Environmental Alteration Analysis of a Large System of Reservoirs: Application to the Connecticut River Watershed

By

DAVID JULIAN
B.S. (Seattle University) 2011

THESIS

Submitted in partial satisfaction of the requirements for the degree of

MASTER OF SCIENCE
In
Civil & Environmental Engineering
In the
OFFICE OF GRADUATE STUDIES
Of the
UNIVERSITY OF CALIFORNIA
DAVIS

Approved:

Jay R. Lund, Chair

Samuel Sandoval Solis

Josue Medellin-Azuara

Committee in Charge

2013

Acknowledgements

There are many people I would like to acknowledge and thank. First I would like to thank everyone at HEC. In particular I would like to thank Woody Fields and Leila Ostadrahimi and the several other employees no longer at HEC for their efforts in helping to construct the ResSim model. I would especially like to thank John Hickey, who helped bring me on to the Connecticut River project and guided me through all the many aspects of the work that went into both the Connecticut Project and this thesis. I would also like to thank employees at New England District. In particular, Chris Hatfield of New England District for also helping to bring me on to the project, Townshend Barker for his work on the ResSim model, Adam Howes for his work constructing the RAS model, and Greg Hanlon for his input on the ResSim model. Another thank you goes to the other members of the Connecticut River project team at UMASS (Rick Palmer and his various graduate students) and TNC (particularly Kim Lutz, Katie Kennedy, Christian Marks, and Eric Krueger) for their work and input on the various models used. Another thank you goes to my graduate advisor & committee chair Jay Lund for his feedback and comments throughout the whole process of writing this thesis. I would also like to thank the other two members of my committee, Sam Sandoval Solis and Josue Medellin-Azuara for their feedback on this thesis. And lastly, I would like to thank all my friends and family, and especially my parents, for their help/patience/guidance/support/all the other appropriate adjectives they gave me through the highs and lows of the whole thesis process.

Abstract

This thesis describes an approach to examine how the management of a large system of reservoirs could decrease environmental alteration from unregulated (no dam) conditions. A reservoir system simulation model was used to model current operations at 73 reservoirs and flows at ecologically significant points in the Connecticut River watershed. The regulated flows from the simulation model were then compared to the unregulated flows using ecological metrics based on specific annual inundations required by floodplain plant communities and flow targets developed by experts for migratory diadromous fish species. The process identified (1) trends in environmental alteration for the Connecticut River mainstem and (2) potential reservoir management changes to reduce environmental alteration while analyzing changes in hydropower generation. Different scenarios were then simulated to assess potential reductions in environmental alteration and potential losses in hydropower generation and flood risk management. The approach described in this thesis could be applied to other watersheds to assess environmental alteration from dams and assist in watershed planning and environmental flow implementation.

Table of Contents

List of Figures

List of Tables

1. Introduction

River flow is an important environmental aspect of river management. Alteration of in-stream flow from natural conditions has greatly affected riverine ecosystems (Bunn & Arthington 2002; Vogel et al. 2007). Native aquatic species are typically adapted to the *natural* flow regime. Different aspects of that flow regime, such as seasonal variability and durations of different flows, cue and sustain their various life stages and provide physical habitat (Poff et al. 1997). When the flow regime changes due to dams, diversions, and land use practices, alteration of the distinct environmental cues and habitat to which the native species are adapted can disrupt the life stages of native aquatic and floodplain species (Nislow et al. 2002). In addition, stream flows support geomorphic processes on which many species rely for habitat creation and maintenance, such as gravel deposition and sediment flushing; these important processes may be disrupted (Bunn & Arthington 2002). Reduced connectivity between suitable habitats, such as rivers and floodplains is yet another consequence of dams and flow alteration (Nislow et al. 2002).

Flows that provide ecological benefits are often defined as *environmental flows* (e-flows) (Hirji & Davis 2009). Historically, reservoir management placed little priority on environmental flows (Petts 2009). Flood control, water supply, and hydropower have dominated reservoir operations and degradated riparian ecosystems (Homa et al. 2005). However, efforts are now being made to address and prioritize environmental flows for in-stream flow management (King & Brown 2006). Managing in-stream flow to mimic the natural cues of different species is the subject of considerable research and debate (Arthington et al. 2010; Jowett 1997; Petts 2009; Hardy 1998). Environmental flows for specific species are often difficult to evaluate, as are the actions needed to implement them.

One approach to estimating e-flows is to characterize the degree that a river's current hydrograph has been altered from its natural hydrograph and then estimating flows that will reduce the degree of alteration (Richter et al. 1996; Bunn & Arthington 2002; Gao et al. 2009; Zimmerman 2006, Sandoval-Solis et al. 2010). This approach assumes that species are adapted to the natural flow regime of a river and that any alteration from the natural flow regime is detrimental for species. However, this approach involves having knowledge of the natural hydrograph through stream gage records or estimating the pre-dam hydrograph through hydrologic modeling or stochastic methods, which can be data intensive, computationally difficult, and prone to uncertainty.

Another approach, sometimes referred to as the instream habitat method, involves linking a specific ecologic function, such as floodplain inundation and sediment flushing, or a specific life stage, such as fish spawning, to a flow characteristic (Jowett 1997; Petts 2009; Monk et al.

2006). These ecologically significant flow characteristics, flow/ecology links, are often based on empirical research and habitat modeling on a small or limited scale (Bockelman et al. 2004; Hardy 1998; Valavanis et al. 2008, Yarnell et al. 2012).

Many studies use one or the other of these techniques to estimate environmental flows for various rivers worldwide (DePhilip & Moberg 2010; Cain & Monohan 2008; Kashaigili et al. 2007; Hughes & Hannart 2003; Lake Simcoe Region Conservation Authority 2011; Apse et al. 2008). This thesis explores an approach that permits quantifying changes from the natural hydrograph while incorporating environmental water requirements based on combining these two approaches.

Implementing e-flows often involves changing reservoir operations (Richter & Thomas, 2007). Several studies have used reservoir optimization models to balance environmental flows with flows for human use (Homa et al. 2005; Yin et al. 2010; Harman & Stewardson 2005; Tilmant et al. 2010; Zhang & Qian 2011, Sandoval-Solis & McKinney 2012, Null & Lund 2011). In a multi-reservoir system, this becomes increasingly complex (Labadie 2004). Changing the operations of multiple reservoirs is difficult to implement from a policy standpoint. The reservoirs often have different water management agencies and objectives with competing management goals. Usually, the optimization objectives must be simplified for computation purposes. Thus it is generally easier and simpler to optimize the operation of a single reservoir for environmental flows. However, in a watershed with many dams, identifying which dams would be most beneficial to re-operate is needed to focus e-flow implementation efforts.

Simulation models can help focus dam re-operation efforts. Simulating the current hydrology within a watershed and the environmental alteration (often referred to hydrologic alteration) from dams within the watershed can allow the locations of the greatest alteration and the dams causing this alteration to be identified. In addition, if the model can simulate dam operations, promising changes in operations can be identified (Fields 2009, Sandoval-Solis & McKinney 2012). Depending on the type of operations simulated, tradeoffs in other reservoir purposes, such as hydropower generation and flood control also can be quantified. However, the ability to determine the dams and operations affecting environmental alteration becomes more difficult as the watershed increases in size and complexity. The interactions between reservoirs themselves and their interactions with tributaries cause fluctuations in the environmental alteration that are hard to track. Simulating these interactions in a model with multiple reservoirs and tributaries adds additional complexity. Developing an approach to evaluating the interactions of dams and tributaries and their effect on environmental alteration will help reservoir re-operation efforts to optimize environmental flows in complex watersheds, while accounting for other reservoir purposes.

As part of The Nature Conservancy (TNC) and US Army Corps of Engineers (USACE) Sustainable Rivers Project[1], a Decision Support System (DSS) for the Connecticut River watershed was developed for a variety of water management purposes, including environmental considerations (HEC 2013). One aspect of this DSS was a reservoir system simulation model that replicates current conditions of the watershed. One purpose for creating the reservoir simulation model was to simulate management alternatives from a reservoir optimization model. The simulation model would be a reality check on the proposed management alternative by accounting for more detailed physical data and existing operating rules.

However, the reservoir simulation model can be used for other purposes than just analyzing management alternatives from an optimization model. The simulation model can help assess the extent of environmental alteration caused by either individual dams or the combination of multiple dams. This can help focus reservoir reoperation efforts by identifying the primary causes of environmental alteration. This thesis discusses how a reservoir simulation model can help quantify environmental alteration to aid aquatic ecosystem management at the watershed scale using ecological flow metrics that quantify change from unregulated flows while also measuring changes in hydropower generation, floodplain inundation, and flood risk management. This would help identify areas that should be focused on for more detailed analyses, such as Pitta 2011, which utilized simulation and optimization models to optimize reservoir operations on the Upper Third of the Connecticut River mainstem to more closely meet unimpaired flows.

This thesis focuses on how a reservoir operations simulation model and other tools can quantify environmental alteration and other water management tradeoffs under different scenarios, which can assist in watershed planning and e-flow implementations. It has four main chapters. Chapter 2 gives an overview of the watershed including the hydrology, dam descriptions, and species of interest/communities of interest. Chapter 3 describes the construction and structure of the reservoir system simulation model and the process for calculating the ecological flow metrics. Chapter 4 then discusses the results of the current conditions and four scenarios, where different dams were removed to simulate what changes in the regulated flows would occur and how environmental alteration on the Connecticut River mainstem would be effected. Chapter 5 offers a discussion and some limitations of the study. Chapter 6 offers some conclusions.

---

[1] The Sustainable Rivers Program is a partnership between TNC and USACE to promote sustainable river management on rivers where the Army Corps has a presence. There are currently 10 project sites, one of which is the Connecticut River watershed.

2. Background

2.1 Study Area

The 410 mile Connecticut River flows from headwaters at the Canada/New Hampshire Border south to Long Island Sound (Zimmerman 2006). Along its 410 mile course, 44 major tributaries join the Connecticut River mainstem, draining 11250 mi^2 in Vermont, New Hampshire, Massachusetts, and Connecticut. Precipitation occurs year-round with mean annual precipitation ranging from 35.4 in. in the north to 47.2 in. by the coast. Peak flows usually occur in early spring from snow melt, and consistent low flows occur during the summer. While high flows can occur in any season, flooding is primarily driven from rain or snow events and remnants of tropical storms in late summer and fall. Roughly 77% of the watershed is forested while the remaining 23% of land use is divided among wetlands and water bodies (7%), urban development (7%), and agriculture (9%). Over 3.2 million people inhabit the watershed (Hatfield & Lutz 2011).

The Connecticut River watershed is one of the most heavily impounded in the United States, based on density of dams, with a 17.0 mi^2 area of watershed impounded per dam (Graf 1999). Despite the prevalence of dams throughout the watershed, the dams only impound 26% of mean annual flow. Over 1000 dams are spread throughout the watershed, with the oldest dating back to the 17th century (Connecticut River Valley Flood Control Commission 2011). The dams were primarily constructed for mill ponds and floating logs downstream, but during the Industrial Revolution they started to be used for power generation (US Fish and Wildlife Service 2011). There are 13 dams on the Connecticut River mainstem, the most downstream of which is Holyoke Dam in Massachusetts (river-mile 84). The dams along the Connecticut River mainstem are all hydropower dams, mostly owned by private interests. There are 125 hydropower dams in the watershed (Zimmerman 2006).

No flood control dams in the watershed existed until the floods of 1936 and 1938, which prompted the USACE to construct the 16 flood control dams currently on major tributaries (Connecticut River Valley Flood Control Commission 2011). There are no dams specifically for flood control on the Connecticut River mainstem. Figure 1 shows the location of over 1000 dams in the watershed. Water withdrawals are also widespread. About 80 surface water withdrawals as well as an uncounted number of groundwater withdrawals are in the upper watershed, with the overall number of withdrawals unknown (Fallon-Lambert 1998).

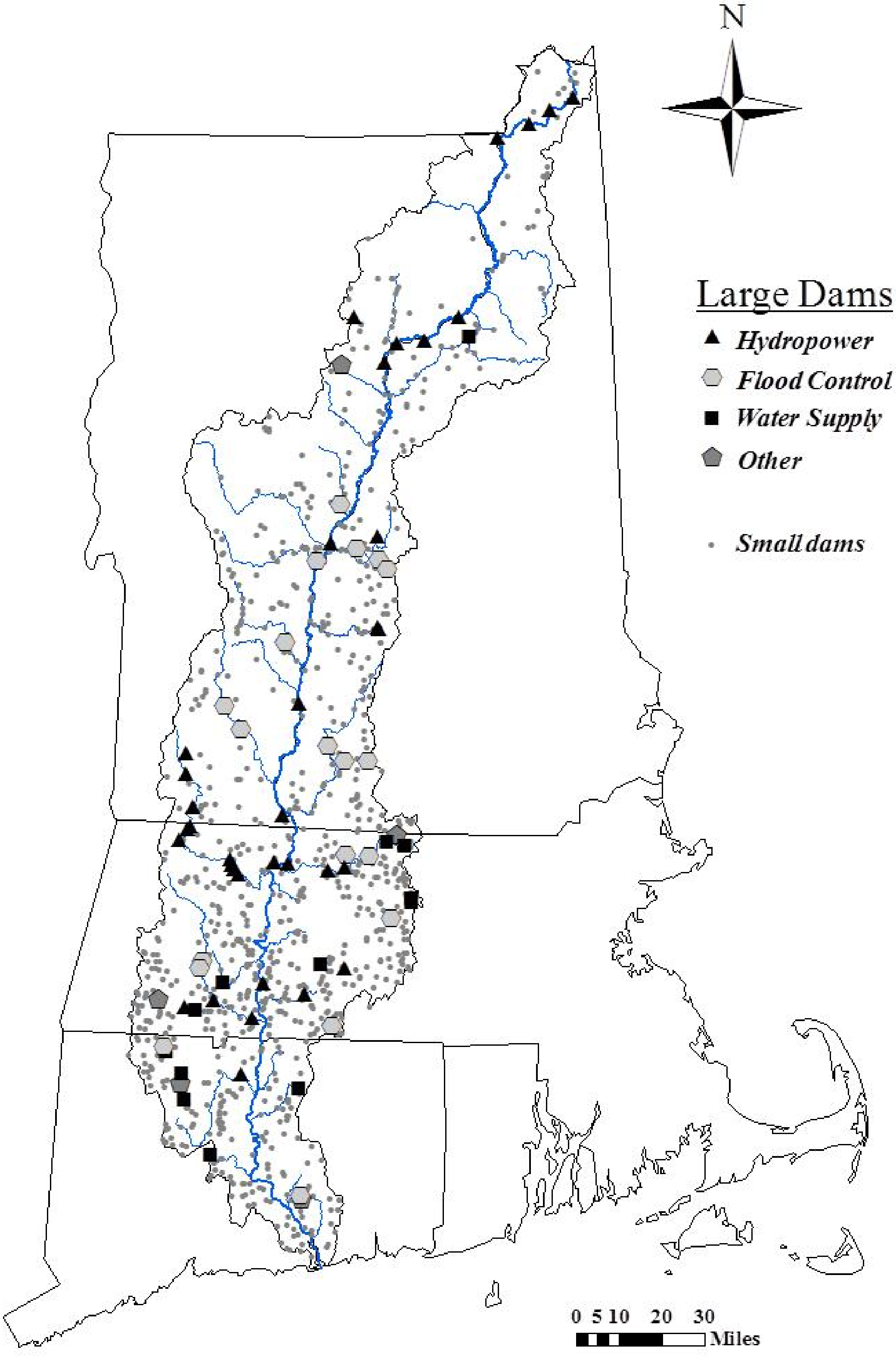


Figure 1: Map of reservoirs in the Connecticut River watershed. Large dams were defined as either storing greater than 10% of annual runoff of the dam's drainage area or having a hydropower generating capacity >1 MW. Small dams stored less than 10% annual runoff of the dam's drainage area.

2.2 Aquatic Species of Interest

The watershed is home to a wide variety of aquatic and riparian species including 10 listed as endangered (NRCS, 2008). Endangered species include Shortnose Sturgeon (*Acipenser brevirostrum)*, Dwarf Wedgemussel (*Alasmidonta heterodon)*, Puritan Tiger Beetles (*Cicindela puritan)*, and the Northeastern Bulrush (*Scripus ancistrochaetus)* (Connecticut River Valley Flood Control Commission 2011). The watershed hosts several diadromous fish spawning runs, including American Shad (*Alosa sapidissima)* and, historically, the Atlantic Salmon (*Salmo salar)*. The populations and ranges of many of these species have declined significantly due to dams (Zimmerman 2006). The dams block the passage of diadromous fish species from reaching their historical spawning grounds. In addition, changes in the flows and geomorphology of the river induced by the dams decrease available spawning habitat (Beasley & Hightower 2000). Water quality degradations in water quality also have harmed native fish species (Mullaney & Trench 2003).

As diadromous fish populations decline, so do the populations of various freshwater mussel species. Individual species of freshwater mussels rely on specific species of fish, for instance the Alewife Floater relies on the Alewife, for habitat and transport during the larval phase (Nedeau 2008). Freshwater mussels also require relative stability in daily flows and so are acutely affected by hydropower dams' daily or hourly variability in discharge.

The watershed is also home to a variety of floodplain forest communities. Specific inundation patterns, high flow timings, and geomorphic features promote unique combinations of floodplain vegetations (Apse et al., 2008). Dams, particularly the flood control dams, have reduced the number of bankfull flows (non-flood) and flood flows per year, resulting in less inundation of the floodplain and thus a decline in floodplain forest communities (Zimmerman 2006; Zimmerman et al. 2008).

3. Methods

Figure 2 shows a schematic of the general process used to analyze environmental alteration. A reservoir simulation model was used to simulate the current operations of 73 major reservoirs in the Connecticut River watershed. The model generated regulated flow timeseries based on watershed data, reservoir physical and operational data, and inflows from a synthetic flow timeseries. The synthetic inflow timeseries was also considered the unregulated timeseries. Environmental flow needs of specific species were then determined and evaluation criteria based on these environmental flow needs were used to quantify environmental alteration of the regulated flow timeseries from the unregulated flow timeseries.

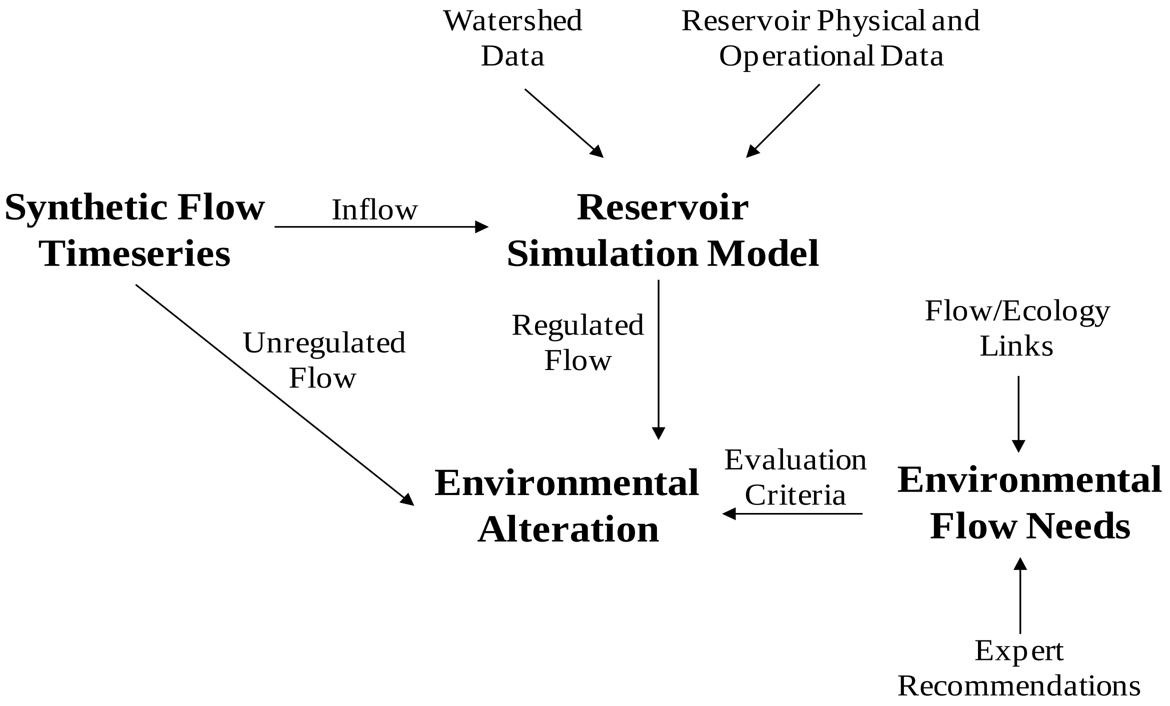


Figure 2: Schematic of the general process to analyze environmental alteration.

3.1 Reservoir Simulation Model

3.1.1 Model Overview

Reservoir operations were simulated using a daily time-step reservoir simulation model of the entire Connecticut River watershed. The model provides flow estimates at points of ecological interest that reflect unregulated conditions and current operations of 73 major dams. The ecological points of interest (hereafter referred to as eco-nodes) were determined by TNC and used to assess flows for either specific or combinations of different species/communities; floodplain forests, diadromous fish, Atlantic salmon, Tiger Beetles, freshwater mussels, resident warm water fish, and resident cold water fish. Of the 1000+ dams in the watershed, dams that were considered major, and thus included in the model, were able to store 10% or more of the total annual runoff from the dam's drainage area or had a hydropower generating capacity >1 MW.

The modeling platform used was HEC-ResSim (Reservoir System Simulation Model) which was developed by the US Army Corps of Engineers Hydrologic Engineering Center (HEC). Technical information on HEC-ResSim can be found in the Users Manual, (HEC 2011). Inflow time series are input and routed at locations throughout the model with reservoirs altering the routed flow based on physical constraints and operating rules. Each reservoir within HEC-ResSim has a target pool elevation (hereafter referred to as *Conservation pool elevation*) that the reservoir tries to maintain through a combination of releases and storage of inflow. These releases and storages are regulated first on the physical capacity of the outlets and then by operating rules. HEC-ResSim can have any point in the stream network be quantified as a *computation point*. Computation points are automatically created for stream junctions and for reservoir inflows and outflows. All computation points have a flow time series generated when the model is run. HEC-ResSim can simulate controlled and uncontrolled reservoir outlets as well as as power plants, taking into account generation efficiency, tailwater, and a variety of hydropower generation types. It also can handle complex reservoir operating rules and many reservoirs and routing reaches. In addition, HEC-ResSim also simulates unregulated flows automatically, by routing inflows through the stream network as if no reservoirs were present.

The HEC-ResSim model used was developed by several USACE engineers from the New England District and HEC as well as a group at the University of Massachussets, and took several years to construct. Watershed data, such as stream alignment and reservoir locations, was collected from the USGS National Hydrography Dataset (NHD). Physical and operational data of the reservoirs, including pool elevation-storage curves, outlet elevation-discharge curves, and operating rules was provided by owner/operators of the dams (HEC 2013)[2].

At least three distinct pool elevations were specified for each reservoir to demark different operating zones. Each zone had operating rules in each zone. One elevation would be the actual target elevation of the reservoir (referred to as Conservation pool elevation). The eco-nodes as well as several USGS gages and downstream reservoir operating points also were included in the model as computation points. In total, 447 computation points were specified. Inflows were inputted at 320 points (called *local flows* in HEC-ResSim).

---

[2] For 19 of the dams, instabilities in the model occurred due to the capability of their reservoir pools to be drained in one time step. There was no specific pattern of why this occurred at these 19 dams but it was generally due to the location of the dams being downstream of other dams, the storage capacity of the dams, and the magnitude of the inflow time series. To mitigate for this instability, 100000 ac-ft was added to the storage capacity at each pool elevation. This did not cause any changes to the model output as no rules are volume based and the amount of water that is being manipulated within the pool is relative to the base volume (the volume at the lowest possible pool elevation). This prevents the dam from draining the entire pool, as it no longer has the capability to do so in a single time step.

3.1.2 Hydrograph Routing

The whole-watershed model for the Connecticut River included roughly 360 river reaches. Some reaches were short, connecting local points of interest; others were many river miles long. This range of reach lengths in a daily time step model was problematic for several of the hydrologic routing HEC-ResSim offers (such as Muskingum) because the mathematical equations employed of methods were designed to route and attenuate flows for travel times greater than a single increment of simulated time. Hydrologic routing is the mathematical transfer of flow downstream. A single approach was used to ensure that routing logic was applied evenly throughout the watershed. This approach involved estimating travel times for each reach of the stream alignment used in the HEC-ResSim model. Travel times for the upper third of the watershed and the Deerfield sub-watershed were estimated using documents provided by TransCanada and a map of routing times provide by USACE's New England District for the rest of the watershed. For many reaches, travel times were subdaily, which posed problems in a daily time step model. To synchronize the travel times with the daily time step, ten locations were identified to represent the point at which all flow upstream reached that location in 24 hours. This resulted in 10 reaches that had a Variable Lag & K method applied as their routing reach, with a lag value of 24 hours and K value of 24 hours. Table 1 shows the 10 routing reaches that received Variable Lag & K routing. All other routing reaches had Null Routing applied as the routing method, meaning no lag occurred within that reach. Attenuation of flow is not accounted for in either routing method used here.

