Appendix H
HEC-ResSim Model

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Reservoir Management Decision Support System for the Connecticut River Watershed

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14. ABSTRACT
This report was developed by the U.S. Army Corps of Engineers (USACE) Hydrologic Engineering Center (CEIWR-HEC) with New England District (CENAE) for assisting in the development of a decision support system for the Connecticut River watershed. The decision support system uses HEC-ResSim, HEC-EFM, HEC-RAS and estimates of unimpaired stream flows prepared by the U.S. Geological Survey. The decision support system will be used to analyze reservoir operating scenarios for a variety of water management purposes, including environmental, hydropower, flood control, water supply, and recreational considerations. This report has a separate Appendix (PR-88b) that contains detailed information about the modeled reservoirs.

15. SUBJECT TERMS
Hydrology, Decision Support System, HEC-ResSim, watershed, river, Connecticut River, water management, streamflow, HEC-EFM, HEC-RAS, Reservoir System Simulation, model, reservoir operation, environmental, ecosystems, hydropower, water supply, flood control, unregulated flows

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Executive Summary

A decision support system for the Connecticut River watershed was developed to analyze potential reservoir re-operating scenarios for a variety of water management purposes, including environmental, hydropower, flood control, water supply, and recreational considerations. Central to this Decision Support System is an HEC-ResSim (Hydrologic Engineering Center's (HEC) Reservoir System Simulation software) model. The HEC-ResSim model simulates the current operations of 73 major reservoirs throughout the entire Connecticut River watershed over 44 years at a daily time-step. The reservoirs modeled are owned and operated by a variety of public and private entities for many different purposes. The Decision Support System was developed as part of an overall Connecticut River Watershed Study that is being conducted by the U.S. Army Corps of Engineers (USACE), The Nature Conservancy (TNC), University of Massachusetts (UMASS), and the US Geological Survey (USGS).

The HEC-ResSim model was constructed using hydrologic data provided by the U.S. Geological Survey (USGS) and physical and operational data provided by the owner/operators of the modeled reservoirs. Modeling strategies were developed for hydrologic routing, hydropower operations, and water supply withdrawals. In addition to the reservoirs, 138 computation points were included in the model to simulate flows at ecological points of interest. Once construction of the model was complete, output was correlated against USGS gages. Alongside the development of the HEC-ResSim model was the application of the HEC-EFM (Ecosystem Functions Model) and HEC-RAS (River Analysis System) software tools to assist in the analysis of the output from the HEC-ResSim model.

After development of the decision support system was complete, it was used in an analysis of the Connecticut River mainstem in order to exemplify how the decision support system can be used. Output from the HEC-ResSim model was analyzed for the extent of hydrologic alteration from unregulated conditions in ecological flow targets using HEC-EFM and changes in inundated area using HEC-RAS. Several run-of-river scenarios were also run in the HEC-ResSim model to measure potential tradeoffs in reduced hydrologic alteration along with changes in hydropower output and flood protection along the Connecticut River mainstem.

Descriptions of how to set up and use the decision support system are included with this project report. The decision support system described in this report was developed to compliment the other models, such as the optimization and climate change models, developed for the Connecticut River Watershed Study and to be used by stakeholders.

Chapter 1
Introduction

The Connecticut River has a watershed of about 11,260 square miles, is 410 miles long and has 44 major tributaries (defined as draining >300 square miles). The river serves as the boundary between Vermont and New Hampshire, and then cuts through Massachusetts and Connecticut before it empties into the Long Island Sound. A map of the Connecticut River watershed, with a majority of the major tributaries labeled is presented in Figure 1.

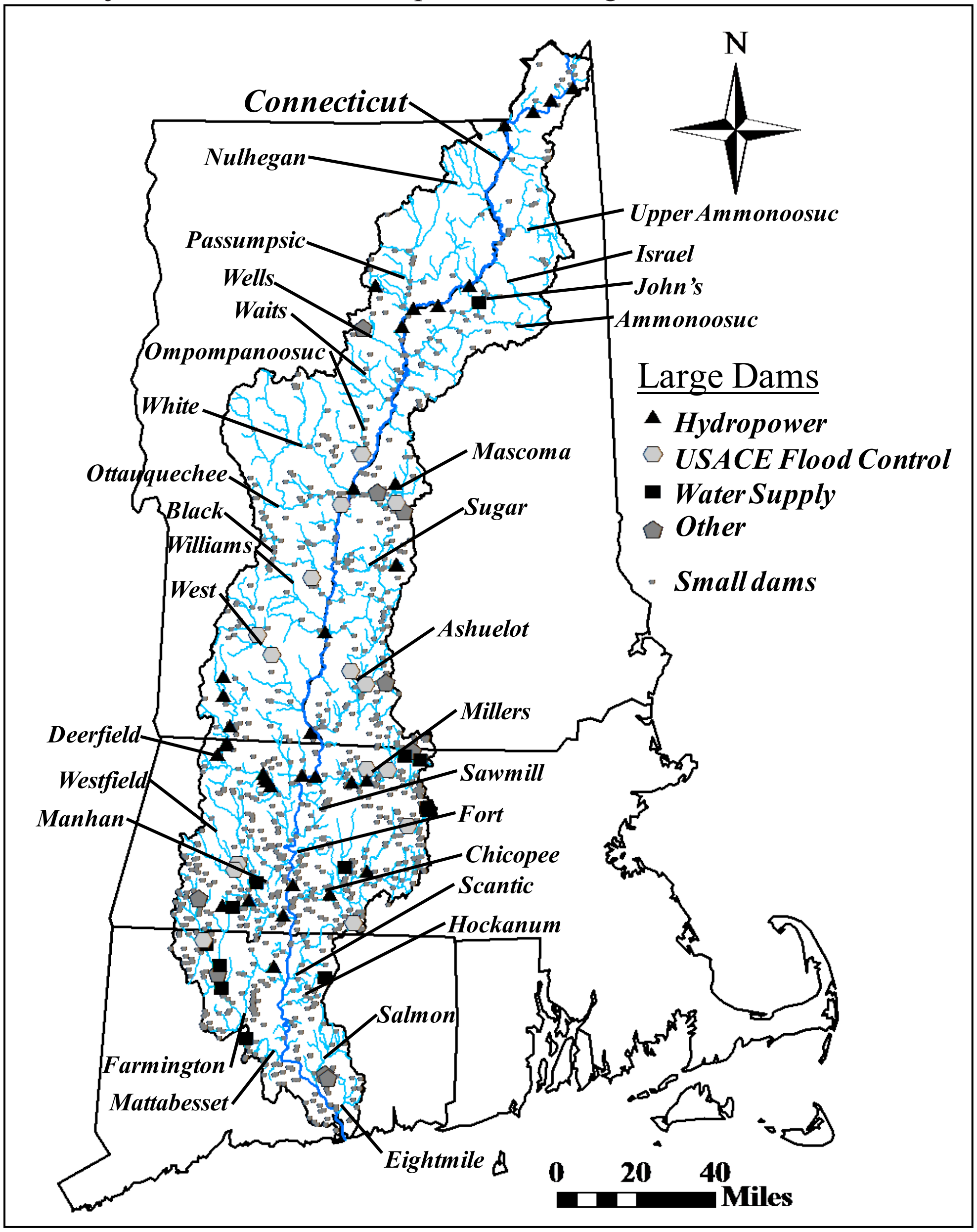

Figure 1. Map of the Connecticut River watershed. The map shows the major tributaries and the locations of large dams (and their primary purposes) as well as the location of over 1,000 small dams.

The ecosystem of the Connecticut River and its tributaries depend on a naturally variable flow of water. High flows in spring and fall help mature fish move to spawning areas and young fish move downstream. Low flows in the summer are critical for certain aquatic plants to take root. For most of the Connecticut River and its tributaries, these seasonal flows have been altered by dams built for hydropower generation and flood control. Other areas are impacted by water withdrawals used for public water supplies and industrial purposes.

The Connecticut River Watershed Study, currently being undertaken by the U.S. Army Corps of Engineers (USACE), The Nature Conservancy (TNC), the University of Massachusetts (UMASS), and the US Geological Survey (USGS) will help determine how management of these dams and water systems can be modified for environmental benefits while maintaining beneficial human uses such as water supply, flood control and hydropower generation. One of the study's key outcomes was the creation of a watershed-wide hydrologic model and decision support system that will allow water managers and other key stakeholders to evaluate environmental and economic outcomes based on various management scenarios. These products will enhance the ability of USACE and other stakeholders to manage their dams to provide more natural stream flows while maintaining authorized water supply, flood control and hydropower uses as in compliance with Corps policy and guidance[1,2]. Data from this study will also assist decision-making for the Federal Energy Regulatory Commission (FERC) licensing processes underway in 2013.

USACE and TNC (the non-Federal sponsor) determined that the Connecticut River Watershed study was necessary in order to develop a watershed-wide hydrologic tool that allows stakeholders to evaluate the impact of various flow manipulations on various ecological objectives. Several stakeholders (primarily hydropower) have developed localized computer models over the years that address their concerns, but nothing that addressed the entire Connecticut River watershed all at once. Stakeholders and model reviewers require a watershed-wide model that is robust enough in its scope and complexity to meet all the demands of a wide range of analyses and recommendations.

The challenges in developing the models were numerous. In terms of sheer scale, the watershed covers over 11,000 square miles in four states, includes 44 major tributaries, and 73 modeled reservoirs with 32 different owners and varying operating purposes. Compiling input data for the reservoir simulation model was a substantial effort, including the preparation of unregulated flow data (led by USGS) as well as physical and operational data to characterize the dams and reservoirs, which required extensive coordination with owner/operators (led initially by UMASS and continued by USACE). Development of the river hydraulics models required field surveys and the creation of the models for multiple river reaches (led by USACE). Environmental flow definitions had to be translated into ecological metrics that could be calculated using the decision support system (led by USACE). And finally, all the pieces of the decision support system had to be linked, calibrated, and then exercised to be capable of analyzing reservoir management alternatives.

