change from Q99-Q90 flows
Shad and herrings	Sep to Nov	Seasonal flows	Outmigration may be delayed or impacted if low flows are prolonged	Q99 to Q90 = 0% daily flow Δ; Q90 to Q50= 10 % Daily Flow Δ; Q50 to Q10 =20 % daily flow Δ allowable
American eel	Jul to Nov	High flows	High flow events provide one of several cues for outmigration of adult (silver) eels	Q50 and above, 10% change allowed in daily flows
Shortnose sturgeon	May to mid-Jun	All flows	Ensure flows stay in critical range during spawning	Velocity preference between 30 cms and 120 cms[a]
Resident fishes (cold water)	mid-Mar to mid-Jun	High flows	Sustained high flows are needed for growth of stenothermic species. Also important is the duration of the monthly spring Q10 (increase OK, but no decrease)	Maintain daily spring flow that fall within Q15 to Q5, flows should not vary by more than +/-15% from unregulated (magnitude, frequency, duration)
Resident fishes (warmwater fluvial specialists)	Mar to Jun	low-midrange flows	Low to midrange flows are needed in spring to allow for spawning (protect against artificially low flows)	No change for monthly Q100-Q50; allow +/-15% change for Q50-Q30

[a] *As of 2017, flow recommendations based on these velocity preferences are being developed for shortnose sturgeon as part of the hydropower relicensing process for the Turners Falls Dam hydropower project.*

4 | Hydrological Modeling

4.1 Overview of Hydrological Models

Following the results of the demonstration project, three model frameworks were selected to support evaluation of current operations and to develop operational alternatives to benefit ecological health and function while maintaining the services provided by dams throughout the Connecticut River watershed[12]. They were as follows:

- Connecticut River Unimpaired Streamflow Estimator (CRUISE) models the natural hydrology of the watershed absent development and dam operation.
- Hydrologic Engineering Center Reservoir Simulation Model (HEC-ResSim) models flows under the current operations of dams in the Connecticut River watershed.
- Connecticut River Optimization Modeling Environment (CROME) is a linear programming model that optimizes flows given user-defined objective functions.

Although simulation and optimization models are capable of evaluating flows at very fine time steps (e.g., hourly or quarter-hourly), a daily time step was chosen for two reasons. First, the model of unimpaired streamflows that was to be used for inputs to the simulation and optimization models was based on mean daily flows; the use of shorter routings would have implied more resolution than the model and input data supported. Second, a finer time step would result in extremely long model run-times that cannot be supported by conventional computer hardware, and would therefore be impractical for broad use.

4.2 Connecticut River Unimpaired Streamflow Estimator

The U.S. Geological Survey (USGS), in cooperation with the Massachusetts Department of Environmental Protection, developed the Sustainable-Yield-Estimator (SYE), an interactive, point-and-click tool built upon a geographic-information system, to estimate streamflow at any location on a perennial stream in Massachusetts (Archfield et al. 2010). The SYE tool was developed to provide water and natural resource managers with an easy-to-use and technically-defensible means to evaluate the impacts of proposed water withdrawals, determine baseline streamflow conditions, and estimate inflows to reservoirs at ungaged locations. It uses regression equations to relate catchment characteristics at a given location to points on a flow-duration curve, and then converts a fully interpolated flow duration curve to an estimated time series of mean daily flows using the timing of an available reference streamgage.

Through a cooperative program with the New England Association of Fish and Wildlife Agencies and the Conservancy, the USGS expanded this tool to include the entire Connecticut River Watershed. Specific expansion and modification of the tool led to the development of the Connecticut River Unimpaired Streamflow Estimator, or CRUISE model (Archfield et al. 2013; https://webdmamrl.er.usgs.gov/s1/sarch/ctrtool/). A complete description of the CRUISE tool is found in Appendix G.

4.3 Reservoir System Simulation Model

To model current operations at dams and reservoirs throughout the Connecticut River watershed, the USACE used their Reservoir System Simulation Model (HEC-ResSim; Version 3.1, May 2013). Developed by the USACE Hydrologic Engineering Center (HEC), HEC-ResSim can model operations at multiple reservoirs for a variety of complex operational goals and constraints. The model developed for the Connecticut River simulates the operations of 73 major reservoirs throughout the entire Connecticut River watershed, owned and operated by a variety of public and private entities for many different purposes. These 73 dams included the 65 major dams identified by Zimmerman and Lester (2006; see section 3.1), plus an additional 8 hydropower dams with at least 1 MW of generational capacity. Using 44 years of data on unimpaired flows from the CRUISE model (Section 4.1), the Connecticut River HEC-ResSim model simulated a

12 As the Study progressed, additional models were developed to address issues related to flow management; while potentially useful for flow management decision making, these models will not be directly addressed in this report. They include a model of climate-altered flows (Connecticut River Variable Infiltration Capacity, CRVIC, Appendix D), a hydraulic model (HEC-RAS, Appendix E), inundation models for specific floodplain targets (HEC Ecosystems Functions Model, HEC-EFM, Appendix E), and a sub-daily flow optimization model (Sub-daily Connecticut River Optimization Modeling Environment, Sub-daily CROME, Appendix F).

baseline of existing operations, as well as the alternative operational scenarios suggested by the optimization model (Section 4.4).

Appendix H includes a detailed description of the Connecticut River HEC-ResSim Model; Appendix I contains a detailed description of the modeled reservoirs including their physical characteristics and the operating rules for existing conditions.

4.4 Connecticut River Optimization Modeling Environment

4.4.1 ▸ Model Overview

The Connecticut River Optimization Modeling Environment (CROME) is an optimization model developed in a linear programming framework (LINGO). The CROME model incorporates streamflows throughout the watershed as hydrological input and computes optimal releases from its component dams given defined objective functions. The model searches all potentially optimal combinations of release strategies to find the one that best achieves the stated criteria. A key element of the optimization model is the specification of a desired system state. This is accomplished by defining constraints (e.g., streamflow in a certain reach will fall into a prescribed range during a specified time period) and an objective function (e.g., maximize the total revenues from hydropower). Once the desired system state is specified, the optimization model computes the specific release strategy that will achieve this desired state given the objective function.

CROME incorporates the operation of 54 large dams on the Connecticut River and its tributaries. These dams were based on the 65 large dams identified by Zimmerman and Lester (2006); the number was reduced after additional analyses confirmed that only 54 dams in the watershed stored at least 10% mean annual flow. The CROME model contains constraints for maximum and minimum storages and releases, and provides the opportunity to optimize for objectives including the provision of prescribed streamflows, maintenance of reservoir storage targets, generation of revenue from hydroelectric production, and allowance of water for municipal supply. The model determines operations for an entire year at a daily time-step using daily hydrologic data as input; for the purposes of this project, data from the CRUISE model were used, but other hydrologic data (e.g., climate-altered streamflows; see Appendix D) may also be used.

4.4.2 ▸ Incorporating Ecological Objectives into CROME

To ensure linear optimization was directed toward locations of highest ecological value, the Conservancy consulted with state and federal natural resource managers and state natural heritage databases to select specific "econodes" for inclusion in the CROME model. These "econodes" are locations that represented high-quality floodplain forest habitat, priority habitat for migratory fishes, and/or known locations of federally-listed freshwater mussel or riparian invertebrate species. Locations of the 28 selected econodes (as well an additional 2 analysis points) are provided in Figure 7, and the specific taxa groups or community types represented at each point are provided in Table 7.

To fit the model framework, ecological objectives represented by flow recommendations and targets (see Section 3.2) were converted to reflect "acceptable deviations" from natural flow. These "acceptable deviations" were developed from expert elicitation in an open workshop format. Experts were asked to define what deviation from natural flow would be acceptable to support each ecological objective, given the flow recommendations that had been developed for that objective (see Section 3.2). Once these "acceptable deviations" were defined, the most-constraining deviation for each time period across all ecological targets was selected as an overall "acceptable deviation" for achieving ecological goals (See Appendix B). The corresponding objective function was therefore related to minimizing the deviations between operational flow and estimated natural flow at each time-step, given the "acceptable deviations" that were developed from the ecological flow targets. This objective function was applied to the 28 "econode" locations along the Connecticut River and its tributaries (Figure 7). For each econode, a loss function was developed that represented the ecological penalty incurred when modeled flows were higher or lower than the identified "acceptable deviation" from natural flow at that location. For more information on the approach for incorporating ecological objectives into CROME, see Appendix J.

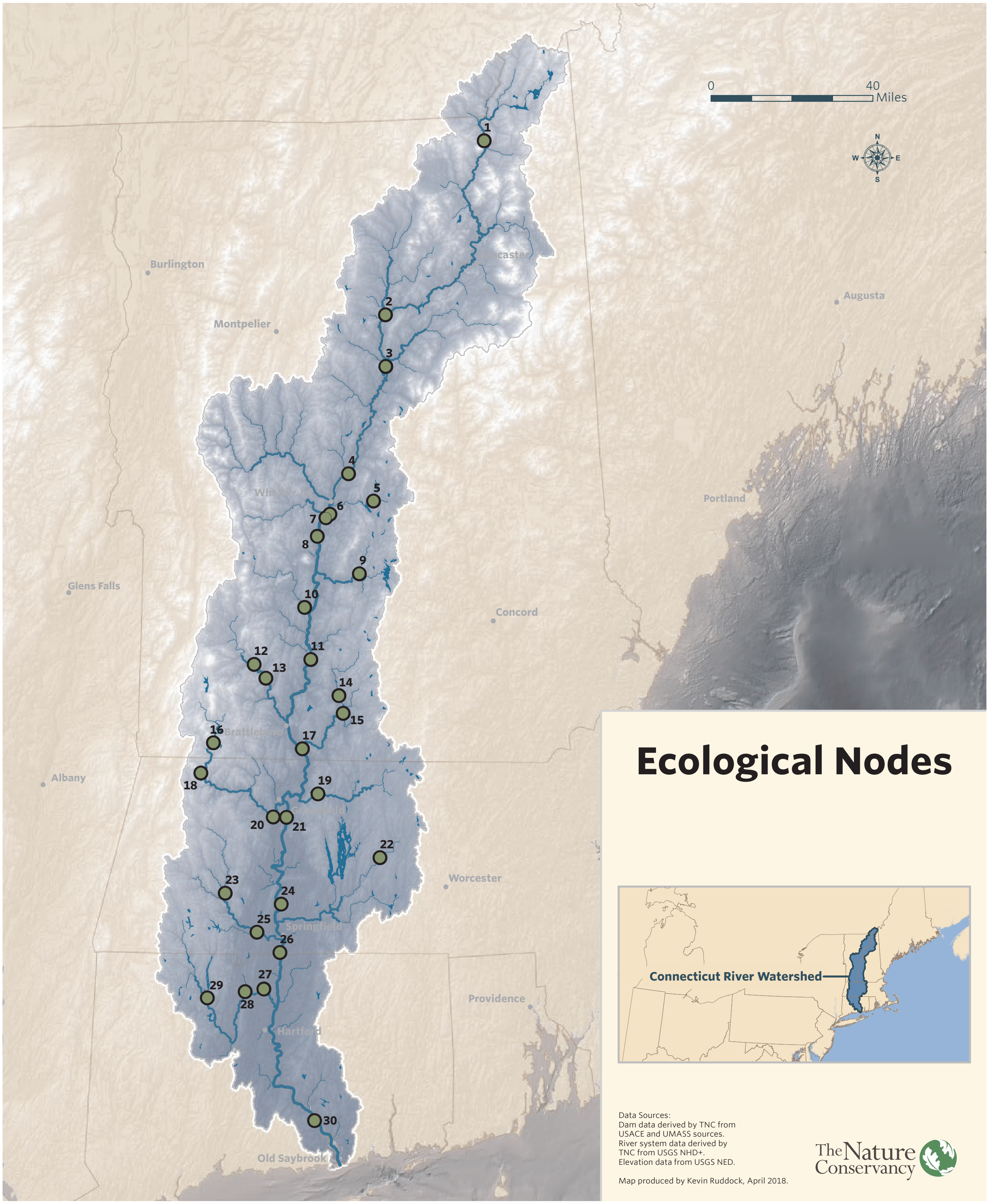


Figure 7. Locations of ecological interest ("econodes") throughout the Connecticut River watershed. Locations are numbered in order of descending latitude. Nodes 7 and 30 were not identified for ecological value, but were added as points of hydrological analysis. See Table 6 for the taxa groups associated with each location.

Table 7. Specific taxa groups and community types represented at each "econode", locations of ecological interest throughout the Connecticut River Watershed. Resident fish species were also included as a target at all econode locations. Econodes 7 and 30 were added for purpose of analysis, and were not selected for ecological value. See Figure 7 for locations of each econode.

Econode	River	Migratory Fishes	Riparian Insects	Freshwater Mussels	Floodplain Forest
1	Connecticut			X	X
2	Connecticut			X	X
3	Connecticut	X		X	X
4	Connecticut			X	
5	Mascoma				X
6	Connecticut		X		X
7	Ottauquechee	Analysis node only			
8	Connecticut	X	X	X	X
9	Sugar		X	X	X
10	Black	X	X	X	
11	Connecticut	X	X	X	X
12	West			X	X
13	West	X		X	
14	Ashuelot			X	X
15	Ashuelot	X		X	X
16	Deerfield				
17	Connecticut	X			
18	Deerfield				X
19	Millers	X			
20	Deerfield				X
21	Connecticut	X	X	X	X
22	Ware			X	X
23	Westfield	X			X
24	Connecticut				X
25	Westfield	X			X
26	Connecticut	X	X		X
27	Farmington	X			X
28	Farmington	X		X	X
29	Farmington				X
30	Connecticut	Analysis node only			

5 | Hydrological Impact Assessment

To evaluate the effectiveness of modeled scenarios to achieve ecological flow benefits, it was first necessary to understand the modeled impacts of current operations on estimated natural flows. Although the Conservancy did a cursory evaluation of flow impacts at the initiation of the Study (see Section 3.1), this analysis focused almost exclusively on the ratio of storage capacity to annual discharge, and not on the actual hydrological pattern of streamflow. With the development of both estimated natural flows in the Connecticut River watershed (CRUISE; Section 4.2) and modeled current operations at 73 dams in the watershed (HEC-ResSim; Section 4.3), it became possible to provide a detailed estimate of the hydrological impact of large dams on Connecticut River hydrology. To assess these impacts, we compared the simulated daily regulated flows (HEC-ResSim) with estimated natural daily flows (CRUISE) using 67 ecologically-relevant flow statistics at 30 locations throughout the watershed (Figure 7; see Section 4.4.2). These statistics were calculated using the Indicators of Hydrologic Alteration software (IHA; Richter et al. 1996), a tool developed by the Conservancy to evaluate the characteristics of large hydrological datasets. Evaluated parameters included monthly median flows and median low flows; frequency and duration of high and low flow pulses; and magnitude, frequency, duration, and timing of annual and interannual extreme high and low flows.

Overall results of the impact assessment suggest that the primary impact to the flow regime across the watershed is a loss of high flow events. Possible loss of low flows and high within-day flow variability were also indicated as potential impacts at specific locations. These results are consistent with those of previous studies (e.g., Magilligan and Nislow 2005; Zimmerman 2006a; 2006b; Zimmerman et al. 2010; Marks et al. 2014). Details of the results follow, along with a brief description of possible corresponding dam operations and ecological consequences associated with each hydrological impact.

5.1 Loss of High Flows

Large (>10-year natural recurrence interval; NRI) flood events are the most widely-impacted component of the flow regime in the Connecticut River watershed, meaning that they are impacted at more locations than any other ecologically-relevant hydrological characteristic. Of 30 locations examined, large floods are completely absent at 11 locations, are reduced to a single event (over the 52-year study period) at seven locations, and are less variable at 12 locations (Table 8; Figure 8). At five locations in three river basins—two in the Deerfield, two in the Ashuelot, and one in the Westfield—impacts on flood events are even greater, with the additional elimination of smaller flood events (2-10 year NRI) from the flow regime (Table 8; Figure 8). At the most-downstream point in the watershed (econode 30; Figures 7 and 8), the largest impact to flows was that of a lower duration of large flood events (from a mean of 65 days to 28.5 days; Table 8).