Table 1: Routing reaches in the model that had Variable Lag & K method used for routing.

River	Reach	Lag (h)
Farmington	FAR_Mussels3-Priority Salmon Stocking2 to Rainbow_In	24
Ashuelot	ASH_Floodplain7 to Ashuelot at Hinsdale	24
Connecticut	MAIN_Floodplain2 to MAIN_Mussels1	24
Connecticut	MAIN_Floodplain6-Mussels6 to Connecticut+Johns	24
Connecticut	Connecticut+West to MAIN_Floodplain17-Mussels19	24
Connecticut	Holyoke_Out to Connecticut+Chicopee	24
Connecticut	MAIN_Floodplain30-Tiger Beetles10 to Connecticut+Mattabesset	24
Millers	MLR_Diadromous Fish to Millers at Mouth	24
Deerfield	DRF_Floodplain3 to Deerfield at Mouth	24
Chicopee	Red Bridge_Out to Chicopee at Mouth	24

3.1.3 Synthetic Flow Timeseries

A synthetic flow timeseries data set was used as inflows to the HEC-ResSim model and as the unregulated flows. The synthetic flow timeseries was calculated using the Sustainable Yield Estimator (SYE) software developed by the USGS (Archfield et al. 2009, Archfield et al. 2013).

SYE quantified the mean daily streamflow hydrograph at ungaged sites in the watershed by first estimating a continuous flow duration curve and then translating that flow duration curve into a timeseries. Specific streamflow quantiles were estimated through a parameter-based regression approach including physical, climate, and watershed characteristics. A regression equation was then used to calculate the remaining quantiles, with each quantile representing one day of streamflow. Then using the $\text{Flow}_{\text{Gage}}$-$\text{Probability}_{\text{Gage}}$-$\text{Probability}_{\text{Unreg}}$-$\text{Flow}_{\text{Unreg}}$ (QPPQ) method, the flow duration curve is translated into a timeseries by correlating the timing of flows at 66 reference stream gages and the flows at ungaged sites. Figure 3 shows a schematic of the QPPQ method. The concept of this approach is that the timing of the flow duration curve at the reference streamgages indicates the timing of the ungaged sites.

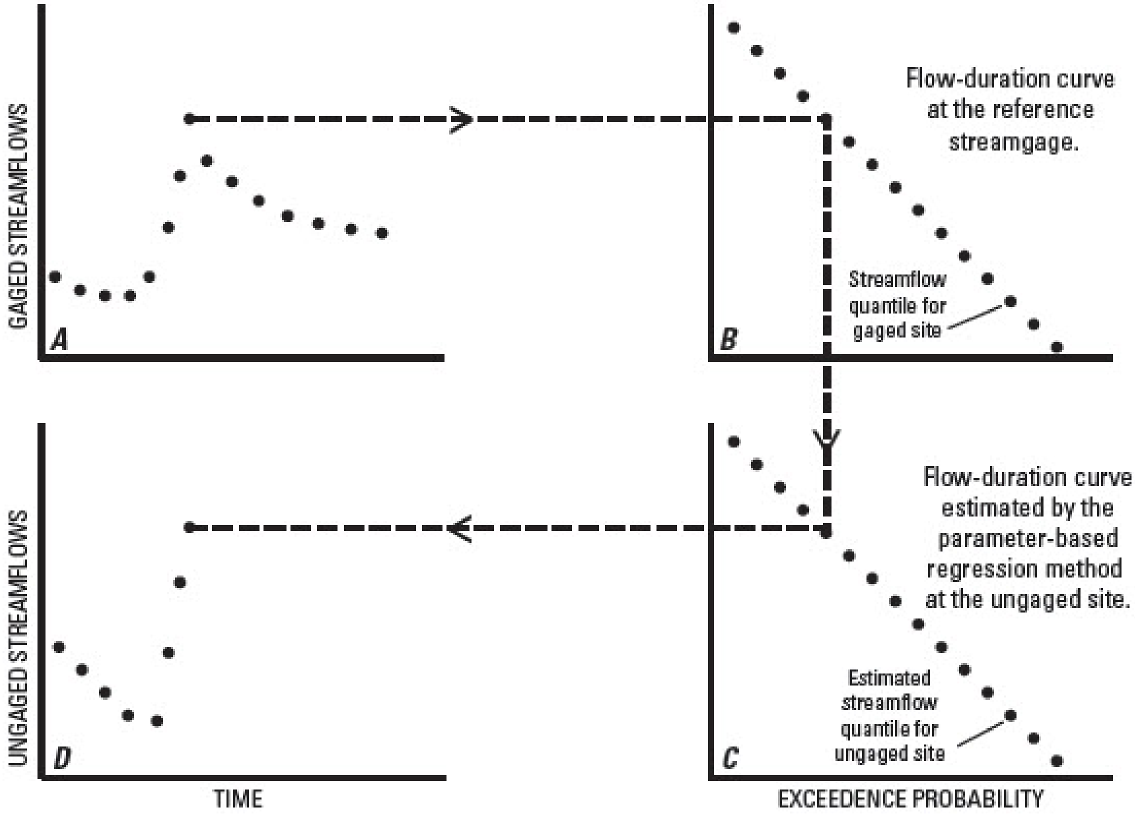


Figure 3: Schematic showing the QPPQ method of translating an FDC into a streamflow timeseries. Plot A is the reference gage's time series. Plot B is the reference stream gage translated into a flow-duration curve. Plot C is the flow-duration curve at the ungaged site calculated using parameter-based regression. Plot D is the ungaged flow-duration curve translated into a timeseries. Figure from Archfield et al. 2009.

Through this method, SYE quantified mean daily streamflow from October 1, 1960 to September 30, 2004, the period of record for the network of reference stream gages. The dataset is both homogeneous and stationary. Comparing flows from several USGS gages on streams that are minimally regulated by dams to the SYE generated streamflows (see Figure 4) shows that overall the SYE simulates the overall timing and magnitude of low and medium flow.

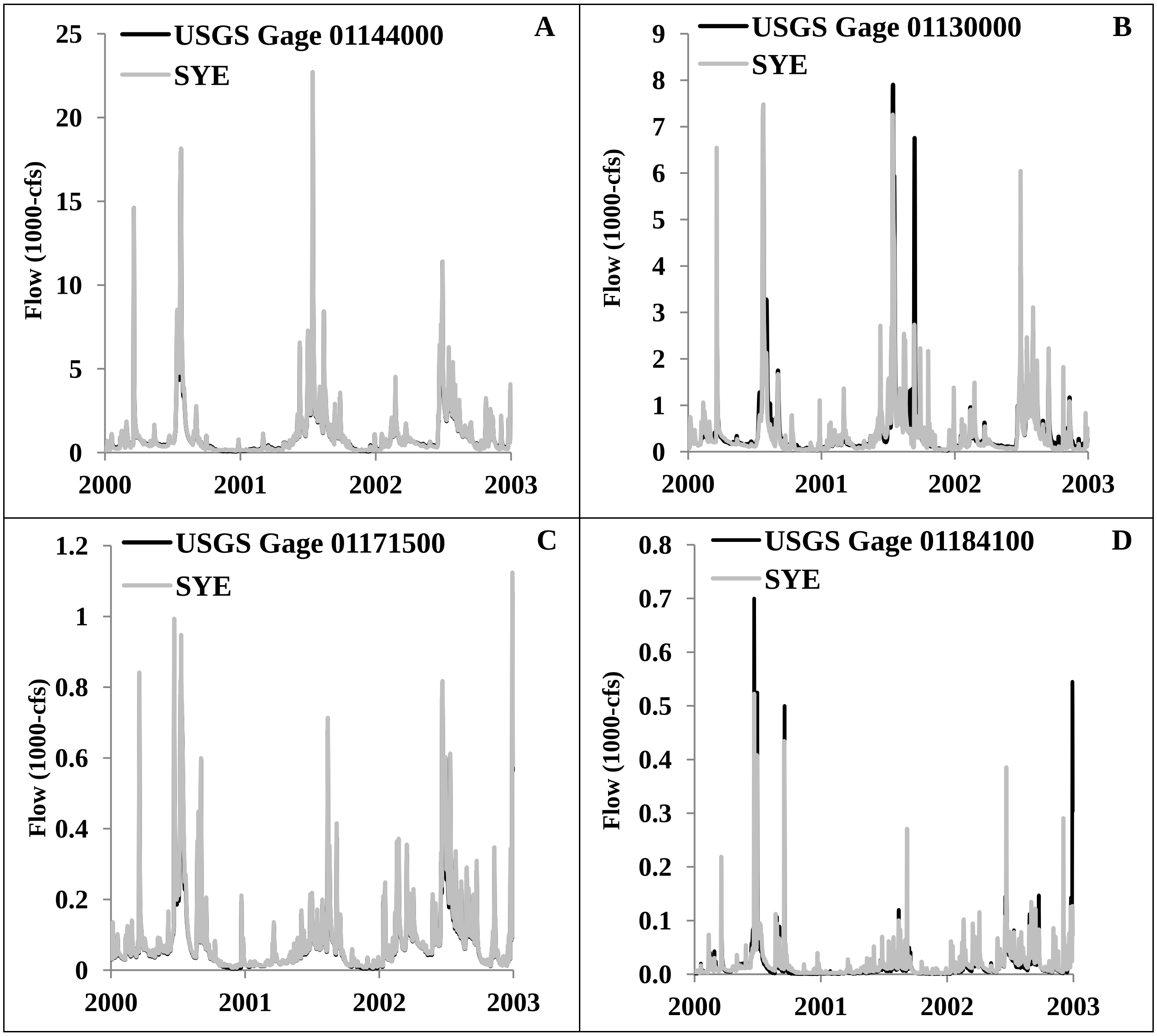


Figure 4: Observed and Sustainable Yield Estimator (SYE) estimated mean daily streamflows at four USGS Gage locations in the Connecticut River Watershed; A – White River at West Hartford, VT, B – Upper Ammonoosuc River at Groveton, NH, C – Mill River at North Hampton, MA, D – Stony Brook at West Suffield, CT.

There are two main differences with the SYE synthetic hydrographs when compared to gage data; the difference in the magnitude of the peaks and the total volume. These two issues add uncertainty to the model output as well as the flow statistics. However, as this study focuses on flow alteration of the unregulated hydrograph caused by the dams, the uncertainty that comes with using a synthetic data was accepted.

There are four primary approaches to estimating unregulated hydrographs; historic data reconstruction hydrologic modeling, stochastic methods, and regression approaches combined with gage data. Hydrologic modeling of the entire Connecticut River watershed to the detail required for the simulation model would have been beyond the scope of the overall project. Stochastic methods are useful in areas with little to no gage data, but are more uncertain in their estimations. Regression approaches that calculate runoff volumes and then translate into a timeseries through the use of gages, such as the SYE method, is an imperfect but more efficient approach than hydrologic modeling and more accurate than stochastic methods.

3.1.4 Watershed Reservoir Management

Four main operating rule types were simulated; (A) hydropower, (B) e-flows, (C) flood control, and (D) water supply. A few dams also had required white water releases or maintenance flows. Appendix A lists all modeled dams and the operating rule types that they follow, and shows a map of the modeled dams. Nine of the dams had no controlled outlet structure and thus no operating rules. All operations modeled are current operations. While, there have been operational changes over the SYE period of record, the analysis performed is based on current operations. So changes in operations over time were not included and it was assumed that all current operations were in place of the simulation period of record. The appendix that accompanies HEC 2013 describes the operations of each reservoir modeled in detail.

A. Hydropower

Thirty of the dams modeled operate for hydropower generation. The hydropower operations in the HEC-ResSim model are entirely hydrology driven and cannot reflect the complexities of actual hydropower operations, which in reality combine several factors, including market energy prices and the actual mechanical state of the generators. Hydropower generation modeling was primarily done through run-of-river hydropower operations. Run-of-river hydropower generation is accomplished by passing inflow through the reservoir, with electricity generated in the process. Little to no inflow is stored. While this ensures that fewer downstream impacts occur from hydropower generation, reliability of electricity generation from run-of-river dams is lower than hydropower facilities having storage capabilities. The electricity generated is subject to fluctuations in the flow. During high flows, electricity generation is high and during low flows, electricity generation is low. Twenty-two of the hydropower dams are currently operated as run-of-river. Five hydropower dams have peaking hydropower operations. Peaking operations involve daily storage to increase head and then releases based on the many factors mentioned earlier.

The Connecticut River mainstem and the Deerfield River are the two river sections modeled most heavily regulated for hydropower. Flow on the Deerfield is dictated by Harriman, Searsburg, and Sherman reservoirs that make hydropower releases for peaking generation. The various dams downstream of Sherman (Development #1,2,3,4,5, Bear Swamp & Gardner Falls) use run-of-river operations to generate additional electricity based on releases from Searsburg, Harriman, and Sherman.

The Connecticut River mainstem has 14 dams, all of which include hydropower. The major owner/operator of the Connecticut River mainstem hydropower dams is TransCanada Hydro Northeast (TransCanada). TransCanada's Connecticut Lakes Project, which includes Second Connecticut, First Connecticut, and Lake Francis are all storage reservoirs that make releases downstream to augment TransCanada's hydropower generation downstream. TransCanada did not provide much operational information about how the Connecticut Lakes Project dams make releases to augment hydropower generation. They did provide 10 years of weekly pool elevation data for the three dams, which were used to generate an annual weekly average pool elevation. These annual weekly average pool elevations were used as Conservation Pool elevations for the three dams. Based off these generated Conservation pool elevation targets, their pool elevations are allowed to fluctuate seasonally. During the spring snowmelt, the reservoirs refill and then slowly drop until the winter when it drops more dramatically. Canaan and Gilman are two run-of-river hydropower dams whose generation is dictated by TransCanada's releases from its Connecticut Lakes projects. Moore, Comerford, and McIndoes dams encompass what is called the 15 Mile Falls project, also owned and operated by TransCanada. In 1997, the 15 Mile Falls Settlement Agreement was signed by TransCanada, the states of Vermont and New Hampshire, and other interested parties that laid out agreed upon changes to the operations of the 15 Mile Falls project for environmental purposes (USGen New England Inc. 2001). In 2002, the three 15 Mile Falls Project dams were relicensed by the Federal Energy Regulatory Commission (FERC) to operate with peaking hydropower operations provided that their operations also are modified for environmental benefits, including increased minimum flows and maintenance of seasonal pool elevations (Low Impact Hydropower Institute 2009). Wilder, Bellows Falls, and Vernon are primarily run-of-river hydropower dams up for FERC relicensing in 2018, presenting the most immediate political opportunity for changing operations for environmental purposes (Connecticut River Watershed Council 2012).

Northfield Mountain and Turners Falls are owned and operated by FirstLight Power Resources. Northfield Mountain generates electricity by pumping water up to its reservoir at night when electricity is cheap and releasing it back down to the river during the day when electricity is more expensive. Turners Falls is located directly downstream of Northfield Mountain. Changing pool levels caused by Northfield Mountain ultimately dictate Turners Falls hydropower generation. Turners Falls and Northfield Mountain also are up for FERC relicensing in 2018. Holyoke, the furthermost downstream dam on the Connecticut River mainstem is owned and operated by Holyoke Water Power Company. Like the 15-Mile Falls Project, Holyoke recently had its FERC license renewed and its operations became closer to run-of-river.

Modeling the hydropower dams involved the formulation of modeling strategies due to lack of specific operational information provided during the data collection. With the exception of a few dams, no explicit information about hydropower operations was provided for any dams with hydropower generation, except the general run-of-river or peaking operation type. Due to the lack of information about the hydropower operations, general operation strategies for run-of-river hydropower projects and peaking projects was formulated (HEC 2013).

1. Run-of-River

Any project lacking indication of its hydropower operation type was assumed to be run-of-river. All run-of-river hydropower projects, with the exception of the five projects mentioned earlier, had logic implemented as follows:

> -If the pool was at or above the conservation pool elevation, then release all inflow for hydropower generation.
>
> -If the pool was below the conservation pool elevation, then release 95% of inflow for hydropower generation. The release 95% of inflow logic was implemented so the pool elevation would return to conservation pool elevation and hydropower would still be generated in the process.

2. Peaking

Five of the dams (Moore, Comerford, Searsburg, Harriman, and Sherman) had peaking hydropower generation for their hydropower operations. In peaking hydropower operations, generating power has higher priority than spilling water. Also, any excess water volume is always run through available hydropower turbine capacity and whenever minimum flow exceeds inflow, it provides power.

Two assumptions are made for generating power in peaking reservoirs:

1) Power was only generated in weekdays.
2) Based on available water, power was generated for 2 and 4 hours per day.

Logic to implement peaking hydropower generation went as follows.

```
$V_I + V_{i-1} = V_i$
If $V_i < (V_S - V_{IS})$
    If $V_i \leq V_{2hr}$
        $G = 0\text{-}2\ hr$
    Else If $V_i \leq V_{4hr}$
        $G = 2\text{-}4\ hr$
Else
    $G = Inflow$
```

Where:
V_I = *inflow volume at current time step*
V_{i-1} = *reservoir storage volume at previous time step*
V_i = *reservoir storage volume at current time step before release*
V_S = *reservoir storage volume at spillway height*
V_{IS} = *reservoir storage volume of inactive zone*
V_{2hr} = *reservoir storage volume to generate hydropower for 2 hours*
V_{4hr} = *reservoir storage volume to generate hydropower for 4 hours*
G = length of hydropower generation

B. Environmental Flows

Forty-four modeled dams had e-flow requirements. These requirements were all stipulated at different times and primarily during FERC relicensing since most of the dams generate hydropower. Most of the e-flow releases are required for water quality or to maintain navigability and aquatic base flows. The e-flow requirements contained in FERC hydropower licenses and other licenses were modeled as flow constraints in HEC-ResSim. Some dams also have fish passage structures and associated releases. Several e-flow requirements also have a seasonal component. In some instances, the elevation of the pool will have some environmental control, such as Sherman and its requirements to maintain pool elevation stability during nesting season for loons. Each e-flow constraint was modeled in HEC-ResSim, as required minimum release rules.

C. Flood Control

Fourteen modeled dams are USACE-operated flood control dams, all on tributaries to the Connecticut River mainstem. The dams provide some direct downstream flood protection on the tributaries, while functioning primarily to limit flooding on the Connecticut River mainstem in highly populated areas like Springfield, MA and Hartford, CT. The dams perform their flood control operations based off of the flows at control points, which are select USGS gages. Union Dam, the highest in the watershed, has four points to which it regulates its releases to reduce flood stage on the Connecticut River mainstem at West Lebanon, New Hampshire. North Hartland Dam, the largest flood control dam in the watershed, and North Springfield Dam regulate their releases to further reduce the flood stage on the Connecticut River mainstem at North Walpole, New Hampshire. Ball Mountain and Townshend Dams work in tandem to reduce flood stage at Montague City, Massachusetts (Connecticut River mainstem) while Surry Mountain Dam and Otter Brook Dam combine to reduce flood stage at Hinsdale, New Hampshire (Ashuelot) and Montague City (Connecticut River mainstem). In the Lower watershed, Tully Dam and Birch Hill Dam additionally work in tandem to reduce flow at Montague City. Montague City is the key regulation point for the upper watershed, as the flow there indicates the flood stage approaching major population centers along the Connecticut River mainstem, Springfield, Massachusetts and Hartford, Connecticut. The tandem dams of Barre Falls Dam and Conant Brook Dam on the Chicopee River and Knightville Dam and Littleville Dam on the Westfield River, both feed into the Connecticut River mainstem at Springfield, are extremely important especially when the flood stage at Montague City is high. Those four dams, along with Colebrook River Dam, are also the last major dams protecting Hartford. Figure 5 shows a schematic of the flood control system.

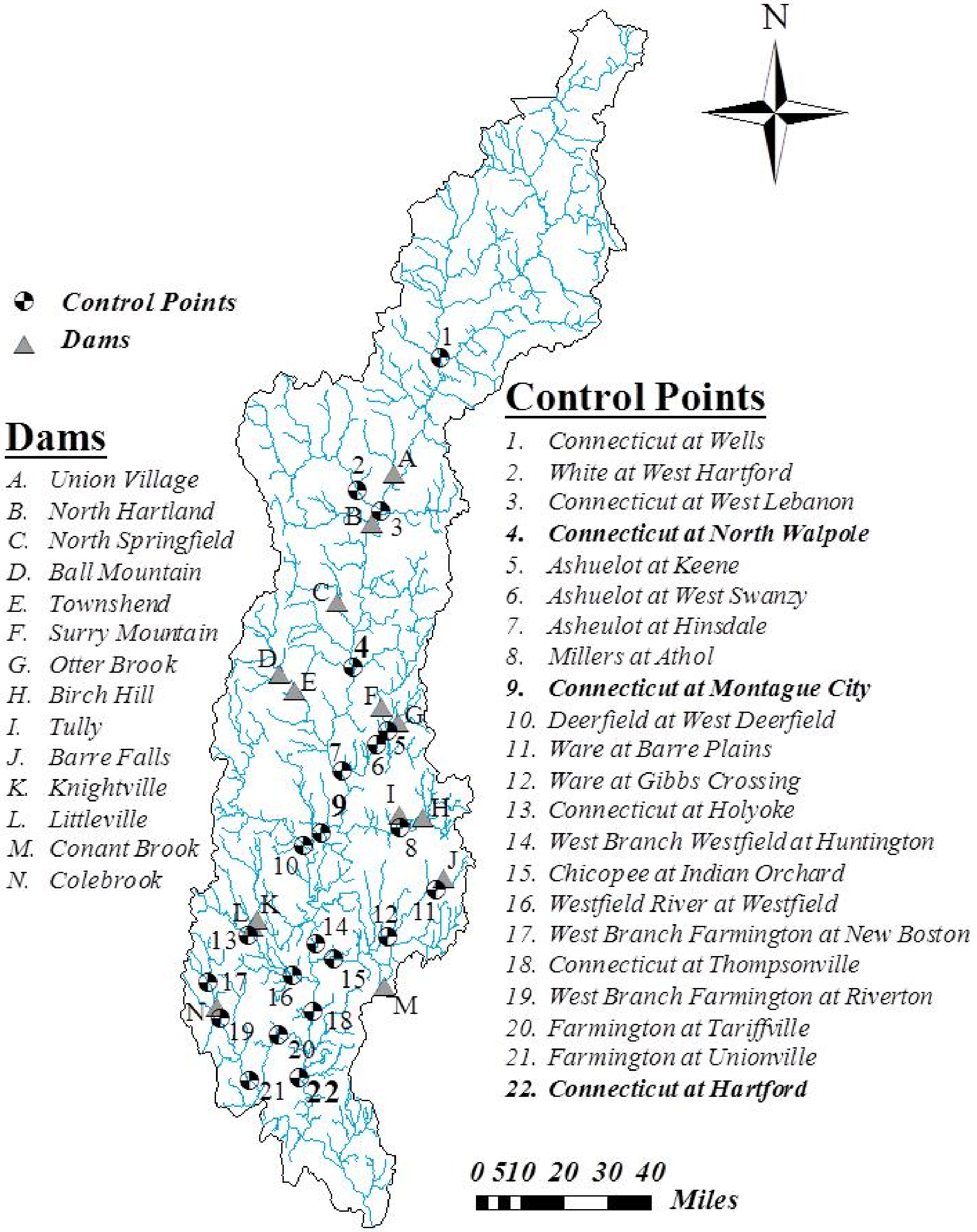


Figure 5: Dams and control points (USGS gages) of the USACE flood control system. The three bolded control points are the principal primary control points.

Modeling the USACE flood control dams incorporated the use of Standard Operating Procedures (SOP) and Outflow Guidance documents that give operating bounds within which the dams can operate. Two additional rules were incorporated based on conversations with USACE New England District dam operators (HEC 2013).

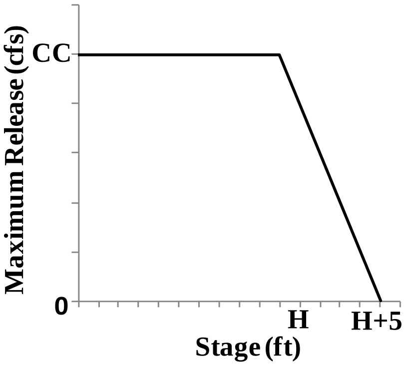
1. Downstream Control for Stage on Connecticut River Mainstem

The flood control dams enter into flood control operations when stage at Connecticut River mainstem locations exceeds specified levels, according to policy for each dam. Conversations with USACE flood operations personnel showed that flood control operators take a more measured approach when the stage at specified points on the Connecticut River mainstem are exceeded. They slowly reduce releases from the dam, rather than immediately cutting back releases. The actual amount the flood control operators cut back varies with each storm, as they also consider downstream conditions and weather forecasts. The individualized operations of each storm were not possible to model in HEC-ResSim. Instead, a linear drawdown as a function of the maximum allowable release (channel capacity (CC)) was implemented for each flood control dam. The curve implemented is shown in Table 2.