[1] USACE, 1982. *Water Control Management*, ER 1110-2-240.
[2] USACE, 1992. *Authorized and Operating Purposes of Corps of Engineers Reservoirs*, PR-19.

Models were selected to address two main issues: how dams in the Connecticut River watershed are currently managed (operations model) and what the historical hydrology of the watershed was like before damming the system (unimpaired flow model).

The following models were used in the Decision Support System: the Connecticut River Unimpaired Streamflow Estimator (CRUISE, developed by the USGS) and HEC-ResSim (operational model developed by USACE, Hydrologic Engineering Center's (HEC) Reservoir System Simulation software), with supporting models HEC-RAS (River Analysis System) and HEC-EFM (Ecosystem Functions Model).

Reservoir operations models simulate the storage and release of waters in systems of reservoirs. These models are typically either rule-based simulations or goal-based optimization models, or a combination of the two. Simulated water releases in rule-based models are guided by rules specified by the modeler (e.g., a minimum flow rule might say "avoid releases less than 10 cfs"). Rules are created, prioritized, and modified in operation sets to make simulated releases agree with how the reservoirs are actually operated. When the model is producing reasonable results after calibration and verification, rule sets can be changed to test different management approaches (start with current operations and change from there). Optimization models take a different approach – they store water and make releases that optimize the net benefits of the water, subject to user defined constraints. This is a nice complement to rule-based approaches because it encourages study teams to consider a different perspective about operations. HEC-ResSim is the rule-based model applied for the Connecticut River; a goal-based optimization model was also developed by UMASS, but as the decision support system described in this report does not incorporate this model, it is not described here further. A description of the Connecticut River optimization model and its uses, including its conjunctive use with the HEC-ResSim model will be a future product of the Connecticut River Watershed Study team.

TNC has estimated that there are over 2,700 dams in the Connecticut River watershed. Decades of research have established that dams and their associated impoundments are disruptive to a river's hydrology and water quality. The vast majority of the dams in the watershed are small, run-of-river structures that do not store much water, and were therefore not considered for the study. TNC also determined that out of all the dams, there are 65 that are capable of controlling ten percent or more of the mean annual discharge at their respective locations[3]. The majority of these are located on the tributaries. An additional eight hydropower dams were also considered for the study, as they had a hydropower generating capacity of at least 1 MW (megawatt). These 73 dams became the focus of the study as it was determined they have the largest impact on the hydrology of the watershed. The purposes of the 73 dams include flood control, hydropower generation, water supply, and recreation; 36 of the dams are operated for hydropower, 16 for water supply, 27 for recreation, 19 for flood control. Of the 73 dams, 24 of the dams have multiple purposes.

The goal of the HEC-ResSim model developed for the Connecticut River watershed is to simulate reservoir operations with enough reality to be useful when planning alternative reservoir management scenarios. To achieve this goal, the HEC-ResSim model incorporates enough hydrologic data (daily stream flows), physical data (outlet capacities, power generation,

[3] Zimmerman, J., A. Lester, K. Lutz, C. Gannon, and E.J. Nedeau, 2008. *Restoring Ecosystem Flows in the Connecticut River Watershed.*

elevation-storage relationships), and operational data (target pool elevations, release rules, minimum flow criteria, power generation logic) to be generally accurate and supported as a good approximation of actual operations and a fair test for any hypothetical scenarios to be simulated. In the Connecticut River watershed study, existing conditions at selected projects will be simulated using the current operating rules, then conditions will be altered to test the effects of alternative management policies, which may be derived from the optimization model or through other means.

HEC-ResSim is a versatile tool. It is capable of simulating a wide range of detailed reservoir operations, but depends on the user to provide the data and logic needed to guide its decisions about how to release water. The program is public domain software, supported and upgraded by the HEC, and is used by many in the hydrologic community. It is hoped that the Connecticut River HEC-ResSim model, combined with the other software tools, will used by the stakeholders in the watershed as a decision support system for a variety of purposes, including FERC relicensing and planning studies.

Chapter 2
Data

Construction of the Connecticut River watershed HEC-ResSim model required two main sets of information: inflow time series data, and reservoir physical and operational data.

2.1 Inflow Data

Reservoir inflows for the HEC-ResSim model were calculated using the CRUISE tool which is based off the Sustainable Yield Estimator (SYE) tool developed by the USGS [4,5]. The SYE tool quantified the mean daily unimpaired streamflow hydrograph at ungauged 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 QPPQ method, the flow duration curve was translated into a timeseries by correlating the timing of flows at 66 reference stream gauges and the flows at ungauged sites. Figure 2 provides 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 ungauged sites.

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 gauges. The dataset is both homogeneous and stationary. Comparing flows from several USGS gauges on streams that are minimally regulated by dams to the SYE generated streamflows (see Figure 3) shows that the SYE simulates the overall timing and magnitude of low and medium flows reasonably well.

There are two main issues with the SYE-generated hydrographs when compared to gauge data: the difference in the magnitude of the peaks and the difference in the total volume. These two issues, particularly the difference in volume, add uncertainty to the model output and temper the ability of the HEC-ResSim model to fully match gauge data. Other approaches to quantifying unregulated hydrographs, such as hydrologic modeling, were not used for this study as the complexity of quantifying unregulated hydrographs through hydrologic modeling was beyond the scope of the study.

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[4] Archfield, S. A., Steeves, P. A., Guthrie, J. D., and Ries III, K. G, *Towards a publicly available, map-based regional software tool to estimate unregulated daily streamflow at ungauged rivers*, Geosci. Model Dev., 6, 101-115, doi:10.5194/gmd-6-101-2013, 2013.

[5] Archfield, Stacey A., Vogel, Richard M., Steeves, Peter A., Brandt, Sara L., Weiskel, Peter W., Garabedian, Stephen P, *The Massachusetts Sustainable-Yield Estimator: A decision-support tool to assess water availability at ungaged sites in Massachusetts*, Reston, Virginia: USGS, 2009.

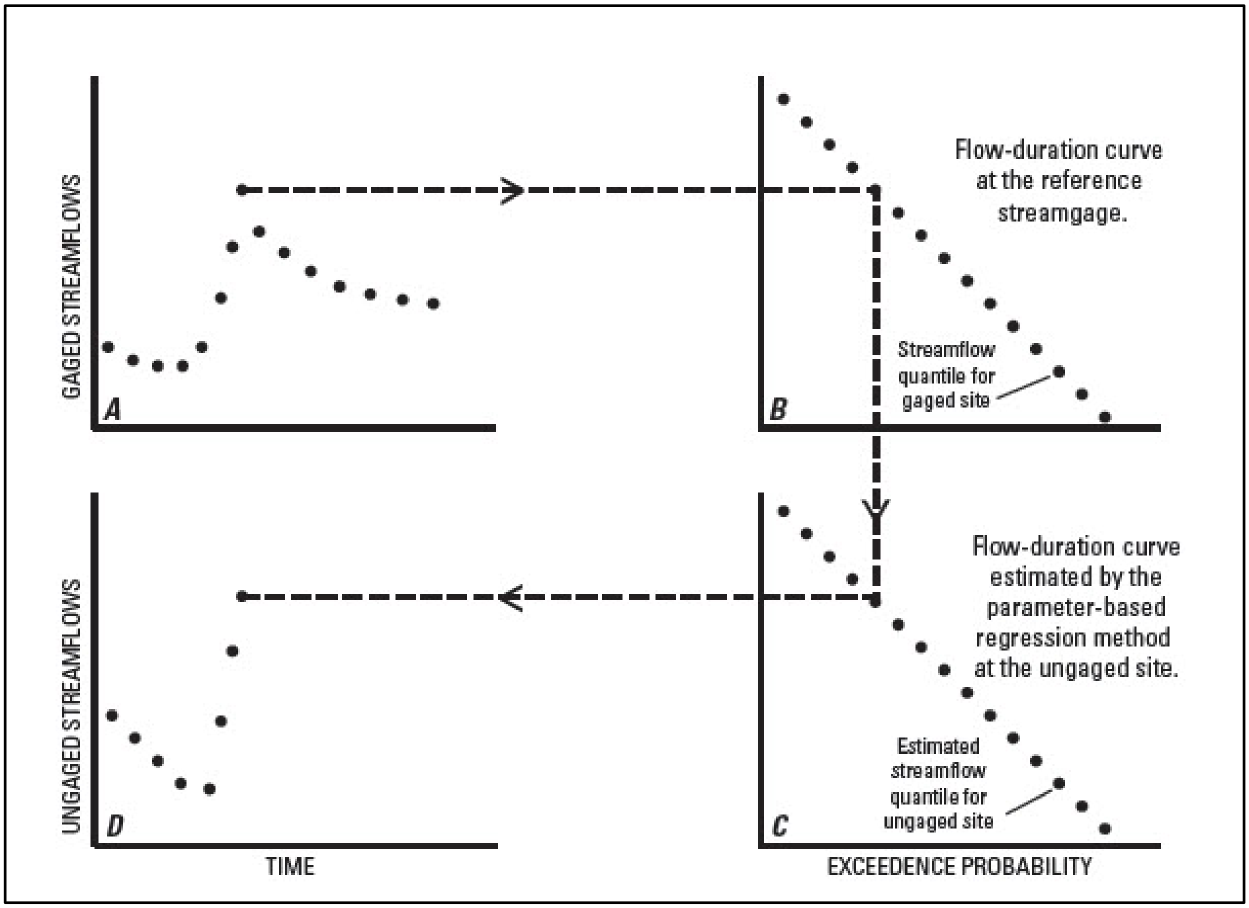


Figure 2. Schematic showing the QPPQ method of translating an FDC into a streamflow time series. Plot A is the reference gauge's time series. Plot B is the reference stream gauge translated into a flow-duration curve. Plot C is the flow-duration curve at the ungauged site calculated using parameter-based regression. Plot D is the ungauged flow-duration curve translated into a time series. Figure from Archfield et al. 2009.