Based on the locations and distribution of impacts to high flows, results indicate that these impacts, in particular the loss of flooding flows, are largely attributable to flood risk management facilities. By design, these dams serve to reduce the magnitude of peak floods by increasing the frequency and duration of moderately-high flows as large flood events are captured and released over time (Richter and Thomas 2007). In the Connecticut River watershed, the 14 flood risk management facilities operated by the USACE are distributed throughout nine tributaries to the mainstem river (Figure 2; Appendix A). These facilities work in concert to desynchronize the peak of high-flow events in order to manage flood risk for the mainstem communities of Hartford, Connecticut and Springfield, Massachusetts. In each of the watersheds containing a USACE flood risk management facility, river hydrology is characterized by high flows that are lower than natural and by a loss of large (>10-year NRI) floods. On two tributaries in particular—the upper Westfield and Ashuelot rivers—the loss of high flows is more severe than in the other watersheds, with flood events > 2-year NRI completely absent from the flow regime (Table 8; Figure 8).

In addition to USACE flood risk management dams, the First and Second Connecticut Lakes and Lake Francis, located on the upper mainstem Connecticut River, are managed partially for flood risk management (CRJC 2009). Downstream of these facilities, high flows are generally lower and longer in duration, and there is a complete loss of large (>10-year NRI) flood events (Table 8; Figure 8). However, because the operator of these facilities manages them primarily to provide extra storage for downstream hydropower projects, with flood risk management only a secondary use, flow alteration downstream of these projects may not be solely attributable to flood risk management operations.

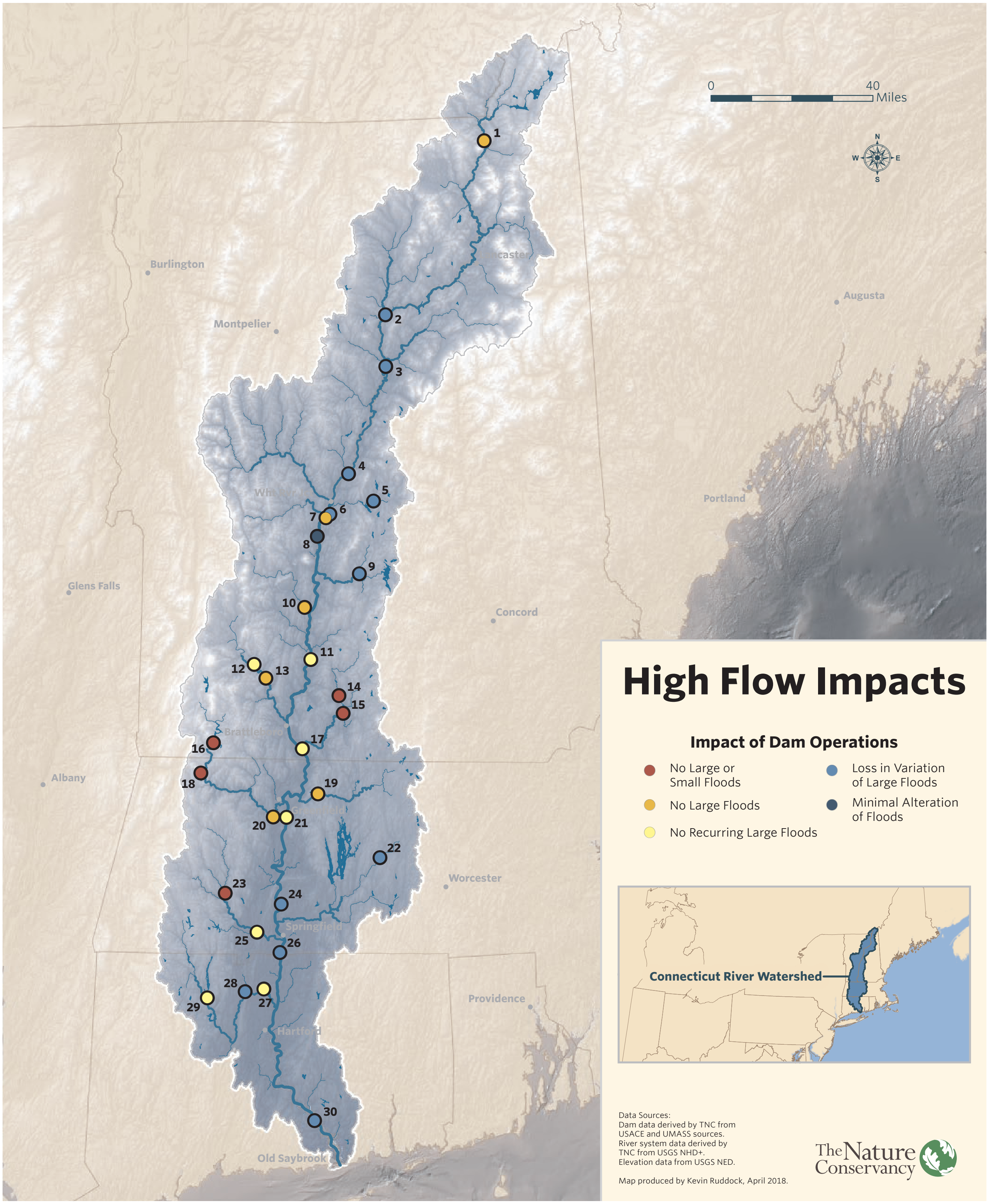


Figure 8. Impacts of dam operations on high flows at 30 locations throughout the Connecticut River watershed (see Figure 6 and Table 6). The greatest impacts to high flows are on tributaries; impacts on the mainstemare reduced by intervening flows from tributaries that have low to minimal impacts on high flows.

Table 8. Summary of high flow impacts at 30 locations in the Connecticut River watershed (see Figure 8).

River	Econode	Upstream Dam Uses	Large Floods	Small Floods	Annual Maxima Lower
Connecticut	1	H, HS	None	*Magnitude* more variable *Duration* lower and less variable	X
Connecticut	2	H, HS	*Magnitude* less variable		
Connecticut	3	H, HS	*Magnitude* less variable		X
Connecticut	4	H, HS, Tr	*Magnitude* less variable		
Mascoma	5	R	*Magnitude* less variable	*Duration* more variable	X
Connecticut	6	H, HS, Tr	*Magnitude* less variable		
Ottauqueechee	7	F	None		
Connecticut	8	H, HS, Tr			
Sugar	9	R	*Magnitude* less variable		
Black	10	F	None		X
Connecticut	11	H, HS, Tr	Not recurring		
West	12	F	Not recurring	*Magnitude* less variable	X
West	13	F	None	*Magnitude* less variable	X
Ashuelot	14	F	None	None	X
Ashuelot	15	F	None	None	X
Deerfield	16	H	None	None	X
Connecticut	17	H, HS, Tr	Not recurring	*Magnitude* less variable	
Deerfield	18	H	None	None	X
Millers	19	F	None	*Magnitude* less variable	X
Deerfield	20	H	None	*Magnitude* less variable	X
Connecticut	21	H, HS, Tr	Not recurring	*Magnitude* less variable	
Ware (Chicopee)	22	W	*Magnitude* less variable		
Westfield	23	F	None	None	X
Connecticut	24	H, HS, Tr	*Magnitude* less variable	*Magnitude* less variable	X
Westfield	25	F, W	Not recurring	*Magnitude* less variable	X
Connecticut	26	H, HS, Tr	*Magnitude* less variable *Duration* less variable		X
Farmington	27	F, H, R, W	Not recurring	*Duration* more variable	X
Farmington	28	W	*Magnitude* less variable Duration lower		X
Farmington	29	F, R, W	Not recurring	*Magnitude* less variable	
Connecticut	30	H, HS, Tr	*Magnitude* less variable *Duration* lower and less variable	*Duration* more variable	

F = flood risk management; H = hydropower; HS = hydropower storage; R = recreation; W = water supply; Tr = upstream tributary dams

Flooding is critical for the creation and maintenance of open bars and beaches as well as floodplain forest habitats; loss of these flows will consequentially lead to the loss of these habitats. Floods are also important for the lateral transfer of nutrients and sediments to and from the floodplain, upon which much of the instream community of a floodplain-dominant river is dependent. Without this transfer of nutrients, there will be a loss of productivity in the river channel, resulting in lower abundance and lower rates of growth of riverine species. The loss of fresh sediment deposits in the floodplain will likewise reduce productivity and floodplain pioneer species abundance (C. Marks, TNC, personal communication).

Observed ecological consequences of the loss of flooding events have been detected throughout the watershed, and include a decrease in floodplain forest area (Anderson et al. 2010) and shifts in species composition (Marks et al. 2014). Impacts may also be linked to the decline of at least two species of tiger beetles in the watershed, which require sand and cobble bar habitat created and maintained by high flow events (USFWS 1993; Pearson et al. 2006; NatureServe 2014). Additional species that may be impacted include wood turtles, which require natural floodplain vegetation for foraging (Jones 2009); species of resident and migratory fishes that depend on flooding to provide habitat for spawning, rearing, and growth (Junk et al. 1989; Schlosser 1991; King et al. 2003); and some species of freshwater mussels that may depend on both depositional substrates and the flow refugia provided by a meandering channel (Strayer 1999; Garcia et al. 2012).

5.2 Impacts to Low Flows

Results also demonstrated that low flows are widely-impacted across the Connecticut River watershed, but in varying ways (Table 9; Figure 9). At most locations with impacts (20 of 26), low flows are either higher in magnitude and/or less frequent than estimated natural flows (Table 9; Figure 9): at two locations on the Ashuelot they are less frequent; at two locations on the mainstem Connecticut they are higher in magnitude; and at 16 locations (Mascoma, Deerfield, lower Farmington, and the remaining mainstem locations) they are both higher in magnitude and less frequent. At two of these locations—on the upper Connecticut River and in the upper Deerfield River—there is a complete loss of flows in the lowest range of variability (i.e., no natural extreme events occur). At the remaining six locations with low flow impacts (West, Millers, Ware, lower Westfield, upper Farmington), modeled low flows are lower than estimated natural flows. It should be noted, however, that for all low flow impacts, very small differences between datasets can result in seemingly large differences in patterns of flow, in particular for those flow characteristics related to magnitude; that is, the lower the flow magnitude, the larger the proportional change per unit of change in flow. In some cases, these small changes may be within the range of measurement or modeling error; therefore, such results should be viewed cautiously.

Model results indicated that at most locations, impacts to low flows are generally attributable to water supply and flood risk management facilities. Although the USACE flood risk management dams in the Connecticut River watershed pass inflows as they are received until downstream conditions warrant flood risk management operations, and thus primarily influence higher flows and large flood events, the structural constraints of the dams (e.g., weirs controlling the pool, conduit dimensions, gate operations) likely have additional impacts that may include impacts on low flows. With regard to water supply, of the 30 study locations in the Connecticut River watershed, none are influenced exclusively by large water supply dams; however, in the Ware, Westfield, and Farmington rivers, study locations are impacted by both water supply and flood risk management dams. Comparison of the two Westfield locations (lower and upper; with and without water supply facilities) demonstrates that the water supply dams in this system likely contribute to the alteration of low flows by decreasing the annual minima (Table 9; Figure 9). It is likely that similar impacts are attributable to water supply in the Ware and Farmington river systems. Furthermore, some water supply dams in the Farmington watershed, such as those associated with the Barkhamsted and Nepaug reservoirs, currently operate without minimum flows, at times resulting in a complete lack of flow directly downstream from these dams.

On the upper Deerfield and upper Connecticut Rivers, at the two locations with a complete loss of natural extreme low flow events, low flow impacts may also be attributable to hydropower operations. On the upper Connecticut River, the First and Second Connecticut Lakes and Lake Francis are managed both for flood risk management and for hydropower storage (see section 5.1). Although most flood risk management dams do not directly manage low flows, the physical structure of the dams still have potential to influence low flows, and could therefore be the source of these impacts at this location. However, on the Deerfield River, all eight modeled dams are operated for hydropower, with the upstream-most facility operated for hydropower storage, similar to the upstream dams on the mainstem Connecticut River (Figure 2; Appendix A). It is therefore likely that the impacts on low flows in both the upper Deerfield and upper Connecticut rivers are related to hydropower operations.

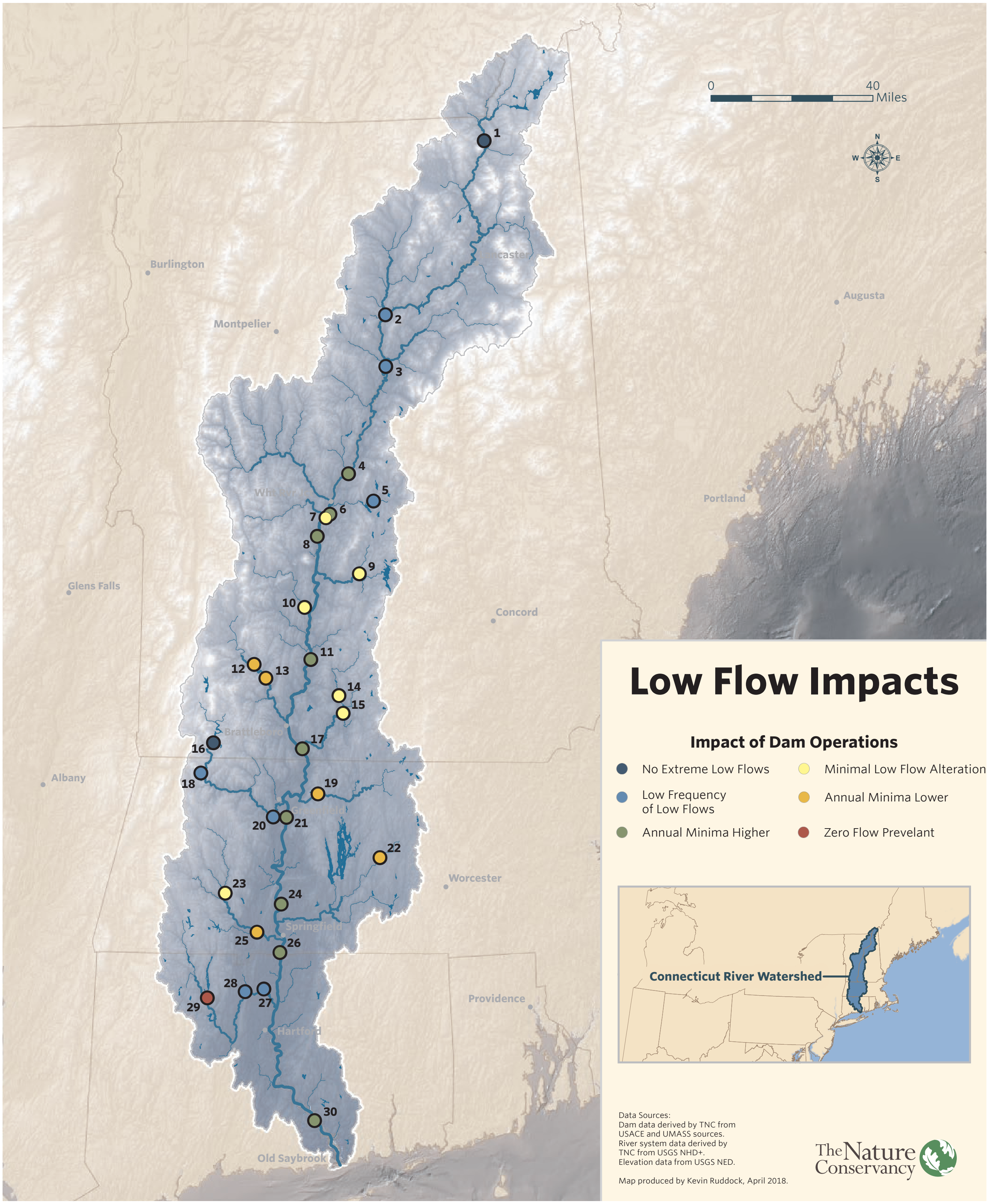


Figure 9. Impacts of dam operations on low flows at 30 locations throughout the Connecticut River watershed (see Figure 6 and Table 6). Impacts are variable across the watershed; the one location with prevalent zero flows (site 29) is below a water supply dam; the two locations without extreme low flows are below hydropower storage dams.