A 20% decrease in the maximum release per one foot increase in stage was used because in all cases for the flood control dams it made the maximum release zero at the stage (or 1 foot above) that the operating policy says the maximum release should be at minimum flow.

Table 2: Maximum release curve implemented for Connecticut River mainstem stage control rules for the USACE flood control dams. H is the stage at which initial regulations should occur. CC is the downstream channel capacity stipulated for each dam.

Stage (ft)	Maximum Release (cfs)
0	CC
H	CC
H+1	0.8*CC
H+2	0.6*CC
H+3	0.4*CC
H+4	0.2*CC
H+5	0
H+25	0



2. Max Releases Not Exceeding Maximum Inflow

Conversations with USACE flood control operators, described how they never allow the maximum release that flood control dams make during a high flow event exceed the maximum inflow the dams receive during the entire event. This would defeat the purpose of the flood control dam. Initial modeling of the flood control reservoirs did not account for this and the operating policies make no mention of this as part of flood operations. To incorporate the flood control operators statements about limiting the maximum outflow to not exceed the maximum inflow, a maximum release rule was incorporated that looked back over a 21-day period from the current time step and then specified that the releases at that time step could not exceed the highest inflow of the 21-day period. A 21-day look back period was used as high flow events lasted at most three weeks.

D. Water Supply

Modeling water supply diversions were performed roughly through the use of negative inflow time series (HEC 2013). While 16 of the dams had water supply as a purpose, only eight of the dams in the model had water supply withdrawals. Two of these dams, Quabbin Windsor and Shuttle Meadow, had their withdrawals estimated from limited available data (described in the accompanying appendix with HEC 2013). Six of the eight projects in the model that had water supply withdrawals, however, did not have any kind of withdrawal data. Due to the lack of daily water withdrawal information, general withdrawal guidelines were developed through discussions with the Metropolitan District (MDC), a municipal water supply district that serves the Hartford, CT area. MDC provided estimates of their winter and summer water supply diversion amounts and percent of diverted flow returned to the river. They estimated a *base flow* diversion amount of 45-50 MGD in the winter with 25-30% increase in demand in the summer months of July and August, up to a peak demand of 60 MGD. For return flows, they estimate 90% of diverted flows were returned in the winter and 70-75% of diverted flows were returned in the summer.

Using the seasonal information provided by MDC, general guidelines, shown in Table 3, were developed for seasonal diversion amounts and the percent of flow returned to the system. Since water demand does not suddenly jump from the winter base demand to the summer peak demand on July 1, June and September were treated as transition months where flows increase linearly between the base flow and peak summer flow.

Table 3: General guidelines for seasonal water supply withdrawals used to make negative inflow time series that represented water supply withdrawals.

	Seasonal Diversion Amount			**% of Diverted Flow Returned**		
	Winter (Oct-May)	**Transition (June/Sept)**	**Summer (July-Aug)**	**Winter (Oct-May)**	**Transition (June/Sept)**	**Summer (July-Aug)**
Given base flow:	Base flow	Linear interpolation between base flow and peak flow	Base flow +25%	90% return	Linear interpolation between 90% and 75%	75% return
Given peak flow:	Peak flow - 25%		Peak flow			

Note – Base flow is 45-50 MGD

Also, withdrawals from Quabbin Windsor and Bickford were for areas outside of the Connecticut River watershed so no return flow time series generated for them. The actual values for the withdrawal and return flow time series, as well as their service area and return flow locations are shown in Table 4.

Table 4: Seasonal water supply withdrawal amounts as well as service area and return flow location for six of the eight projects that were modeled with negative inflow time series for water supply withdrawals.

Reservoir	**Seasonal Diversion**		**Return Flow**		**Municipalities/ Service Area**	**Return flow locations**
	Winter	**Summer**	**Winter**	**Summer**		
	Base Flow, cfs	*Peak flow, cfs*	*90% return, cfs*	*75% return, cfs*		
Barkhamsted	46.4	61.9	41.8	46.4	Hartford, CT (MDC)	Hartford, Rocky Hill, Windsor, E. Hartford,
Bickford	1.8	2.4	Out of watershed		Fitchburg, MA	Out of watershed
Cobble Mountain	46	62	42	46	Springfield, MA	Below Holyoke Dam
Nepaug	23.2	30.9	20.9	23.2	Hartford, CT (MDC)	Hartford, Rocky Hill, Windsor, E. Hartford,
Tighe Carmondy	10.2	13.7	7.2	8	Holyoke, MA	Below Holyoke Dam
Upper Naukeag Lake	0.5	0.7	0.5	0.5	Ashburnham, MA	Upper Naukeag Lake

3.1.5 Model Testing

After creating the model and several rounds of data collections and calibration, a current conditions scenario was run for the period of record, 01Jan1961-31Dec2003 to quantify the current changes in the above described ecosystem metrics.

The results at 40 computation points were then compared with 40 USGS gages that had flow data during the simulation period of record. Twenty one of the gages had data over the entire period of record. The correlation function in Excel (Equation 1) and Nash-Sutcliffe Model Efficiency Coefficient (Equation 2) were used to do the comparison:

$$r = \frac{\sum_{t=1}^{T}\left(Q_s^t - \overline{Q_s}\right)\left(Q_g^t - \overline{Q_g}\right)}{\sqrt{\sum_{t=1}^{T}\left(Q_s^t - \overline{Q_s}\right)^2 \sum_{t=1}^{T}\left(Q_g^t - \overline{Q_g}\right)^2}} \qquad (1)$$

where r is the correlation value, Q_s^t is the simulated flow at time t, $\overline{Q_s}$ is the mean simulated flow over the period of record, Q_g^t is the gaged flow at time t, and $\overline{Q_g}$ is the mean gaged flow over the period of record. The r values can range from -1 to 1, with values closer to 1 indicating better agreement between the simulated flow and the gage data.

$$E = 1 - \frac{\sum_{t=1}^{T}(Q_g^t - Q_s^t)^2}{\sum_{t=1}^{T}(Q_g^t - \overline{Q}_g)^2} \qquad (2)$$

where E is the Nash-Sutcliffe Efficiency Coefficient value, Q_s^t is the simulated flow at time t, Q_g^t is the gaged flow at time t, and $\overline{Q}_g$ is the mean gaged flow over the period of record. The E values can range from -∞ to 1, with values closer to 1 indicating better agreement between the simulated flow and the gage data.

The average r value was 0.78 indicating overall good agreement between the HEC-ResSim computation points and gages. The r values ranged from 0.21 to 0.97, although only five points had r values below 0.6 and these points had significant operational knowledge gaps. The r values were generally highest on the Connecticut River mainstem, Millers River, and Ashuelot River. Points below the USACE flood control dams averaged 0.75, with a range from 0.64 to 0.81. This spread was expected due to the event individualized flood operations that characterize USACE flood control operations in the watershed. The lowest r values were at points with the most operational uncertainty due to lack of operational information.

Similar results to the r values were also seen in the E values. The average E value was 0.43, again indicating overall good agreement between the HEC-ResSim computation points and gages. Five points had negative E values and these were the same points that had r values below 0.6, where there were significant operational knowledge gaps. The lowest E value, -2.79, was below Quabbin-Windsor which had estimated water withdrawals.

Volumetric differences were generally pretty low (35 of 40 points were between ±20%), mostly due SYE. The largest discrepancies were around computation points that were close to the reservoirs with water supply withdrawals, which approximated in the HEC-ResSim model.

The period of record correlations do not account the change in operations over time that would be reflected in the gage data. If the whole period of record were split into operation periods, such as 20 year or 10 year periods, the later periods should have higher r values because operations would move closer to current operations reflected in HEC-ResSim. This analysis was performed on the 21 gages that had flow data for the entire HEC-ResSim period of record and almost no difference was found in the r values between the earlier and later operational periods.

Figure 6 is a map the locations of computation points that were compared to a USGS gage. A table of r values, E values, as well as the percent difference in total flow volume from gaged, is in Appendix B as well as hydrograph comparisons of HEC-ResSim output versus USGS gage at 10 of the listed locations.

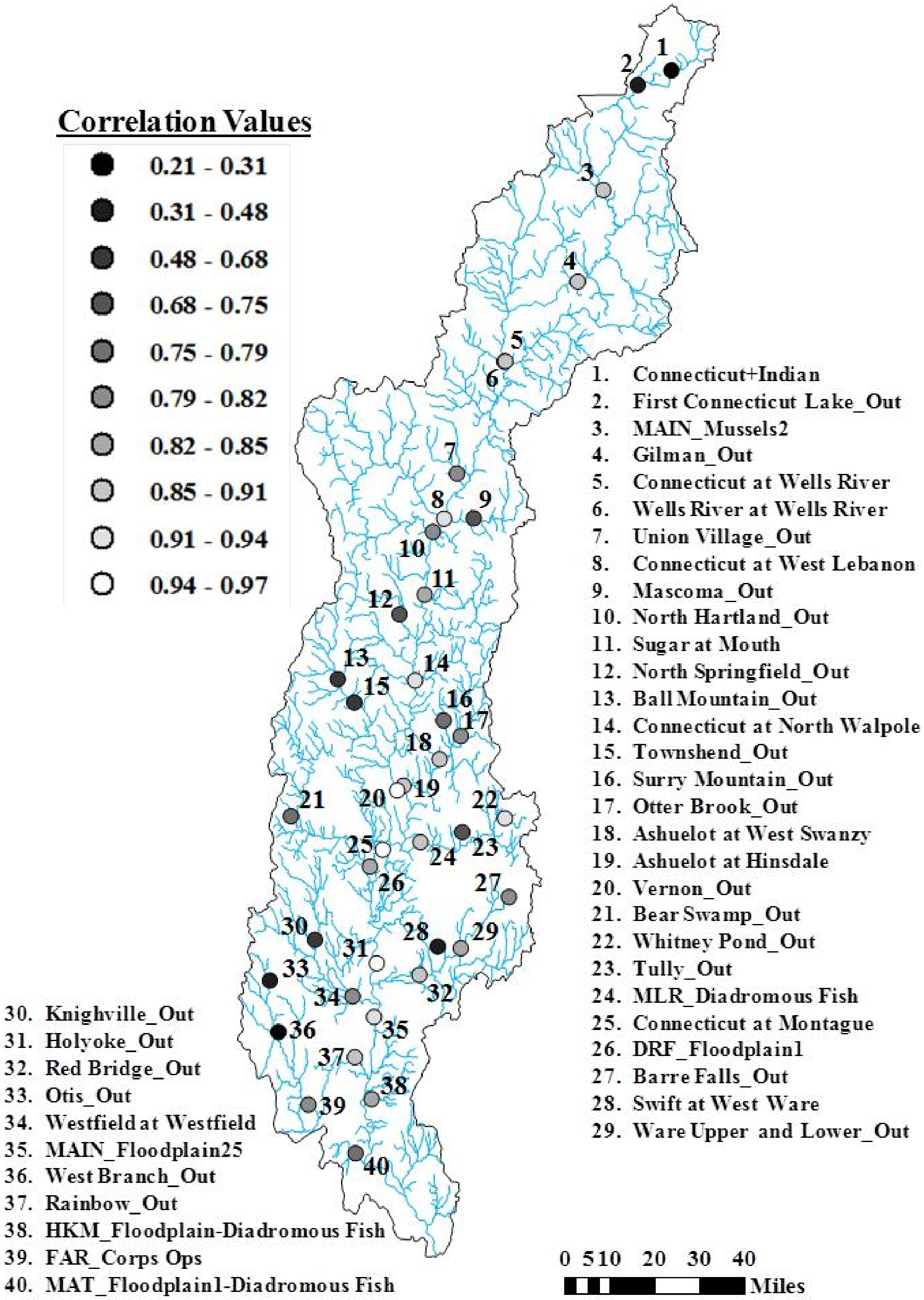


Figure 6: Map of the Connecticut River watershed showing the correlation (r) values of the 40 HEC-ResSim computation points that were compared to USGS gages.

3.2 Environmental Flows and Evaluation Criteria

3.2.1 Natural Flow Regime

Figure 7 shows the annualized unregulated hydrograph generated from SYE at five USGS gage locations (which had a corresponding HEC-ResSim computation point) along the Connecticut River mainstem. The annualized unregulated hydrographs shows the natural flow regime and how it changes along the Connecticut River mainstem. From the natural flow regime paradigm, native species are adapted to these seasonal flow patterns and deviations from these patterns and magnitudes are detrimental to the native species.

The high flow period is during the Spring when snowmelt is occurring. The peak flow period has a longer duration at the two downstream locations compared to the two upstream locations. The increased duration most likely is due to the large volumes and timing of the peak flows from the many sub-basins feeding the downstream locations. The lowest flow period is from June to August and the pattern stays relatively uniform between the different locations. The flow increases during the Fall where it stabilizes in the Winter, with the exception of small pulses due to Winter storms.

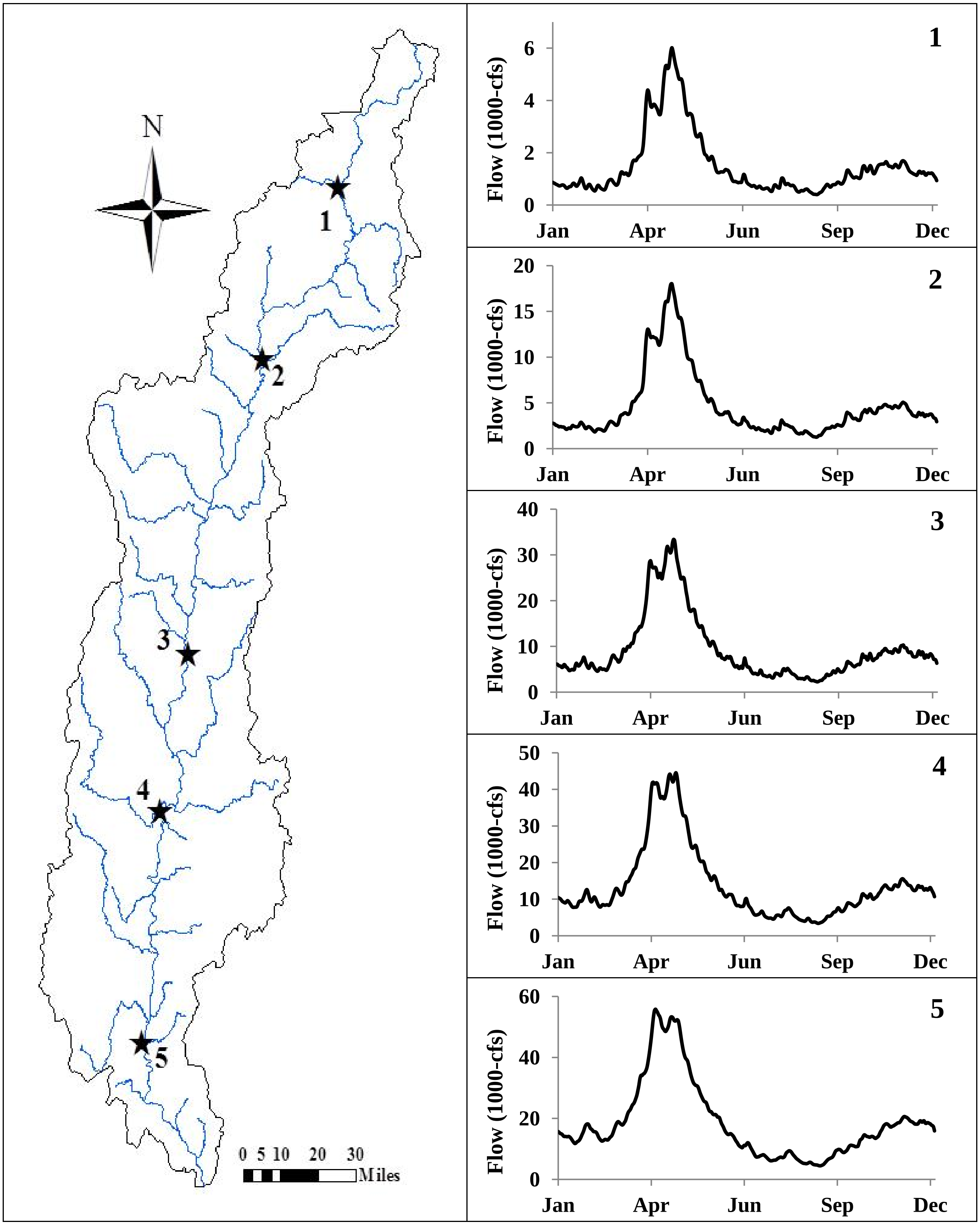


Figure 7: Map of the Connecticut River watershed and corresponding plots of the annualized unregulated hydrograph at five USGS gage locations on the Connecticut River mainstem; 1-Connecticut at North Stratford, 2-Connecticut at Wells River, 3-Connecticut at North Walpole, 4-Connecticut at Montague, 5-Connecticut at Hartford.

3.2.2 Environmental Flow Requirements

Environmental flow requirements were defined using two approaches. One approach was the flow/ecology link, where the flow needs of a particular ecological need are defined. In this case, the annual inundation duration of different floodplain plant communities was the flow/ecology link analyzed. The other approach sets flow targets as allowable percent deviations from unregulated seasonal flow statistics that experts hypothesized as being significant to different species. The implications of these flow targets are that percent changes in a flow target outside its allowable deviation will harm that species. These flow targets were developed in a workshop hosted by the TNC hosted in 2011 that brought aquatic and riparian ecologists together to develop these flow targets. Flow targets were developed for a wide variety of species including diadromous fish, Tiger Beetles, freshwater mussels, and resident coldwater fish, among others. This thesis describes an analysis of only two of the diadromous fish flow targets, but could be applied to any of the other flow targets developed from that workshop.

A. Flow/Ecology Links – Floodplain Plant Communities

Several studies have linked annual inundations to the composition of floodplain plant communities (Zimmerman 2006; Metzler & Damman 1985). From 2008 to 2010, a field survey was performed that sought to line distributions of floodplain plant communities to inundation and other variables for the Connecticut River Watershed. One variable that was determined was the linkage of specific annual durations of inundation (hereafter referred to as *annual inundation*) to general floodplain plant community types. Table 5 shows the annual inundation and Marks's classification of the floodplain plant community type.

Table 5: Days of annual inundation and different floodplain vegetation types (Marks, unpublished data)

Annual Inundation (days)	Community Type
300	Buttonbush
200	Tree to Shrub Transition
50	Floodplain Forest-Median
20	Floodplain Forest-Dry

These different vegetation communities provide habitat to many native species and are an integral part of the riparian ecosystem. Changes to the composition of the floodplain vegetation communities, due to changes in flow, results in changes to habitat and is a contributing factor to the decline of some of the native species (Zimmerman 2006).

To calculate the annual flow that corresponded to that number of days of annual inundation, the 20th, 50th, 200th, and 300th highest flows were determined for each year of the period of record, as shown in Figure 8. For example, the 20th highest flow represents the maximum area that received 20 days of annual inundation. These are not consecutive days of inundations but total annual days of inundation.

The median (50% exceedance) of each the annual inundations was then calculated to get the average annual inundation at each of the four durations. Median was chosen at it exemplifies typical year conditions.

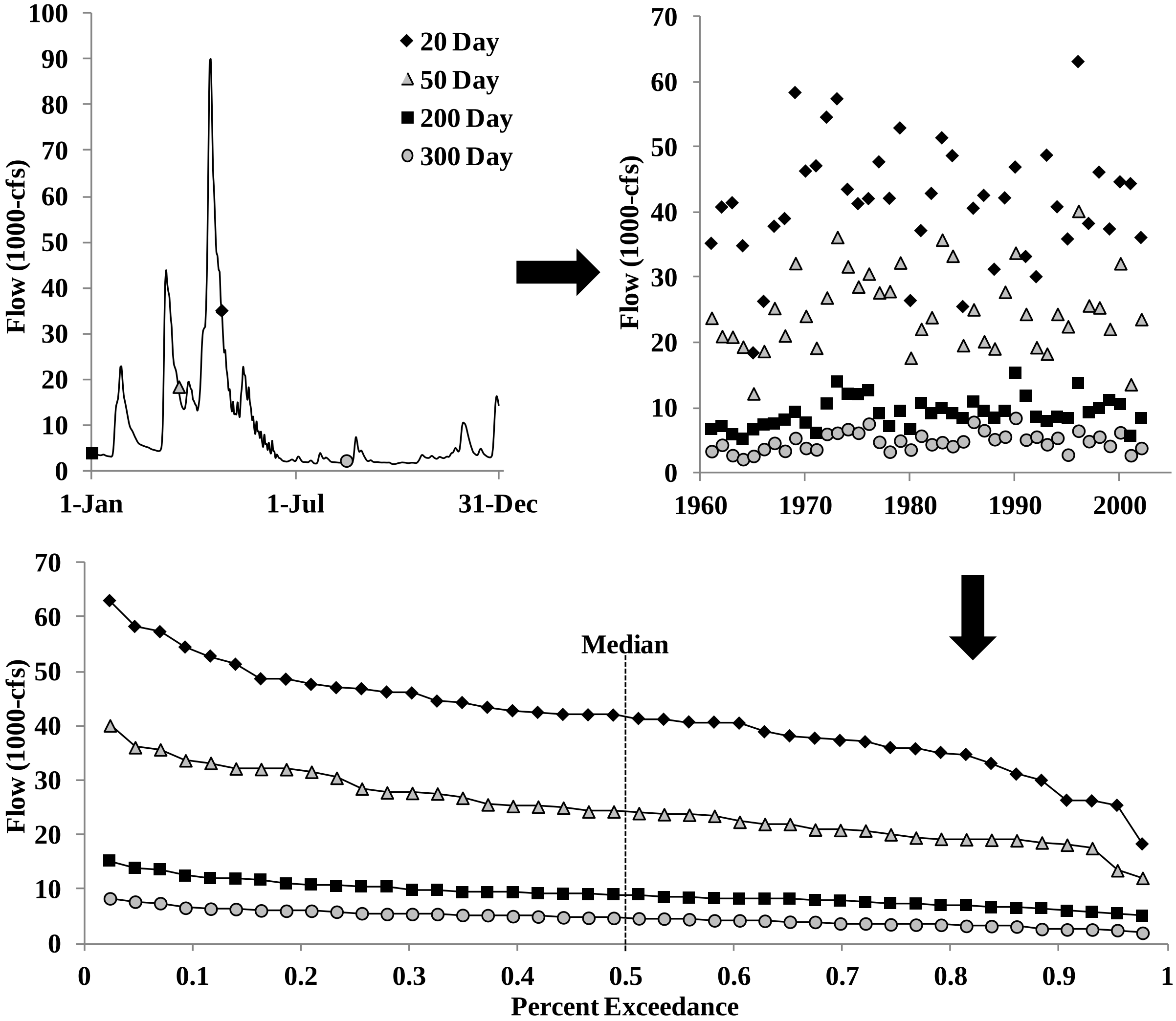


Figure 8: Plot of a hydrograph showing the 20th, 50th, 200th, and 300th highest flows for that year and the annual flows corresponding to the four annual inundation durations over the period of record.

The HEC-EFM software was used to calculate these annual inundations. The HEC-EFM (Ecosystem Functions Model) program was developed by HEC to link hydraulic and hydrologic time series with different ecosystem flow relationships: season, flow frequency, flow duration, and rate of change (HEC, 2009). The program takes a time series and ecosystem flow relationship and calculates a specific flow value based on the criteria in the relationship. HEC-

EFM can handle many time series and relationships and compute time is rapid, which was useful when calculating these values at many different points throughout the watershed. HEC-EFM was chosen over TNC's Indicators of Hydrologic Alteration (IHA) software tool as it cannot calculate flow needs and is less capable of handling large numbers of time series.

B. Expert Based Flow Targets – Diadromous Fish

Several seasonal flow targets were developed in the 2011 TNC workshop for diadromous fish, which focused on three primary species: American Shad (*alosa sapidissima*), Alewife (*alosa pseudoharengus*), and Blueback Herring (*alosa aestivalis*). The metrics were allowable percent changes in three ranges of seasonal unregulated flow duration curves. Seasonal flow duration curves are created by taking all flows from that season over the period of record and ranking them from lowest to highest. It shows the range of flows that the season experiences and can be used to characterize different levels of flow (Vogel & Fennessey 1995). Comparing flow duration curves shows the changes in variability of the flow. The metrics analyzed in this study are shown in Table 6.

Table 6: Seasonal flow metrics specified by ecological experts as ecological flow targets for diadromous fish.