2.2 Reservoir Physical and Operational Data

Information about the dams required for the model included physical and operational data. Physical data describes the infrastructure of the dam and operational data describes how that infrastructure is used to fulfill the purposes of the dam. Required physical data included pool elevation-storage curves, outlet types, outlet capacities and rating curves. Operational data knowledge such as minimum flow requirements and pool elevation targets were required to develop rules and operation sets. This data was collected in several parts. Initially, data collection efforts were led by UMASS and data collected was shared with USACE. Data gaps from the initial round of data collection were then filled as much as possible through outreach done by USACE, where owner/operators of dams with data gaps were contacted and asked questions directly pertaining to the physical and operational characteristics of their projects that were necessary for HEC-ResSim. When available, data was collected from models that owner/operators already had of their dams. Because the SYE period of record is from 1960 to 2004, it was assumed that the current operations gathered during the data collection were in place for the entire SYE period of record. No operational changes over time were accounted for.

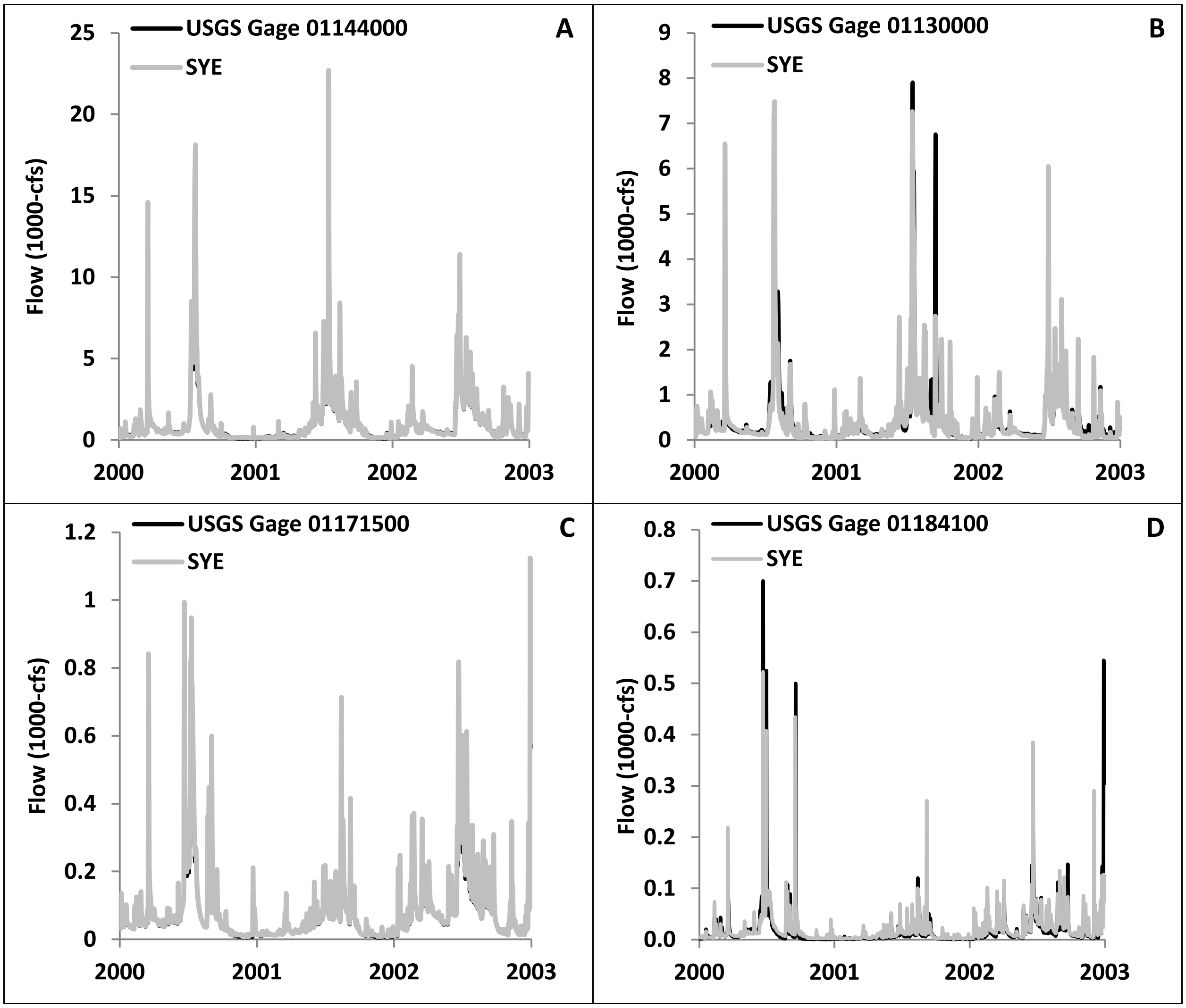


Figure 3. Observed and SYE estimated mean daily streamflows at four USGS Gauge locations in the Connecticut River Watershed; A – White River at West Hartford, VT, B – Upper Ammonoosuc River at Groveton, NH, C – Mill River at North Hampton, MA, D – Stony Brook at West Suffield, CT.

Even with the extensive outreach and data collection efforts, there were still knowledge gaps for both physical and operational data. Five dams remained that had no physical or operation data of any kind. These projects were Gardner Falls, Red Bridge, Ware Upper and Lower, West Springfield Hydro Project, and Woronoco. Information about these remaining projects was collected from the National Inventory of Dams (NID) database and the web to ensure that each project had at least some physical data that could be incorporated into the model. Operational knowledge gaps were more prevalent among the larger scale hydropower projects. For reservoirs with limited operational data, general modeling strategies were employed. Of all projects modeled, the USACE flood control dams had the most complete set of physical and operational data. All physical and operational data used for the model is in Appendix A.

Chapter 3
Model Development

3.1 Watershed Setup

The first phase of creating the model involved constructing what is called a "watershed" in HEC-ResSim. First, the skeleton of the watershed, the stream alignment, was constructed based on the USGS National Hydrography Dataset[6] (NHD) stream polyline shapefile for the Connecticut River basin. After finishing the stream alignment, the locations of the upstream and downstream ends of the reservoirs chosen to be modeled were input into the watershed. In addition, 138 points of ecologic interest, called "econodes" for the Decision Support System, were input into the watershed, as well as points at the mouths of the major tributaries and current USGS gauge locations. In HEC-ResSim, the points where a flow hydrograph is generated during a simulation are called computation points. The computation points are connected to each other through routing reaches. Inflow time series were generated using SYE for all computation points in the model, excluding reservoir outflow points and stream junctions, and incorporated into the model.

3.2 Reservoir Network Development

Once the watershed setup was completed, the physical and operational data for the dams were incorporated into the model, into what is called a "Reservoir Network" in HEC-ResSim. Physical and operational data were incorporated into the model as they were received[7]. Operation strategies were developed and implemented for hydropower generation and water supply. A routing strategy was developed and implemented to address the many sub-daily routing reaches while maintaining the use of one routing method throughout the model.

3.2.1 Operation Strategies

General strategies for modeling hydropower and water supply were used to guide the simulation of reservoirs that had incomplete operational data. A routing strategy was also devised to handle the many sub-daily travel times the routing reaches had in reality; this strategy is presented in Section 3.2.2.

[6] http://nhd.usgs.gov/index.html

[7] For nineteen 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 consistent pattern of why this occurred at these nineteen dams but it was generally due to 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, 100,000 acre-feet were added to the storage capacity at each pool elevation. This does 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).

3.2.1.1 Hydropower

Thirty-six of the dams modeled had hydropower generation as a purpose, with a total installed capacity of 1,839 megawatts (1,119 megawatts supplied by Northfield Mountain alone). Thirty-one of the dams actually generated hydropower while five of the dams were used only for hydropower storage. Only two dams provided explicit information about hydropower operations. The rest were assumed to operate either as daily run-of-river or peaking projects. Due to the lack of information about the hydropower operations, this analysis assumed the following general strategies for each method of operation:

i. Daily Run-of-River

Daily run-of-river hydropower is generated during the act of passing inflow through turbines at a dam, with little to no daily change in the pool elevation. Most of the dams that had hydropower generation as one of their purposes generated hydropower through daily run-of-river operations, as their pools had limited storage. Unless otherwise indicated, all hydropower projects were assumed to be daily run-of-river. All daily run-of-river hydropower projects[8] received operational logic as follows:

- If the pool was at or above the conservation pool elevation, then release all inflow through hydropower generation.
- If the pool was below the conservation pool elevation, then release 95 percent of inflow for hydropower generation. The release 95 percent of inflow logic was implemented, keeping in mind the limited storage, so that the pool elevation would return to conservation pool elevation and hydropower would still be generated in the process.

ii. Daily Peaking

Five of the dams (Moore, Comerford, Searsburg, Harriman, and Sherman) had daily peaking hydropower generation for their hydropower operations. Daily peaking dams allow their pool elevations to fluctuate daily in order to generate hydropower during peak consumption periods. These dams tend to have a large amount of storage that can be utilized as compared to daily run-of-river dams. In daily peaking hydropower operations, generating power has higher priority than spilling water. Also, any excess volume of water is always run through the hydropower system and whenever minimum flow is greater than inflow, it provides power.