Table 9. Summary of low flow impacts at 30 locations in the Connecticut River watershed (see Figure 9).

River	Econode	Upstream Dam Uses	Extreme Low Flows	Annual Minima	Low Flow Pulses	
					Frequency	Duration
Connecticut	1	H, HS	None	Higher	Lower	
Connecticut	2	H, HS	*Frequency* lower	Higher	Lower	Lower
Connecticut	3	H, HS	*Frequency* lower	Higher	Lower	
Connecticut	4	H, HS, Tr		Higher	Lower	
Mascoma	5	R	*Frequency* lower	Higher	Lower	Higher
Connecticut	6	H, HS, Tr		Higher		
Ottauqueechee	7	F				
Connecticut	8	H, HS, Tr		Higher	Lower	
Sugar	9	R				
Black	10	F				
Connecticut	11	H, HS, Tr		Higher	Lower	
West	12	F		Lower		
West	13	F		Lower		
Ashuelot	14	F			Lower	
Ashuelot	15	F			Lower	
Deerfield	16	H	None	Higher	Lower	Higher
Connecticut	17	H, HS, Tr		Higher	Lower	
Deerfield	18	H	*Frequency* lower	Higher	Lower	Higher
Millers	19	F		Lower		
Deerfield	20	H	*Frequency* lower *Duration* lower	Higher	Lower	Higher
Connecticut	21	H, HS, Tr		Higher	Lower	
Ware (Chicopee)	22	W		Lower		
Westfield	23	F				
Connecticut	24	H, HS, Tr		Higher	Lower	
Westfield	25	F, W		Lower		
Connecticut	26	H, HS, Tr		Higher	Lower	
Farmington	27	F, H, R, W	*Frequency* lower	Higher	Lower	Lower
Farmington	28	W	*Frequency* lower *Magnitude* lower	Higher	Lower	Lower
Farmington	29	F, R, W	*Frequency* higher *Duration* higher	Lower	Higher	Higher
Connecticut	30	H, HS, Tr		Higher		

F = flood risk management; H = hydropower; HS = hydropower storage; R = recreation; W = water supply; Tr = upstream tributary dams

Most of the hydropower facilities on the mainstem Connecticut and Deerfield rivers are operated as peaking hydropower, such that flows can change from very low to very high in a matter of hours, and hydrological impacts are thus most pronounced on a sub-daily scale. When such operations are observed on a daily scale, these extremes in flows are averaged, creating daily flow values that are higher than the lowest hourly flows and lower than the highest hourly flows. This effect is consistent with the estimated impacts on the natural high and low flows at these locations (Tables 8 and 9; Figures 8 and 9; see also section 5. 3); that is, low flows tend to be higher than estimated natural low flows, and high flows tend to be lower than estimated high flows.

Low flows that are too low are clearly undesirable, as they can limit habitat and lead to lethal temperatures and anoxic conditions for all aquatic taxa groups. However, low flows that are too high can also be ecologically detrimental. Perhaps the most critical taxa group dependent upon the occurrence of natural low flows are the riparian tiger beetles (Section 2.4.4). These taxa require relatively stable flows, particularly in the summer after the spring freshet, to provide conditions necessary for foraging, reproduction, and larval development (USFWS 1993; Pearson et al. 2006; NatureServe 2014). Whereas these insects can tolerate the periodic high flows due to regular summer thunderstorms, persistent high flows will considerably limit habitat and the ability of these organisms to persist.

Low flows also provide valuable spawning and rearing habitat for many fish species. As the high spring flows recede, newly available shallow habitats are used for spawning, and the low, stable, warm flows that continue through the summer are ideal for growth and development of young fish. Without these conditions, fish may be ill-prepared to survive through the winter months. At the extremes, just as occasional large floods are important to maintain river function, extreme low flows are important as well, and may be a critical natural control against the spread of invasive species in the Connecticut River watershed.

5.3 Sub-daily Flow Fluctuation

Although the impacts analysis focused exclusively on the daily hydrograph, as both the CRUISE and HEC-ResSim models were developed at this scale, some results indicated potential for sub-daily impacts as well. Specifically, analysis of impacts on the Deerfield River, which has eight modeled dams that are operated for hydropower, indicated a flow regime that is characterized by a dampening of daily hydrological variability; that is, as estimated on a mean daily basis, low flows tend to be higher in magnitude and high flows tend to be lower in magnitude than would occur naturally (Tables 8 and 9; Figures 8 and 9). These changes in the flow regime likely correlate to the sub-daily peaking hydropower operations at these facilities, where flows fluctuate between a prescribed minimum flow and the maximum capacity of the facility, sometimes at multiple times per day, corresponding to peak energy demands and energy pricing. In other words, an increase in sub-daily hydrological variability at these facilities may result in a decrease in daily hydrological variability. As stated in the previous section, when hourly changes in flows are observed as mean daily flows, extremes in flows are averaged, creating daily values that are higher than the lowest hourly flows and lower than the highest hourly flows. Under a natural flow regime with less sub-daily variability, a given flow event lasts many hours, resulting in less of a difference between hourly flow values and daily mean flow values.

In a 2010 study, Zimmerman et al. reported substantial alteration of sub-daily flows in the Connecticut River watershed, demonstrated by the total number of days in which natural ranges of sub-daily variability were exceeded. The results further suggested that although most tributaries to the Connecticut River may have variable sub-daily flow, river reaches with dams exhibit this variability at a greater frequency, with river reaches with peaking hydropower projects (including the Deerfield River) having the most highly-altered sub-daily flows (e.g., unregulated sites had an average of 32 days of "high flashiness" annually and peaking hydropower sites had an average of 202 days of "high flashiness"). The study also reported significantly-altered ranges of sub-daily variability downstream of some flood risk management facilities and some run-of-river hydropower dams.

While sub-daily variation is natural, when the variability exceeds the normal range it can reduce the diversity, abundance, reproductive success and survival of riverine species. Specifically, reproductive success and abundance of freshwater mussels can be impacted by high water temperatures and stranding caused by peaking operations (Galbraith et al. 2015; Gates et al. 2015). Likewise, some fish species have been documented in lower numbers downstream from peaking facilities (Bain et al. 1988; Freeman et al. 2001). Fluctuations outside of the normal range may also reduce stable bar and beach habitat for the puritan and cobblestone tiger beetles (Zimmerman 2006b).

Although the modeling effort described in this report did not evaluate or address the sub-daily impacts and flow management of Connecticut River dams, a separate sub-daily model was developed to address management at five hydropower projects on the mainstem Connecticut River. This model is described in detail in Appendix F.

6 | Assessment of Management Alternatives

6.1 Whole System Connecticut River Flow Management Alternatives

Alternative scenario development in the CROME model requires a desired system state and a specified objective function (see section 4.4). The desired system state for Connecticut River dam operations was defined as the estimated natural flow regime plus daily "acceptable deviations" (see section 4.4.2 and Appendix G). Because the most prevalent impacts to Connecticut River hydrology were identified as those to high flow events (see section 5), and because the Conservancy and the USACE have a standing agreement to pursue alternative management strategies under the Sustainable Rivers Program (see Section 1), development of management alternatives began with a focus on the coordinated operations of the watershed's 14 USACE projects to meet the objective function of flood risk management while also meeting ecological objectives across the watershed. Results suggested, however, that ecological objectives could not be met without a potential increase in flood risk nor without trading decreased alteration in some locations or time periods for increased alteration in others (Pitta 2011; Steinschneider et al. 2013). Although the expert recommendations of "acceptable deviations" allow for some prioritization among species and time periods, increasing alteration at any location to levels greater than under current conditions was not considered an acceptable alternative by the Study partners at this time. Results also suggested that additional opportunity for ecological gain could be realized by focusing on independent management of tributary dams to meet ecological objectives at local tributary econodes (Pitta 2011; Steinschneider et al. 2013). Further analyses therefore focused on evaluating operational alternatives to reach ecological flow targets within individual tributary basins.

6.2 Connecticut River Tributaries Flow Management Alternatives

To evaluate the potential for re-operation of USACE dams on Connecticut River tributaries, two flow scenarios were evaluated for the flood risk management dams on four tributaries of the Connecticut River: the Ashuelot, Farmington, West, and Westfield rivers. One scenario focused on the removal of operational constraints; the other on optimizing operations to meet both flood risk management and ecological objectives. The scenarios were as follows:

1. **Pinch Point Removal Scenario:** This scenario simulated the elimination of "pinch points" below the USACE dams. "Pinch points" are specific locations downstream of USACE dams where rising flows first cause damages. Typically, these locations include roads, parking lots, golf courses, athletic fields, and—although pinch points are not usually associated with major damage centers—residential homes and property. When making releases from its projects, the USACE attempts to manage all flood risk; however, certain circumstances (e.g., making releases to prepare for a coming storm) require partial flooding of some of these pinch points. This scenario evaluates the degree to which these pinch points affect the operations and consequent hydrology of the selected tributaries; it did not utilize the CROME optimization model. A full description of each of the pinch points evaluated in this scenario is provided in Table 10.

2. **Optimized Scenario:** This scenario utilized the CROME optimization model to evaluate potential changes in operation that would aim to achieve a more natural hydrology, given "acceptable deviations," without compromising the ability of the USACE facilities to manage flood risk.

For the West and Ashuelot rivers, one additional scenario was evaluated for each system that applied a set of constraints to the CROME optimization model. They were as follows:

1. **Optimized Scenario 2—Ashuelot River:** This scenario removes Keene as a constraint to evaluate its impact on the hydrologic regime; as a major damage center, the city of Keene was not included in the pinch point scenario.

2. **Optimized Scenario 2—West River:** At Ball Mountain Dam, there is a 25-foot pool rule to provide adequate flows for downstream salmon smolt passage[13]; this scenario removes this rule to evaluate its impact on the hydrologic regime.

13 Current operations no longer include a 25-foot pool for salmon passage, but do include a year-round 35-foot pool that is maintained for sediment management.

Table 10. "Pinch points" downstream from USACE flood risk management dams in four Connecticut River tributary watersheds: Ashuelot, Farmington, West, and Westfield. "Pinch points" are specific locations downstream of USACE dams where rising flows first cause damages. When making releases from its projects, the USACE attempts to avoid flooding these locations.

Pinch Point	Tributary	Upstream Dam	Threshold (cfs)	Notes
Private home, Branch Road, Keene, NH	Ashuelot, Otter Brook	Otter Brook	650	a
Golf course, Route 12A, Keene, NH	Ashuelot	Surry Mountain	800	b
Athletic fields, Keene State College, Keene, NH	Ashuelot	Surry Mountain	1200-1250	a
Parking lot, Winchester Street, Keene, NH	Ashuelot	Surry Mountain	1200-1250	a
Parking lot and dorms, Appleton Street, Keene, NH	Ashuelot	Surry Mountain	1200-1250	a
Private homes, Castle Street, Keene, NH	Ashuelot	Surry Mountain	1200-1250	a
Trailer homes, Tanglewood Estates, Keene, NH	Ashuelot	Surry Mountain	1200-1250	a
Below Goodwin Dam, Barkhamsted, CT	Farmington, West Branch	Colebrook	3000	c
Agricultural fields, Route 185, Simsbury, CT	Farmington	Colebrook	5600	b, d
Businesses, Main Street, Unionville, CT	Farmington	Colebrook	9100	d
Private homes, Island Lane, Jamaica, VT	West	Ball Mountain	5000	a
Private homes, Route 30 & River Road, Jamaica, VT	West	Ball Mountain	5000	a
Campground, Depot Road, Townshend, VT	West	Townshend	9000	a, b
Private home, State Forest Road, Townshend, VT	West	Townshend	9000	a
Trailer homes, Ellen Ware Road, Newfane, VT	West	Townshend	9000	a
Private lawns, Rocky Brook Drive, Huntington, MA	Westfield	Knightville	2500	
Private homes, Arnold Drive, Huntington, MA	Westfield	Knightville	4500	e
Private homes, Rocky Brook Drive, Huntington, MA	Westfield	Knightville	4500	
Private homes, Arnold Drive, Huntington, MA	Westfield	Littleville	4500	e
Private homes, Goss Hill Road Bridge, Huntington, MA	Westfield, Middle Branch	Littleville	1500	

[a] *Presence of ice can affect the flooding threshold;*
[b] *Threshold is seasonal;*
[c] *Colebrook Dam discharges to Goodwin Dam, which makes the final releases; Goodwin operates with a 3000 cfs restriction;*
[d] *Flows from the intervening drainage area (between the dam and the pinch point) can affect the flooding threshold;*
[e] *Flows only impact this area if Knightville and Littleville dams are at channel capacity concurrently.*

To determine the degree of improvement to the natural hydrology in each watershed, the resulting hydrology of each scenario was compared to CRUISE estimated natural flows and HEC-ResSim current simulated flows using flow metrics that were identified as impacted during the impact analysis, in particular the magnitude and frequency of small and large floods (see Section 5).

6.2.1 ▸ Ashuelot River

The Ashuelot River has two USACE dams: Surry Mountain and Otter Brook dams. Surry Mountain Dam is located 35 miles (56 km) upstream from the confluence of the Ashuelot and Connecticut Rivers, and Otter Brook Dam is located on Otter Brook, a tributary of the Ashuelot, which meets the river about 9 miles (14.5 km) downstream from Surry Mountain (see Appendix A). There are two ecological locations of interest on the Ashuelot River: one is located about 5 miles downstream from Surry Mountain dam; the other is located about 2.5 miles downstream from the confluence of Otter Brook, near the confluence with the South Branch of the Ashuelot River (econodes 14 and 15, respectively; Figure 7). Both sites are valued for their floodplain forest habitat as well as their instream habitat for resident fishes and freshwater mussels (Table 7).

Pinch Point Removal Scenario: There are several pinch points in the Ashuelot River watershed, most of which are below Surry Mountain Dam in the city of Keene, New Hampshire (Table 10). They include locations with mobile homes, parking lots, college dorms, private residences, athletic fields, and a golf course. There is one pinch point on Otter Brook, at a private residence. Removing the pinch points from simulated operations resulted in some improvements to the flow regime on the Ashuelot River, in particular below Surry Mountain Dam (econode 14; Figure 7), with increases to the annual maxima in some years (Figure 10). However, changes were not substantial enough to restore the larger events among years (i.e., small and large floods); nor were impacts to low flows substantially improved.

Optimized Scenario: There were minimal operational changes suggested in the optimized scenario, with only the summer reservoir storage target at Surry Mountain Dam changing from an elevation of 15 feet to 17 feet. Otherwise, Otter Brook Dam maintained its constant storage target throughout the year (at the conservation pool); and both dams maintained release patterns where outflows equal inflow unless inflow exceeds channel capacity. This scenario resulted in minimal changes to operations, and no improvements to the evaluated flow metrics.