	Allowable Percent Change from Unregulated		
Season	**Q99-Q90 (low)**	**Q90-Q50 (medium)**	**Q50-Q10 (high)**
Spring (March-May)	±0%	±10%	±20%
Fall (September-November)	±0%	±10%	±20%

March to May is the season when the adult diadromous fish migrate upstream and spawn. Alewife and Blueback Herring spawn up until end of May while American Shad can spawn as late as June (Zimmerman 2006). September to November is the season of juvenile outmigration. The experts' flow targets specify that during these two seasons, no change should occur to the lowest 10% of flows, the Q99-Q90 (low) range of the flow duration curve. At the low to medium range of flows, Q90-Q50 (med) there is a 10% allowable change from the unregulated flow duration curve. For the medium to high flows, Q50-Q10 (high), the allowable change from unregulated is 20%. By setting these allowable flow deviations from unregulated conditions, the experts are hypothesizing that these three diadromous fish species can tolerate changes in the unregulated flow regime at higher flows. The fish can tolerate less change in low flow conditions. At the lowest flows, the fish cannot tolerate any change from unregulated.

3.2.3 Evaluation Criteria

Three sets of evaluation criteria were used to measure environmental alteration in the annual inundations for floodplain plant communities; A) Reliability, which measured changes in timing, B) Percent Change, which measured changes in magnitude, C) Inundated Area, which measured spatial changes. Only Percent Change was used to measure environmental alteration in the diadromous fish flow metrics, as the two evaluation criteria were not applicable.

A. <u>Reliability</u>

Reliability, as defined in this analysis, is the ability of the regulated flow to meet unregulated conditions. Specifically, it is the percent of years the annual regulated flow values for the four floodplain annual inundations exceed the median unregulated floodplain annual inundation flow values. Figure 9 shows an example calculation of reliability.

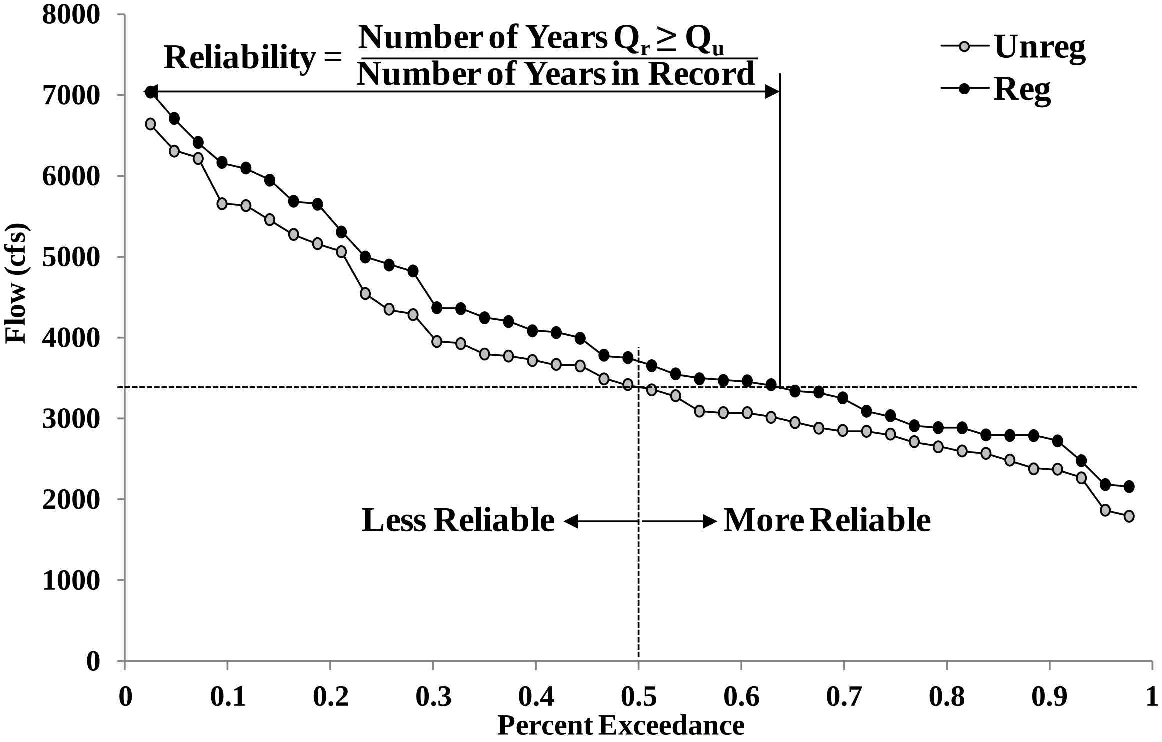


Figure 9: Example calculation of reliability.

A reliability value greater than 50% indicates that the regulated floodplain annual inundation flow values are meeting the median unregulated flow values in a majority of years. Conversely, a reliability value below 50% means the regulated flow values are meeting the median unregulated flow values in less than a majority of years. This criteria was not applied to the diadromous fish flow metrics because this criteria was frequency based and the diadromous fish metrics are flow duration based.

B. Percent Change

Percent change from unregulated was used to evaluate the change in magnitude of both the floodplain annual inundations and the diadromous fish flow metrics. Percent change was calculated using Equation 3:

$$\% \text{ Change} = \frac{Q_r - Q_u}{Q_u} * 100\% \tag{3}$$

where Q_r is the regulated flow, Q_u is the unregulated flow.

Percent change normalizes the change from unregulated so that differences in magnitudes can be compared across the watershed, where there is a wide range of total flow received.
To calculate the percent change in the three flow duration curve ranges, the percent change between the midpoint and endpoints of each range were averaged. Using more points within the flow duration curve yielded similar results overall. This gave an accurate representation of the overall percent change from regulated and allowed the HEC-EFM to be used to compute the percent change for these different metrics at many locations quickly.

C. Inundated Area

A spatial analysis of the change in inundated area was performed in areas that had a river hydraulics model. The USACE New England District created an HEC-RAS (River Analysis System) model for a section of the Connecticut River mainstem; a 7-mile reach by North Hampton, MA. HEC-RAS is a hydraulic modeling software that can perform many functions including simulating water surface elevations and floodplain inundation for 1-d steady and unsteady flow analyses (HEC 2010). The average unregulated and regulated flow of the four annual inundation durations (Table 7) were calculated at a computation point that was closest to the midpoint of the modeled section of river. The regulated and unregulated flows were then simulated in a 1-dimensional steady hydraulic flow simulation in HEC-RAS, to get the water surface profiles of each flow. Boundary conditions were known water surface elevations from a rating curve provided by USACE New England District. Inundation grids for the resulting water surface profiles were then calculated using the RAS Mapper tool in HEC-RAS. The resulting inundation grids were then rendered in Environmental Systems Research Institutes's (ESRI) ArcMap software and ArcMap's area calculator was used to calculate to the total area of the inundation grids. This gave the total inundated area at that flow and was used to calculate changes from unregulated in the areas that received the four annual inundations. Future analysis using this approach could incorporate additional variables, such as depth, velocity, and soil type to achieve more refined maps of floodplain habitat.

4. Results

An analysis was performed to quantify the percent change from unregulated flows of the two types of ecological metrics described earlier along the entire Connecticut River mainstem. Unregulated hereafter refers to flow in the natural (no dam) condition. The current environmental alteration (hereafter referred to as Current Conditions) was analyzed for both the floodplain plant inundations and the diadromous fish flow metrics. The floodplain plant inundations were analyzed for change in reliability, percent change from unregulated, change in inundated area, and hydropower generation tradeoffs. The diadromous fish flow metrics were analyzed for percent change from unregulated and seasonal hydropower generation tradeoffs. The current conditions analysis identified the extent of environmental alteration along the Connecticut River mainstem as well as dams where reductions in the alteration would be the greatest. Once these dams were identified, four dam removal scenarios were analyzed for the changes in environmental alteration, floodplain inundation, hydropower generation, and flood protection. The 106 points analyzed on the Connecticut River mainstem, shown in, were every dam outflow, tributary confluence, and eco-node. Figure 10 shows a map of the Connecticut River watershed with all 106 points that were analyzed. The numbered points are the dams on the Connecticut River mainstem.

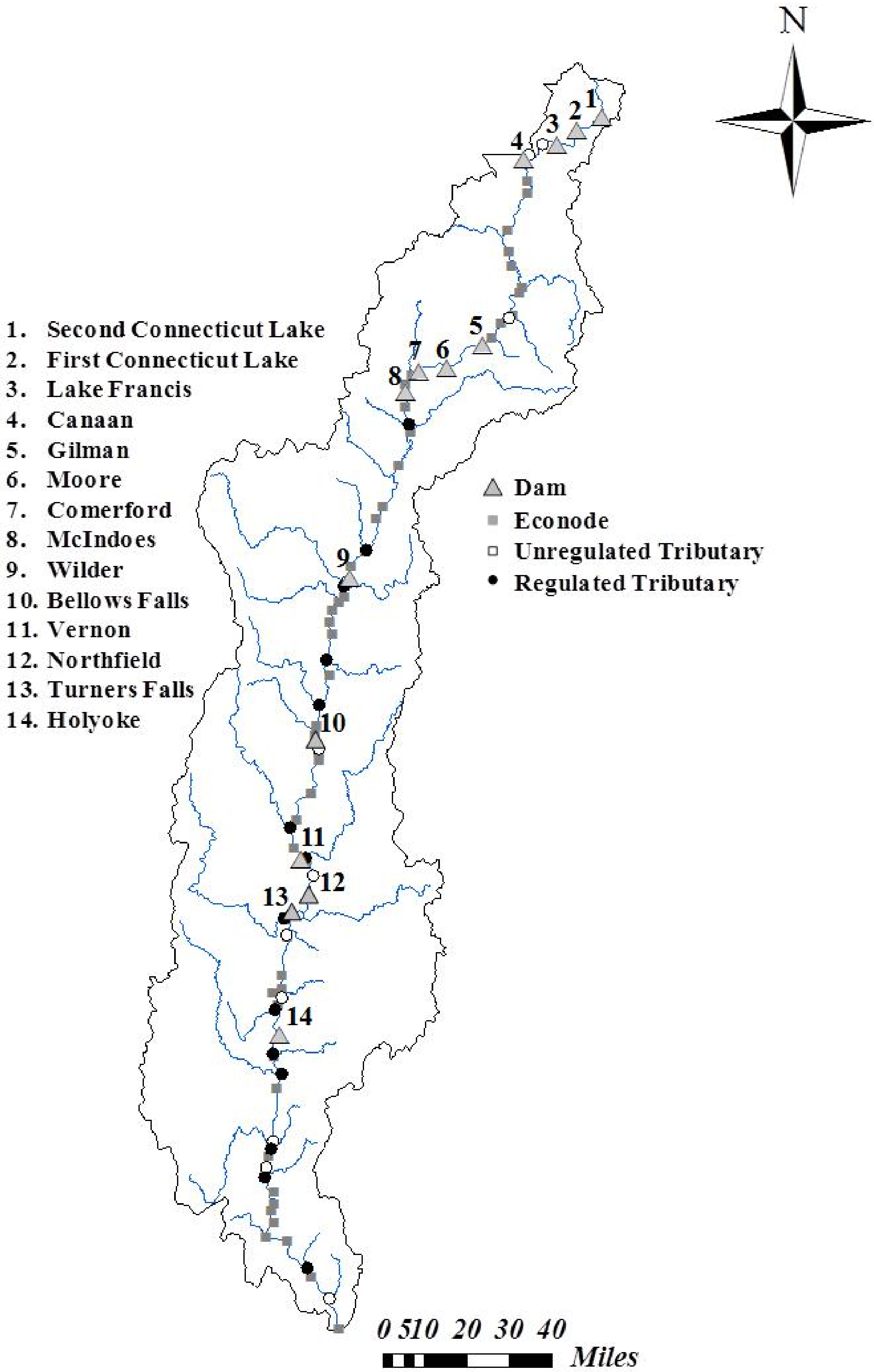


Figure 10: Map of points along the Connecticut River mainstem that were analyzed for changes in ecological flow metrics and the annualized unregulated and regulated hydrographs at five points.

4.1 Current Environmental Alteration (Current Conditions)

4.1.1 Flow Regime Alteration

Figure 11 shows the annualized regulated and unregulated hydrographs at the five USGS gage locations from Figure 7. The plots show how the regulated flow regime has altered the natural flow regime. The upstream locations have the highest degree of alteration and decreases moving downstream due to increases in flow from tributaries. Overall variation between the lowest and highest flows is decreased. At the most upstream location, this is most pronounced. The magnitude of the Spring high flows are decreased and the magnitude of Winter flows are increased. At the downstream locations, the alteration in the natural flow regime appears to be small except for the differences in the peak flow. The seasonal flow patterns appear to be unchanged. Analyzing the change in the flow regime at this point does not necessarily indicate what dams are causing the alteration. Analyzing the two environmental flow metrics at all the points will shed more insights into the current state of environmental alteration.

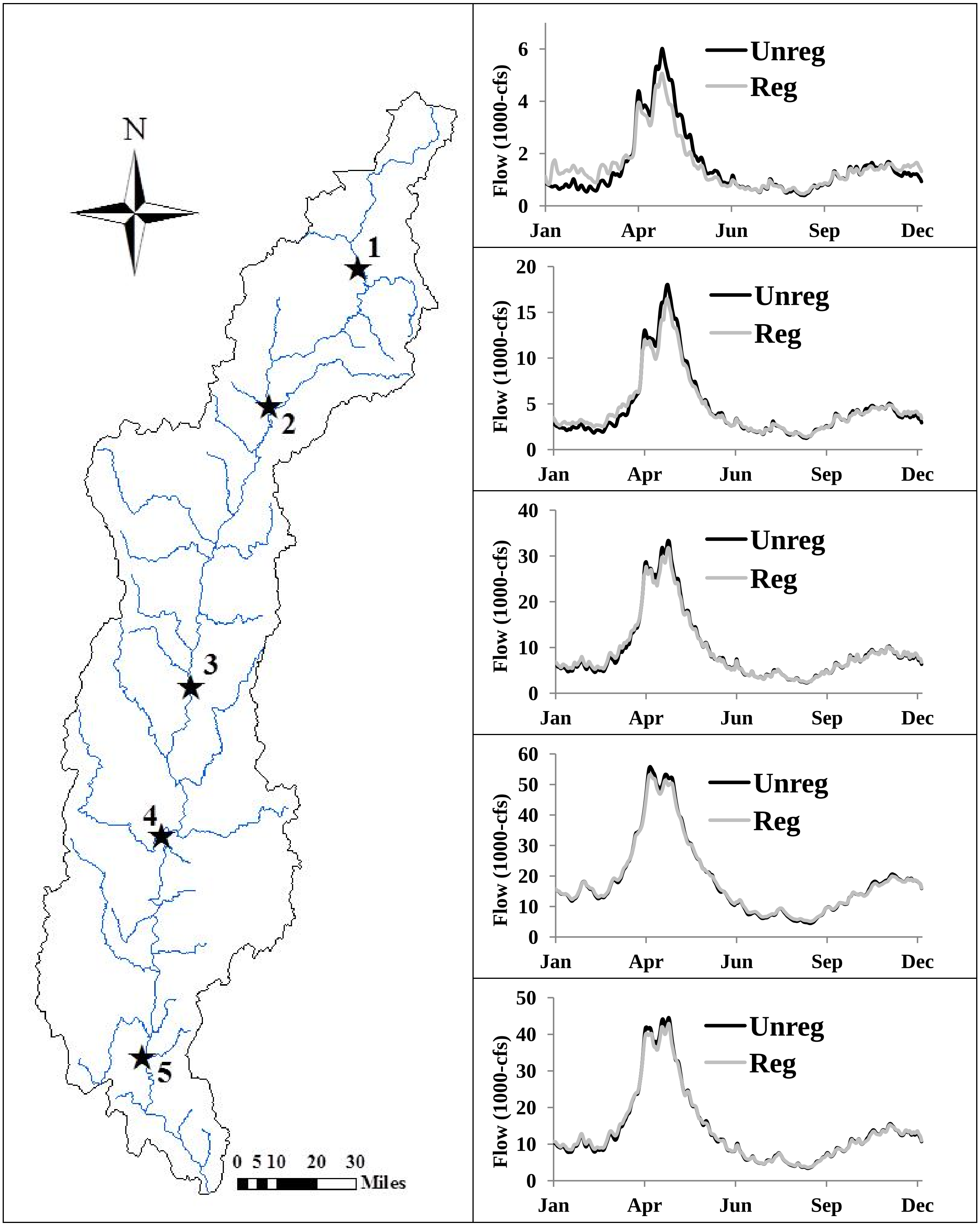


Figure 11: Map of the Connecticut River watershed and corresponding plots of the annualized regulated and unregulated hydrograph at five USGS gage locations on the Connecticut River mainstem; 1-Connecticut at North Stratford, 2-Connecticut at Wells River, 3-Connecticut at North Walpole, 4-Connecticut at Montague, 5-Connecticut at Hartford.

4.1.2 Floodplain Plant Communities Alteration

A. Reliability

Figure 12 shows reliability (in percent of years) of the current conditions for the four floodplain plant inundation durations at the five USGS gage locations on the Connecticut River mainstem. The closer the reliability value is to 50%, the closer the timing of regulated annual inundations are to typical unregulated conditions.

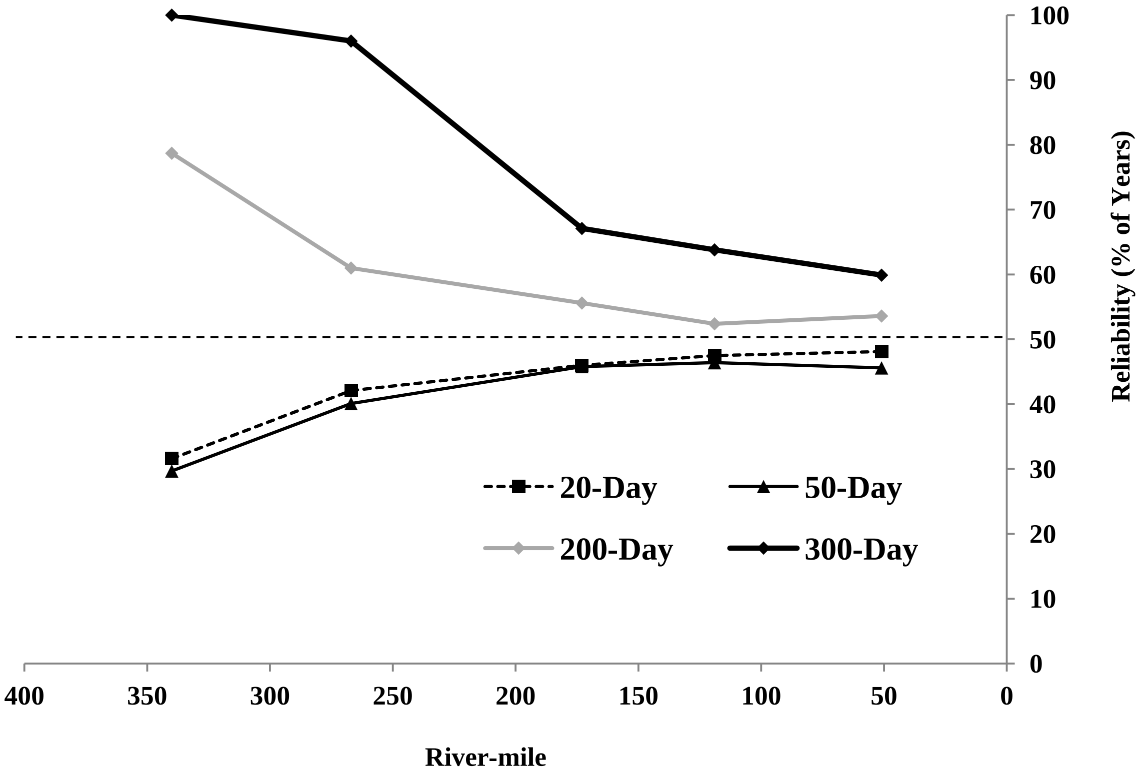


Figure 12: Plot of reliability (in percent of years) at five computation points along the Connecticut River mainstem of the current conditions to exceed the median unregulated annual inundations.

At the top of the watershed, below the Connecticut Lakes projects, reliability for the 300-day and 200-day annual inundations are the highest and the lowest for the 50-day and 20-day annual inundations. The reliability of all four annual inundations moves towards 50% moving downstream, indicating that the median regulated flow approaches the median unregulated flow. The reliability results show that the median value of the unregulated 200-day and 300-day annual inundations occurs more often under current conditions, indicating that regulated low flows are higher throughout the whole Connecticut River mainstem than unregulated conditions. Conversely, the current conditions meet the meet unregulated 50-day and 20-day annual inundations in fewer years, indicating that regulated high flows are lower than unregulated.

B. Percent Change

Figure 13 shows the percent change from unregulated to regulated in the average 20-day, 50-day, 200-day, 300-day annual inundations at every single dam outflow, tributary confluence, and eco-node point in the HEC-ResSim model along the entire of the Connecticut River mainstem. Again, the four annual durations of flow correspond to different floodplain plant communities.

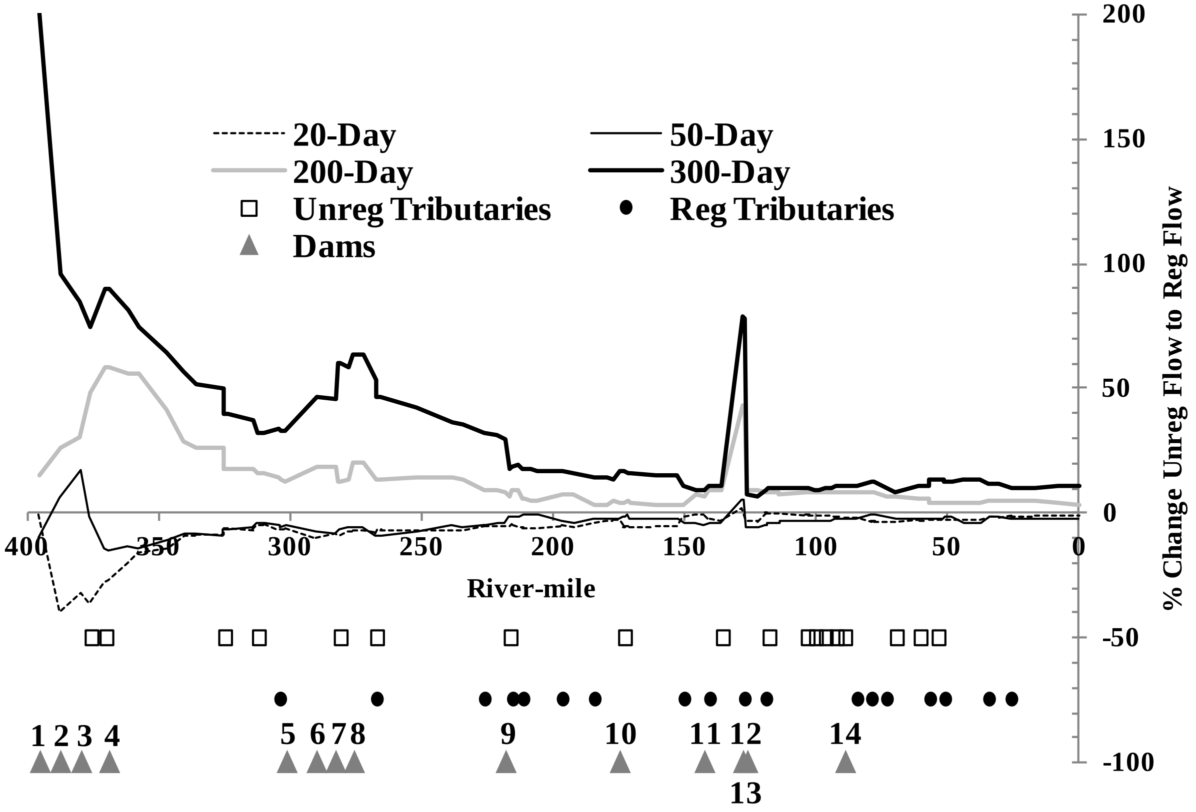


Figure 13: The percent change from unregulated to regulated in the median annual inundation for the four different durations at every dam outflow, tributary confluence, and eco-node on the Connecticut River mainstem.

Alteration of the unregulated hydrograph is more pronounced at the top of the watershed because the three dams of the Connecticut Lakes heavily regulate the flow. As one moves down the watershed, the percent change from unregulated flow generally decreases as more drainage area supplies more unregulated flow, diluting the alteration. The percent change appears to stabilize after river-mile 200**.** Larger decreases after the Connecticut Lakes dams are due to unregulated tributaries or eco-nodes that contribute a larger percentage of the total drainage area at the point they enter the Connecticut River mainstem. Regulated tributaries primarily also decrease in percent change. However, the extent of the regulation that is occurring on those tributaries can affect this and in some cases even cause increases in the alteration. The most notable tributary in this regard is the Chicopee River, which has the Quabbin Windsor water supply reservoir.

The two most noticeable increases are due to dams. The largest relative increase, at river-mile 130 is due to Northfield; however, its alteration is almost instantly muted due to Turners Falls downstream, indicating that current operations at Turners Falls are important for mitigating the large effects of Northfield. Moore, at river-mile 290, causes the largest relative increase in environmental alteration after Northfield. The run-of-river hydropower dams do not cause any alteration in the four annual inundations.