There were two assumptions made for generating power in daily peaking reservoirs:

- Power was only generated on weekdays.
- Based on available water, power was generated for two- and four-hours per day.

[8] The five projects mentioned in the Reservoir Physical and Operational Data section for which no physical or operational data were obtained did not have the run-of-river hydropower strategy applied; they were modeled as purely run-of-river.

Logic to implement daily peaking hydropower generation 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
G = length of hydropower generation

3.2.1.2 Water Supply

Water supply diversions can be modeled two ways in HEC-ResSim: either as a diverted outlet or as a negative inflow time series at the reservoir inlet. Modeling diversions with a diverted outlet incorporates diversions into the release logic and gives the modeler more operational flexibility. However, using diverted outlets would have added an additional layer of complexity as well as additional data needs to the model. Thus the negative inflow time series method was used to account for water supply diversions in this HEC-ResSim model.

While sixteen of the dams had water supply as a purpose, only eight of the dams in the model had water supply withdrawals modeled as the withdrawal volumes for the other eight were considered negligible. Two of the reservoirs with modeled withdrawals, Quabbin and Shuttle Meadow, had their withdrawals estimated from limited available data. Quabbin had monthly average withdrawal data and Shuttle Meadow had daily withdrawal data that were taken from previous models[9]. 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 diversion amount of 45-50 MGD (million gallons per day) in the winter with 25-30 percent increase in demand in the summer months of July and August, up to a peak demand of 60 MGD (million gallons per day). For return flows,

[9] Descriptions of the data and method to estimate the water withdrawals are in the individual project descriptions located in the Appendix.

they estimated ninety percent of diverted flows were returned in the winter and 70-75 percent of diverted flows were returned in the summer.

Using the seasonal information provided by MDC, general guidelines (Table 1) were developed for seasonal diversion amounts and the percent of flow returned to the system and applied to the six projects without existing withdrawal data. It was assumed that general water withdrawal patterns were uniform throughout the watershed, thus the MDC guidelines were applied to projects operated by other municipalities. 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 1. General guidelines for seasonal water supply withdrawals used to make negative inflow time series that represented water supply withdrawals.

	Seasonal Diversion Amount			Percent of Diverted Flow Returned		
	Winter (Oct-May)	**Transition (June/Sep)**	**Summer (July-Aug)**	**Winter (Oct-May)**	**Transition (June/Sep)**	**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			

Also, withdrawals from Quabbin and Bickford were for areas outside of the Connecticut River watershed, so no return flow time series were generated for these reservoirs. 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 2.

Table 2. Estimated seasonal water supply withdrawal amounts as well as service area and return flow location for the six projects that were modeled with negative inflow time series for water supply withdrawals and did not have existing withdrawal data. Quabbin and Shuttle Meadow are not included in this table because they had some existing withdrawal data.

	Seasonal Diversion		Return Flow			
	Winter	**Summer**	**Winter**	**Summer**		
Reservoir	*Base Flow, cfs*	*Peak flow, cfs*	*90% return, cfs*	*75% return, cfs*	**Municipalities/ Service Area**	**Return flow locations**
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

3.2.2 Routing Strategy

The whole-watershed model for the Connecticut River included roughly 360 river reaches. Reach lengths ranged from 300 feet to many river miles in length. This range of reach lengths in a daily time step model was problematic for several of the hydrologic routing methods HEC-ResSim offers (such as Muskingum) because the mathematical equations employed by those methods were designed to route and attenuate flows for travel times greater than a single increment of simulated time. Therefore, 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 provided by USACE's New England District (CENAE) was used for the rest of the watershed. For many reaches, travel times were less than a day, 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 twenty-four hours. This resulted in ten reaches that had a Variable Lag & K method applied as their routing reach, with a lag value of twenty-four hours and K value of twenty-four hours. Table 3 shows the ten 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. It is important to note that attenuation of flow is not accounted for in either routing method used here.

Table 3. 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

Table 4 provides a list of every dam modeled in the watershed, including its river, owner, purpose, and level of confidence the HEC-ResSim modelers had in the dam's physical and operational data. Low confidence indicates significant knowledge gaps, medium confidence indicates few knowledge gaps, and high confidence indicates insignificant or no knowledge gaps. Figure 4 displays a map of the HEC-ResSim model for the entire watershed. Figures 5 through 8 indicate the location of every dam modeled in HEC-ResSim. Red dots on the maps indicate computation points in HEC-ResSim. A red dot with a white border indicates a computation point that receives inflows (called "Local Flow" in HEC-ResSim). Blue lines are routing reaches and teal lines represent the spatial extent of the reservoir pools. Blue rectangles at the downstream end of the reservoirs represent the actual dams.

Table 4. All dams modeled in the Connecticut River HEC-ResSim model as well as the sub-watershed, owner, and purposes of each dam.

Dam	Subbasin	Owner	Purpose(s)	Physical Data Confidence	Operational Data Confidence
Ball Mountain	West	USACE	FC, R	High	Med
Barkhamsted	Farmington	Metropolitan District Commission	**WS**	High	Low
Barre Falls	Chicopee	USACE	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	USACE	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	USACE	H, FC, WS	Med	Med
Comerford	Connecticut	TransCanada Hydro Northeast	**H**	High	Med
Conant Brook	Chicopee	USACE	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	USACE	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	USACE	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

Dam	Subbasin	Owner	Purpose(s)	Physical Data Confidence	Operational Data Confidence
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	USACE	FC, R	High	Med
North Springfield	Black	USACE	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	USACE	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	USACE	FC, R	High	Med
Tighe Carmondy*	Manhan	Holyoke Water Works	**WS**	High	Med
Townshend	West	USACE	FC, R	High	Med
Tully	Millers	USACE	FC, R	High	Med
Turners Falls	Connecticut	FirstLight Power Resources	H	High	High
Union Village	Ompompanoosuc	USACE	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

The dam purposes are labeled as FC--Flood Control, R--Recreation, H--Hydropower, HS--Hydropower Storage, WS--Water Supply. Bolded purposes had a hydropower or water supply modeling strategy applied.
*Dams that are not included in the simplified reservoir network. See Chapter 7 for complete details.

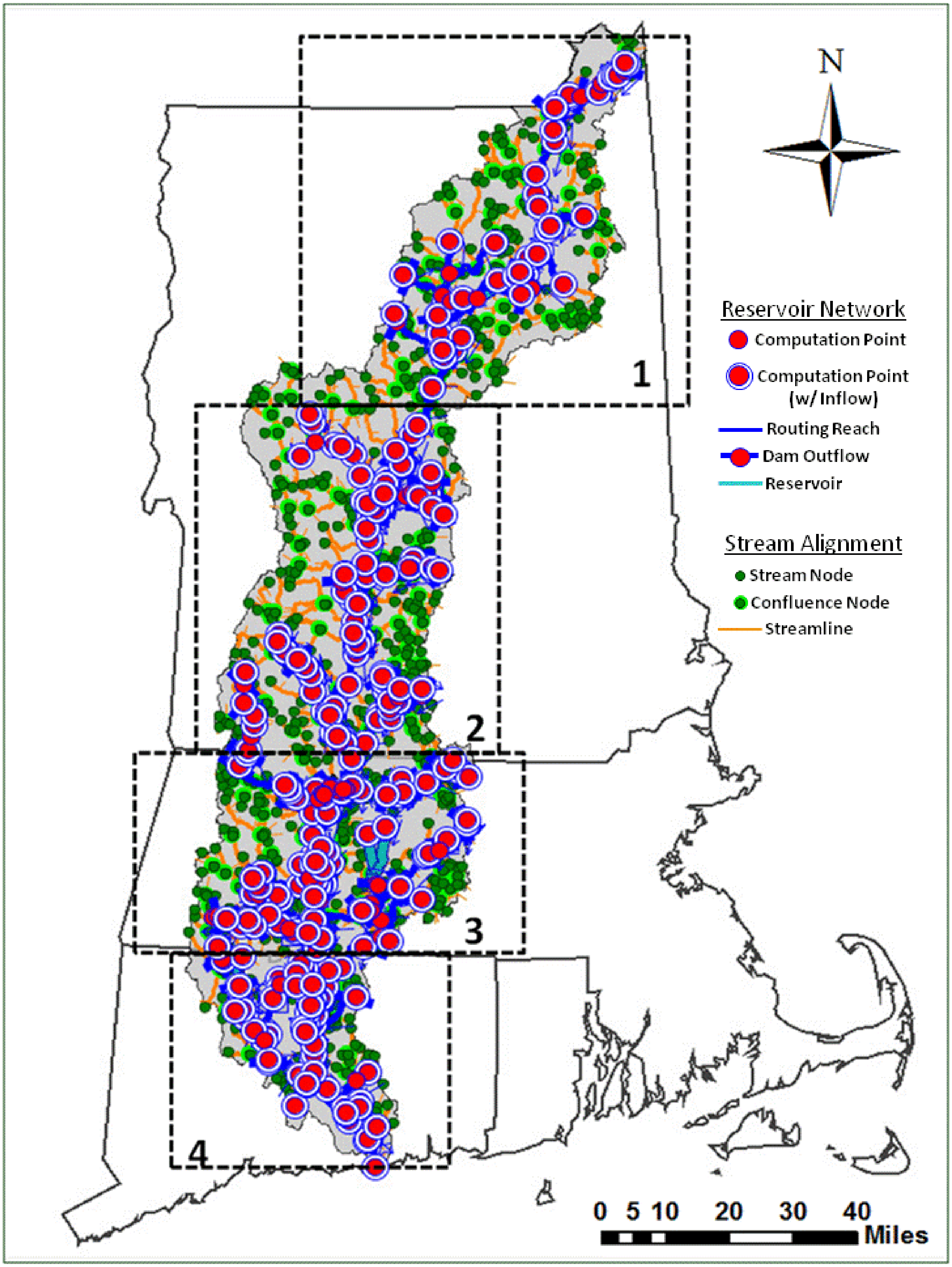


Figure 4. Map of the HEC-ResSim model of the whole Connecticut River watershed. The Reservoir Network are the nodes and reaches that are modeled in the HEC-ResSim model. The stream alignment nodes and streamlines are part of the NHD data set but are not part of the HEC-ResSim model.The outlined sections are shown in Figures 5 through 8.