Optimized Scenario 2—Ashuelot River: The second optimized scenario evaluated the impact of the city of Keene on simulated operations and on ecological flow metrics. At the upper location below Surry Mountain Dam, there were some improvements to high flows, with annual maxima increasing in some years (Figure 10). At the lower site below the confluence of the Ashuelot River and Otter Brook, substantial benefits were demonstrated in this scenario, indicating the strong effect of the city of Keene on the natural flow regime in the Ashuelot River. In particular, this scenario restored the magnitude of small floods 2-10 year NRI (large floods, >10 year, NRI remain absent); however, these floods occurred about half as many times as under estimated natural conditions (Figure 11).

6.2.2 ▸ West River

The West River has two USACE projects: Ball Mountain and Townshend dams. Townshend Dam is located about 20 miles (32 kilometers) upstream from the mouth of the West River, and Ball Mountain is located an additional 10 miles (16 kilometers) upstream of Townshend (Appendix A). There are two locations of ecological value in the West River, one about 8 miles downstream from Ball Mountain Dam, and the other about 4 miles downstream from Townshend dam (econodes 12 and 13, respectively; Figure 7). Both sites are valued for their floodplain forest and open bar and beach habitats, as well as instream habitat for resident and migratory fishes and freshwater mussels (Table 7).

Pinch Point Removal Scenario: There are two pinch points below Ball Mountain Dams, both locations with private residences, and three pinch points below Townshend Dam: a campground, a site with mobile homes, and another with private residences (Table 10). Removing these pinch points did not substantially improve the evaluated flow metrics; that is, the impacts identified under current operations persisted under simulated pinch point removal.

Optimized Scenario: The optimized scenario maintains the current storage targets at Townshend Dam, which stay constant year-round (at the conservation pool), but drawdown rates are reduced from 10 feet per day to 1 foot per day. For both dams (Ball Mountain and Townshend), this scenario maintains current release patterns, for which outflows equal inflows unless inflows exceed channel capacity. When implemented in HEC-ResSim, this scenario resulted in little change to operations, and there were consequently no improvements to the impacted natural flow metrics.

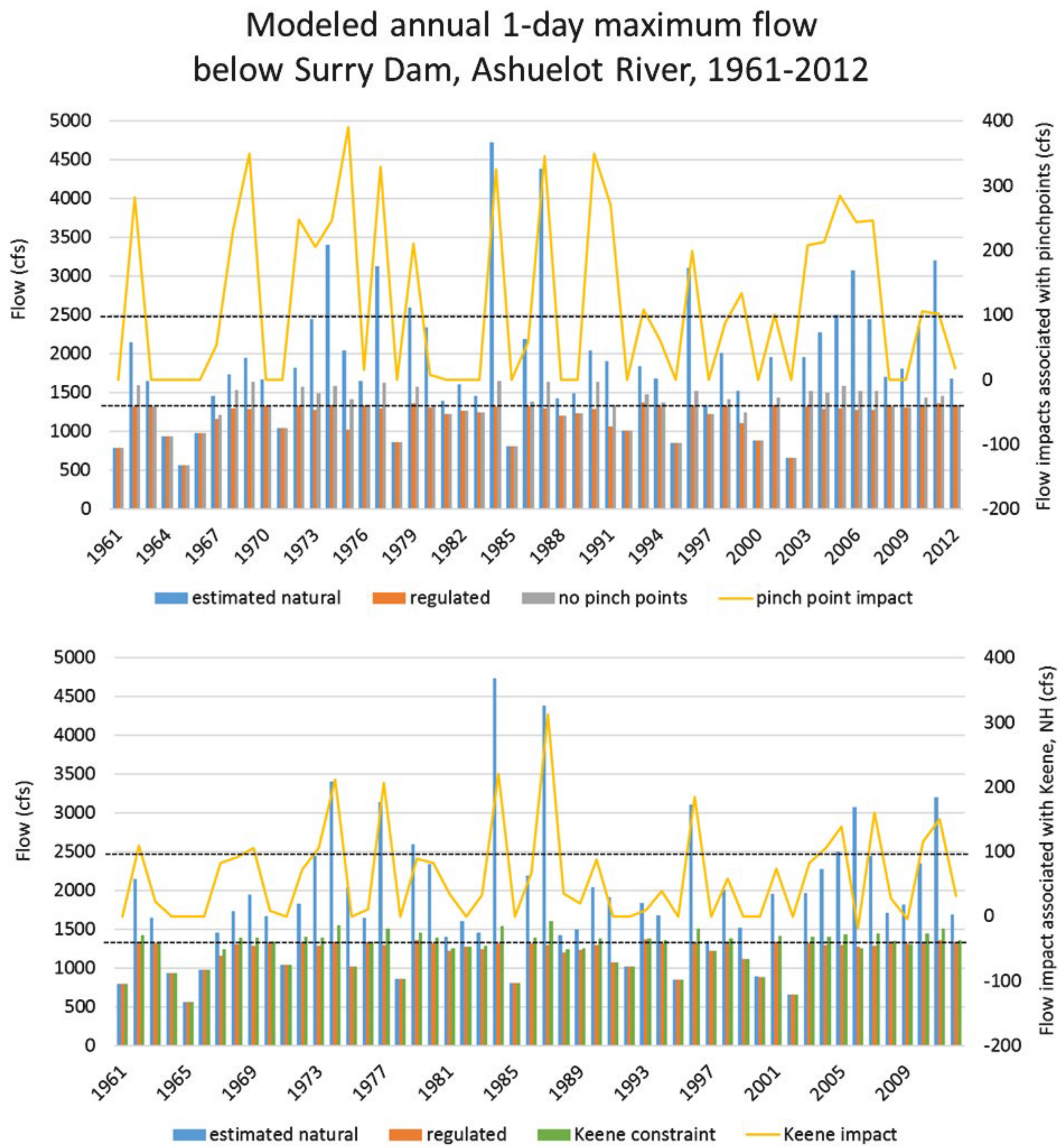


Figure 10. Annual maxima below Surry Mountain Dam, Ashuelot River, New Hampshire among four modeled scenarios (left y-axis): estimated natural flows (blue bars), current regulated flows (orange bars), a scenario that removed the hydrologic constraints of multiple downstream "pinch points" (residential areas, parking lots, camping grounds, etc.; gray bars, top panel), and a scenario that removed the hydrologic constraint of the city of Keene, New Hampshire (green bars, bottom panel). The yellow line represents the difference in flow (right y-axis) between the current regulated flows (orange bars) and the "pinch point" scenario (gray bars, top panel) or the scenario without the Keene constraint (green bars, bottom panel). In both panels, the top dotted horizontal line represents the 10-year natural recurrence interval flood (NRI; 3124 cfs); the bottom dotted horizontal line represents the 2-year NRI flood (1770 cfs). The pinch point constraint scenario resulted in some improvements to the flow regime below Surry Mountain Dam, with increases to the annual maxima in some years. The Keene constraint scenario demonstrated a restoration of small floods, but these floods remained in the low range of variability and 10-year NRI floods remained absent.

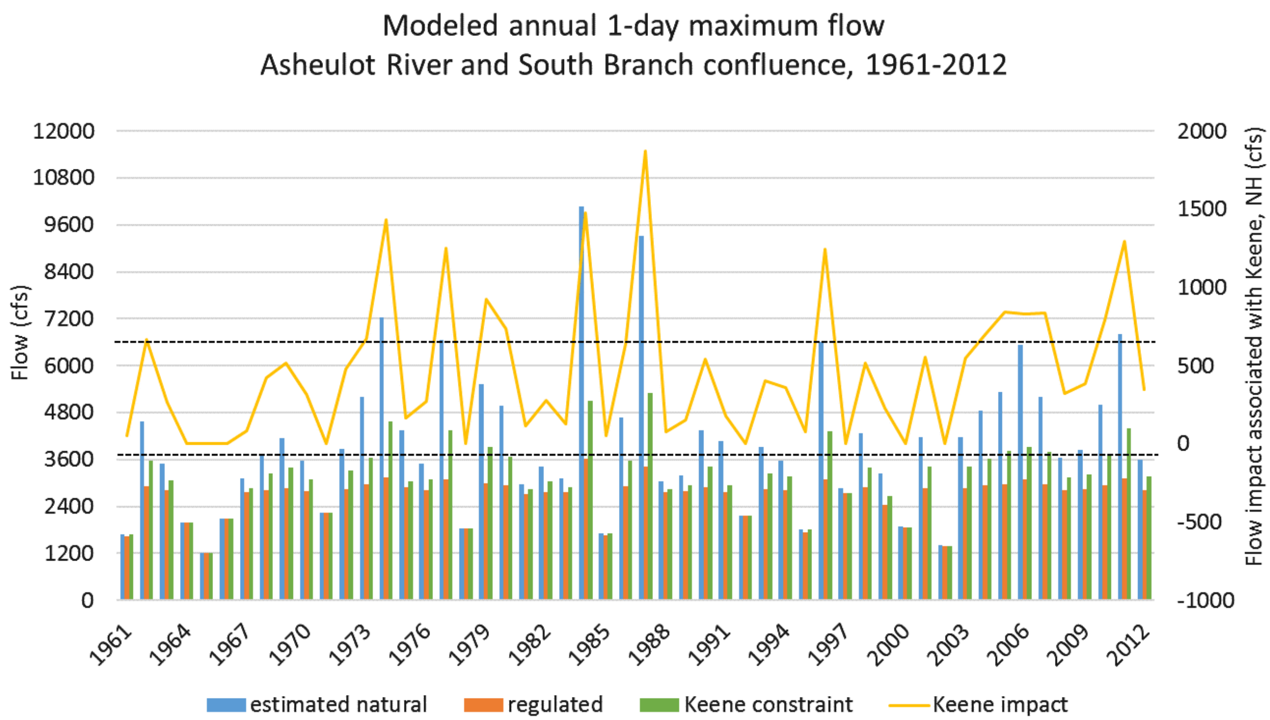


Figure 11. Annual maxima at Ashuelot River South Branch confluence, New Hampshire among three modeled scenarios (left y-axis): estimated natural flows (blue bars), current regulated flows (orange bars), and a scenario that removed the hydrologic constraint of the city of Keene, New Hampshire (green bars). The yellow line represents the difference in flow (right y-axis) between the current regulated flows (orange bars) and the scenario without the Keene constraint (green bars). The top dotted horizontal line represents the 10-year natural recurrence interval flood (NRI; 6651 cfs); the bottom dotted horizontal line represents the 2-year NRI flood (3769 cfs). The Keene constraint scenario demonstrated restoration of the magnitude of small floods (2-10 y NRI), but small floods were about half as frequent as under estimated natural conditions.

Optimized Scenario 2—West River: Under the second optimized scenario, the 25-foot pool rule for downstream passage of salmon smolt at Ball Mountain was removed from simulated operations. This resulted in improvement in the flow regime, specifically with regard to restoration of low flows (Figure 12). However, high flows were still impacted in this reach, including the loss of large floods (>10 year NRI).

6.2.3 ▸ Westfield River

The Westfield River has two USACE dams: Knightville and Littleville dams. Knightville Dam is located on the East Branch of the Westfield River, about 30 miles (48 kilometers) upstream from the mouth; Littleville Dam is located on the Middle Branch of the Westfield, just one mile (1.6 km) upstream of its confluence with the East Branch (Appendix A). There are two points of ecological interest located on the Westfield River; both sites are valued for their floodplain forest habitat, as well as instream habitat for resident and migratory fishes and freshwater mussels. The lower site is also an important location for open bar and beach habitat (Table 7; Figure 7).

Pinch Point Removal Scenario: There are four pinch points in the Westfield River watershed: two below Knightville representing yards and private residences, one site of private residences below Littleville Dam, and another site of private residences below the confluence of the Middle and East Branches. Removing these pinch points did not substantially improve natural flow metrics in the Westfield River.

Optimized Scenario: The optimized scenario for the Westfield River included adjusting the Knightville Dam storage target to change more gradually and to release high spring flows over a longer period of time. Storage targets for Littleville Dam continue to be maintained (conservation pool year-round). The optimized scenario resulted in little change to simulated operations, and there were consequently no improvements to the impacted natural flow metrics.

6.2.4 ▸ Farmington River

The Farmington River has one large USACE facility, the Colebrook River Dam, located in the upper reaches of the West Branch of the Farmington River in Colebrook, Connecticut near the Connecticut-Massachusetts border, about 57 miles (92 kilometers) upstream from the confluence of the Farmington and Connecticut rivers (Appendix A). In addition to flood risk management, Colebrook River reservoir provides reserve drinking water for Hartford, Connecticut's Metropolitan District Commission (MDC), which also operates a small hydropower station at the dam. There are two points of ecological interest downstream from Colebrook River Dam; both sites are valued for their floodplain forest and open bar and beach habitats, as well as instream habitat for resident and migratory fishes and freshwater mussels (Table 7; Figure 7).

Pinch Point Removal Scenario: There are three pinch points in the Farmington River watershed. One is a group of businesses in Unionville, Connecticut; another is agricultural fields in Simsbury, Connecticut. The third pinch point is Goodwin Dam, which is located directly below Colebrook River Dam, and has a release restriction of 3000 cfs (95 cms). Removing these pinch points did not substantially improve the natural flow metrics in the Farmington River.

Optimized Scenario: The optimized scenario for the Farmington River was not different from current operations, and there were therefore no changes to the impacted natural flow metrics.

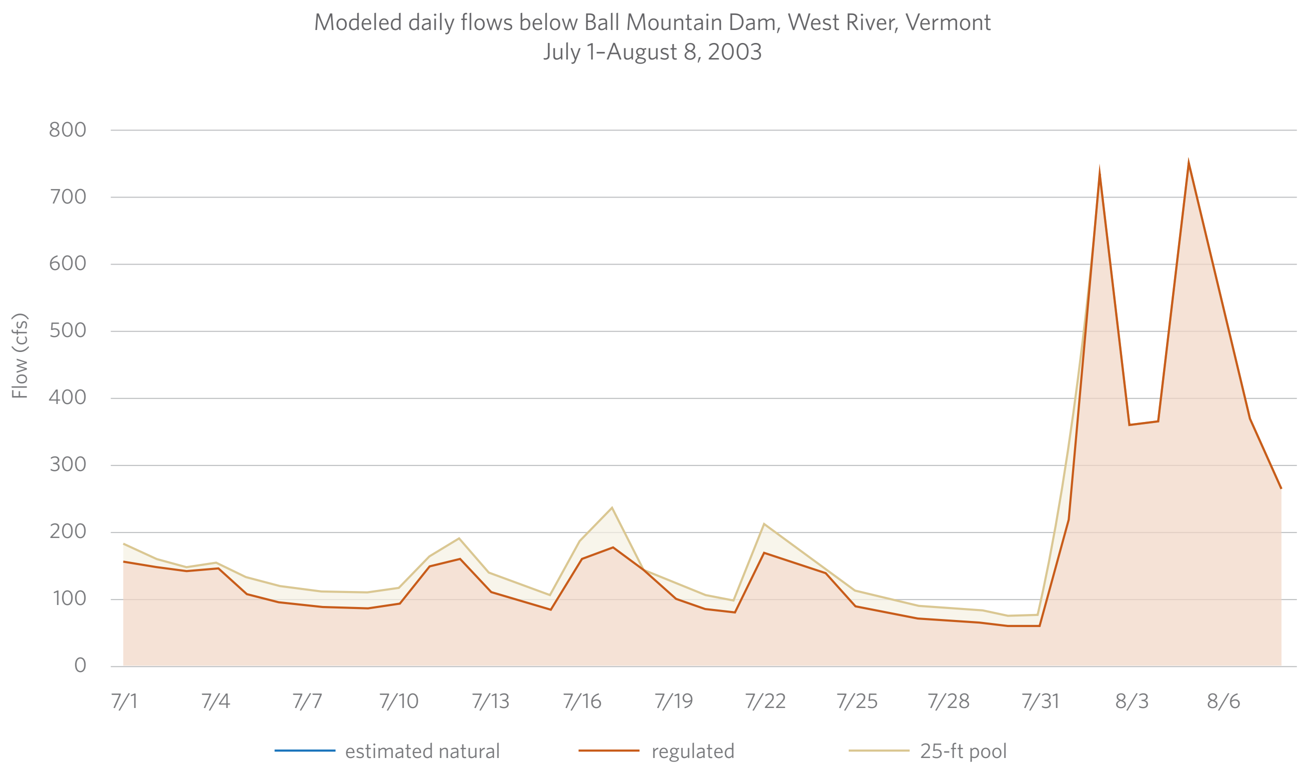


Figure 12. Modeled flows below Ball Mountain Dam, West River, Vermont. Three modeled scenarios are represented: estimated natural flows (blue line), current regulated flows (orange line), and a scenario that modeled the effect of removing a 25-foot pool constraint for downstream fish passage (gray line). The 25-foot pool scenario restored low flows such that modeled flows under this scenario were identical to estimated natural flows, thus the blue line representing the estimated natural flows is obscured by the overlying orange line representing current regulated flows.