The regulated 300-day annual inundation is considerably higher than the unregulated 300-day annual inundation at the top of the watershed, compared to the other three annual inundations. The 300-day annual inundation also stabilizes out at a higher percentage above unregulated than the other three annual inundations. The 200-day annual inundation behaves similarly to the three hundred day, but does so at lower percentages above unregulated in both the upper watershed and at the point it stabilizes.

In general, the patterns indicate that regulation by dams has caused, more land along the entire Connecticut River mainstem to be inundated at least 200 days annually than if there were no regulation from dams, with even more land receiving at least 300 days of inundation. More vegetation along the river channel is of buttonbush or mixed shrub composition. Also, the increased inundations, especially in the upstream areas where the alterations are the highest, mean less open beach habitat along the channel is available. Open beach habitat loss is documented as one of the primary reasons for the decline in Puritan Tiger Beetle populations (New Hampshire Fish and Game Department 2005).

The regulated 20-day and 50-day annual inundations, on the other hand, are reduced from their respective unregulated durations. However, as compared to the 200-day and 300-day annual inundations, the magnitude of that reduction is much lower. The 20-day annual inundation is more reduced at the top of the watershed but the percent change decreases soon afterwards, ultimately stabilizing at a percentage close to unregulated. The 50-day annual inundation behaves similarly to the 20-day annual inundation but stabilizes higher up in the watershed. Conversely, less land is receiving inundation of 50 and 20 days annually due to regulation by dams, reducing in floodplain forest areas. Higher up in the watershed, these differences are more pronounced than in the lower watershed. These results are similar to results obtained Nislow *et al.* 2002, which found a reduction in higher elevation floodplain forests.

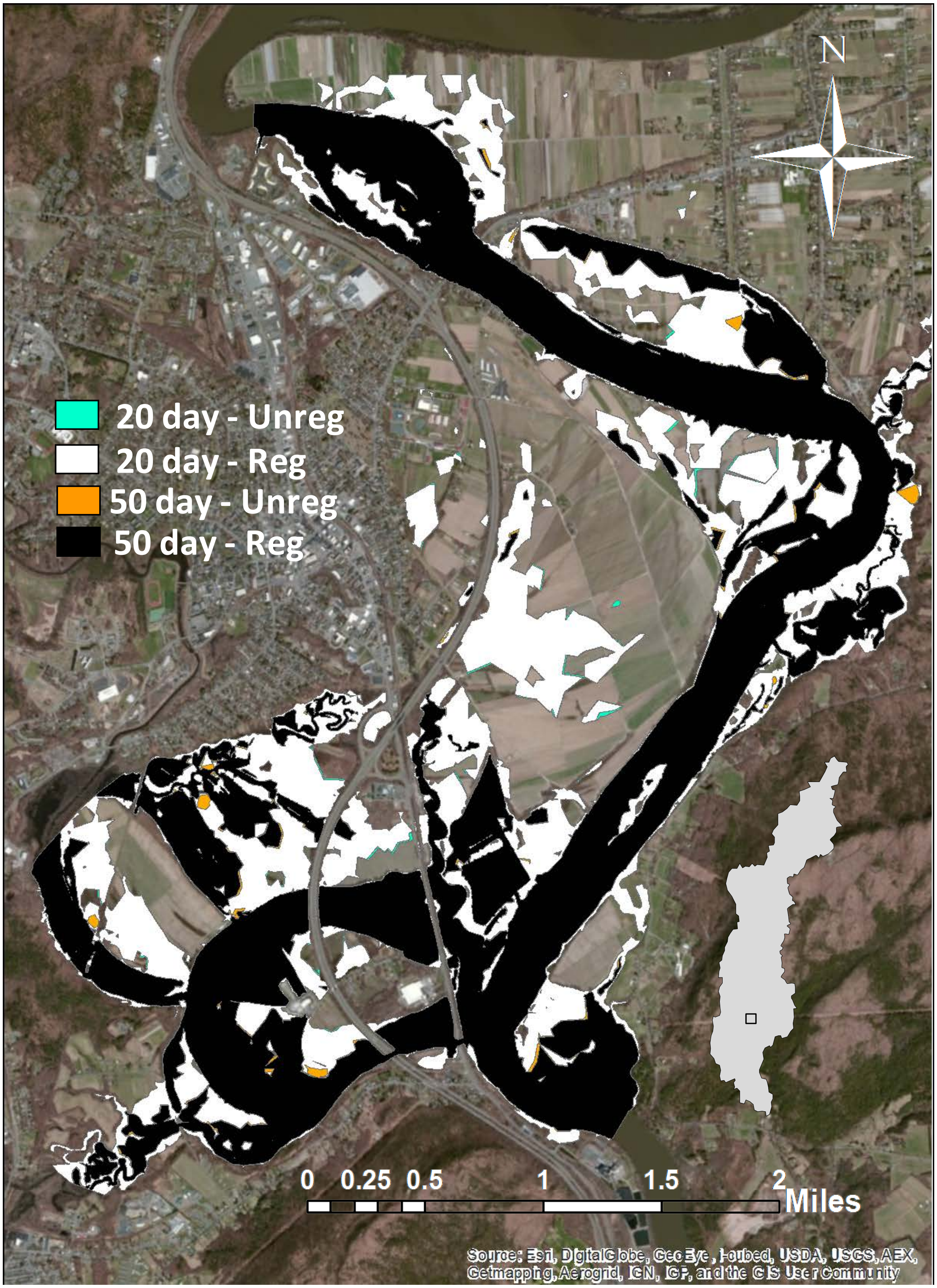
C. Change in Inundated Area

The topography of the each section of river determines how the changes in the different annual durations translate into changes in inundated area. Table 7 shows this translation from percent change in annual duration of flow to inundated area for the 7 river-mile stretch of the Connecticut River mainstem where hydraulic data was present by North Hampton, MA.

Table 7: Percent change from unregulated in both flow and inundated area of the four annual inundation durations for a 7 river-mile stretch of the Connecticut River mainstem by North Hampton, MA.

Annual Inundation (days)	Unreg Flow (cfs)	Reg Flow (cfs)	Change in Flow (cfs)	% Change Flow	Unreg Inundated Area (acres)	Reg Inundated Areas (acres)	Change in Inundated Area (acres)	% Change Area
20	44,480	43,930	-550	-1.2	3,564	3,524	-40	-1.1
50	24,878	24,148	-730	-2.9	2,160	2,106	-54	-2.5
200	7,641	8,268	627	8.2	1,148	1,174	26	2.3
300	3,511	3,856	345	9.8	941	942	11	1.2

The relatively large percent change in the expected annual 300-day annual inundation flow does not convert to a large percent change in the amount of acres receiving 300 days of annual inundation. It translates to an 11 acre increase because the stage at this flow has not reached high enough to spill onto the much larger floodplain. The 200-day inundated area gained more acreage than the 300-day, despite having a smaller percent change in the flow. At the lower annual inundations, more inundated area is lost or gained at smaller percent changes in flow. At a -1.1% percent change (-40 acres) in the median 20-day annual inundation, almost five times as much inundated area is lost as was gained by the 300-day inundation (+11 acres). The 50-day inundated area lost about the same amount of acreage as the 20-day inundated area, despite twice as much change in flow. The loss in acres receiving 20 days and 50 days of inundation were concentrated in a few patches and slight increases in encroachment of existing patches. However, these differences are small compared to the total amount of acres that receive inundation and probably not worth the potential costs of changing operations up stream. Also, any steps to return flows along this stretch to the unregulated condition would not significantly change the composition of the floodplain plant communities (and riparian habitat) along this stretch. Figure 14 shows a map of the actual changes in inundated area for the 20-day and 50-day annual inundation durations. The changes in inundated area for the 300-day and 200-day were not visible enough to be worth plotting.



Source: Esri, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, and the GIS User Community

Figure 14: Map of a 7 river-mile section of the Connecticut River mainstem by North Hampton, MA showing the change in area receiving 50 and 20 days of annual inundation due to the change in unregulated flow.

D. Hydropower Tradeoffs

Since all dams are operated for hydropower generation, the tradeoff of changing their operations will be potential reductions in the hydropower generation. To get a sense of which dams would have the highest percent change reduction per loss of hydropower output, the average annual hydropower generated from each dam was divided by the difference between the percent change of each average annual inundation at each Connecticut River mainstem dam and the percent change at the point directly upstream of the dam. This creates a metric that is percent change per megawatt generated and allows for the Connecticut River mainstem hydropower dams to be compared to see which dams would have more benefits gained per loss of annual hydropower. The hydropower generation data was from the HEC-ResSim model, which gives time series for power as part of its output. This gives a percent change per megawatt of hydropower generated. Table 8 gives the difference in percent change from the preceding point on the Connecticut River mainstem and the average annual hydropower generated[3].

Table 8: Average annual hydropower generated and the percent change in the four annual inundation durations caused by the hydropower generating dams on the Connecticut River mainstem.

Hydropower Projects	Average Annual Hydropower Generated (MW)	Difference in Percent Change (20-Day)	Difference in Percent Change (50-Day)	Difference in Percent Change (200-Day)	Difference in Percent Change (300-Day)
Gilman	1,370	-0.004	0.04	-0.1	-0.1
Moore	4,260	2.0	2.2	-3.3	-7.6
Comerford	9,460	0.4	-0.7	-3.1	13.0
McIndoes	2,039	-0.1	-0.2	0.8	1.9
Wilder	6,125	-0.3	0.0	-0.1	-1.5
Bellows Falls	9,310	0.1	-0.1	0.1	0.2
Vernon	5,939	-0.2	-0.7	0.5	0.8
Northfield	40,403	5.0	10.0	35.4	57.6
Holyoke	7,588	0.1	0.0	-0.1	0.0

---

[3] Canaan and Turner Falls were excluded from the percent change per megawatt analysis because their hydropower generations are dependent on reservoir operations upstream.

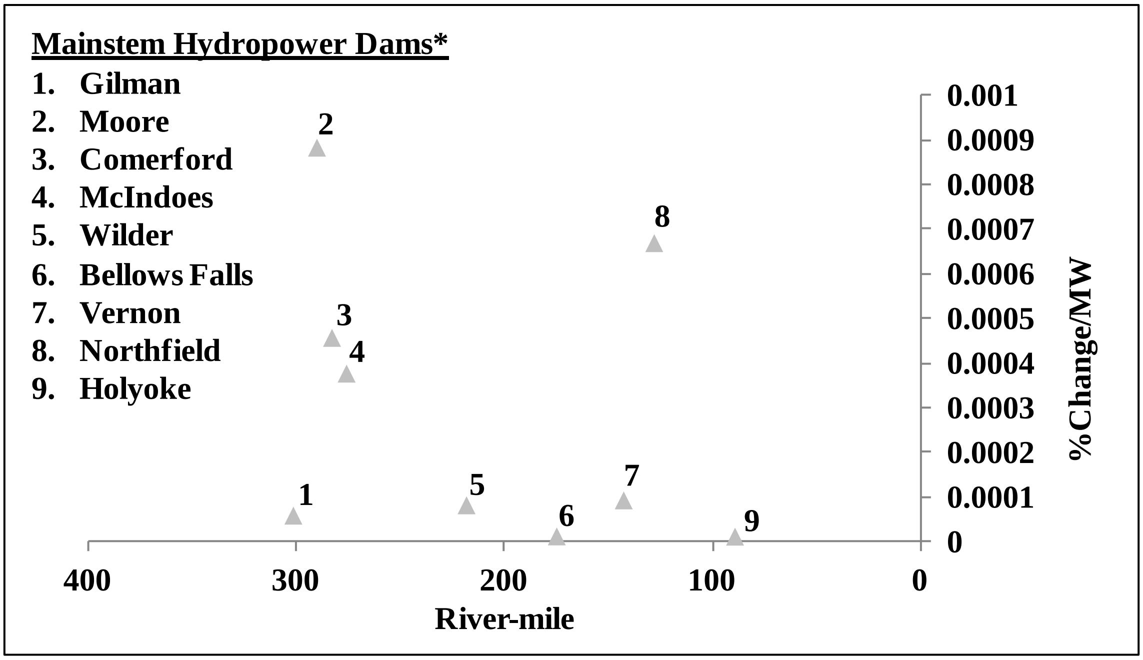


Figure 15: Absolute value of the average percent change from unregulated conditions of the four floodplain annual inundations per megawatt generated of each Connecticut River mainstem hydropower dam. *Excluding Canaan and Turners Falls.

Higher values in this figure indicate higher tradeoffs of environmental alteration and hydropower generation among the Connecticut River mainstem hydropower dams. Moore and Northfield have the two highest percent change per megawatt values. Northfield has a slightly higher value than Moore, even though Northfield generates almost 10 times as many megawatts, the proportion of percent change per megawatt is the same. This would indicate that Northfield has a slightly higher tradeoff of environmental alteration and hydropower than Moore. These two reservoirs are operated for peaking hydropower generation. Comerford is also a peaking hydropower facility but generates enough annual megawatts to have its percent change per megawatt be comparatively lower than Moore and Northfield. Ultimately, this metric points to the elimination of the hydropower operations of these two dams as having more benefits, where benefits in this case are reductions in environmental alteration, per loss of hydropower compared to the other Connecticut River mainstem dams. Also, based on this figure, more benefits would be realized for lower flows than higher flows.

4.1.3 Diadromous Fish

A. Percent Change

The same analysis for the floodplain inundations was applied to the seasonal flow metrics that are significant to diadromous fish. Figure 16 shows a plot of the percent change in the Fall (September to November and Spring (March to May) low flow (Q99-Q90), medium flow (Q90-Q50), and high flow (Q50-Q10) at different points along the Connecticut River mainstem. Diadromous fish eco-nodes do not extend all the way up the Connecticut River mainstem like the floodplain forest do so a line is included to show where the importance of the percent change actually starts, at River-mile 265.

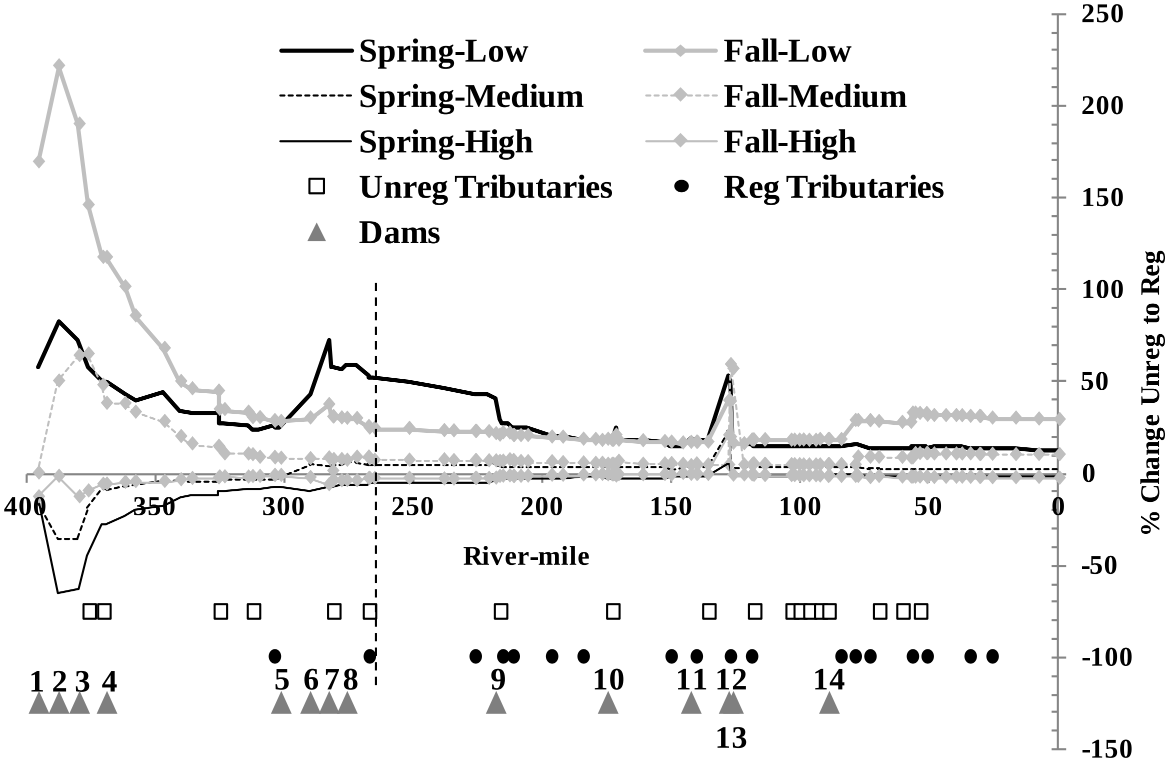


Figure 16: The percent change from unregulated to regulated in the six seasonal flow metrics for diadromous fish at every dam outflow, tributary confluence, and eco-node on the Connecticut River mainstem. The line delineates the range of the diadromous fish.

Similar to the floodplain inundations, the percent change in the seasonal flow metrics is larger at the top of the watershed and then decreases moving down the watershed. The low flows for both seasons saw an increase from unregulated flows and the magnitude of percent change was much more than the medium flows and high flows. This is consistent with the floodplain inundation results, which also pointed to an increase in low flows and which pointed to a larger alteration of lower flows than higher flows. The percent change in the high flows is negative, indicating lower high flows from unregulated, which also is consistent with the floodplain inundation results.

The differences in the seasons of the flow metrics appear to make a major difference. The Fall high flows are less disturbed than the Spring high flows at the top of the watershed, when seasonal storage targets in the Connecticut Lakes reservoirs are storing the Spring snowmelt and then making releases during the Fall. The Fall medium flows are more disturbed than the Spring medium flows and both are positive, indicating the seasonal store and release of the Connecticut Lakes reservoirs have increased the Fall and Spring medium flows. However, the seasonal differences of both the high and medium flows are small (< 20%) at the point that on the Connecticut River mainstem when the metrics are actually significant. The Spring and Fall medium and high flows fall within the expert recommended tolerances along the entire Connecticut River mainstem. The seasonal differences are a factor for the low flows. The Fall low flow appears to less affected (< 40%) by dams or tributaries below river-mile 265 (with the exception of Northfield). It gradually decreases in percent change until the Chicopee and Farmington Rivers enter the Connecticut River mainstem, where small increases in the percent change of alteration occur. Meanwhile, the Spring low flow is more altered upstream (river-miles 265 to 125) and less altered downstream of river-mile 125. The Spring low flow is affected much more by Moore than the Fall low flow, which is just starting point of significance for diadromous fish.

The significant increase in the Fall low flows along the whole Connecticut River mainstem means that during Fall higher flows happen during the juvenile outmigration from the river, which is detrimental according to the natural flow regime paradigm. The regulated Fall low flows are considerably above the tolerance the experts recommend for diadromous fish, indicating negative consequences for out-migrating juveniles along the entire Connecticut River mainstem. This alteration is roughly uniformly distributed along the whole Connecticut River mainstem. Similarly, the Spring low flows also indicate more water is available from regulated flows than unregulated flows during Spring up-migration. Once again, in the natural flow regime context, this will result in negative consequences for the fish. However, unlike the Fall low flows, these are not evenly distributed across the Connecticut River mainstem. Below the White River confluence, the percent change steadily drops which would indicate that the Connecticut River mainstem becomes more and more conducive to diadromous fish moving downstream. However, they are still outside the recommended tolerance of diadromous fish for changes in spring low flows.

B. Hydropower Tradeoffs

A hydropower tradeoff analysis similar to the analysis described for the floodplains was also done for the two seasonal diadromous fish metrics. However, instead of average annual hydropower generation; average hydropower generation during the two seasons was analyzed. The difference in percent change of each hydropower dam from the preceding point was divided by the average seasonal hydropower each Connecticut River mainstem hydropower dam generated. This creates a metric that is seasonal percent change per megawatt generated. Table 9 gives the difference in percent change for the six seasonal diadromous fish metrics and the seasonal average hydropower generated of the Connecticut River mainstem hydropower dams. Figure 17 shows the absolute value of the percent change per megawatt of the metrics per season averaged together. Turners Falls and Canaan are excluded from Figure 17 for the reasons described in the floodplain hydropower analysis.

Table 9: Average seasonal hydropower generated and the difference in percent change from unregulated flow to regulated of the six season diadromous fish flow metrics caused by the hydropower generating dams on the Connecticut River mainstem.

	Spring				**Fall**			
Hydropower Projects	**Hydropower Generated (MW)**	**Low (% Change)**	**Medium (% Change)**	**High (% Change)**	**Hydropower Generated (MW)**	**Low (% Change)**	**Medium (% Change)**	**High (% Change)**
Gilman	430	-0.3	-0.1	0.2	330	-0.1	-0.2	0.07
Moore	3,314	17.6	7.3	-2.1	276	1.9	0.4	-1.2
Comerford	3,889	30.2	-0.6	1.2	1,913	7.3	-7.1	-3.9
McIndoes	788	2.2	1.9	0.4	437	-0.2	1.7	0.1
Wilder	2,608	-2.3	1.5	0.1	1,269	-1.1	-0.3	0.1
Bellows Falls	3,616	1.3	0.2	-0.1	1,941	0.6	-0.02	-0.2
Vernon	2,550	4.4	1.4	-0.1	1,127	0.3	0.9	-0.5
Northfield	9,667	35.8	19.4	6.9	10,179	22.6	54.7	21.3
Holyoke	2,769	-0.02	-0.1	0.1	1,615	-0.1	-0.2	-0.3

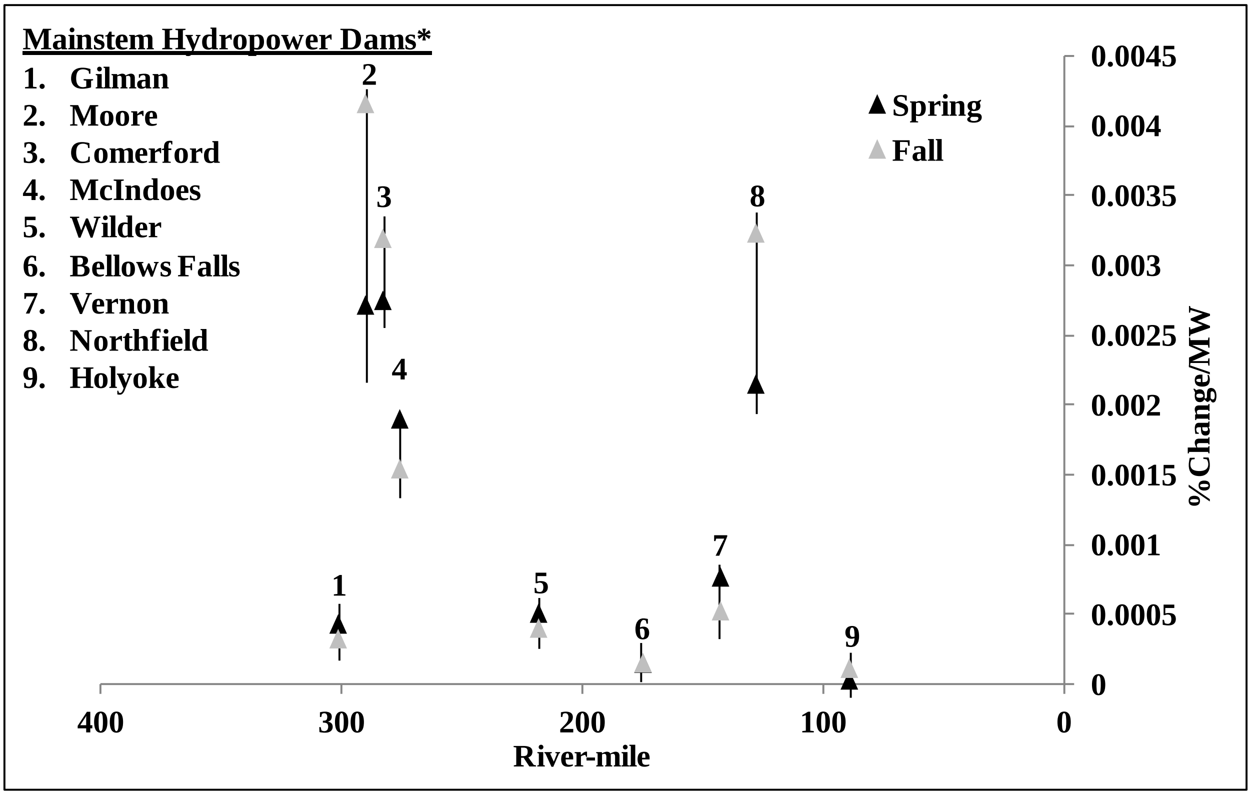


Figure 17: Absolute value of the average percent change from unregulated of the diadromous fish flow metrics for Spring and Fall per megawatt generated of each Connecticut River mainstem hydropower dam. *Excluding Canaan and Turners Falls.

A lot more hydropower generation occurs in the spring compared to the fall due to the spring high flows. This large difference in hydropower generation means that the percent change per megawatt metric is much more significant for the spring. Northfield, Moore, and Comerford have the highest percent change per megawatt for both seasons but the magnitude varies greatly between seasons. Moore has the highest value in both seasons. The differences between Moore and Comerford are likely due to their conservation pool elevation targets that have different seasonal variation. In the Fall, Moore maintains a relatively constant conservation pool elevation target while Comerford draws its pool down during that season, which means Comerford makes much larger releases during that season. In the Spring, both Moore and Comerford fill their pools but Moore fills its pool in a much shorter period of time. Changing Moore and Comerford conservation pool elevation targets in both seasons may lead to the most ecological benefits. Also, the result for the run-of-river hydropower dams indicates few benefits will be gained by changing their hydropower operations.