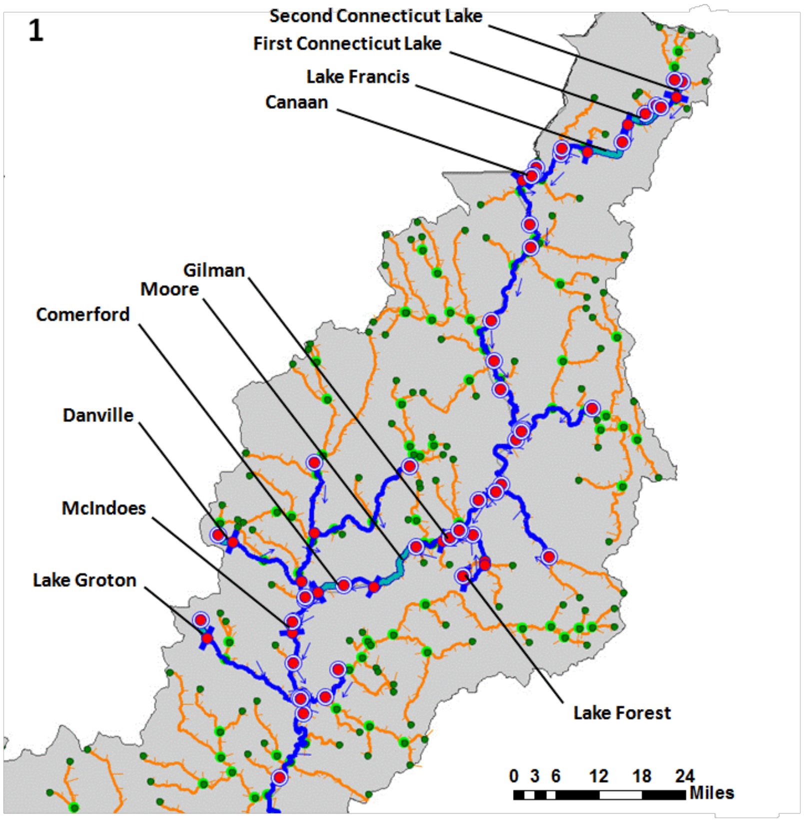


Figure 5. Map of the HEC-ResSim model from Section 1 in Figure 4.

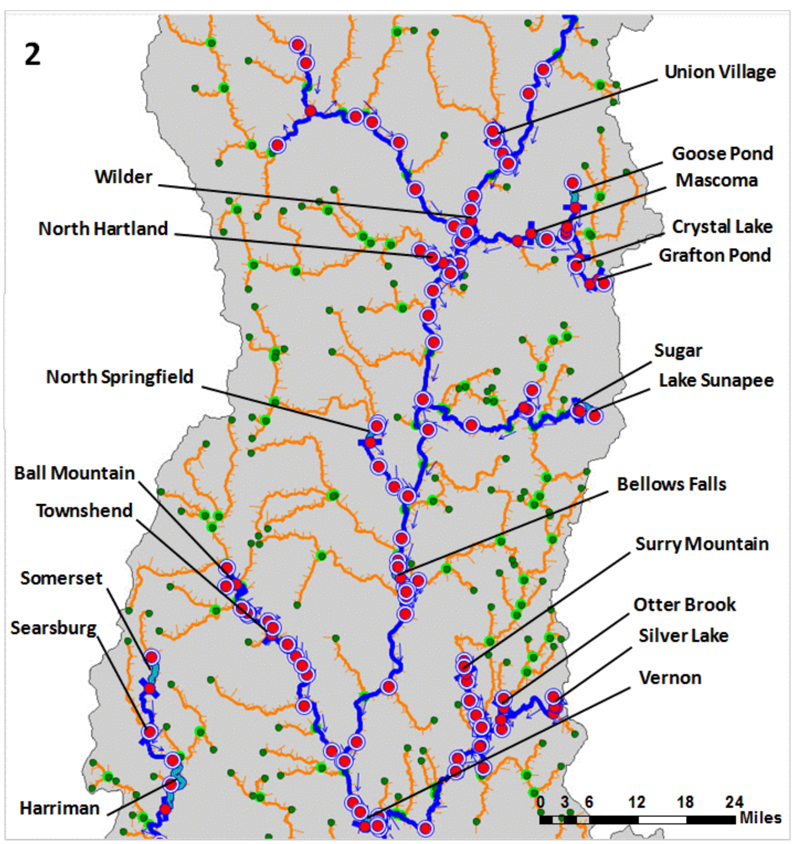


Figure 6. Map of the HEC-ResSim model from Section 2 in Figure 4.

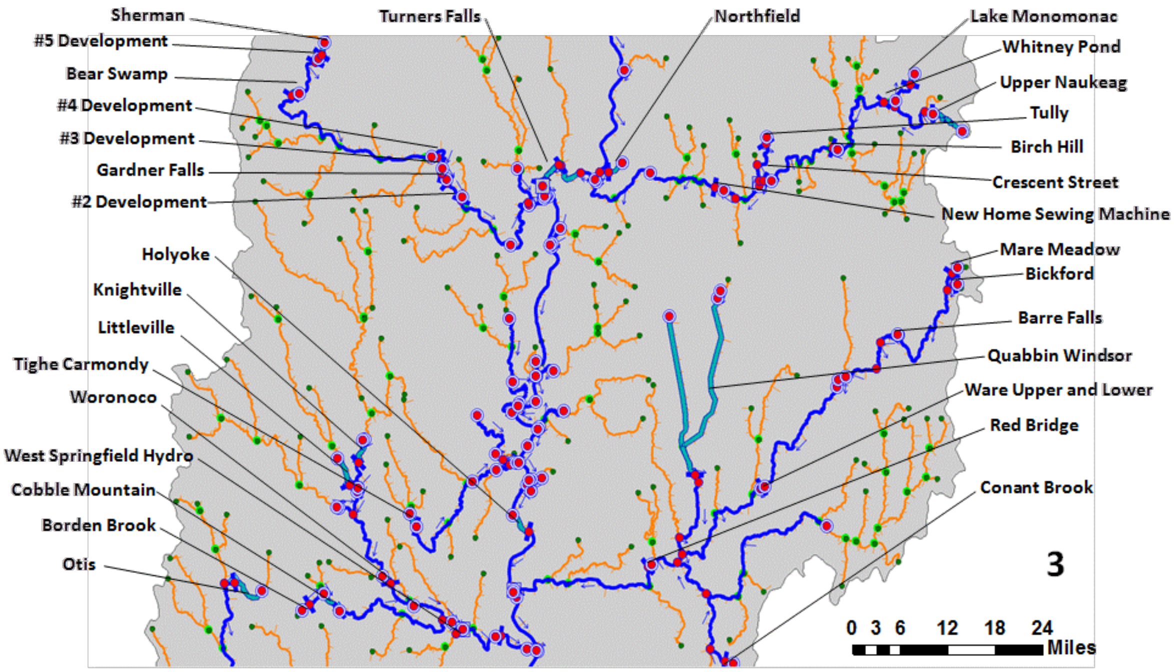


Figure 7. Map of the HEC-ResSim model from Section 3 in Figure 4.