6.3 Summary of Alternative Flow Regimes and Recommendations

Applying the optimization model to USACE operations yielded limited potential for improvement under the alternative flow management scenarios. In the West River, some improvement to low flows was predicted under the second optimization scenario, which modeled the removal of the 25-foot spring pool level for downstream passage of Atlantic salmon smolt at Ball Mountain Dam. Since the U.S. Fish and Wildlife Service Atlantic salmon restoration program was terminated in 2012, and fish passage needs are being addressed by the privately-owned hydropower facility on Ball Mountain Dam, the USACE no longer operates this 25-foot pool. However, it does continue to maintain a 65-foot summer and a 35-foot winter pool at Ball Mountain Dam, which prevent winter gate icing and unwanted sediment releases (for which the permanent pool was originally installed in the 1960's), and promotes other project purposes such as recreation and storage for hydropower generation. Any further adjustment to this operational constraint will require consultation with state agencies and local stakeholders, as well as careful consideration of the ecological gain achieved versus the resulting impacts.

Among the alternative scenarios evaluated, the largest improvements to ecological flows were observed on the Ashuelot River, when operational constraints directed toward protecting the city of Keene were removed from the model. Although it was interesting to observe this difference, removing the existing constraints that minimize damages in Keene cannot be considered as a management alternative, given that doing so would cause significant commercial and residential property damage. An effort to bypass flows around Keene could both further protect the city from damaging floods and provide the flows necessary to benefit floodplains and other habitats downstream. However, such an effort would likely be very costly with uncertain ecological results, and would require careful evaluation to determine whether benefits would warrant costs.

These results suggest that effective flow management in the Connecticut River watershed may require consideration of management alternatives beyond dam re-operation (in particular, daily flow re-operation at USACE dams). As mentioned previously, efforts to restore river health and function often employ dam removal; in this study we examined the potential for dam re-operation as another means to achieve river restoration in the Connecticut River watershed. However, additional alternatives such as bypass flows, structural changes to dams (including, but not exclusive to fish passage structures), purchase of conservation and flood easements, and riparian and floodplain restoration, may be more effective options for river restoration than dam re-operation in some cases. Because this Study focused on dam re-operation and did not attempt to quantify or evaluate these additional management alternatives, and due to limits in time and available funding, further investigation into these additional alternatives by the USACE and TNC will not be pursued under this study authority at this time. In the future, additional management scenarios and/or new ecological and other scientific information may result in requests by Study partners or basin stakeholders for new studies. Before these new studies are undertaken, the Study team recommends the development of specific, measurable conservation objectives, and careful cost-benefit analyses to determine whether the benefits to restoring habitat and maintaining services for people, are commensurate to the costs of large infrastructure or other high-investment alternatives.

7 | Discussion

The purpose of the Connecticut River Flow Restoration Study was to evaluate the feasibility of operational changes at large dams throughout the watershed to benefit ecological health and function while maintaining the important services provided by these dams. Initially, the Study aimed to evaluate the coordinated operation of multiple dams to meet watershed restoration goals. Because watersheds have an inter-connected network structure, and river flows above tidal influence are uni-directional, the coordinated management of many dams to meet an objective generally means meeting that objective at a point downstream from all of the dams. However, in the Connecticut River watershed, the downstream-most point (econode 30; Figure 7), although certainly hydrologically altered, is not the most-impacted point in the watershed. Rather, hydrologic impacts are localized and distributed throughout the Connecticut River watershed, and are most severe on tributaries. This pattern is related in part to reservoir storage capacity and the distribution of dams in the watershed, and may have contributed to the results of the initial alternative scenario, which suggested undesirable trade-offs for flood risk and hydrologic alteration under coordinated operations of multiple facilities across the watershed.

As mentioned earlier, most reservoirs in the watershed have relatively limited storage capacity, with "large" dams in the Study constituting those with only 10% storage of mean annual flow, a much smaller proportion of storage than that of large dams in other regions of the United States (Graf 1999). In some cases, as for the hydropower dams on the mainstem Connecticut River, this translates to relatively little impact on daily hydrology compared to the more significant impacts on a sub-daily scale (Zimmerman et al. 2010), which were not directly evaluated in this Study. Furthermore, in comparison to the total drainage area of the Connecticut River, only a relatively small proportion (13.9%; 1,567 mi^2 of 11,260 mi^2; 29,163 km^2) of drainage area is managed by USACE flood risk management dams. Thus, operations of these facilities are not affecting total mainstem volume as much as they are affecting tributary hydrology and the timing of mainstem flows, managing flood risk with strategically-placed dams on watershed tributaries that desynchronize flood peaks on the mainstem river. These localized and distributed hydrological impacts in the Connecticut River watershed requires a fundamentally different conceptual basis for watershed management than one based on singular downstream objectives. Watershed management goals may still be developed at the scale of the whole basin, but actions and measures of response will need to be considered in a localized and distributed fashion. That is, restoration of a particular ecological target will require establishing measurable goals that may be evaluated at multiple locations of desired restoration, and implementing flow management (or other restoration) actions in a manner that targets those locations.

Another fundamentally important management consideration raised by the results of this Study is the necessity of considering a broad set of management alternatives for meeting ecological restoration goals, beyond those traditionally relied upon for management of altered river systems. Because the Connecticut River has such a high density of dams and a long history of water management, a reasonable assumption was made that there would be enough operational flexibility among the many large dams in the watershed to warrant development of watershed-wide hydrological models. Although the analyses presented in this report are not exhaustive, they do target the greatest hypothesized and modeled impacts in the system—those to the large flood events—and flexibility in the operations of the facilities that cause these impacts is clearly limited. Upon close review of the operations of the 14 USACE flood risk management facilities, it is perhaps not surprising that there is limited operational flexibility, as these facilities intentionally pass all but the highest flows, and have limited to no permanent pools to provide flows when the river is not flooding (pools that do exist, for example at Ball Mountain Dam on the West River, are proportionally small compared to total storage). When the river is flooding, operations are intended to manage flood risk, and model results suggest that physical points (e.g., homes, businesses, and communities) in the landscape are the principal operational constraints to meeting high-flow ecological targets. These results confirm that flow restoration—in particular regarding high flow and flood events—is extremely challenging when operators must consider risk management of downstream communities.

Thus, management alternatives to meet targets related to flooding, or to the species and the communities dependent on flooding, will require creativity, as well as potentially high capital investment. Alternative management options could include pursuing structural changes to dams, developing ways to bypass flow, implementing sediment management actions, or purchasing and restoring land to provide floodplain storage or to remove downstream constraints. In addition, hydropower installations on existing USACE dams could potentially increase accessibility to management of flows outside of flood risk management operations. For example, small run-of-river hydropower units have recently been added to the USACE Ball Mountain and Townshend dams on the West River, allowing the projects to control flow more finely than what had been possible with existing gate infrastructure alone. It will also be important to consider factors related to hydrology, but not directly managed by flow-related dam operations. For example, a significant ecological effect of dams is the interruption of the natural sediment regime, yet restored sediment delivery is often not achieved by simple flow re-management. Restoration of some ecological targets, such as floodplain forests, freshwater mussels, and riparian tiger beetles, will likely also depend upon restoration of these additional critical processes.

Assessment of creative management alternatives will require clear identification of ecological objectives with measurable attributes that will allow for an adequate assessment of costs and benefits of actions. For example, if ecological benefits to the floodplain forest ecosystem are most likely achieved through actions that are not operational, it will be important to understand what the desired outcomes for floodplain forests are, and what the predicted benefits of proposed alternatives will be, to assess the costs and benefits of management actions. Ideally, a management action with a lower financial cost and flood risk and a higher ecological benefit will be desired over an action with higher financial cost, higher flood risk, and a lower ecological benefit. Cost-benefit analyses may depend on understanding what current and predicted floodplain forest area would be, which may depend on having additional models developed to aid this prediction. However, investment in any such potential future investigation by Study partners or other stakeholders should only be made once quantifiable management objectives have been explicitly identified.

Although operations of the USACE dams were the focus of management alternative development due to estimated impacts to high flows and to the current collaboration between the Conservancy and the USACE through the Sustainable Rivers Program, these dams comprise just a portion of the large dams in the watershed. Recreational dams may also have limited flexibility due to their general lack of control (they often have just physical, and not operational constraints), and water supply reservoirs are often constrained by the need to store water for residential and municipal needs during those periods when water is most needed for ecological flow augmentation. Perhaps the greatest potential for re-operation lies with the many hydropower dams in the Connecticut River watershed. These dams represent the greatest proportion of large dams in the system (Appendix A), and may have the greatest operational flexibility given their multiple points of control (via gates and one or more turbines). The watershed models evaluated in this Study were focused on the daily hydrology of the Connecticut River, and therefore did not capture the primary hydrological impacts of hydropower facilities, in particular peaking hydropower facilities, which are principally observed at the sub-daily scale. Peaking hydropower facilities in the Connecticut River watershed hold and release water in a pattern that follows the hourly energy price curve, so that water is held when prices are low, and released when prices are high. A sub-daily model that is an extension of the CROME model has been developed (Section 4.4; Appendices K and L) to be used by stakeholders for evaluation of alternative operational scenarios in the hydropower re-licensing process for the Wilder, Bellows Falls, and Vernon dams, and for the Northfield Mountain/Turners Falls hydropower project (underway as of 2018).

Under the current modeling effort, the linear programming model used for optimization imposed strict constraints on how many objectives could be evaluated, and how those objectives could be represented in the model. This led to a focus on using the natural hydrology as a target in order to capture all taxa groups of interest in one objective function, based on the theory of the natural flow paradigm (Poff et al. 1997; Bunn and Arthington 2002; Poff et al. 2010; Richter et al. 2011). The extensive set of flow hypotheses and recommendations developed by natural resource experts at the 2011 workshop (Section 3.2; Appendix B) were thus never fully incorporated into the flow management alternatives analysis due to the constraints of the optimization model. However, achievement of a natural hydrology may not be a feasible management goal in a system as historically heavily-managed as the Connecticut River watershed. Rather, a designed approach where explicit ecological goals are identified, and hypotheses of impact and response are developed to link to specific management alternatives may be more appropriate, given the unlikelihood of ever returning to a "natural" state (Acreman et al. 2014). Even if all of the dams were removed at once, the existing flow regime may not be the same as it was when the dams were built due to changes in channel shape and structure, geomorphology, and in the overall landscape. Furthermore, the natural community has been changed dramatically, due in part to the introduction of a large number of non-native species. It is therefore crucial that managers and conservationists think about what desired conditions would be, and develop measurable objectives that reflect these conditions. In light of this, the set of information from the 2011 workshop will be an invaluable resource for development of management objectives and alternatives specific to Connecticut River conservation targets. The developed hypotheses of hydrological requirements for ecological targets may be used in concert with modeled changes in hydrology to design management actions aimed at achieving ecological objectives, while also meeting other important objectives, such as managing flood risk, maximizing energy production, meeting water supply demands, and maintaining recreational opportunities.

When the Connecticut River Flow Restoration Study was initiated in 2005, the re-operation of dams to provide environmental flows to benefit downstream ecosystems was a relatively new management strategy that was founded on strong science and had demonstrated potential for positive results across the world (Arthington and Pusey 2003; Poff et al. 2003; Tharme 2003; Acreman and Dunbar 2004; Rood et al. 2005). Development of watershed-wide models to support flow restoration in the Connecticut River was a logical application of this scientific and management knowledge and experience (Poff et al. 2010; Kendy et al. 2012). Indeed, the model of estimated natural flows (CRUISE; Section 4.2; Appendix G) and the model of current operations at 73 dams in the watershed (HEC-ResSim; Section 4.3; Appendix H) proved particularly useful for evaluating the potential for flow restoration through dam re-operation in the Connecticut River watershed by demonstrating 1) where the greatest impacts to hydrology were estimated to occur, and 2) how potential management alternatives performed in terms of identified ecological flow parameters at these locations. Together these models have made a substantial contribution to our understanding of Connecticut River watershed hydrology. However, given the results of the optimization model, we would encourage watershed managers in highly-developed watersheds like the Connecticut River watershed to consider a more "designed approach" (Acreman et al. 2014), being explicit about desired conservation objectives and the hypothesized links to hydrology, so that alternatives may be developed to meet defined conservation objectives, and if possible, evaluated with tools similar to CRUISE and HEC-ResSim.

In the Connecticut River watershed, the models developed for this Study will continue to be used (and are being used; see Appendix F) by stakeholders in various management contexts to evaluate the hydrological consequences of action alternatives—whether operational or physical. In support of these efforts, the re-operation of dams will continue to be an effective strategy for river restoration—especially in the context of hydropower management. However, as demonstrated by the results of this Study, dam re-operation alone is unlikely to be sufficient to achieve restoration goals in the Connecticut River watershed. As we continue to expand our understanding of the science and management of watershed and flow restoration, additional conservation strategies beyond dam re-operation, such as sediment and land use management, will necessarily play an increasing role. Incorporation of these and other creative management strategies into a holistic approach to watershed management will be instrumental in the achievement of successful watershed restoration in the Connecticut River and in similar watersheds across the globe.

References

Acreman, M., A.H. Arthington, M.J. Colloff, C. Couch, N.D. Crossman, F. Dyer, I. Overton, C.A. Pollino, M.J. Stewardson, W. Young. 2014. Environmental flows for natural, hybrid, and novel riverine ecosystems in a changing world. Frontiers in Ecology and the Environment 12:466-473.

Acreman, M.C. and M.J. Dunbar. 2004. Defining environmental flow requirements—a review. Hydrology and Earth System Sciences 8:861-876.

Anderson, M.G., C.E. Ferree, A.P. Olivero, and F. Zhao. 2010. Assessing floodplain forests: using flow modeling and remote sensing to determine the best places for conservation. Natural Areas Journal 30:39-52.

Archfield, S.A., R.M. Hirsch, A. Viglione, and G. Blöschl. 2016. Fragmented patterns of flood change across the United States. Geophysical Research Letters 43:10232-10239.

Archfield, S.A., P.A. Steeves, J.D. Guthrie, and K.G. Ries III. 2013. Towards a publicly available, map-based regional software tool to estimate unregulated daily streamflow at ungauged rivers. Geoscientific Model Development 6:101-115.

Archfield, S.A., R.M. Vogel, P.A. Steeves, S.L. Brandt, P.K. Weiskel, and S.P. Garabedian. 2010. The Massachusetts Sustainable-Yield Estimator: A decision-support tool to assess water availability at ungagged stream locations in Massachusetts: U.S. Geologial Survey Scientific Investigations Reprot 2009-5227, 41 pp.

Armstrong, W.H., M.J. Collins, and N.P. Snyder. 2012. Increased frequency of low-magnitude floods in New England. Journal of the American Water Resources Association 48:306-320.