4.1.4 Current Conditions Summary

The current conditions analysis indicates several insights about the current state of environmental alteration due to dams.

1. Environmental alteration from unregulated conditions is much higher on the upper half of the Connecticut River mainstem than the lower half.

2. In a typical year, annual inundations of 300 and 200 days are higher than unregulated conditions along the entire Connecticut River mainstem. Annual inundations of 50 and 20 days are lower than unregulated conditions.

3. Alterations in the annual inundations translate into small changes in actual inundated area for a 7-mile stretch of the Connecticut River mainstem by North Hampton, MA.

4. Spring and Fall low flows are higher than unregulated conditions and outside the tolerance specified for diadromous fish. Fall medium flows are higher than unregulated while Spring medium flows are for the most part within the tolerance zone. Spring and Fall high flows are slightly lower than unregulated. Both the medium and high flows fall within the tolerance specified for diadromous fish.

5. Connecticut River mainstem dams causing the largest environmental alteration appear to be the Connecticut Lakes dams, Moore, and Northfield.

6. Tradeoffs for both annual and seasonal hydropower generation lost versus reduced environmental alteration are highest for Moore and Northfield.

4.2 Scenario Analysis

To analyze the maximum benefit that could be achieved on the Connecticut River mainstem through reservoir reoperation, four dam removal scenarios of the HEC-ResSim model were run. Benefits are lower percent change from unregulated in both the flow needs of the floodplain plant communities and the flow targets of the important diadromous fish species. Each simulation had a different dam(s) removed:

1. Connecticut Lakes (Second Connecticut Lake, First Connecticut Lake, Lake Francis)
2. Moore
3. Northfield & Turners Falls
4. All 13 USACE Flood Control dams

4.2.1 Hydropower and Flood Risk Management Changes

The change in the average annual, September to November, and March to May hydropower generation for each Connecticut River mainstem hydropower dam was calculated for each of the four scenarios. The Northfield and Turner Falls scenario saw no changes in the hydropower outputs of any of other dams. The USACE Flood Control scenario caused no changes in the hydropower outputs except for Northfield, Turners Falls, and Holyoke and these changes were small (<0.5%). The Connecticut Lakes scenario saw the largest changes in hydropower generation but it varied between the reservoirs. The average annual output saw reductions in hydropower output of almost all the projects, with Canaan seeing the largest reduction of 18%, or 45MW. The 15-Mile Falls Project, which the Connecticut Lakes operate to augment hydropower generation at those dams, saw reductions in annual hydropower generation at two of the three dams of 2.5% for Comerford (-234MW) and 2.9% for McIndoes (-59MW). Moore slightly increased its annual output (1.2%). The Connecticut Lakes scenario caused a 760MW loss in average annual hydropower output for all the dams combined. The Moore scenario saw the loss of 1165 MW in average annual hydropower from all the dams combined. Both scenarios had a decreased total Spring hydropower generation of 167 MW for the Connecticut Lakes scenario and 205 MW for the Moore Scenario. The other scenarios saw negligible changes in Spring hydropower generation and no scenario had significant change in the Fall hydropower generation. Overall, the Moore scenario has the most tradeoffs of total average annual lost hydropower generation. The Connecticut Lakes scenario is the next most significant in terms of tradeoffs.

To measure changes in flood risk management, the total number of days over the period of record that exceeded flood stage for the three Connecticut River mainstem flood control operating points described in the flood control operations sections, North Walpole, Montague City, and Hartford, were counted for the current conditions and four scenarios. Table 10 shows these results. The flood stage for North Walpole, Montague City, and Hartford is 30ft, 30ft, and 22ft respectively (USACE RRT 2012).

Table 10: Number of days over the period of record that flood stage was exceeded at the three flood control operating points for the unregulated, current conditions, and dam removal scenarios.

	North Walpole (days)	Montague City (days)	Hartford (days)
Unregulated	15	92	51
Current Conditions	11	58	21
Connecticut Lakes	11	60	21
Moore	11	59	22
Northfield & Turners Falls	11	57	21
USACE Flood Control	12	79	37

The total number of days the unregulated hydrograph exceeded flood stage was significantly more than the current conditions at all three locations, showing that all the dams combined in the watershed do reduce flooding. The results of the hydropower dam scenarios indicate that little to no increase in flood stage will occur at the three control points, indicating that flood risks are not necessarily a concern if those dams were not there. The only scenario that significantly affected flood risk management dynamics on the Connecticut River mainstem was the USACE Flood Control because the scenario removed the attenuation of peak flows.

4.2.2 Floodplain

A. Reliability

Figure 18 shows plots of the reliability of the dam removal scenarios to exceed the median unregulated annual flow durations. Again, reliability values that approach 50% are getting closer to meeting the unregulated timing of the annual inundations.

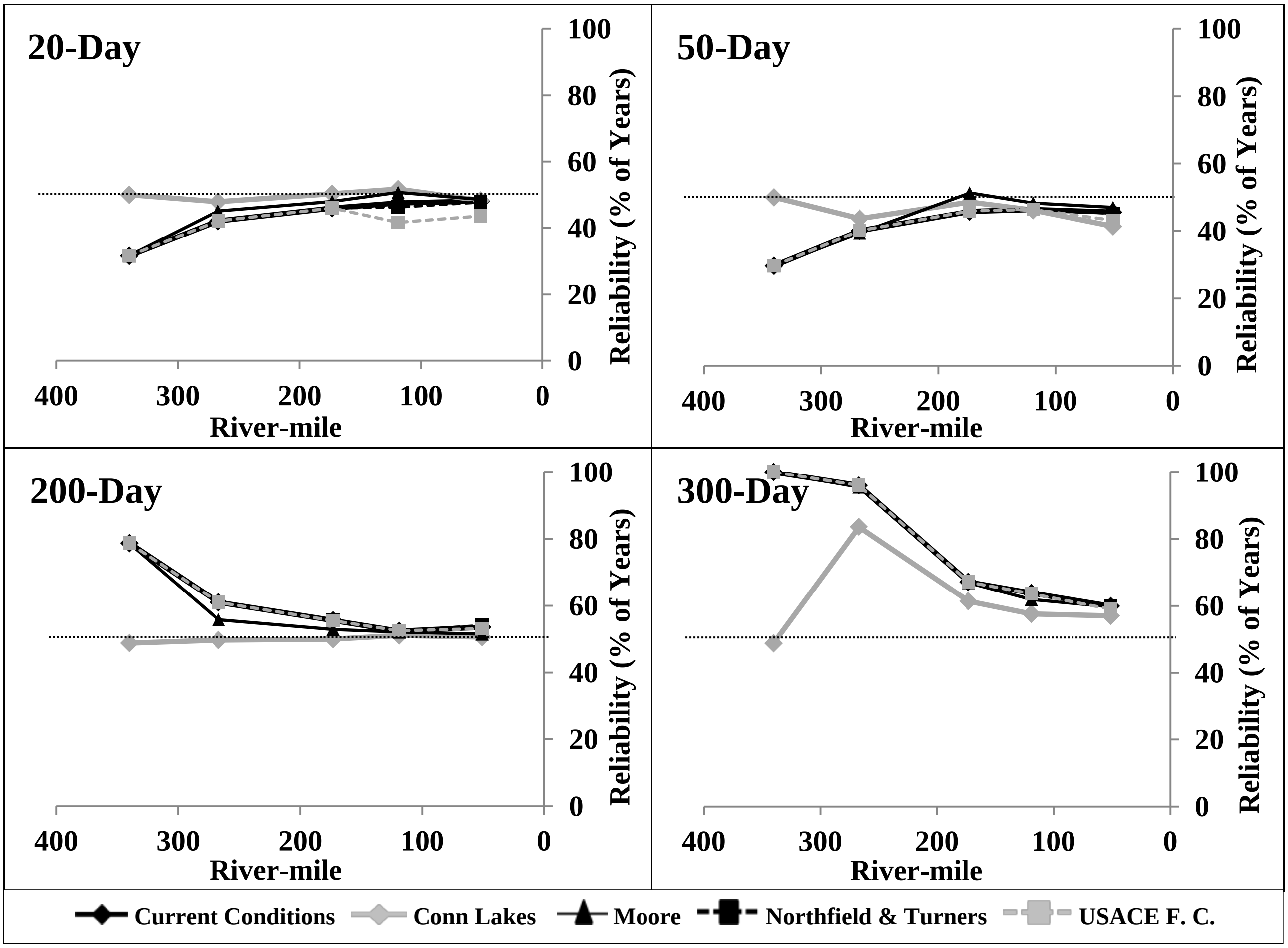


Figure 18: Plot of reliability of the different dam removal scenarios to exceed the median unregulated annual inundations.

Reliability of the dam removal scenarios does not change much compared to the reliability of the current conditions, except in a few cases. The exceptions for the 20-day annual inundations are the Connecticut Lakes and the USACE Flood Control scenarios. Reliability of the 20-day annual inundation becomes 50% along the entire Connecticut River mainstem for the Connecticut Lakes scenario and decreases below 50% along the lower third for the USACE Flood Control scenario. The exception for the other three annual inundations is the Connecticut Lakes scenario. Reliability for the 50-day and 200-day annual inundations becomes 50% at the top of the Connecticut River mainstem and stays closer to 50% moving downstream. The reliability of the

300 day inundation drops to 50% initially but increases drastically downstream due to the 15-Mile Falls project. The USACE Flood Control scenario moves the 20-day inundations further from unregulated. The Connecticut Lakes scenario reduces environmental alteration of the annual inundations the most, indicating that unregulated conditions will be replicated the most.

B. Percent Change

Figure 19 shows the percent change moving down the Connecticut River mainstem of the four different annual inundation durations for the current conditions scenario and the four dam removal scenarios.

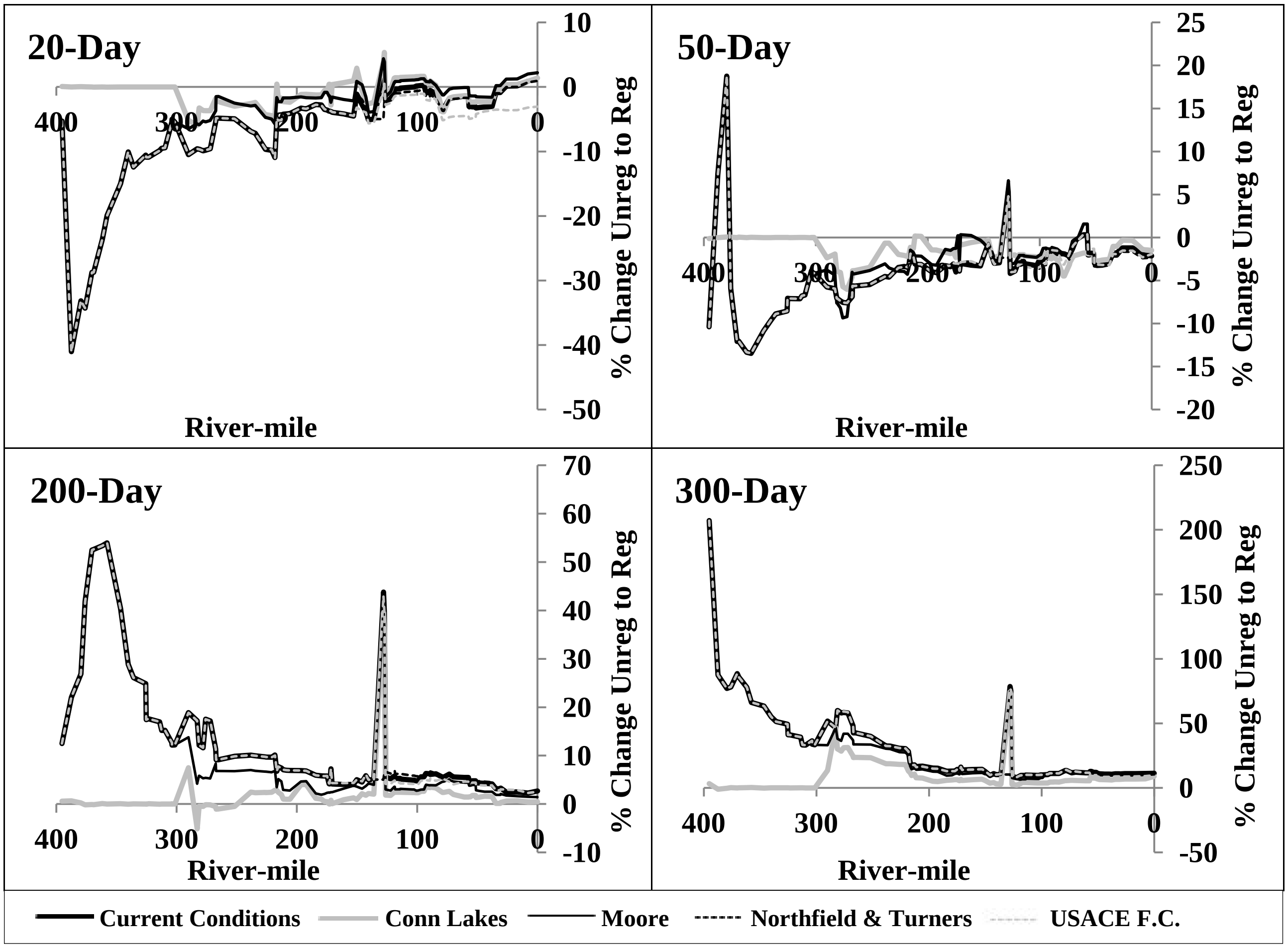


Figure 19: Comparison of percent change from unregulated flow to regulated flow moving down the Connecticut River mainstem of the four annual inundation durations between the current conditions and dam removal scenarios.

The Connecticut Lakes scenario reduces the change from unregulated substantially for the upper half of the Connecticut River mainstem compared to the other two hydropower dam scenarios. It still reduces the percent change for the lower half but much less, with that reduction decreasing as a function of distance from the dams. The increase in percent change caused by Moore and Comerford are basically the same magnitude. The Moore scenario reduces the percent change as well but not as substantially as the Connecticut Lakes scenario. Its biggest reductions came close to the dam, although, reductions are still seen all the way to the river mouth. The Northfield and Turners Falls scenario provides almost no noticeable change.

The USACE Flood Control scenario actually increased the percent change from unregulated conditions of the 20-day and 50-day annual inundations. The reason for this is that the USACE Flood Control dams reduce the highest peaks during a high flow event and then release that flow at higher and steady amount during the receding limb of the event.

C. Change in Inundated Area

Table 11 shows the change in inundated area of the four annual inundation durations for the different dam removal scenarios.

Table 11: Percent change in area and actual acreage change from unregulated of the four annual inundation durations for the current conditions and dam removal scenarios.

	% Change in Area					**Change in Area (acres)**				
	Current Conditions	Connecticut Lakes	Moore	Northfield & Turners Falls	USACE Flood Control	Current Conditions	Connecticut Lakes	Moore	Northfield & Turners Falls	USACE Flood Control
20-Day	-1.2	-0.8	-0.9	-2.0	-2.5	-40	-30	-33	-74	-91
50-Day	-2.5	-1.8	-0.3	-1.3	-0.5	-54	-38	-7	-27	-12
200-Day	1.7	1.1	1.0	2.3	1.9	26	13	11	26	22
300-Day	1.2	0.2	1.0	1.2	1.2	11	3	9	11	11

The Connecticut Lakes and Moore scenarios actually increase the amount of 20 day inundated area compared to current conditions. Spring peak flow is higher so the USACE flood control dams act to reduce that higher peak flow by cutting the peak and then releasing longer sustained high flows (at a lower magnitude). By increasing the Spring peak flow but keeping the USACE Flood Control operations the same, the extent of 20-day inundated area increases compared to unregulated. Conversely, more 20-day inundated area is lost for the USACE Flood Control scenario and the Northfield & Turners Falls scenario compared to current conditions. The USACE scenario results indicate that changing flood control operations to allow for the unregulated magnitude of spring high flow events actually decreases the extent of floodplain forests along the Connecticut River mainstem. Northfield & Turners Falls are not far upstream of the hydraulics model location and thus it appears that the loss of Northfield’s pump storage releases also decreases the extent of floodplain forests. However, little additional floodplain forest area overall is gained or lost from any of the scenarios.

4.2.3 Diadromous Fish

Figure 20 shows the percent change from unregulated conditions of the six seasonal diadromous fish metrics for the current conditions and the dam removal scenarios.

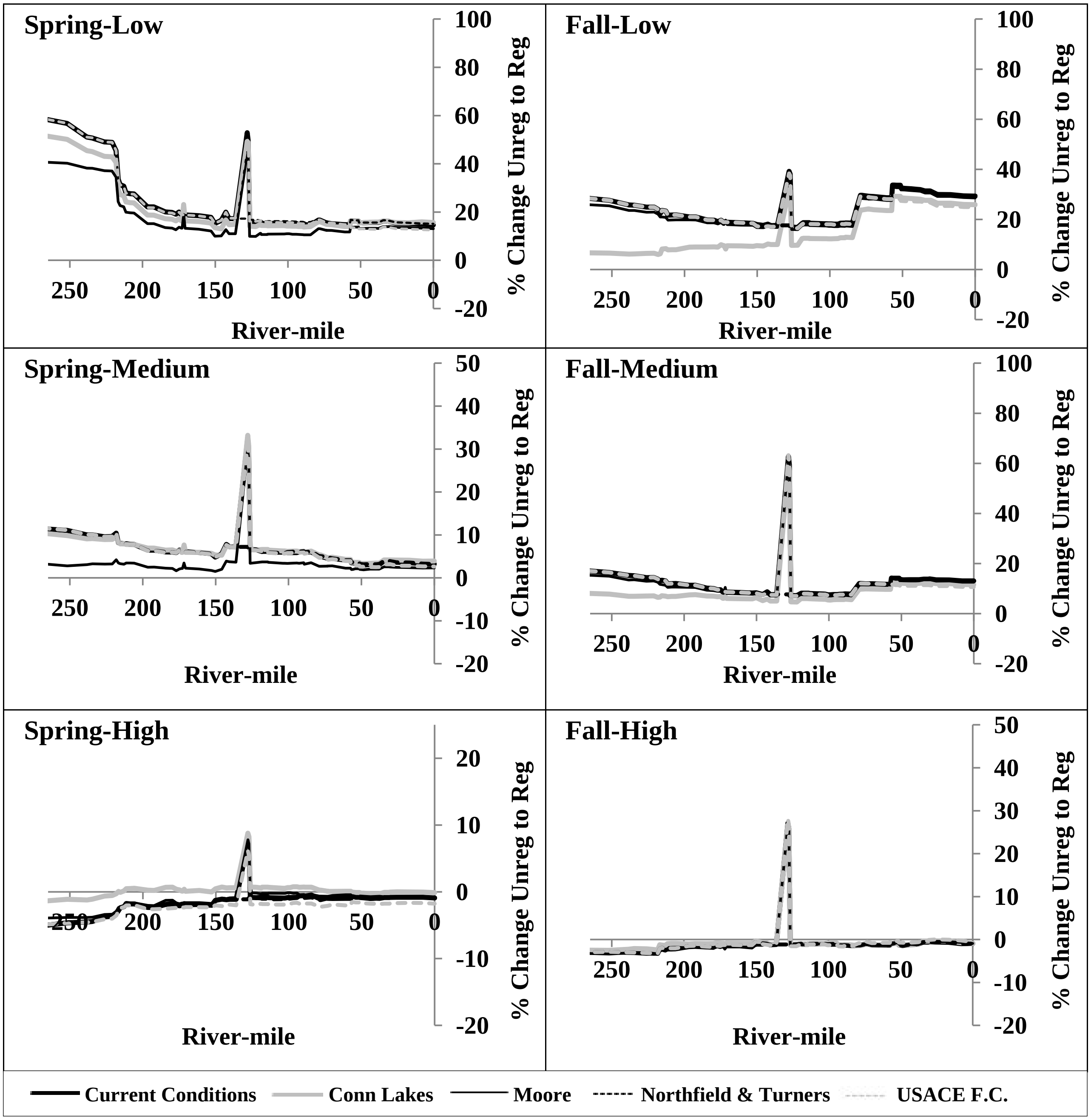


Figure 20: Percent change from unregulated in the six seasonal diadromous fish metrics for the different dam removal scenarios. The plots start at river-mile 265, which is the most upstream point of the Connecticut River mainstem for diadromous fish stipulated by the experts.

The dam removal scenario with the largest reduction in percent change varies between the two seasons and the flow duration curve ranges. For the Spring low flows and medium flows, the

Moore scenario causes a noticeable reduction in percent change while the Connecticut Lakes scenario has little effect. These results point to adjustment of Moore's seasonal conservation pool elevation to reduce percent change. However, the Spring high flows achieves the greatest percent change reduction from the Connecticut Lakes scenario, although, the percent change is already well within the allowable range. The USACE Flood Control scenario actually increases the percent change of the Spring high flows but this again is well within the allowable range. For the Fall percent changes, none of the scenarios projects appears to have little effect.

4.2.4 Summary of Scenario Analysis

The dam removal scenario analysis indicates several insights about re-operating reservoirs to reduce environmental alteration.

1. The largest reduction in environmental alteration would be achieved through re-operation of the Connecticut Lakes dams.

2. Re-operating Moore would cause the greatest reductions in hydropower output.

3. Re-operating Northfield & Turners Falls and the USACE Flood Control dams will lose additional 20-day inundated area at least on the Connecticut River mainstem by North Hampton, MA.

4. Re-operating Moore would reduce alteration of Spring low, medium, and high flows more than the other dams analyzed.

5. Re-operating all the USACE Flood Control dams would increase flooding on the Connecticut River mainstem while re-operating the other dams analyzed would not affect flooding as much.

5. Discussion

Overall, the results of both the floodplain and diadromous fish ecological metrics point to the Connecticut Lakes scenario as achieving the greatest environmental benefits. The Connecticut Lakes scenario eliminates the environmental alteration in the upstream half of the Connecticut River mainstem and achieves the largest reductions in environmental alteration in the downstream half. For reducing environmental alteration through re-operation, the reduction in the changes in hydropower augmentation outflows would be the primary operational avenue to pursue. However, this is infeasible in the near future because the Connecticut Lakes dams had their outflows set during FERC relicensing of the 15-Mile Falls Project in 2002. Their environmental flow requirements are locked in until the next FERC relicensing for the 15-Mile Falls Project, in 2052.

In reality, reservoir re-operations usually require a regulatory opportunity. In the Connecticut River watershed, this primarily involves FERC relicensing, where dams with a hydropower purpose receive a new license to generate hydropower and is the principal time when operations can be changed for environmental purposes. Five projects on the Connecticut River mainstem are up for FERC relicensing, Wilder, Bellows Falls, Vernon, Northfield, and Turners Falls. However, for reducing environmental alteration along the whole Connecticut River mainstem, few if any watershed scale environmental benefits from re-operating these five dams can be achieved. Changing operations for environmental purposes as part of FERC relicensing should probably focus more on local impacts from those dams. Re-operating the Connecticut Lakes dams would achieve the greatest benefits but they are not up for relicensing for several decades. Changing operations at Moore would achieve some environmental benefits as well but it also recently had its FERC license renewed (as did the other dams in the 15-Mile Falls Project). FERC licenses last for 50 years so it will be many years before the regulatory opportunity arises again.

The large hydropower dams on the upstream section of the Connecticut River mainstem exemplify a trend of many watersheds worldwide. The upstream areas of watersheds are higher elevation with often steep terrain. Hydropower dams use the steep terrain to increase head for the generators, allowing more electricity to be generated with less flow. However, while the efficiency of the hydropower generation makes the upstream areas more appealing for hydropower, environmental alteration is often at its highest. As the results in this thesis show, those dams can be responsible for environmental alteration at the downstream ends as well. With current regulations of hydropower dams in the U.S. through the FERC relicensing process, when an upstream high elevation hydropower dam is up for relicensing, this is often the only chance for major reductions in environmental alteration.

While the focus of this thesis is on the flow regime, temperature regime also is important for aquatic ecosystems. For fish, temperature regime is often more important than flow regime. Several studies have shown relationships between changes in temperature and life-stage cues/habitat of various Connecticut River fish species, including American Shad (Crecco & Savoy 1985). Temperature regime could not be included in the reservoir simulation, which would require daily time series of temperature beyond the scope of the Connecticut River study. However, flow can often be used as proxy for temperature. For instance, temperatures are generally higher in the late summer when the flow is lower (Nilsson & Renofalt 2008). If flow is reduced in the summer, stream temperature generally increases. Thus general changes in temperature regime could be estimated roughly through analysis of the change in the flow regime.