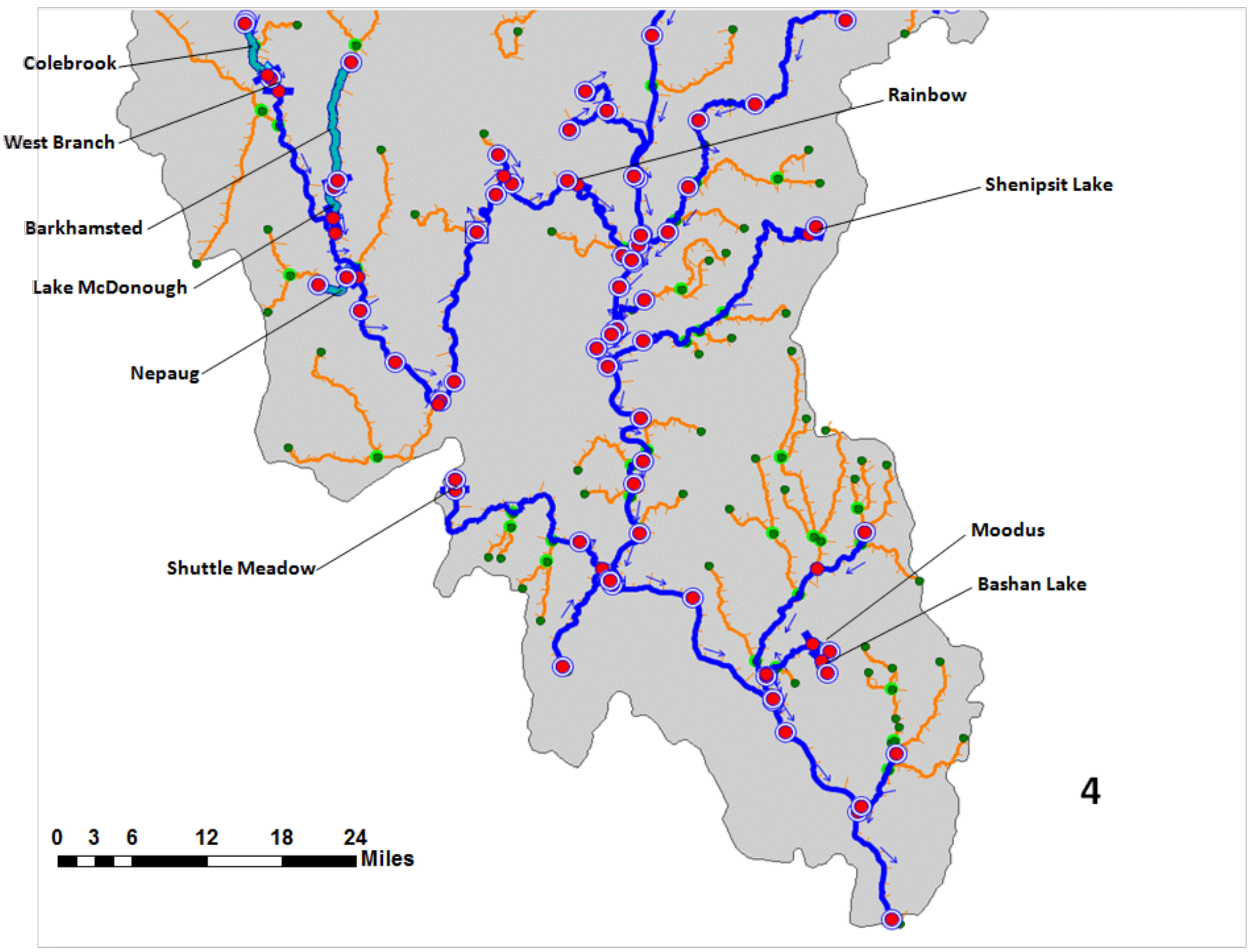


Figure 8. Map of the HEC-ResSim model from Section 4 in Figure 4.

Chapter 4
Calibration/Verification

After implementing the data gathered through the data outreach phase, an initial simulation of the period of record (01Jan1961 - 31Dec2003) was run and results were checked against historical data from forty USGS gauges that were distributed throughout the watershed and in close proximity to computation points influenced by reservoir operations. When significant differences were found, reservoir managers were contacted to clarify operations and in some cases the expert knowledge obtained was incorporated into the model to improve the reality of simulated results. This was done primarily for USACE reservoirs.

4.1 Calibration

4.1.1 USACE Flood Control Operations

Initial simulations based purely on the physical and operational information gathered during data collection showed that the results of the fourteen USACE flood control dams did not align well with gauge data for high flow events. The output from HEC-ResSim prior to calibration is compared to the gauged record of Ball Mountain during a high flow event in 2001[10] in Figure 9. The initial results in Figure 9 are typical of all the results from USACE flood control dams prior to calibration.

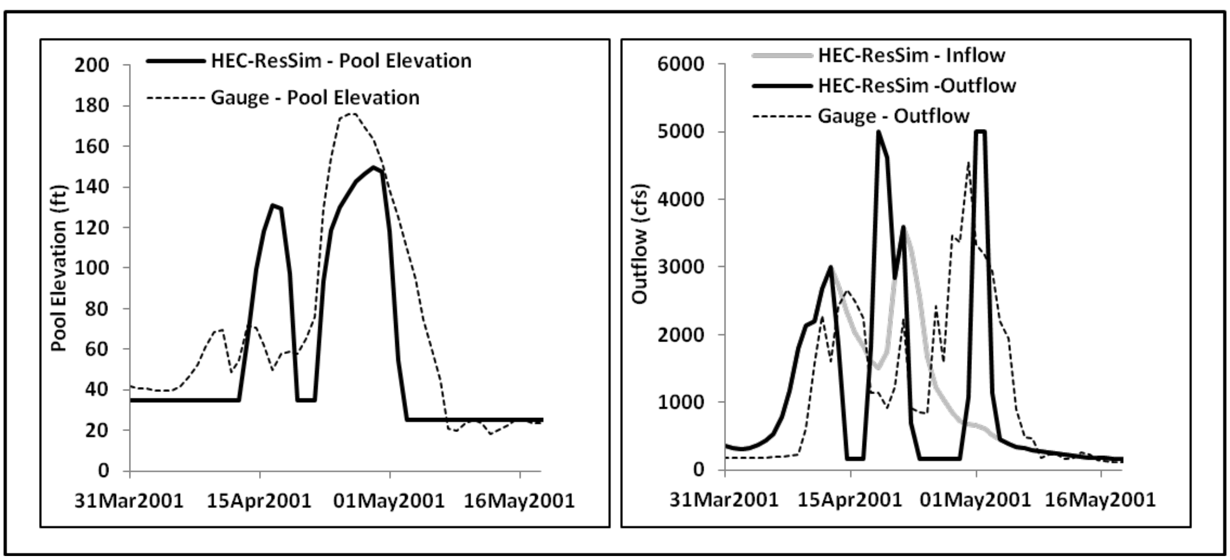


Figure 9. Comparison of HEC-ResSim pool elevation and outflow prior to calibration from Ball Mountain during the 2001 high flow event versus pool elevation and outflow data provided by USACE New England District.

[10]It is important to note that the volume difference between the measured flows and the simulated flows is particularly large on the tributary Ball Mountain regulates, the West River, due to overestimation of total volume by SYE.

The initial results showed three main issues with modeled flood control dams. First, these modeled dams were cutting back releases due to maximum downstream stage control rules on the Connecticut River mainstem more often than gauge records indicated. Second, they made large release spikes that returned pool elevations to conservation pool elevation too quickly. Third, the maximum releases the modeled dams made exceeded the maximum inflow the dams received during high flow events. Calibration of the modeled USACE flood control dams to address these issues is described below. In reality, CENAE's Reservoir Regulation Center uses operational flexibility in managing high flow events, and considers the storage, inflow, downstream conditions, and forecasts before making decisions on an individual basis for each reservoir. The operational data that were gathered from the Standard Operating Procedure (SOP) of each dam are the operating bounds within which the flood control dams can be operated. The following rules implemented for calibrating the USACE flood control dams approximate this operational flexibility.

4.1.1.1 Downstream Control for Maximum Stage on Connecticut River Mainstem

The USACE flood control dams are all on tributaries to the Connecticut River mainstem but are primarily used to control flooding on the Connecticut River mainstem. The dams enter into flood control operations when the stages at specific points (North Walpole, NH, Montague City, MA, and Hartford, CT) on the Connecticut River mainstem exceed a certain value, according to the SOP for each dam[11]. A strict interpretation of the Connecticut River mainstem stage control rules yielded the results displayed in Figure 9. However, this strict interpretation caused the modeled flood control dams to reduce releases due to flood control operations far more often than gauge records indicated.

In conversations with USACE flood operations personnel, it became apparent that the Reservoir Regulation Center (RRC) takes a more measured approach to reducing releases when the stage at specified points on the Connecticut River mainstem approaches flood levels. The RRC slowly reduces releases from the dam, rather than immediately reducing releases to minimum flows. The actual amount the flood control operators reduce varies with each storm, as they also take into account downstream conditions and weather forecasts when deciding how much to reduce releases. The individualized operations of each storm event were not modeled in HEC-ResSim. Instead, a linear drawdown that was a function of the maximum allowable release (channel capacity) was implemented for each flood control dam. The curve implemented is shown in Table 5.

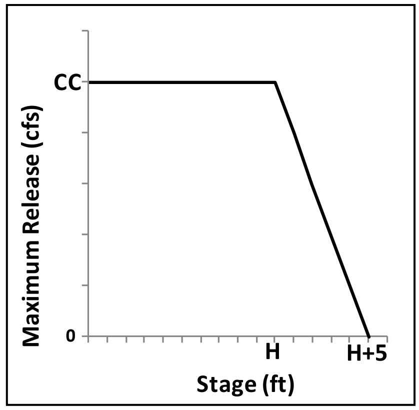
4.1.1.2 Pool Elevation Rate of Change Limits

Initial modeling of the USACE flood control dams did not incorporate the maximum pool elevation drawdown allowed in a 24-hour period specified by SOP. This operation was incorporated into the flood control dam operations and helped the drawdown releases at the end of a high flow event more closely match gauge data.

[11]The stages on the Connecticut River are calculated from rating curves that were provided by USACE. The rating curves are inputs at the three corresponding computation points.

Table 5. Maximum release curve implemented for the Connecticut River mainstem stage control rules for the USACE flood control dams. H is the stage at which initial regulations should occur according to the SOP for each dam. CC is the downstream channel capacity of each dam specified in the SOP. As the stage increases, the maximum release decreases.

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



4.1.1.3 Maximum Releases Not Exceeding Maximum Inflow

In conversations with USACE flood control operators, they described how the maximum release that flood control dams make during a high flow event rarely exceed the maximum inflow the dams receive during the entire event. In most cases this would defeat the purpose of the flood control dam. Initial modeling of the flood control dams did not account for limiting outflow to the maximum inflow and the SOP makes no mention of this as part of flood control 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 because high flow events generally lasted at most three weeks.

The updated simulation results of Ball Mountain during the 2001 high flow event after implementing the three above described changes are provided in Figure 10.