Arthington, A.H., and B.J. Pusey. 2003. Flow restoration and protection in Australian rivers. River Research and Applications 19:377-395.

Bain, M.B., J.T. Finn, and H.E. Booke. 1988. Streamflow regulation and fish community structure. Ecology 69:382—392. doi:10.2307/1940436.

Bednarek, A.T. 2001. Undamming rivers: A review of the ecological impacts of dam removal. Environmental Management 27: 803-814.

Bogan, A.E. 2008. Global diversity of freshwater mussels (Mollusca, Bivalvia) in freshwater. Hydrobiologia 595:139-147.

Bowen, Z.H., K.D. Bovee, and T.J. Waddle. 2003. Effects of flow regulation on shallow-water habitat dynamics and floodplain connectivity. Transactions of the American Fisheries Society 132:809-823.

Brown, J.J., K.E. Limburg, J.R. Waldman, K. Stephenson, E.P. Glenn, F. Juanes, and A. Jordaan. 2013. Fish and hydropower on the U.S. Atlantic coast: failed fisheries policies from half-way technologies. Conservation Letters 6:260-286

Bunn, S.E., and A.H. Arthington. 2002. Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. Environmental Management 30:492-507.

Burke M., K. Jorde, and J.M. Buffington. 2009. Application of a hierarchical framework for assessing environmental impacts of dam operation: Changes in streamflow, bed mobility and recruitment of riparian trees in a western North American river. Journal of Environmental Management 90 (Supplement 3): S224-S236.

Canada Centre for Remote Sensing (CCRS), Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (CONABIO), Comisión Nacional Forestal (CONAFOR), Insituto Nacional de Estadística y Geografía (INEGI), U.S. Geological Survey (USGS). 2013. 2010 Land Cover of North America at 250 meters [GIS data]. CCRS, Ottawa. Available: http://www.cec.org/tools-and-resources/map-files/land-cover-2010. (Accessed 30 December 2016).

Carpenter, B. 2007. Connecticut River Floodplain Forest Inventory: Essex County, Vermont & Coos County, New Hampshire. Essex County Natural Resources Conservation District, St. Johnsbury, Vermont, USA.

Castro-Santos, T., and B.H. Letcher. 2010. Modeling migratory energetics of Connecticut River American shad (*Alosa sapidissima*): implications for the conservation of an iteroparous anadromous fish. Canadian Journal of Fisheries and Aquatic Sciences 67:806-830.

Connecticut River Atlantic Salmon Commission (CRASC). 1998. Strategic plan for the restoration of Atlantic salmon to the Connecticut River. CRASC, Sunderland, MA. Available: http://www.fws.gov/r5crc/stuff/stplan.html. (Accessed: 29 April 2014).

Connecticut River Joint Commissions (CRJC). 2009. Connecticut River Corridor Management Plan, Water Management Plan, Headwaters Region. Charlestown, New Hampshire.

Cooney, P.B., and T.J. Kwak. 2013. Spatial extent and dynamics of dam impacts on tropical island freshwater fish assemblages. BioScience 63:176-190.

U.S. Department of Energy (USDOE). 2016. Hydropower vision: A new chapter for America's first renewable electricity source. U.S. Department of Energy, Wind and Water Power Technologies Office. Available: https://energy.gov/eere/water/articles/hydropower-vision-new-chapter-america-s-1st-renewable-electricity-source. (Accessed 21 February 2017).

Demaria, E.M.C., J.K. Roundy, S. Wi, and R.N. Palmer. 2016. The effects of climate change on seasonal snowpack and the hydrology of the northeastern and upper Midwest United States. Journal of Climate. 29:6527-6541.

Dixon, M.D., C.J. Boever, V.L. Danzeisen, C.L. Merkord, E.C. Munes, M.L. Scott, W.C. Johnson, and T.C. Cowman. 2015. Effects of a "natural' flood event on the riparian ecosystem of a regulated large-river system: the 2011 flood on the Missouri River, USA. Ecohydrology 8:812-824.

Dynesius, M., and C. Nilsson. 1994. Fragmentation and flow regulation of river systems in the northern third of the world. Science 266:753-762.

Fenneman, N.M. 1938. Physiography of eastern United States. McGraw-Hill, New York.

Fenneman, N.M. and D.W. Johnson. 1946. Physical divisions of the United States, scale: 1:7,000,000. U.S. Geological Survey, Reston, VA. Available: https://water.usgs.gov/lookup/getspatial?physio. (Accessed 30 December 2016).

Freeman, M.C., Z.H. Bowen, K.D. Bovee and E.R. Irwin. 2001. Flow and habitat effects on juvenile fish abundance in natural and altered flow regimes. Ecological Applications 11:179-190.

Friedl, G., and A. Wüest. 2002. Disrupting biogeochemical cycles—Consequences of damming. Aquatic Sciences 64:55-65.

Galbraith, H.S., C.J. Blakeslee, and W.A. Lellis. 2015. Behavioral responses of freshwater mussels to experimental dewatering. Freshwater Science 34(1):42-52.

Garabedian, S.G., F.G. Coles, S.J. Grady, E.C. Todd Trench, and M.J. Zimmerman. 1998. Water quality in the Connecticut, Housatonic, and Thames river basins, Connecticut, Massachusetts, New Hampshire, New York, and Vermont, 1992-1995. U.S., Geological Survey Circular 1155. U.S. Geological Survey, Marlborough, Massachusetts.

Garcia, X.-F., I. Schnauder, and M.T. Pusch. 2012. Complex hydromorphology of meanders can support benthic invertebrate diversity in rivers. Hydrobiologia 685:49-68.

Gates, K.K., C.C. Vaughn, and J.P. Julian. 2015. Developing environmental flow recommendations for freshwater mussels using the biological traits of species guilds. Freshwater Biology 60:620-635.

Gay, P.S., J. O'Donnell, and C.A. Edwards. 2004. Exchange between Long Island Sound and adjacent waters, Journal of Geophysical Research 109:C06017.

Gephard, S., and J. McMenemy. 2004. An overview of the program to restore Atlantic salmon and other diadromous fishes to the Connecticut River with notes on the current status of these species in the river. American Fisheries Society Monograph 9:287-317.

Gope, E.T., U.G.W. Sass-Klaassen, K. Irvine, L. Beevers, and E.M.A. Hes. 2015. Effects of flow alteration on Apple-ring Acacia (Faidherbia albida) stands, Middle Zambezi floodplains, Zimbabwe. Ecohydrology 8:922-934.

Govatski, D. 2010. Maidstone Bird Survey. Final Report submitted to The Nature Conservancy, New Hampshire Chapter. Unpublished report.

Graf, W.L. 1999. Dam nation: a geographic census of American dams and their large-scale hydrologic impacts. Water Resources Research 35:1305-1311.

Graf, W.L. 2006. Downstream hydrologic and geomorphic effects of large dams on American rivers. Geomorphology 79:336-360.

Greene, K.E., J.L. Zimmerman, R.W. Laney, and J C. Thomas-Blate. 2009. Atlantic coast diadromous fish habitat: a review of utilization, threats, recommendations for conservation, and research needs. Atlantic States Marine Fisheries Commission Habitat Management Series No. 9, Washington, DC.

Hanfling, B., and D. Weetman. 2006. Concordant genetic estimators of migration reveal anthropogenically enhanced source-sink population structure in the river sculpin, *Cottus gobio*. Genetics 173:1487-1501.

Hodgkins, G.A., and R.W. Dudley. 2006. Changes in the timing of winter-spring streamflows in eastern North America, 1913-2002. Geophysical Research Letters 33:L06402.

Hodgkins, G.A., R.W. Dudley, and T.G. Huntington. 2003. Changes in the timing of high river flows in New England over the 20th century. Journal of Hydrology 278:244-252.

Horton, R., G. Yohe, W. Easterling, R. Kates, M. Ruth, E. Sussman, A. Whelchel, D. Wolfe, and F. Lipschultz. 2014. Chapter 16: Northeast. In J.M. Melillo, T.C. Richmond, G.W. Yohe, eds. Climate change impacts in the United States: The third national climate assessment. U.S. Global Change Research Program. Available: http://nca2014.globalchange.gov/report/regions/northeast.

Huntington, T.G., G.A. Hodgkins, B.D. Keim, and R.W. Dudley. 2004. Changes in the proportion of precipitation occurring as snow in New England (1949-2000). Journal of Climate 17:2626-2636.

Jahns, R.H. 1947. Geologic features of the Connecticut Valley, Massachusetts as related to recent floods. U.S. Government Printing Office, Washington, D.C.

Jager, H.I., J.A. Chandler, K.B. Lepla, W. Van Winkle. 2001. A theoretical study of river fragmentation by dams and its effects on white sturgeon populations. Environmental Biology of Fishes 60:347-361

Johnson, W.C., M.D. Dixon, M.L. Scott, L. Rabbe, G. Larson, M. Volke, and B. Werner. 2012. Forty years of vegetation change on the Missouri River floodplain. Bioscience 62:123-135.

Jones, M.T. 2009. Spatial ecology, population structure, and conservation of the wood turtle, *Glyptemys insculpta*, in central New England. PhD Dissertation, University of Massachusetts Amherst, Amherst, Massachusetts.

Junk, W.J., P.B. Bayley, and R.E. Sparks. 1989. The flood pulse concept in river-floodplain systems. Canadian Special Publication of Fisheries and Aquatic Sciences 106:110-127.

Junker, J., P. Armin, C.E. Wagner, S. Mwaiko, B. Germann, O. Seehausen, I. Keller. 2012. River fragmentation increases localized population genetic structure and enhances asymmetry of dispersal in bullhead (*Cottus gobio*). Conservation Genetics 13:545-556.

Kendy, E., C. Apse, and K. Blann. 2012. A practical guide to environmental flows for policy and planning. The Nature Conservancy. Available: http://conservationgateway.org/ConservationPractices/Freshwater/EnvironmentalFlows.

Kieffer, M., and B. Kynard. 2012. Spawning and non-spawning migrations, spawning, and the effect of river regulation on spawning success of Connecticut River shortnose sturgeon. Pages 73-113 in B. Kynard, P. Bronzi, and H. Rosenthal, eds. Life history and behaviour of Connecticut River shortnose and other sturgeons. Special Publication 4, World Sturgeon Conservation Society, Norderstedt, Germany.

King, A.J., P. Humphries, and P.S. Lake. 2003. Fish recruitment on floodplains: the roles of patterns of flooding and life history characteristics. Canadian Journal of Fisheries and Aquatic Sciences 60:773-786.

Kynard, B. 1997. Life history, latitudinal patterns, and status of the shortnose sturgeon, *Acipenser brevirostrum*. Environmental Biology of Fishes 48:319-334.

Kynard, B., M. Kieffer, M. Horgan, B.E. Kynard, M. Burlingame, and P. Vinogradov. 2012. Seasonal movements among river reaches, migration strategies, and population structure of the divided Connecticut River shortnose sturgeon population: the effects of Holyoke Dam. Pages 1-49 in B. Kynard, P. Bronzi, and H. Rosenthal, eds. Life history and behaviour of Connecticut River shortnose and other sturgeons. Special Publication 4, World Sturgeon Conservation Society, Norderstedt, Germany.

Lawrence, E.R., A. Kuparinen, and J.A. Hutchings. 2016. Influence of dams on population persistence in Atlantic salmon (*Salmo salar*). Canadian Journal of Zoology 94:329-338.

Lehner, B., C.R. Liermann, C. Revenga, C. Vörösmarty, B. Fekete, P. Crouzet, P. Döll, M. Endejan, K. Frenken, J. Magome, C. Nilsson, J.C. Robertson, R. Rödel, N. Sindorf, and D. Wisser. 2011. High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management. Frontiers in Ecology and the Environment 9:494-502.

Limburg, K.E., and J.R. Waldman. 2009. Dramatic declines in North Atlantic diadromous fishes. BioScience 59:955-965.

Magilligan, F.J., and K.H. Nislow. 2001. Long-term changes in regional hydrologic regime following impoundment in a humid-climate watershed. Journal of the American Water Resources Association 37:1551-1569.

Magilligan, F.J., and K.H. Nislow. 2005. Changes in hydrologic regime by dams. Geomorphology 71:61-78.

Mahoney, J.M., and S.B. Rood. 1998. Streamflow requirements for cottonwood seedling recruitment— An integrative model. Wetlands 18:634-645.

Marks, C.O., K.H. Nislow, and F.J. Magilligan. 2014. Quantifying flooding regime in floodplain forests to guide river restoration. Elementa: Science of the Anthropocene 2:000031.

Martin, E.H., and C.D. Apse. 2011. Northeast aquatic connectivity: an assessment of dams on northeastern rivers. The Nature Conservancy, Eastern Freshwater Program. Available: http://rcngrants.org/sites/default/files/final_reports/NEAquaticConnectivity_Report.pdf.

Massachusetts Water Resources Authority (MWRA). 2016. Water Supply and Demand. Available: http://www.mwra.state.ma.us/04water/html/wsupdate.htm

Mims, M.C., and J.D. Olden. 2012. Life history theory predicts fish assemblage response to hydrologic regimes. Ecology 93:35-45.

Mims, M.C., and J.D. Olden. 2013. Fish assemblages respond to altered flow regimes via ecological filtering of life history strategies. Freshwater Biology 58:50-62.

Naiman, R.J., J.J. Latterell, N.E. Pettit, and J.D. Olden. 2008. Comptes Rendus Geoscience 240:629-643.

NatureServe. 2014. NatureServe Explorer: An online encyclopedia of life [web application]. Version 7.1. NatureServe, Arlington, VA. Available: http://explorer.natureserve.org. (Accessed: 15 May 2014).

Nedeau, E.J. 2008. Freshwater mussels and the Connecticut River watershed. Connecticut River Watershed Council, Greenfield, Massachusetts.

Nilsson, C., and B. Malm-Renöfält. 2008. Linking flow regime and water quality in rivers: a challenge to adaptive catchment management. Ecology and Society 13(2):18 [online]. Available: http://www.ecologyandsociety.org/vol13/iss2/art18/.

Nilsson, C., C.A. Reidy, M. Dynesius, and C. Revenga. 2005. Fragmentation and flow regulation of the world's large river systems. Science 308:405-408.

Nislow, K.H., F.J. Magilligan, H. Fassnacht, D. Bechtel, and A. Ruesink. 2002. Effects of dam impoundment on the flood regime of natural floodplain communities in the upper Connecticut River. Journal of the American Water Resources Association 38:1533-1548.

Northeast Utilities Presentation. 1969. Presented to The City of Springfield Water Commission, January 2, 1969

O'Connor, J.E., J.J. Duda, and G.E. Grant. 2015. 1000 dams down and counting. Science 348:496–497.

Pearson, D.L., C.B. Knisley, and C.J. Kazilek. 2006. A field guide to the tiger beetles of the United States and Canada: identification, natural history, and distribution of the Cicindelidae. Oxford University Press, New York.

Petts, G.E., and A.G. Gurnell. 2005. Dams and geomorphology: research progress and future directions. Geomorphology 71:27-47.

Pitta, B. 2011. Utilizing a decision support system to optimize reservoir operations to restore the natural flow distribution In the Connecticut River watershed. Masters Thesis. University of Massachusetts at Amherst, Amherst, Massachusetts.

Poff, N.L., J.D. Allan, M.B. Bain, J.R. Karr, K.L. Prestegaard, B.D. Richter, R.E. Sparks, and J.C. Stromberg. 1997. The natural flow regime. BioScience 47:769-784.

Poff, N.L., J.D. Allan, M.A. Palmer, D.D. Hart, B.D. Richter, A.H. Arthington, K.H. Rogers, J.L. Meyer, and J.A. Stanford. 2003. River flows and water wars: Emerging science for environmental decision making. Frontiers in Ecology and the Environment 1(6):298-306.