There are several limitations to this overall environmental alteration analysis approach. The first is the amount of data, time and resources needed to make such a comprehensive reservoir simulation model. Also, getting reservoir physical and operational data involves either the willingness of owner/operators to share information or other estimates of such information. There was no mechanism in the data collection effort that required owner/operators to share information, so a few did not share some essential operational information. This added some uncertainty to the results.

Another issue is the use of a synthetic inflow data set as both the driver of the model and the representative of the unregulated hydrograph. As mentioned in Section 3.1.3, there were differences in volume and peak magnitudes in the SYE dataset from gage records that varied in significance between sub-watersheds. These can be explained by the uncertainty associated with using the methods to develop the SYE dataset as well and local inflows between the gage locations and the points where SYE flows were calculated adding additional volume. This adds uncertainty to the results. However, the use of SYE methods is currently one of the most robust approaches to creating daily, unregulated streamflow. The other approaches mentioned in Section 3.1.3 for estimating unregulated flows bring as much, if not more, uncertainty. Also, in an environmental alteration analysis such as the one performed in this thesis, relative change between unregulated and regulated are what conclusions should be based off of. However, the uncertainty of using a synthetic inflow dataset must be acknowledged.

Additional uncertainty occurs because the model is a daily-time step model but some of the operations are sub-daily. Simulating the SYE period of record at a sub-daily time step is currently more or less computationally prohibitive due to the long compute time HEC-ResSim already has for the daily time step and the methods utilized by SYE. Again, software and hardware upgrades may make this possible.

An interesting extension of the inundation mapping analysis described would be to incorporate additional variables, such as depth, velocity, and soil type. The inundated area analysis described is not a complete indication of where exactly floodplain plant communities have changed. Additional flow needs, such as depth and velocity, could be incorporated into future floodplain vegetation mapping that uses this approach.

6. Conclusions

This thesis described the use of a reservoir simulation model to calculate environmental alteration in ecological flow metrics along the Connecticut River mainstem. The process helped identify potential reservoir reoperations that would reduce environmental alteration while also measuring potential hydropower generation and flood protection tradeoffs. From the analysis, environmental alteration is highest at the top of the Connecticut River mainstem and much lower for the lower two thirds, where it is generally much smaller than environmental alteration in other regions of the U.S. The range of annual flows is smaller, with low flows generally increased while high flows are generally decreased. Changing operations of the Connecticut Lakes Project and the USACE Flood Control Projects would provide the greatest reductions in environmental alteration but would also have the highest losses of hydropower generation (Connecticut Lakes Project) and flood control (USACE Flood Control Projects). The costs of these losses may not be worth the environmental benefits achieved, which again would be small relative to other U.S. regions. Also, the 15-Mile Falls Project, which includes the Connecticut Lakes Project, is not up for FERC relicensing for many years. Changes in operations for reductions in environmental alteration along the Connecticut River mainstem will most likely need to focus on other dams.

Changing reservoir operations for management of aquatic and riparian ecosystems at the watershed scale is complex in a heavily regulated watershed. Understanding which reservoirs are particularly important and have the most potential to achieve the ecosystem objectives with fewer tradeoffs, such as hydropower generation, allows for better, more focused, and integrated environmental management strategies. The general ecosystem management strategy here is the watershed flow regime, where benefits are reductions in environmental alteration from the natural flow regime. Depending on its location within the watershed, size, and operations, changing the operations at one reservoir may gain benefits for ecosystems across a far reaching stretch of river, whereas changing operations at other reservoirs may only have localized ecosystem benefits. In a watershed with multiple types of operations, such as hydropower generation and flood risk management, changing operations at one reservoir influence the operations at other reservoirs. This may lead to inadvertent gains or losses in ecosystem benefits or other water management objectives. In addition, when analyzing an entire watershed to identify particular areas of importance for ecosystem benefit gains, it is important to have metrics that quantify ecosystem change that can be applied universally through the watershed as well as metrics that can measure tradeoffs in hydropower, flood control, or other purposes. The reservoir simulation model, ecosystem metrics, and software technologies described in this paper illustrate an approach to analyzing a heavily regulated watershed that incorporates environmental considerations and measures water management tradeoffs that can assist in watershed planning and environmental flow implementation.

References

Apse, C., DePhilip, M., Zimmerman, J. & Smith, M. P., 2008. *Developing Instream Flow Criteria to Support Ecologically Sustainable Water Resource Planning and Management,* Harrisburg, PA: The Nature Conservancy.

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

Archfield, S. A. et al., 2009. *The Massachusetts Sustainable-Yield Estimator: A decision-support tool to assess water availability at ungaged sites in Massachusetts,* Reston, Virginia: US Geological Survey.

Arthington, A. H., Naiman, R. J., McClain, M. E. & Nilsson, C., 2010. Preserving the biodiversity and ecological services of rivers: new challenges and research opportunities. *Freshwater Biology,* Volume 55, pp. 1-16.

Beasley, C. A. & Hightower, J. E., 2000. Effects of a Low-Head Dam on the Distribution and Characteristics of Spawning Habitat Used by Stroped Bass and American Shad. *Transactions of the American Fisheries Society,* 129(6), pp. 1316-1330.

Bockelman, B. N., Fenrich, E. K., Lin, B. & Falconer, R. A., 2004. Development of an ecohydraulics model for stream and river restoration. *Ecological Engineering,* Volume 22, pp. 227-235.

Bunn, S. E. & Arthington, A. H., 2002. Basic Principles and Ecological Consequences of Altered Flow Regimes for Aquatic Biodiversity. *Environmental Management,* 30(4), pp. 492-507.

Cain, J. & Monohan, C., 2008. *Estimating Ecologically Based Flow Targets for the Sacramento and Feather Rivers,* s.l.: The Natural Heritage Institute.

Connecticut River Valley Flood Control Commission, 2011. *crvfcc.org.* [Online]
[Accessed 20 May 2012].

Connecticut River Watershed Council, 2012. *Hydropower.* [Online]
Available at: http://www.ctriver.org/programs/advocacy/hydro_power/
[Accessed 11 6 2013].

Crecco, V. A. & Savoy, T. F., 1985. Effects of Biotic and Abiotic Factors on Growth and Relative Survival of Young American Shad, Alosa sapidissima, in the Connecticut River. *Canadien Journal of Fish & Aquatic Sciences,* Volume 42, pp. 1640-1648.

DePhilip, M. & Moberg, T., 2010. *Ecosystem Flow Recommendations for the Susquehanna River Basin,* s.l.: The Nature Conservancy.

Fallon-Lambert, K., 1998. *Instream Flow Uses, Values and Policies in the Upper Connecticut River watershed,* Charlsetown, NH: Connecticut River Joint Commissions Report.

Fields, W. L., 2009. *Managing Alamo Dam to Establish Woody Riparian Vegetation on the Bill Williams River, Arizona,* s.l.: s.n.

Gabriela Goldfarb Consulting, 2009. *Review of Low Impact Hydropower Institute Application for Low Impact Hydropower Certification: Fifteen Mile Falls Hydroelectric Project,* Portland, OR: s.n.

Gao, B., Zhao, T. & Yang, H., 2012. Changes in the eco-flow metrics of the Upper Yangtze River from 1961 to 2008. *Journal of Hydrology,* Volume 448-449, pp. 30-38.

Gao, Y. et al., 2009. Development of Representative Indicators of Hydrologic Alteration. *Journal of Hydrology,* Volume 374, pp. 136-147.

Graf, W. L., 1999. Dam nation: A geographic census of American dams and their large-scale hydrologic impacts. *Water Resources Research,* 35(4), pp. 1305-1311.

Hardy, T., 1998. The Future of Habitat Modeling and Instream Flow Assessment Techniques. *Regulated Rivers: Research & Management,* Volume 14, pp. 405-420.

Harman, C. & Stewardson, M., 2005. Optimizing Dam Release Rules to Meet Environmental Flow Targets. *River Research and Application,* Volume 21, pp. 113-129.

Hatfield, C. & Lutz, K., 2011. *Innovative Partnerships: Connecticut River Restoration Study.* s.l.:TNC & USACE.

HEC, 2009. *HEC-EFM Ecosystem Functions Model Quick Start Guide*, Davis, CA: USACE.

HEC, 2010. *HEC-RAS River Analysis System,* Davis, CA: HEC.

HEC, 2011. *HEC-ResSim Reservoir System Simulation User's Manual Version 3.1,* Davis, CA: USACE.

HEC, 2013. *Reservoir Management Decision Support System for the Connecticut River Watershed,* Davis, CA: USACE.

Hirji, R. & Davis, R., 2009. *Environmental Flows in Water Resources Policies, Plans, and Projects,* Washington DC: The World Bank.

Homa, E. S. et al., 2005. *An Optimization Approach for Balancing Human and Ecological Flow Needs.* Anchorage, Alaska, ASCE, pp. 1-12.

Hughes, D. A. & Hannart, P., 2003. A desktop model used to provide an initial estimate of ecological instream flow requirements of rivers in South Africa. *Journal of Hydrology,* Volume 270, pp. 167-181.

Jowett, I. G., 1997. Instream Flow Methods: A Comparison of Approaches. *Regulated Rivers: Research & Management,* Volume 13, pp. 115-127.

Kashaigili, J. J., Mccartney, M. & Mahoo, H. F., 2007. Estimation of environmental flows in the Great Ruaha River Catchment, Tanzania. *Physics and Chemistry of the Earth, Parts A/B/C,* 32(15-18), pp. 1007-1014.

King, J. & Brown, C., 2006. Environmental Flows: Striking the Balance between Development and Resource Protection. *Ecology and Society,* 11(2), p. Article 26.

Labadie, J. W., 2004. Optimal Operation of Multireservoir Systems: State-of-the-Art Review. *Journal of Water Resources Planning and Management,* 130(2), pp. 93-111.

Lake Simcoe Region Conservation Authority, 2011. *Towards a Framework for Determining Ecological Flows and Water Levels in the Lake Simcoe Watershed - A Guidance Document,* Ontario: Lake Simcoe Region Conservation Authority.

Low Impact Hydropower Institute, 2009. *LIHI Certificate # 39 --- 15 Mile Falls Project (FERC No. 2077) Connecticut River, New Hampshire and Vermont (FERC No. 2077).* [Online]
Available at: http://www.lowimpacthydro.org.php5-11.dfw1-2.websitetestlink.com/lihi-certificate-39-15-mile-falls-project-connecticut-river-new-hampshire-and-vermont-ferc-no.-2077.html
[Accessed 11 06 2013].

Magilligan, F. J. & Graber, B. E., 1996. Hydroclimatological and geomorphic controls on the timing and spatial variability of floods in New England, USA. *Journal of Hydrology 178,* pp. 159-180.

Metzler, K. J. & Damman, A. W. H., 1985. Vegetation patterns in the Connecticut River flood plain in relation to frequency and duration of flooding. *Le Naturaliste Canadien,* Volume 112, pp. 535-547.

Monk, W. A. et al., 2006. Flow Variability and MacroInvertebrate Community Response Within Riverine Systems. *River Research and Application,* Volume 22, pp. 595-615.

Mullaney, J. R. & Trench, E. C. T., 2003. *Water Quality Trends in the Connecticut River Watershed in Connecticut.* East Hartford, CT, US Geological Survey.

Nedeau, E. J., 2008. *Freshwater Mussels and the Connecticut River Watershed.* xviii+132 pp. ed. Greenfield, MA: Connecticut River Watershed Council.

New Hampshire Fish and Game Department, 2005. *New Hampshire Wildlife Action Plan,* Concord, NH: New Hampshire Fish and Game Department.

NHDES, 2008. *Environmental Fact Sheet: Connecticut River,* Concord, NH: New Hampshire Department of Environmental Services.

Nilsson, C. & Renofalt, B. M., 2008. Linking Flow Regime and Water Quality in Rivers: a Challenge to Adaptive Catchment Management. *Ecology and Society,* 13(2).

Nislow, K. H. et al., 2002. Effects of Dam Impoundments on the Flood Regime of Natural Floodplain Communities in the Upper Connecticut River. *Journal of the American Water Resources Association,* 38(6), pp. 1533-1348.

NRCS, 2008. *Connecticut River Watershed.* [Online]
Available at: http://www.ma.nrcs.usda.gov/programs/csp/CSP_2008_ConnecticutRiver.html
[Accessed 4 September 2012].

Null, S. E. & Lund, J. R., 2011. Fish Habitat Optimization to Prioritize River Restoration Decisions. *River Research and Applications.*

Omland, K. S., 2002. Larval Habitat and Reintroduction Site Selection for Cicindela Puritana in Connecticut. *Northeastern Naturalist,* 9(4), pp. 433-450.

Petts, G. E., 2009. Instream Flow Science for Sustainable River Management. *Journal of the American Water Resources Association,* 45(5), pp. 1071-1086.

Pitta, B., 2011. *Utilizing a Decision Support System to Optimize Reservoir Operations to Restore the Natural Flow Distribution in the Connecticut River Watershed,* Amherst: University of Massachusetts.

Poff, N. L. et al., 1997. The Natural Flow Regime: A paradigm for river conservation and restoration. *BioScience,* 47(11), pp. 769-784.

Richter, B. D., Baumgartner, J. V., Powell, J. & Braun, D. P., 1996. A Method for Assessing Hydrologic Alteration within Ecosystems. *Conservation Biology,* 10(4), pp. 1163-1174.

Richter, B. D. & Thomas, G. A., 2007. Restoring Environmental Flows by Modyifying Dam Operations. *Ecology and Society,* 12(1).

Sandoval-Solis, S. & McKinney, D., 2012. Integrated water Management for Environmental Flows in the Rio Grande. *ASCE Journal of Water Resources Planning and Management,* Volume 10.

Sandoval-Solis, S., Reith, B. & McKinney, D., 2010. *Hydrologic Analysis Before and After Reservoir Alteration at the Big Bend Reach, Rio Grande/Rio Bravo,* Davis: Center for Research in Water Resources.

Shafroth, P. B. et al., 2010. Ecosystem effects of environmental flows: modelling and experimental floods in a dryland rive. *Freshwater Biology,* Volume 55, pp. 68-85.

Smakhtin, V. & Weragala, N., 2005. *An Assessment of Hydrology and Environmental Flows in the Walawe River Basin, Sri Lanka,* Colombo, Sri Lanka: International Water Management Institute.

Tilmant, A., Beevers, L. & Muyunda, B., 2010. Restoring a flow regime through the coordinated operation of a multireservoir system: The case of the Zambezi River basin. *Water Resources Research,* Volume 46, pp. 1-11.

U.S. Fish and Wildlife Service, 1993. *Purtian tiger beetle (Cicindela puritana G. Horn)) recovery plan.,* Hadley, MA: U.S. Fish and Wildlife Service Northeast Region.

US Fish and Wildlife Service, 2011. *About the Connecticut River Coordinator's Office.* [Online]
Available at: http://www.fws.gov/r5crc/about_crc.htm
[Accessed 12 May 2012].

USACE RRT, 2012. *NAE Reservoir Regulation Section.* [Online]
Available at: https://rsgis.crrel.usace.army.mil/NE/pls/cwmsweb/cwms_web.cwmsweb.cwmsindex
[Accessed 22 May 2012].

Valavanis, D. V. et al., 2008. Modelling of essential fish habitat based on remote sensing, spatial analysis and GIS. *Hydrobiologia,* Volume 612, pp. 5-20.

Vermont Department of Environmental Conservation, 1989. *Water Quality Certification: Gilman Project,* Waterbury, VT: Vermont Department of Environmental Conservation.

Vermont Department of Environmental Conservation, 2008. *Water Quality Certification: Canaan Hydroelectric Project,* Waterbury, VT: Vermont Department of Environmental Conservation.

Vogel, R. M. & Fennessey, N. M., 1995. Flow Duration Curves I: New Interpretation and Confidence Intervals. *Journal of Water Resources Planning and Management,* 120(4), pp. 485-504.

Vogel, R. M. et al., 2007. Relations among storage, yield, and instream flow. *Water Resources Research,* Volume 43, pp. 1-12.

Whittington, J. et al., 2002. *Ecological Assessment of Flow Managemen Scenarios for the Lower Balonne,* s.l.: Cooperative Research Centre for Freshwater Ecology.

Yarnell, S. M., Lind, A. J. & Mount, J. F., 2012. Dynamic flow modelling of riverine amphibian habitat with applicaiton to regulated flow management. *River Research and Applications,* Volume 28, pp. 177-191.

Yin, X. et al., 2010. Optimized reservoir operation to balance human and riverine ecosystem needs: model development, and a case study for the Tanghe reservoir, Tang river basin, China. *Hydrologic Processes,* Volume 24, pp. 461-471.

Zhang, H.-b. & Qian, H., 2011. *Response of multireservoir system on the main Yellow River to eco-enivornment flow change.* s.l., Power and Energy Engineering Conference.

Zimmerman, J., 2006. *Hydrologic Effects effects of flood control dams in the Ashuelot River, New Hampshire, and West River, Vermont,* North Hampton, MA: TNC Connecticut River Program.

Zimmerman, J., 2006. *Response of physical processes and ecological targets to altered hydrology in the Connecticut River Basin,* North Hampton, MA: TNC.

Zimmerman, J. et al., 2008. *Restoring Ecosystem Flows in the Connecticut River Watershed,* North Hampton, MA: TNC.

Appendix A

Table A1 shows each dam that was modeled and the operating purposes of each dam. Figure shows a map of the Connecticut River watershed as it is displayed in HEC-ResSim. Figures A2-A5 show the close-ups of sections of HEC-ResSim model with the locations of each dam labeled. Both the table and the figures are from HEC 2013.

Table A1: All dams modeled in the Connecticut River ResSim model as well as the river, owner, and purposes of each dam. The dam purposes are labeled as FC--Flood Control, R--Recreation, H--Hydropower, HS--Hydropower Storage, WS--Water Supply. Bolded purposes had a hydropower, flood control, or water supply modeling strategy applied.

Dam	River	Owner	Purpose(s)	Physical Data Confidence	Operational Data Confidence
Ball Mountain	West	US Army Corps of Engineers	FC, R	High	Med
Barkhamsted	Farmington	Metropolitan District Commission	**WS**	High	Low
Barre Falls	Chicopee	US Army Corps of Engineers	FC, R	High	Med
Bashan Lake	Salmon	State of Connecticut	R	High	High
Bear Swamp	Deerfield	Brookfield Renewable Power Inc.	**H**, R	High	Med
Bellows Falls	Connecticut	TransCanada Hydro Northeast	**H**	High	Med
Bickford	Chicopee	City of Fitchburg	**WS**	Med	Low
Birch Hill	Millers	US Army Corps of Engineers	FC, R	High	Med
Borden Brook	Westfield	City of Springfield	H, WS	High	Med
Canaan	Connecticut	Public Service of New Hampshire	**H**	Med	Med
Cobble Mountain	Westfield	City of Springfield	**WS**	High	Med
Colebrook	Farmington	US Army Corps of Engineers	H, FC, WS	Med	Med
Comerford	Connecticut	TransCanada Hydro Northeast	**H**	High	Med
Conant Brook	Chicopee	US Army Corps of Engineers	FC	High	High
Crescent Street	Millers	L.S. Starrett Company	H	High	Med
Crystal Lake	Mascoma	New Hampshire Water Resources Board	FC, R	High	High
Danville	Passumpsic	Green Mountain Power Corporation	H	Med	High
#2 Development	Deerfield	TransCanada Hydro Northeast	**H**	High	Med
#3 Development	Deerfield	TransCanada Hydro Northeast	**H**	High	Med
#4 Development	Deerfield	TransCanada Hydro Northeast	**H**	High	Med
#5 Development	Deerfield	TransCanada Hydro Northeast	**H**	High	Med
First Connecticut Lake	Connecticut	TransCanada Hydro Northeast	HS	High	Low
Forest Lake	Johns	New Hampshire Water Resources Board	R, WS	High	High
Gardner Falls	Deerfield	Consolidated Edison	H	Low	Med
Gilman	Connecticut	Ampersand Gilman Hydro	**H**	Med	Low

Goose Pond	Mascoma	State of New Hampshire	HS, R	High	High
Grafton Pond	Mascoma	New Hampshire Water Resources Board	FC, R	High	High
Harriman	Deerfield	TransCanada Hydro Northeast	H	High	Med
Holyoke	Connecticut	Holyoke Water Power Company	**H**	High	Med
Knightville	Westfield	US Army Corps of Engineers	FC, R	High	Med
Lake Francis	Connecticut	TransCanada Hydro Northeast	HS	High	Low
Lake Groton	Wells	VT Department of Water Resources	R	High	High
Lake McDonough	Farmington	Metropolitan District Commission	R	Med	Low
Lake Monomonac	Millers	Town of Winchendon	R	High	Med
Lake Sunapee	Sugar	Town of Sunapee	H, R	High	Med
Littleville	Westfield	US Army Corps of Engineers	FC, R	High	Low
Mare Meadow	Chicopee	City of Fitchburg	WS	Med	Low
Mascoma	Mascoma	New Hampshire Water Resources Board	FC, R, WS	High	Med
McIndoes	Connecticut	TransCanada Hydro Northeast	**H**	High	Med
Moodus	Salmon	State of Connecticut	FC, R	High	High
Moore	Connecticut	TransCanada Hydro Northeast	**H**	High	Med
Nepaug	Farmington	Metropolitan District Commission	**WS**	High	High
New Home Sewing Machine	Millers	Chase Industrial Supply Company	H	High	High
North Hartland	Ottauquechee	US Army Corps of Engineers	FC, R	High	Med
North Springfield	Black	US Army Corps of Engineers	FC, R	High	Med
Northfield	Connecticut	FirstLight Power Resources	H	High	High
Otis	Farmington	MA Department of Conservation and Rec.	R	Med	Med
Otter Brook	Ashuelot	US Army Corps of Engineers	FC, R	High	Med
Quabbin Winsor	Chicopee	MA Water Resources Authority	**WS**	High	Med
Rainbow	Farmington	Farmington River Power Company	**H**	High	Med
Red Bridge	Chicopee	Essential Power LLC	H	Low	Low
Searsburg	Deerfield	TransCanada Hydro Northeast	H	High	Med
Second Connecticut Lake	Connecticut	TransCanada Hydro Northeast	HS	High	Low
Shenipsit Lake	Hockanum	Connecticut Water Company	WS	High	Med
Sherman	Deerfield	TransCanada Hydro Northeast	H	High	Med
Shuttle Meadow	Mattabesset	Towns of New Britain and Southington	**WS**	High	High
Silver Lake	Ashuelot	New Hampshire Water Resources Board	FC, R	HIgh	Med
Somerset	Deerfield	TransCanada Hydro Northeast	HS	High	High
Sugar	Sugar	Sweetwater Hydroelectric	H	High	Med
Surry Mountain	Ashuelot	US Army Corps of Engineers	FC, R	High	Med
Tighe Carmondy	Manhan	Holyoke Water Works	**WS**	High	Med
Townshend	West	US Army Corps of Engineers	FC, R	High	Med

Tully	Millers	US Army Corps of Engineers	FC, R	High	Med
Turners Falls	Connecticut	FirstLight Power Resources	H	High	High
Union Village	Ompompanoosuc	US Army Corps of Engineers	FC, R	High	Med
Upper Naukeag	Millers	Towns of Winchendon and Ashburnham	**WS**	High	Med
Vernon	Connecticut	TransCanada Hydro Northeast	**H**	High	Med
Ware Upper and Lower	Chicopee	Ware River Hydroelectric Company	H	Low	Low
West Branch	Farmington	Metropolitan District Commission	R, WS	High	Low
West Springfield Hydro Project	Westfield	A&D Hydro	H	Low	Low
Whitney Pond	Millers	Town of Winchendon	WS	High	High
Wilder	Connecticut	TransCanada Hydro Northeast	**H**	High	Med
Woronoco	Westfield	Swift River Hydro Operations Company	H	Low	Low

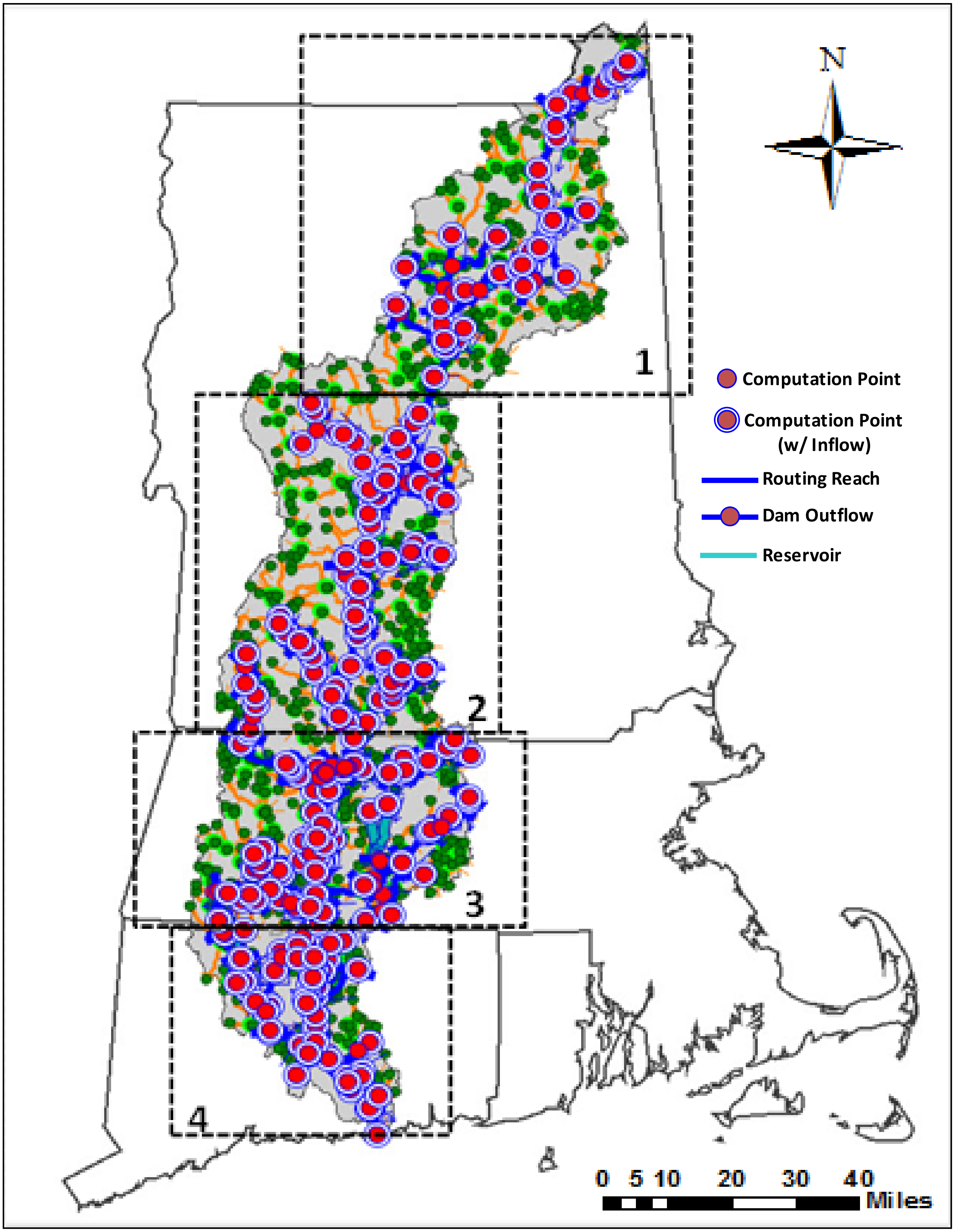


Figure A1: Map of the HEC-ResSim model of the Connecticut River watershed. The sections (the squares number 1-4) are shown in Figures A2-A5.