After implementing the changes described above at the fourteen USACE flood control dams, reductions in releases during the 2001 high flow calibration event were not as drastic and occurred less often. Emptying of the flood control pool was achieved more gradually and maximum releases never exceeded the maximum inflow over the entirety of a high flow event. These results were considered the best that could be achieved for a generalized daily time step approach, given the constraints of the HEC-ResSim model and the individualized operations that characterize USACE flood control operations in the watershed.

4.2 Verification

4.2.1 Correlation with USGS Gauges

Simulated flows at forty computation points were compared with recorded data at forty USGS gauges for the simulation period of record. Twenty-one of the gauges had data over the

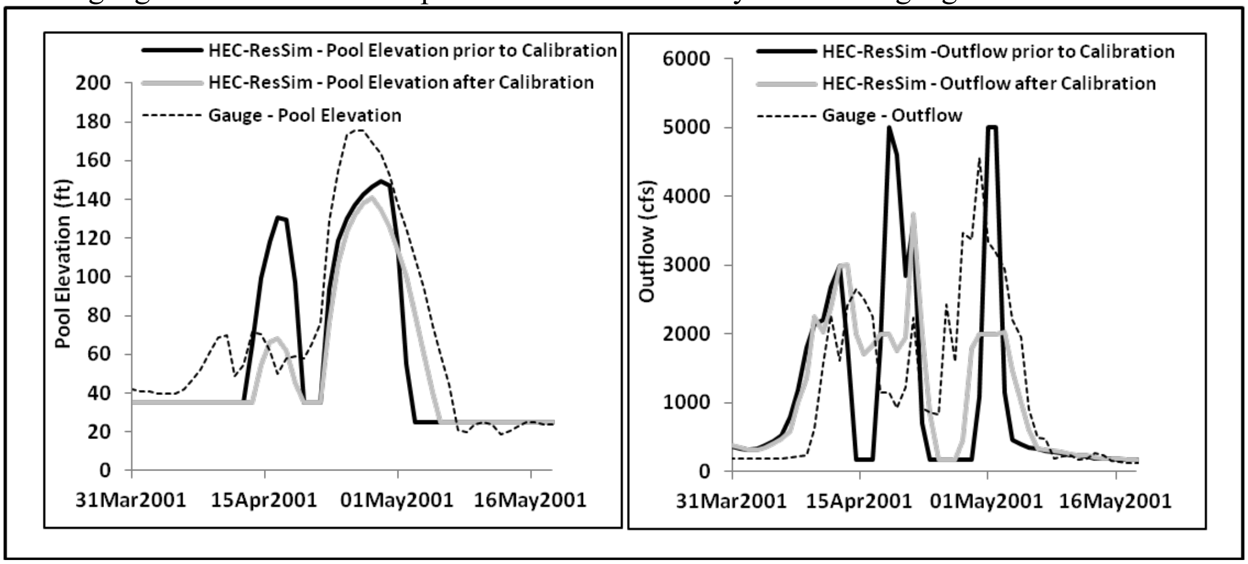


Figure 10. Comparison of HEC-ResSim pool elevation and outflow prior to calibration and after calibration from Ball Mountain during the 2001 high flow event versus pool elevation and outflow data provided by USACE New England District.

entire period of record, while the rest had data over a portion of the period of record. The comparison method used was a standard correlation, which indicates the overall agreement of every daily flow between the simulated and gauged flows. The standard correlation formula was used:

$$r = \frac{\Sigma(Q_s - \overline{Q_s})(Q_g - \overline{Q_g})}{\sqrt{\Sigma(Q_s - \overline{Q_s})^2 \, \Sigma(Q_g - \overline{Q_g})^2}} \quad (1)$$

where r is the correlation value, Q_s is the simulated flow, and Q_g is the gauged flow.

Table 6 provides the correlation values of all forty HEC-ResSim computation points that were compared to gauges, as well as the percent difference between modeled and gauged total flow volumes. Correlation values range from minus one to plus one, with a higher positive correlation value indicating better agreement between the simulated flow data and the gauge data. Figure 11 represents a color coded map of the correlations in the watershed. Figure 12 shows actual comparison plots of hydrographs generated by ResSim versus USGS gauge hydrographs.
The average correlation value was 0.78, indicating overall good agreement between the HEC-ResSim computation points and gauges. The correlation values ranged from 0.21 to 0.97, although only five points had a correlation value below 0.6 and these points had significant operational knowledge gaps. Correlation 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. Lower values also tended to be in headwater areas where there is more inherent uncertainty in the SYE flow data. Volumetric differences were generally pretty low but represented the bulk of the uncertainty associated with SYE.

Table 6. Correlation values between USGS gauges and closest point in the HEC-ResSim model

River	USGS Gauge (Gauge ID)	HEC-ResSim Point	Record of Comparison	r	Volume Percent Difference
Wells	Wells River, VT (01139000)	Wells at Mouth	01Oct60-30Sep73	0.99	3.9
Connecticut	Vernon, VT (01156500)	Vernon_Out	01Oct60-30Sep04	0.95	-1.8
Connecticut	Holyoke, MA (01172003)	Holyoke_Out	01Oct60-30Sep04	0.95	20.9
Connecticut	West Lebanon, NH (01144500)	Connecticut at West Lebanon	13Dec83-30Sep02	0.95	0.9
Connecticut	North Walpole, NH (01154500)	Connecticut at North Walpole	20Nov78-30Sep04*	0.95	-4.4
Millers	Winchendon, MA (01162000)	Whitney Pond_Out	01Oct60-30Sep04	0.95	-36.6
Connecticut	Montague City, MA (01170500)	Connecticut at Montague	01Oct60-30Sep04	0.94	-3.4
Ashuelot	West Swanzy, NH (01160350)	Ashuelot at West Swanzy	01Oct60-30Sep04	0.92	1.2
Millers	Erving, MA (01166500)	MLR_Diadromous Fish	01Apr94-30Sep04	0.91	-0.04
Chicopee	Indian Orchard, MA (01177000)	Red Bridge_Out	01Oct60-30Sep04	0.9	13.5
Connecticut	Thompsonville, CT (01184000)	MAIN_Floodplain25	01Oct60-30Sep04	0.9	-1.5
Connecticut	Wells River, VT (01138500)	Connecticut at Wells River	01Oct60-30Sep04	0.9	-9.7
Ashuelot	Hinsdale, NH (01161000)	Ashuelot at Hinsdale	01Oct60-30Sep04	0.88	-3.4
Westfield	Westfield, MA (01183500)	Westfield at Westfield	01Oct60-30Sep04	0.88	9.6
Farmington	Unionville, CT (01188090)	FAR_Corps Ops	01Oct60-30Sep86	0.87	24.5
Connecticut	Dalton, NH (01131500)	Gilman_Out	01Oct60-30Sep04	0.86	-6.9
Mattabesset	Route 327 at East Berlin (01192704)	MAT_Floodplain1-Diadromous Fish	26Aug76-30Sep04*	0.85	43.6
Sugar	West Claremont, NH (01152500)	Sugar at Mouth	01Oct60-30Sep04	0.85	1
Connecticut	North Stratford, NH (01129500)	MAIN_Mussels2	01Oct60-30Sep04	0.84	-7.1
Deerfield	West Deerfield, MA (01170000)	DRF_Floodplain1	01Oct60-30Sep04	0.84	-6.1
Farmington	Rainbow, CT (01190000)	Rainbow_Out	01Oct60-30Sep04	0.84	16
Ware	Gibbs Crossing, MA (01173500)	Ware Upper and Lower_Out	01Oct77-30Sep04	0.83	-4.5
Deerfield	Charlemont, MA (01168500)	Bear Swamp_Out	01Oct60-30Sep90	0.81	-32
Ottauquechee	North Hartland, VT (01151500)	North Hartland_Out	01Oct60-30Sep04	0.81	4.2
Otter Brook	Keene, NH (01158600)	Otter Brook_Out	01Oct60-30Sep04	0.81	-3.4
Ware	Barre, MA (01172500)	Barre Falls_Out	01Oct95-30Sep04*	0.81	-5.5
Ashuelot	Keene, NH (01158000)	Surry Mountain_Out	01Oct95-30Sep04*	0.8	-6.8
Ompompanoosuc	Union Village, VT (01141500)	Union Village_Out	15Jan95-29Sep00	0.8	-4.7
Black	North Springfield, VT (01153000)	North Springfield_Out	01Oct60-30Sep04	0.77	-1.5

East Branch Tully	Athol, MA (01165000)	Tully_Out	01Oct60-30Sep90	0.76	7.6
Mascoma	Mascoma, NH (01150500)	Mascoma_Out	01Oct60-30Sep89	0.74	7.3
Hockanum	East Hartford, CT (01192500)	HKM_Floodplain-Diadromous Fish	01Oct60-30Sep04	0.71	15.4
West	Newfane, VT (01156000)	Townshend_Out	01Oct95-30Sep04*	0.7	-6.4
Westfield	Knightville, MA (01179500)	Knightville_Out	01Oct60-30Sep04	0.69	-2.9
West	Jamaica, VT (01155500)	Ball Mountain_Out	01Oct95-30Sep04*	0.66	-0.2
Connecticut	Pittsburgh, NH (01129200)	Connecticut+Indian	01Oct95-30Sep04*	0.49	-17.1
Swift	West Ware, MA (01175500)	Swift at West Ware	01Oct60-30Sep04	0.41	103.4
Fall	Otis, MA (01185100)	Otis_Out	01Oct60-30Sep04	0.39	-0.9
West Branch Farmington	Riverton, CT (01186000)	West Branch_Out	14Aug69-30Sep82	0.32	-1
Connecticut	First Conn Lake Nr Pittsburg, NH (01128500)	First Connecticut Lake_Out	01Oct60-30Sep04	0.2	-15.4
Wells	Wells River, VT (01139000)	Wells at Mouth	01Oct60-30Sep90	0.99	3.9

Gauge record had gaps. Additional periods of record: West Lebanon, NH (01144500) – 01Oct60-30Nov76. East Hartford, CT (01192500) – 01Oct60-07Oct71. Keene, NH (01158600) – 01Oct60-30Sep89. Keene, NH (01158000) – 01Oct60-30Sep89. Newfane, VT (01156000) – 01Oct60-30Sep89. Jamaica, VT (01155500) – 01Oct60-30Sep89. Knightville, MA (01179500) – 01Oct60-30Sep90.