Poff, N. L., B.D. Richter, A.H. Arthington, S.E. Bunn, R.J. Naiman, E. Kendy, M. Acreman, C. Apse, B.P. Bledsoe, M.C. Freeman, J. Henriksen, R.B. Jacobson, J.G. Kennen, D.M. Merritt, J.H. O'Keeffe, J.D. Olden, K. Rogers, R. Tharme, and A. Warner. 2010. The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. Freshwater Biology 55:147-170.

Poff, N.L., and J.K.H. Zimmerman. 2010. Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows. Freshwater Biology 55:194-205.

Richter, B.D., Baumgartner, J.V., Powell, J., and Braun, D.P. 1996. A method for assessing hydrologic alteration within ecosystems. Conservation Biology 10:1163-1174.

Richter, B.D., M.M. Davis, C. Apse, and C. Konrad. 2011. A presumptive standard for environmental flow protection. River Research and Applications 28:1312-1321.

Richter, B.D., and G.A. Thomas. 2007. Restoring environmental flows by modifying dam operations. Ecology and Society 12(1):12.

Rolls, R.J., C. Leigh and F. Sheldon. 2012. Mechanistic effects of low-flow hydrology on riverine ecosystems: ecological principles and consequences of alteration. Freshwater Science 31:1163-1186.

Rood, S.B., G.M. Samuelson, J.H. Braatne, C.R. Gourley, F.M.R. Hughes, and J.M. Mahoney. 2005. Managing river flows to restore floodplain forests. Frontiers in Ecology and the Environment 3:193-201.

Schlosser, I.J. 1991. Stream fish ecology: A landscape perspective. BioScience 41:704-712.

Stallins, J.A., M. Nesius, M. Smith, and K. Watson. 2010. Biogeomorphic characterization of floodplain forest change in response to reduced flows along the Apalachicola River, Florida. River Research and Applications 26:242-260.

Steinschneider, S., A. Bernstein, R. Palmer, and A. Polebitski. 2013. Reservoir management optimization for basin-wide ecological restoration in the Connecticut River. Journal of Water Resources Planning and Management 140(9):04014023.

Strayer, D.L. 1999. Use of flow refuges by unionid mussels in rivers. Journal of the North American Benthological Society 18:468-476.

Strayer, D.L., J.A. Downing, W.R. Haag, T.L. King, J.B. Layzer, T.J. Newton, and S.J. Nichols. 2004. Changing perspectives on pearly mussels, North America's most imperiled animals. BioScience 54:429-439.

Tharme, R.E. 2003. A global perspective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies for rivers. River Research and Applications 19:397-441.

Tockner, K., and J. A. Stanford. 2002. Riverine flood plains: present state and future trends. Environmental Conservation 29:308-330

U.S. Fish and Wildlife Service (USFWS). 1993. Puritan tiger beetle (*Cicindela puritana* G. Horn) recovery plan. Hadley, MA. Available: http://ecos.fws.gov/docs/recovery_plan/930929a.pdf. (Accessed: 15 May 2014).

U.S. Geological Survey (USGS). 1991. National water summary 1988-89: Hydrologic events and floods and droughts. Water Supply Paper 2375. USGS, Reston, VA. Available: https://pubs.usgs.gov/wsp/2375/report.pdf.

Vaughn, C.C., and C.M. Taylor. 1999. Impoundments and the decline of freshwater mussels: a case study of an extinction gradient. Conservation Biology 13:912-920.

Vedachalam S., and Riha S. J. 2014. Small is beautiful? State of the dams and management implications for the future. River Research Applications 30:1195–1205, doi: 10.1002/rra.2698.

Wolman, M.G. and Eiler, J.P. 1958. Reconnaissance study of erosion and deposition produced by the flood of August 1955 in Connecticut. Transactions, American Geophysical Union 39: doi: 10.1029/TR039i001p00001. issn: 0002-8606.

Wood, P.J., and P.D. Armitage. 1997. Biological effects of fine sediment in the lotic environment. Environmental Management 21:203-217.

Yamamoto, S., K. Morita., I. Koizumi, and K. Maekawa. 2004. Genetic differentiation of white-spotted char (*Salvelinus leucomaenis*) populations after habitat fragmentation: spatial-temporal changes in gene frequencies. Conservation Genetics 5:529-538.

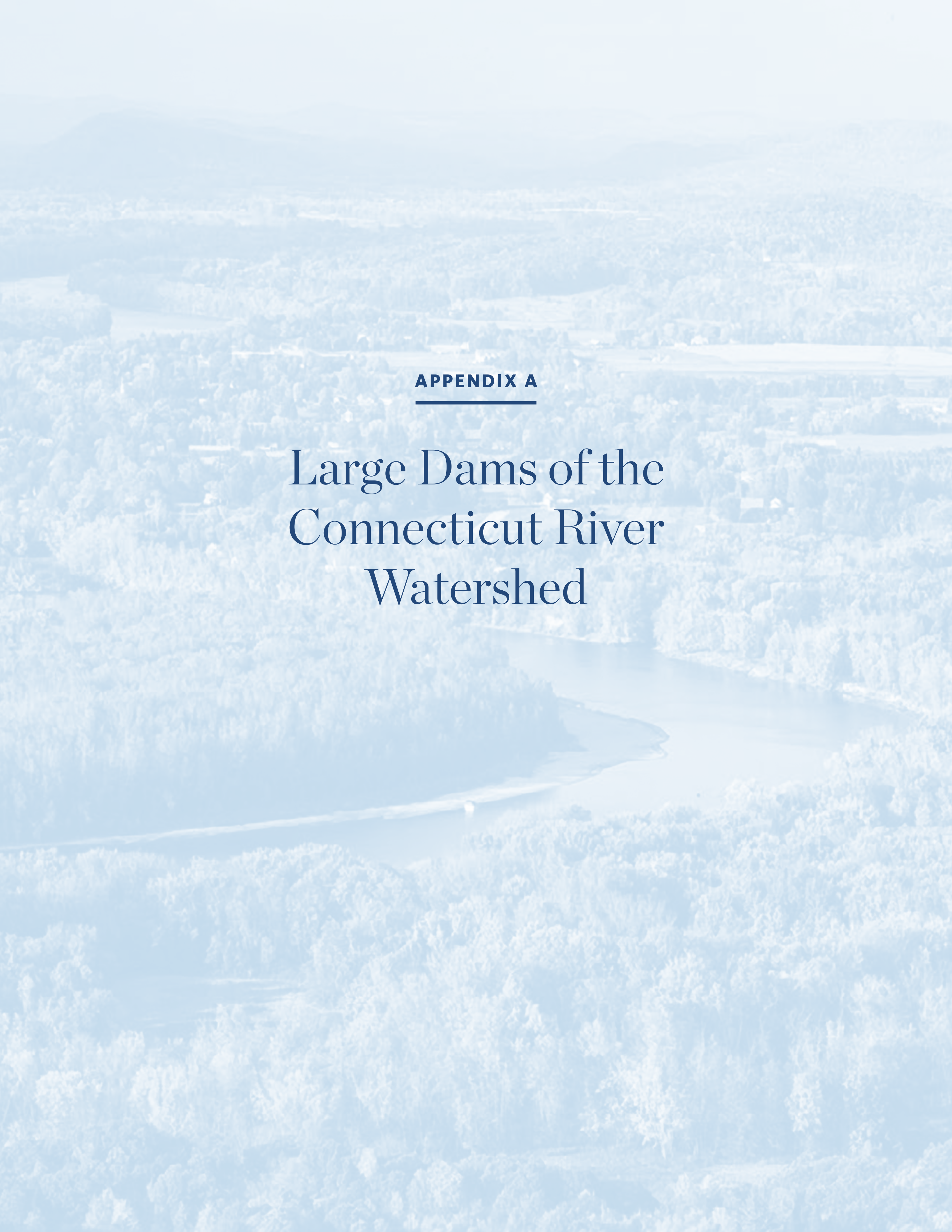
Young, P.S., J.J. Cech Jr, and L.C. Thompson. 2011. Hydropower-related pulsed-flow impacts on stream fishes: a brief review, conceptual model, knowledge gaps, and research needs. Reviews in Fish Biology and Fisheries 21:713-731.

Zimmerman, J. 2006a. Hydrologic effects of flood control dams in the Ashuelot River, New Hampshire and West River, Vermont. The Nature Conservancy, Connecticut River Program, Northampton, MA.

Zimmerman, J. 2006b. Response of physical processes and ecological targets to altered hydrology in the Connecticut River basin. The Nature Conservancy, Connecticut River Program, Northampton, MA.

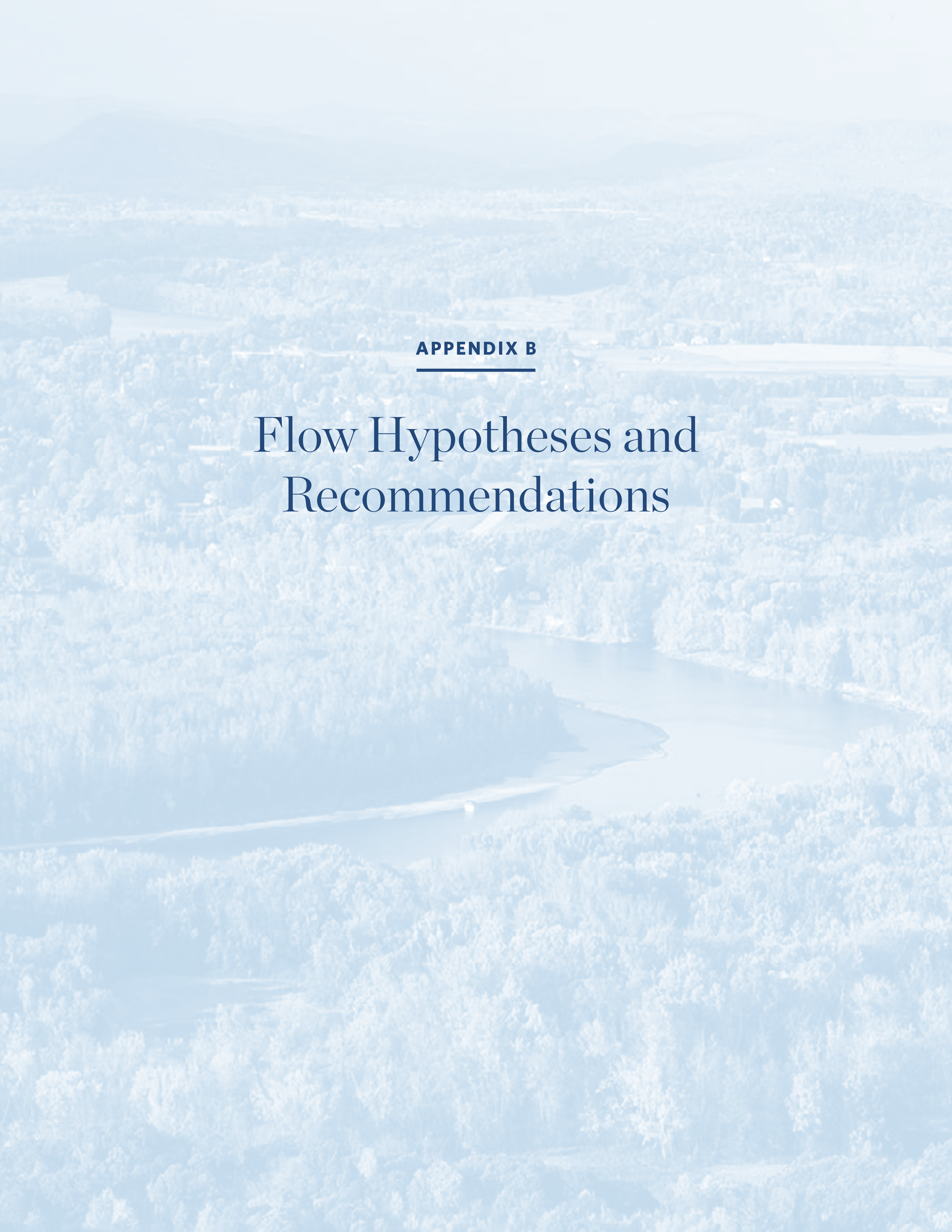
Zimmerman, J., and A. Lester. 2006. Spatial distribution of hydrologic alteration and fragmentation among tributaries of the Connecticut River. The Nature Conservancy, Connecticut River Program, Northampton, MA.

Zimmerman, J., B.H. Letcher, K.H. Nislow, K.A. Lutz, and F.J. Magilligan. 2010. Determining the effects of dams on subdaily variation in river flows at a whole-basin scale. River Research and Applications 26:1246-1260.