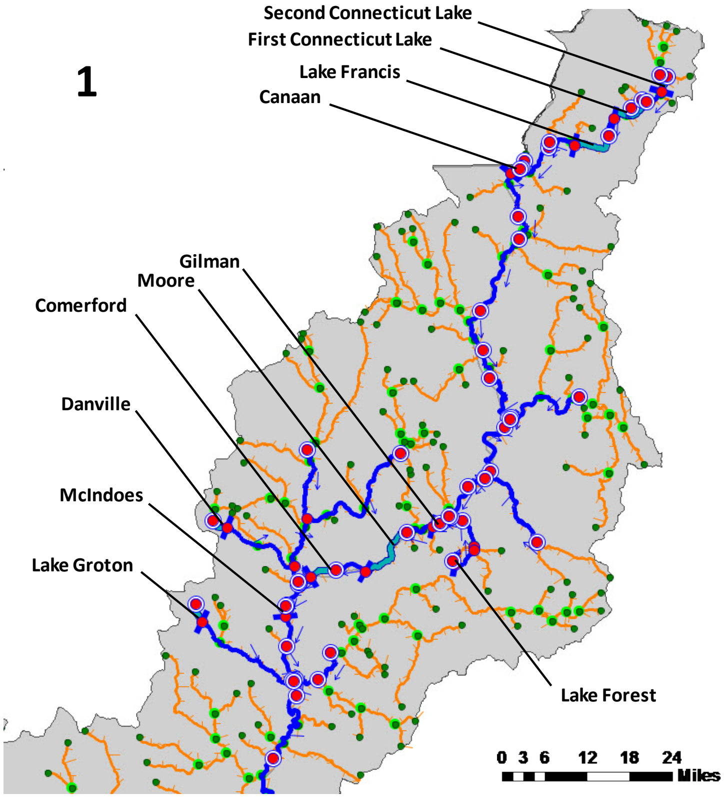


Figure A2: Map of the HEC-ResSim model from Section 1 in Figure A1.

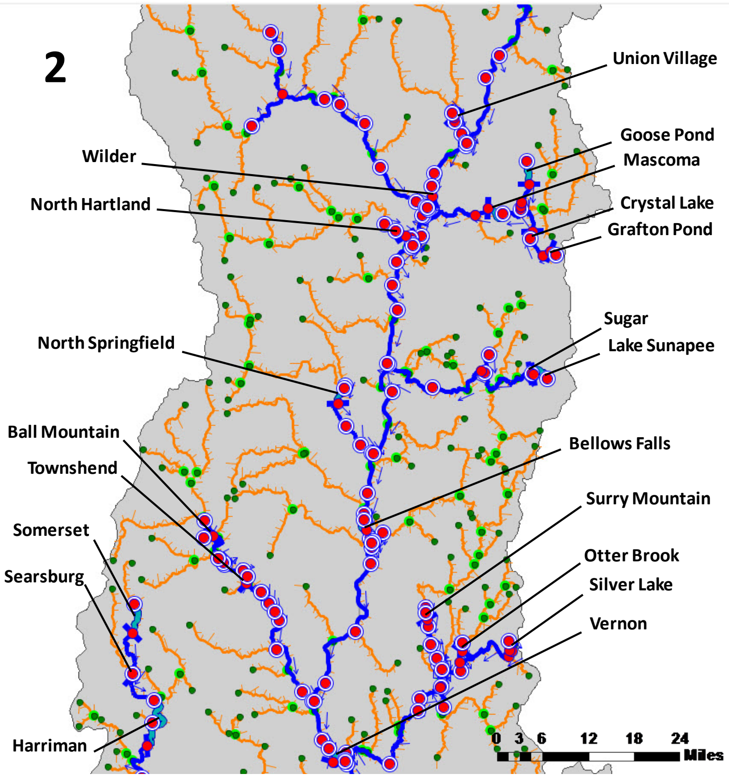


Figure A3: Map of the HEC-ResSim model from Section 2 in Figure A1.

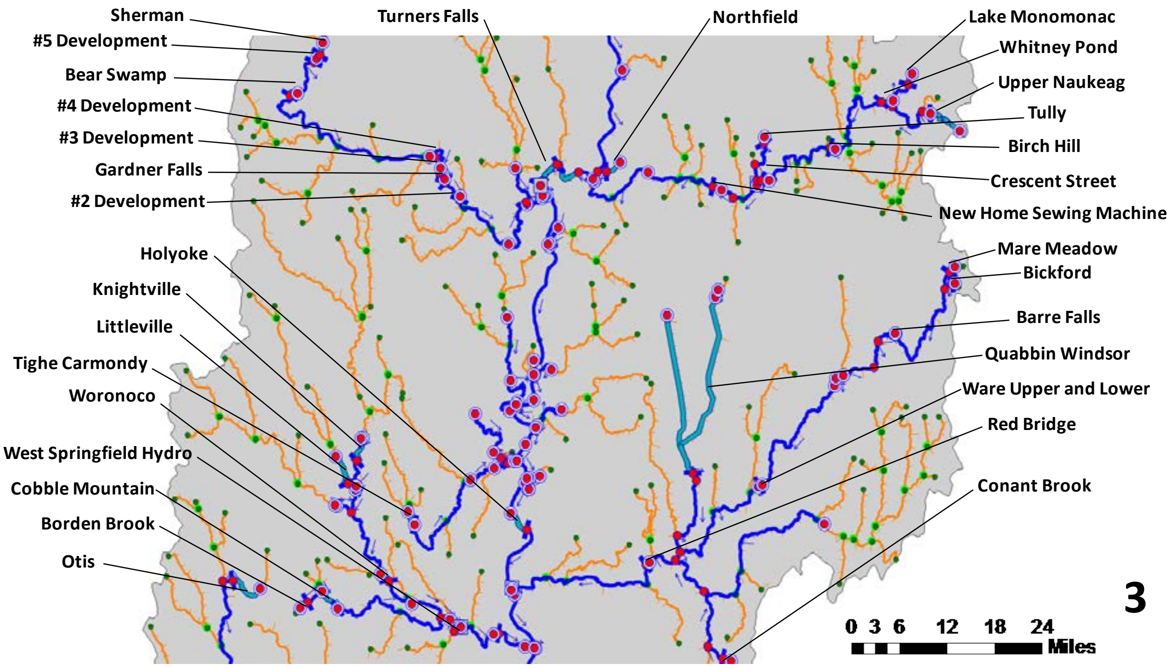


Figure A4: Map of the HEC-ResSim model from Section 3 in Figure A1.

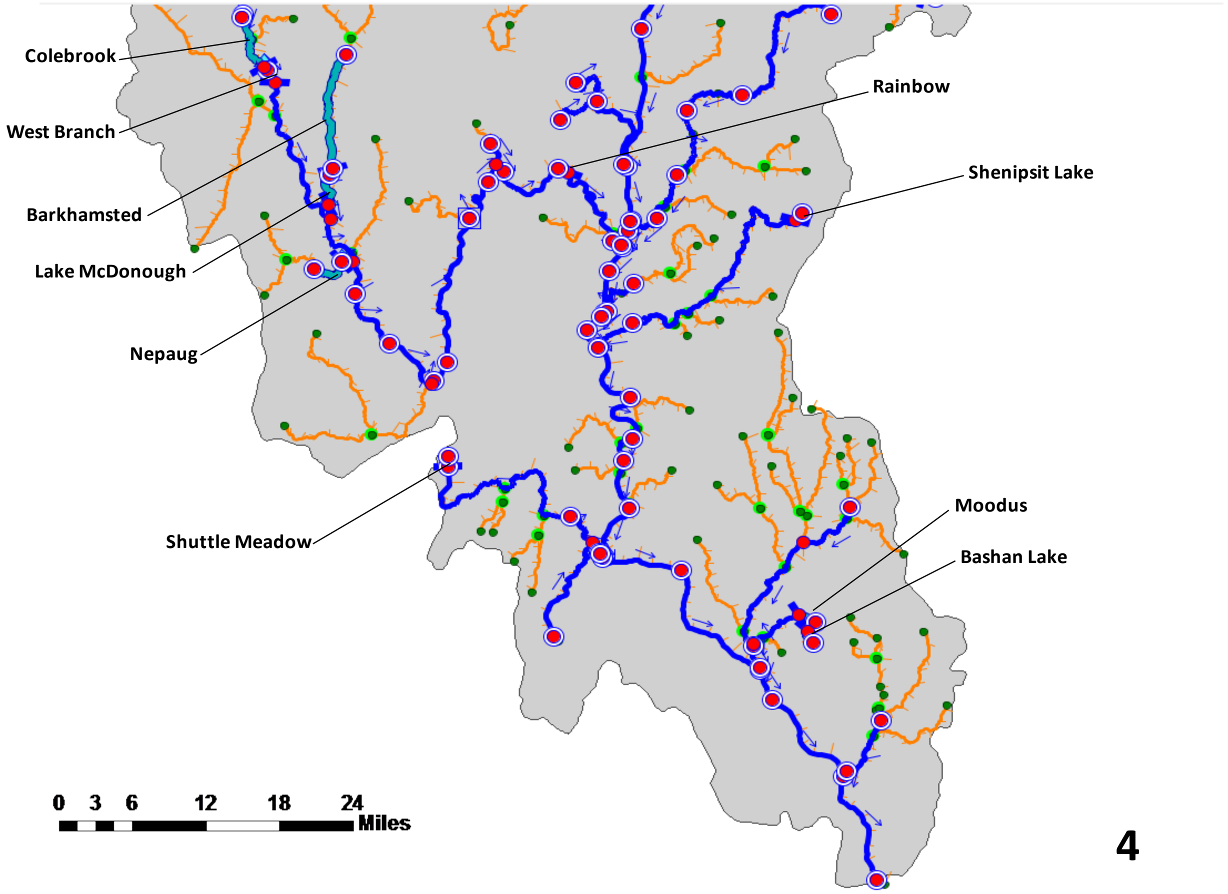


Figure A5: Map of the HEC-ResSim model from Section 4 in Figure A1.

Appendix B

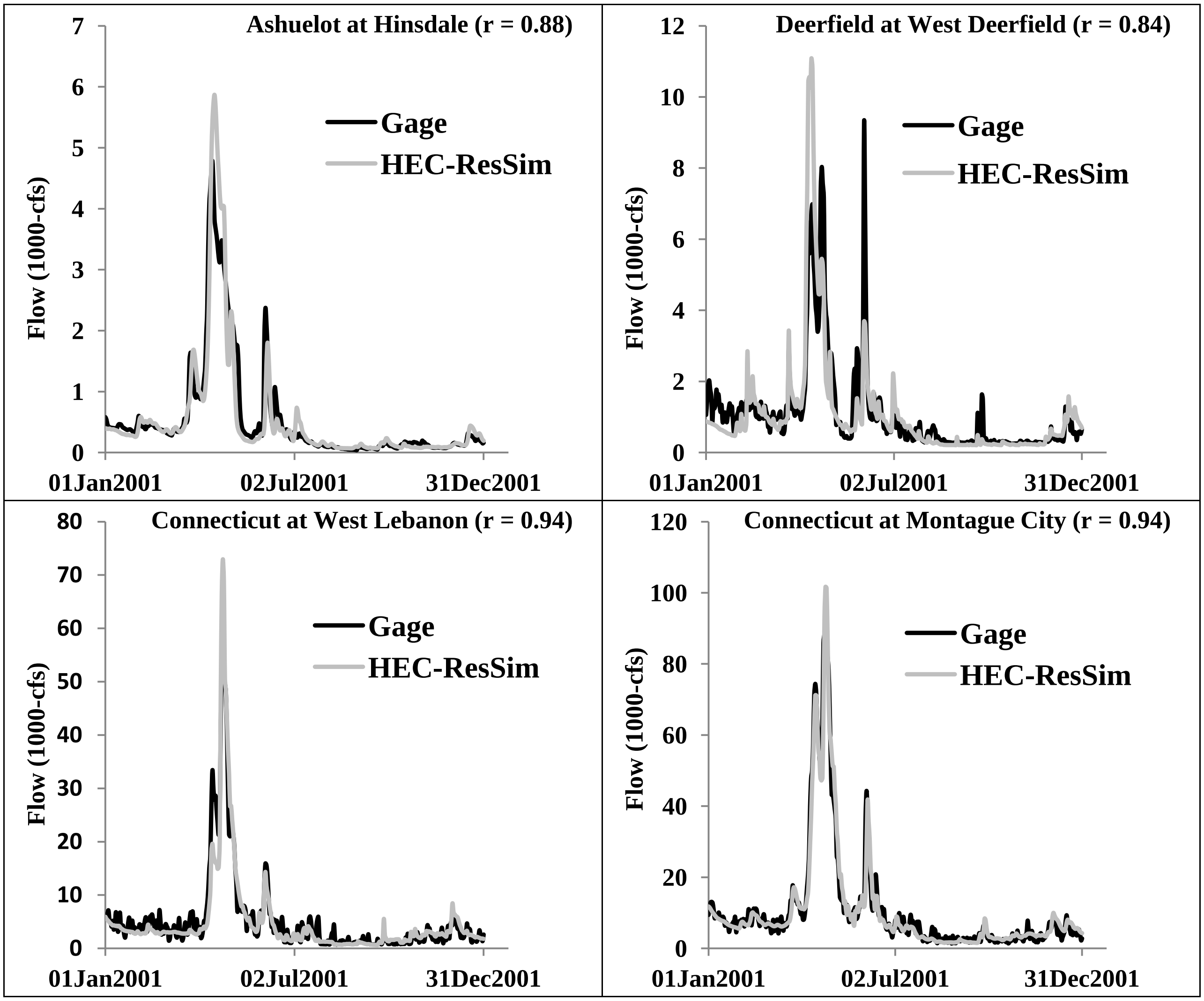
Table B1 shows the correlation values (r), Nash Sutcliffe Model Efficiency Coefficients (E), and percent change from gaged in total flow volume, calculated for each point in HEC-ResSim that had a USGS gage at or extremely close to its location in the watershed, as well as the percent difference in total flow volume from gaged (HEC 2013).

Table B1: Correlation values and % difference from gage in total flow volume between USGS gages and closest computation point in HEC-ResSim.

River	USGS Gage (Gage ID)	HEC-ResSim Point	r	E	% Difference in Volume
Ashuelot	West Swanzy, NH (01160350)	Ashuelot at West Swanzy	0.92	0.79	1.2
Ashuelot	Hinsdale, NH (01161000)	Ashuelot at Hinsdale	0.88	0.82	-3.4
Ashuelot	Keene, NH (01158000)	Surry Mountain_Out	0.8	0.6	-6.8
Black	North Springfield, VT (01153000)	North Springfield_Out	0.77	0.48	-1.5
Chicopee	Indian Orchard, MA (01177000)	Red Bridge_Out	0.9	0.55	13.5
Connecticut	Vernon, VT (01156500)	Vernon_Out	0.95	0.92	-1.8
Connecticut	Montague City, MA (01170500)	Connecticut at Montague	0.95	0.92	20.9
Connecticut	Holyoke, MA (01172003)	Holyoke_Out	0.95	0.88	0.9
Connecticut	West Lebanon, NH (01144500)	Connecticut at West Lebanon	0.95	0.85	-4.4
Connecticut	North Walpole, NH (01154500)	Connecticut at North Walpole	0.94	0.86	-3.4
Connecticut	Thompsonville, CT (01184000)	MAIN_Floodplain25	0.9	0.85	-1.5
Connecticut	Wells River, VT (01138500)	Connecticut at Wells River	0.9	0.76	-9.7
Connecticut	Dalton, NH (01131500)	Gilman_Out	0.86	0.77	-6.9
Connecticut	North Stratford, NH (01129500)	MAIN_Mussels2	0.84	0.72	-7.1
Connecticut	Pittsburgh, NH (01129200)	Connecticut+Indian	0.49	-0.46	-17.1
Connecticut	First Conn Lake Nr Pittsburg, NH (01128500)	First Connecticut Lake_Out	0.2	-0.54	-15.4
Deerfield	West Deerfield, MA (01170000)	DRF_Floodplain1	0.84	0.63	-6.1
Deerfield	Charlemont, MA (01168500)	Bear Swamp_Out	0.81	0.5	-32
East Branch Tully	Athol, MA (01165000)	Tully_Out	0.76	0.43	7.6
Fall	Otis, MA (01185100)	Otis_Out	0.39	-0.73	-0.9

Farmington	Rainbow, CT (01190000)	Rainbow_Out	0.87	0.61	24.5
Farmington	Unionville, CT (01188090)	FAR_Corps Ops	0.84	0.24	16
Hockanum	East Hartford, CT (01192500)	HKM_Floodplain-Diadromous Fish	0.71	0.4	15.4
Mascoma	Mascoma, NH (01150500)	Mascoma_Out	0.74	0.4	7.3
Mattabesset	Route 327 at East Berlin (01192704)	MAT_Floodplain1-Diadromous Fish	0.85	0.52	43.6
Millers	Winchendon, MA (01162000)	Whitney Pond_Out	0.95	0.71	-36.6
Millers	Erving, MA (01166500)	MLR_Diadromous Fish	0.91	0.8	-0.04
Ompompanoosuc	Union Village, VT (01141500)	Union Village_Out	0.8	0.63	-4.7
Ottauquechee	North Hartland, VT (01151500)	North Hartland_Out	0.81	0.63	4.2
Otter Brook	Keene, NH (01158600)	Otter Brook_Out	0.81	0.61	-3.4
Sugar	West Claremont, NH (01152500)	Sugar at Mouth	0.85	0.69	1
Swift	West Ware, MA (01175500)	Swift at West Ware	0.41	-2.79	103.4
Ware	Gibbs Crossing, MA (01173500)	Ware Upper and Lower_Out	0.83	0.64	-4.5
Ware	Barre, MA (01172500)	Barre Falls_Out	0.81	0.65	-5.5
Wells	Wells River, VT (01139000)	Wells at Mouth	0.99	0.92	3.9
West	Newfane, VT (01156000)	Townshend_Out	0.7	0.42	-6.4
West	Jamaica, VT (01155500)	Ball Mountain_Out	0.66	0.47	-0.2
West Branch Farmington	Riverton, CT (01186000)	West Branch_Out	0.32	-0.93	-1
Westfield	Westfield, MA (01183500)	Westfield at Westfield	0.88	0.52	9.6
Westfield	Knightville, MA (01179500)	Knightville_Out	0.69	0.3	-2.9

Figure B1 shows the comparison plots of the simulated flows and gaged flows at ten of the locations. There were two main differences between the simulated and gaged flows. The simulated high flow event peaks were generally higher than the gaged high flow event peaks due to SYE. The simulated low flows were much smoother than the gaged low flows due to HEC-ResSim's inability to account for local variability in runoff and minor operation adjustments.



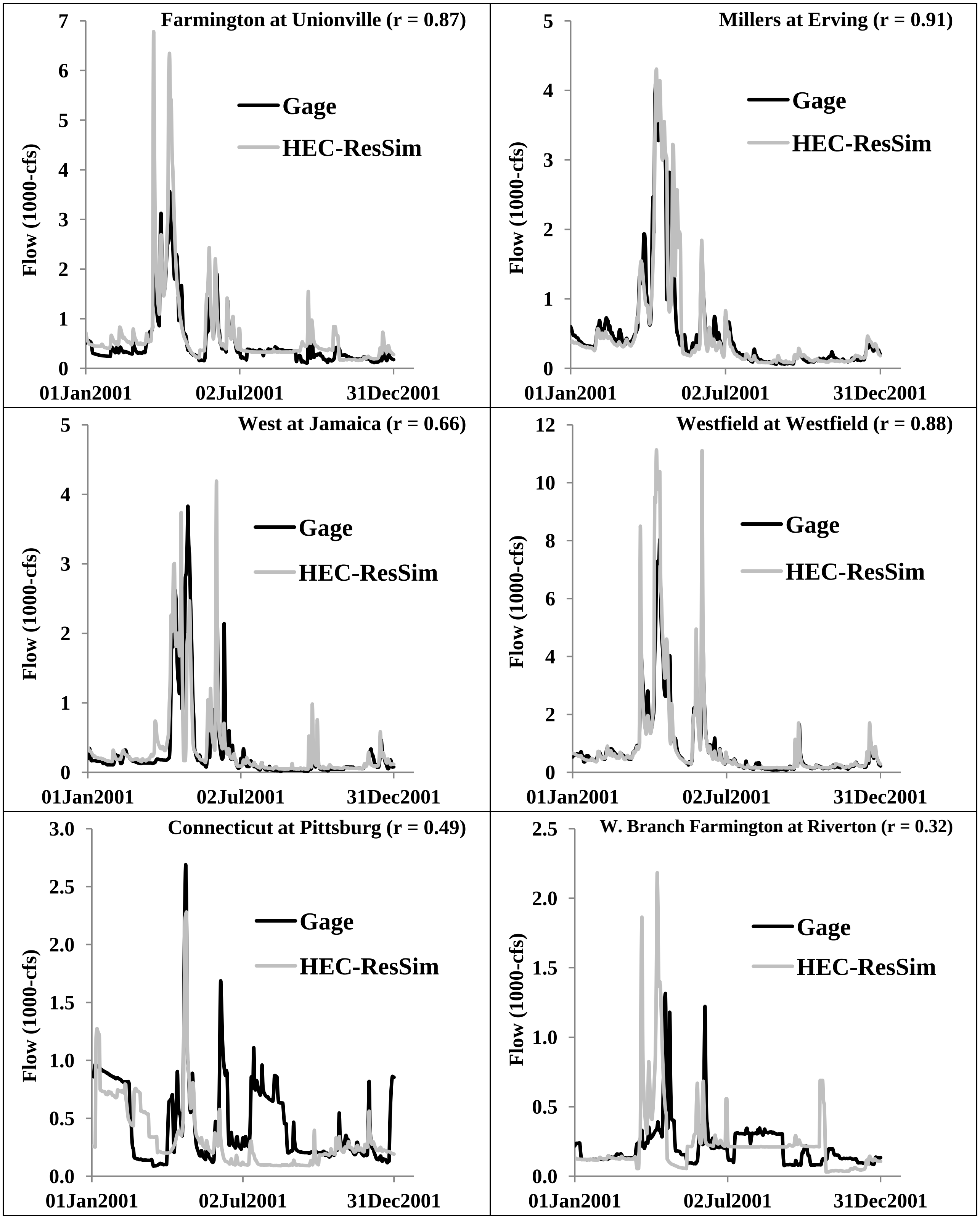


Figure B1: Comparison plots of HEC-ResSim generated hydrographs versus USGS gage hydrographs.