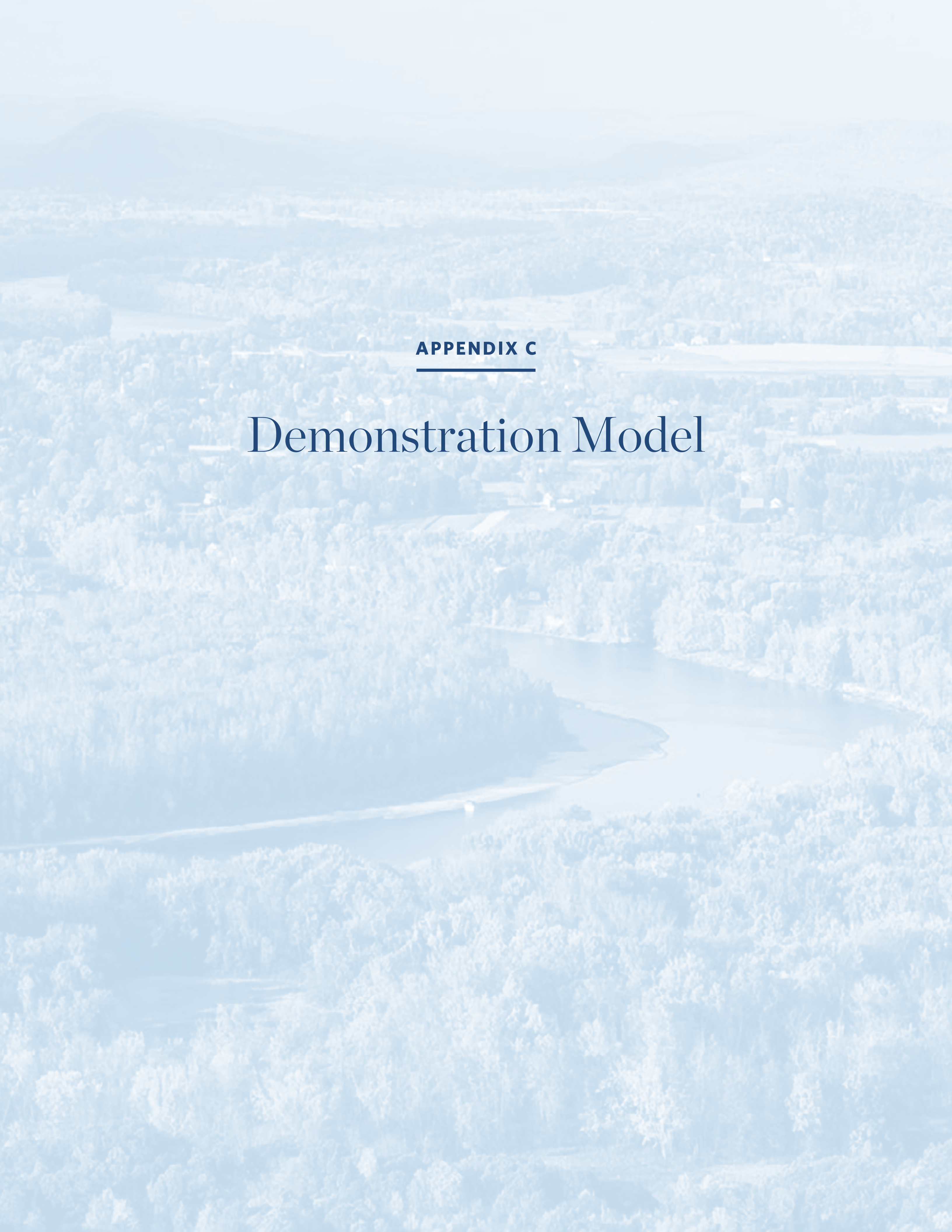
APPENDIX A

Large Dams of the Connecticut River Watershed



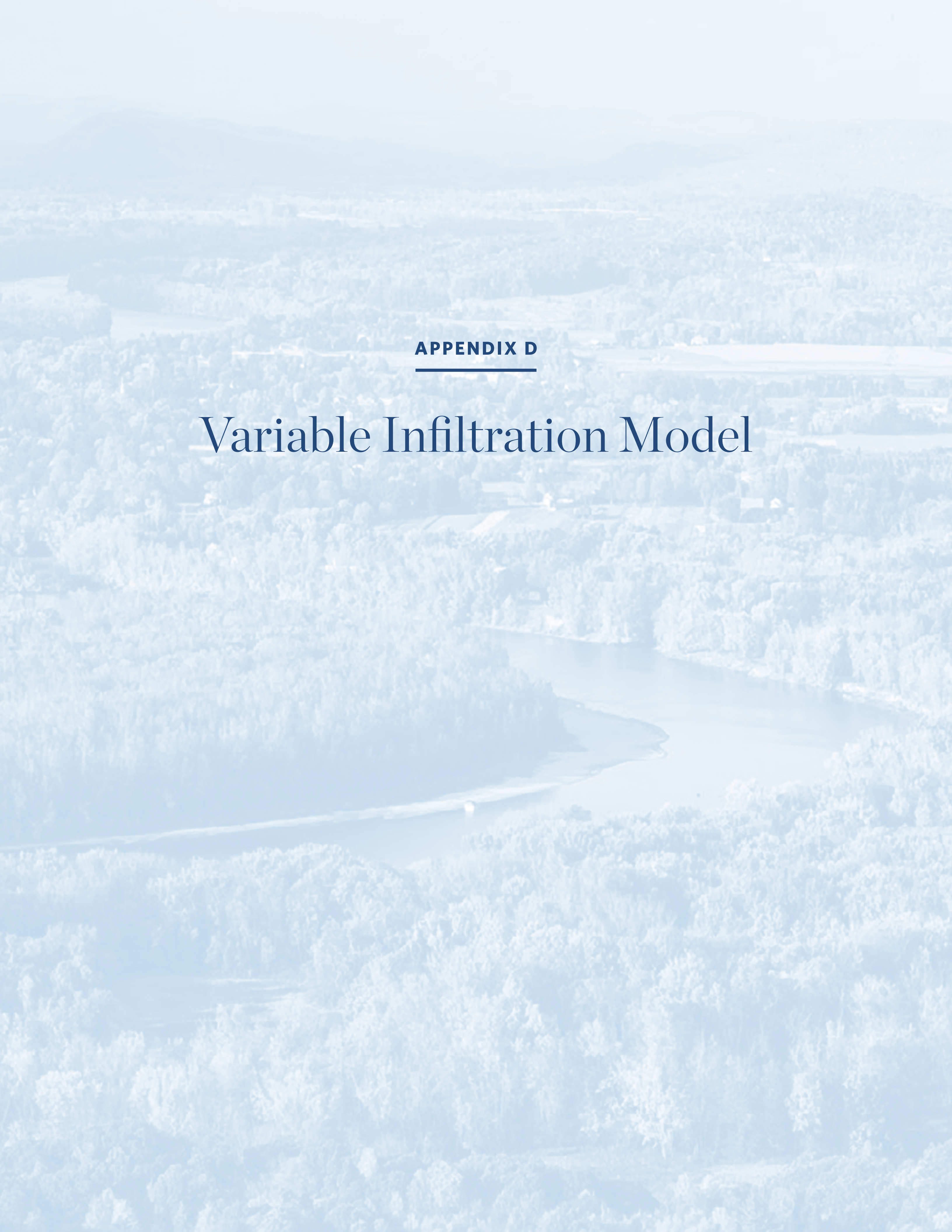
APPENDIX B

Flow Hypotheses and Recommendations



APPENDIX C

Demonstration Model

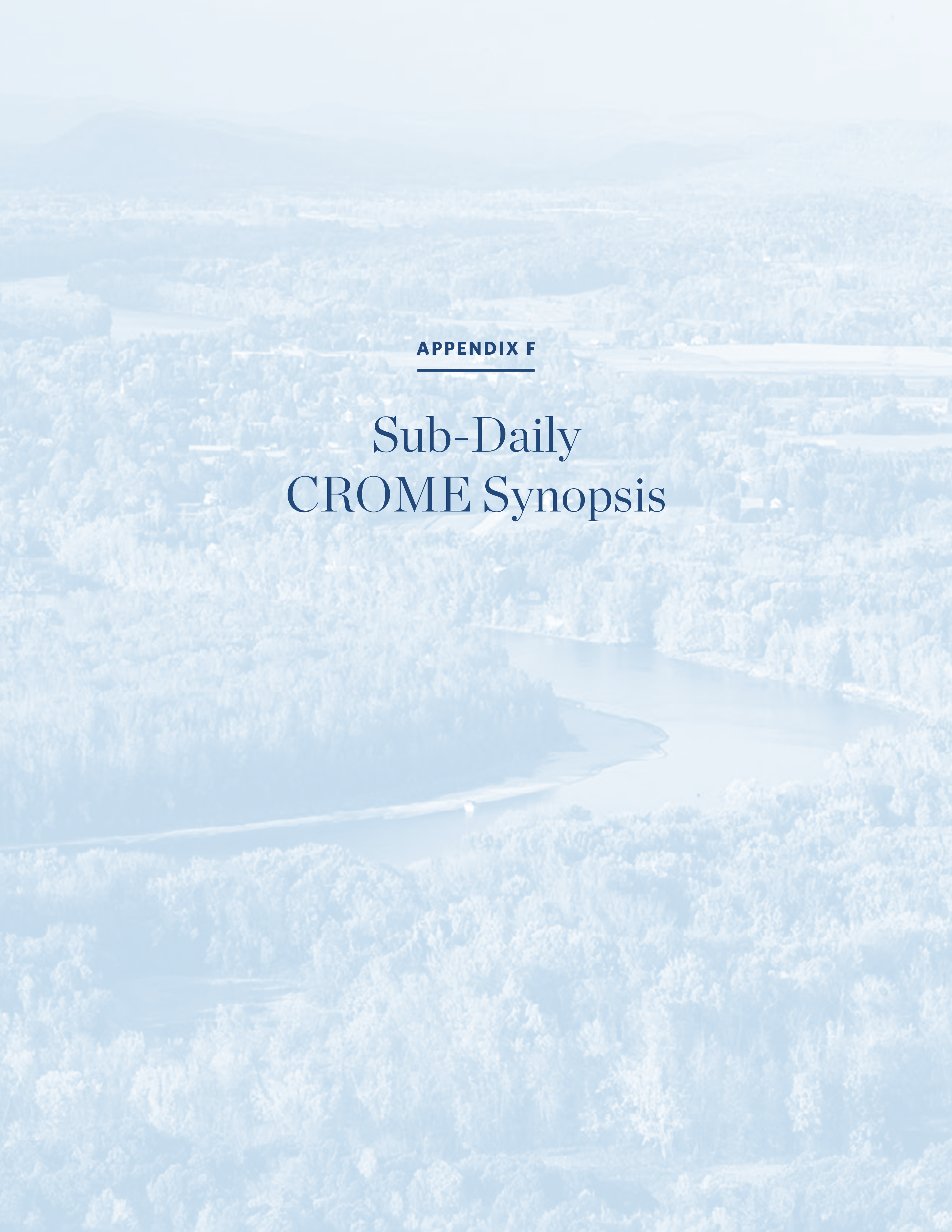


APPENDIX D

Variable Infiltration Model

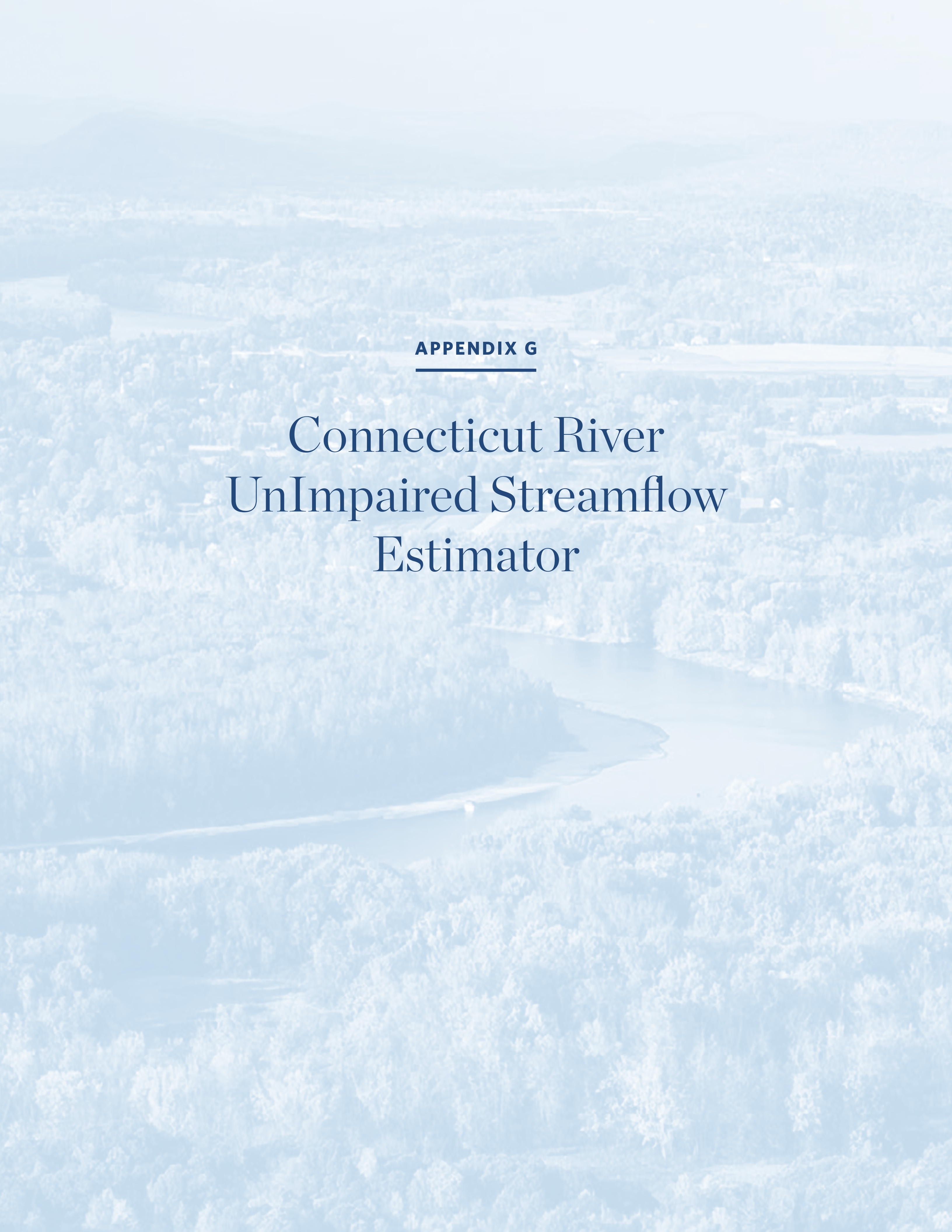
APPENDIX E

HEC-RAS and HEC-Ecosystems Function Models



APPENDIX F

Sub-Daily CROME Synopsis



APPENDIX G

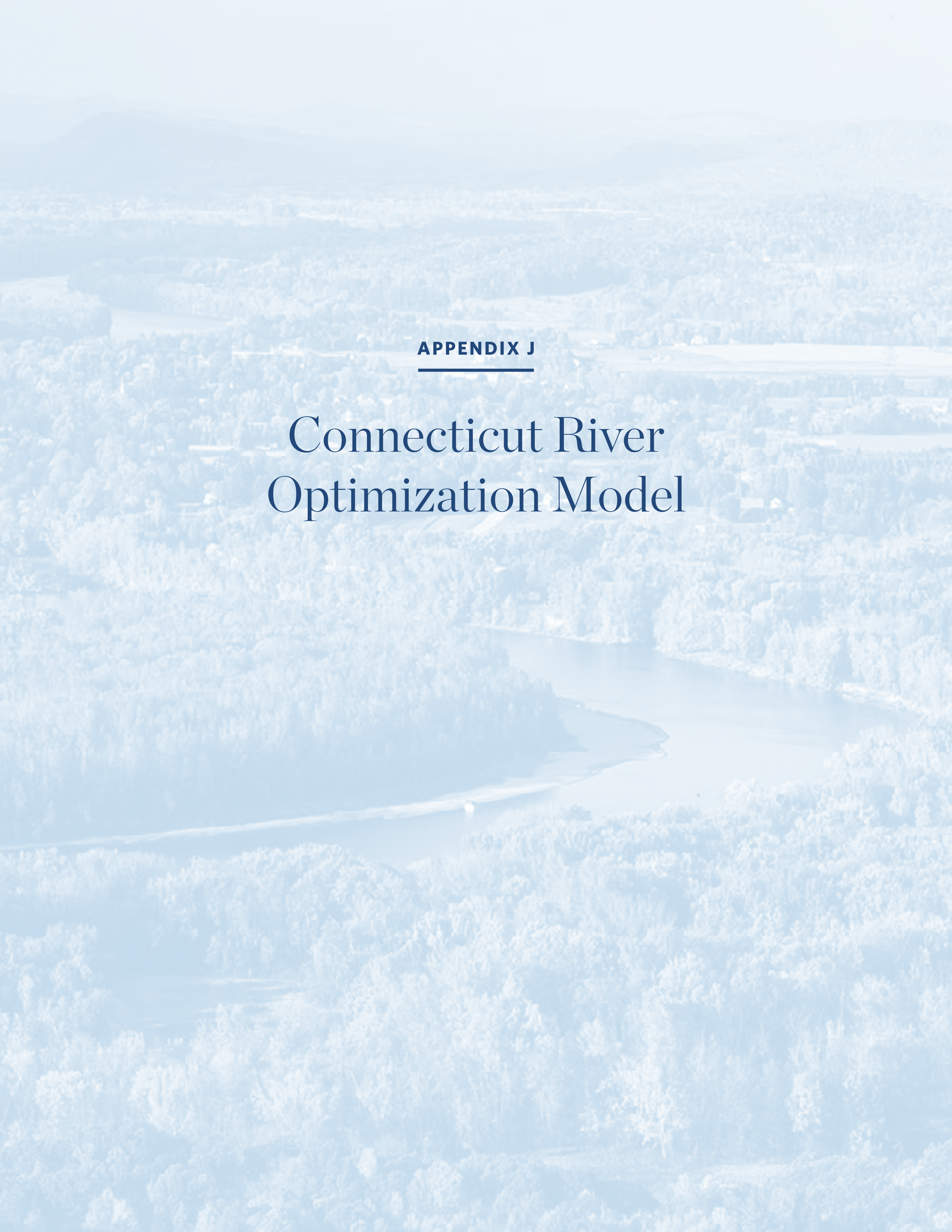
Connecticut River UnImpaired Streamflow Estimator

APPENDIX H

HEC-ResSim Model

APPENDIX I

Large Dams of the Connecticut River Watershed



APPENDIX J

Connecticut River Optimization Model