The period of record correlations do not account for the change in operations over time that could be reflected in the gauge data. Later periods could have higher correlation values because operations would more closely resemble the current operations reflected in HEC-ResSim. An analysis was performed on the 21 gauges that had flow data for the entire HEC-ResSim period of record to evaluate this possibility, but the results indicated only negligible differences in the correlation values between the earlier and later operational periods.

4.2.2 Hydrograph Comparisons

The comparison of the simulated flows and gauged flows at ten of the computation points is displayed in Figure 12. As mentioned in the inflow data section, there were two main differences between the simulated regulated flows and gauged flows. Application of SYE resulted in differences in the magnitude and timing of the peaks. It also resulted in differences in total inflow volume. These differences in inflow hydrographs account for much of the differences in the outflow hydrographs. A minor difference was that the simulated low flows were much smoother than the gauged low flows due to HEC-ResSim's inability to account for local variability in runoff and minor operational adjustments. Another reason for differences between simulated regulated flows and gauged flows were the operational knowledge gaps. The Connecticut at Pittsburgh and W. Branch Farmington at Riverton plots are two examples of results where there were significant operational knowledge gaps.

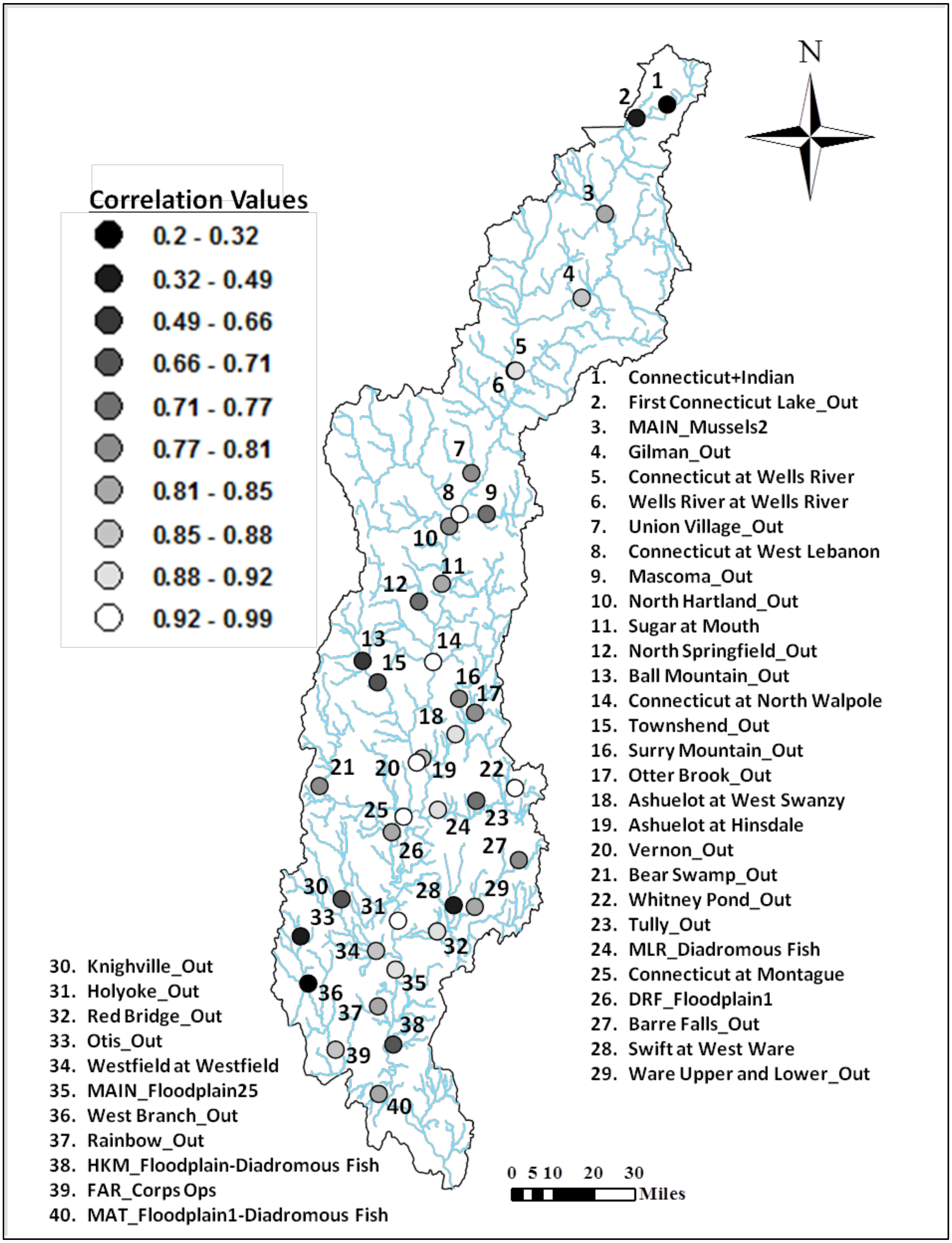


Figure 11. Map of the Connecticut River watershed showing the correlation values of the 40 ResSim computation points that were compared to USGS gauges.

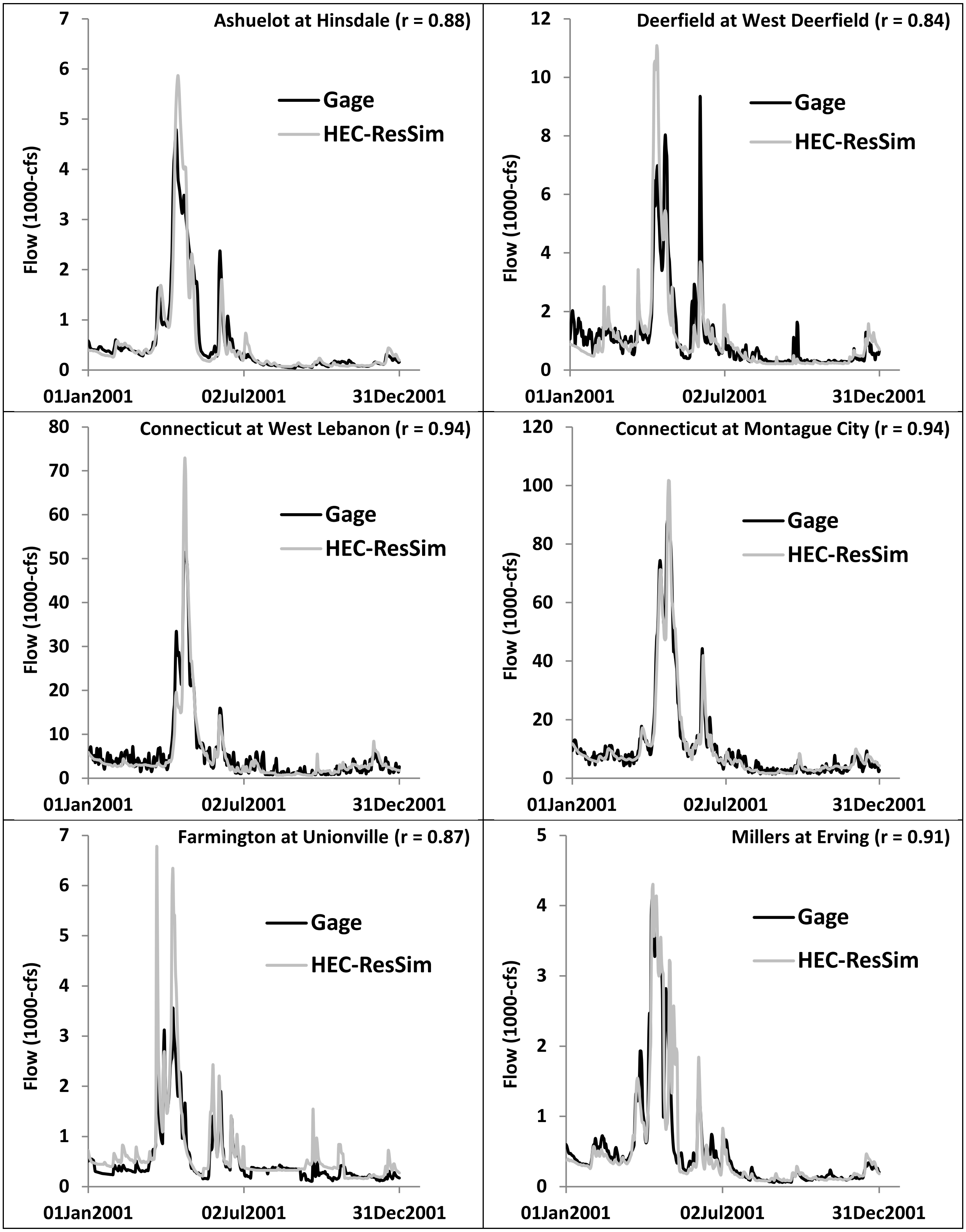


Figure 12. Comparison of HEC-ResSim generated hydrographs versus USGS gauge hydrographs

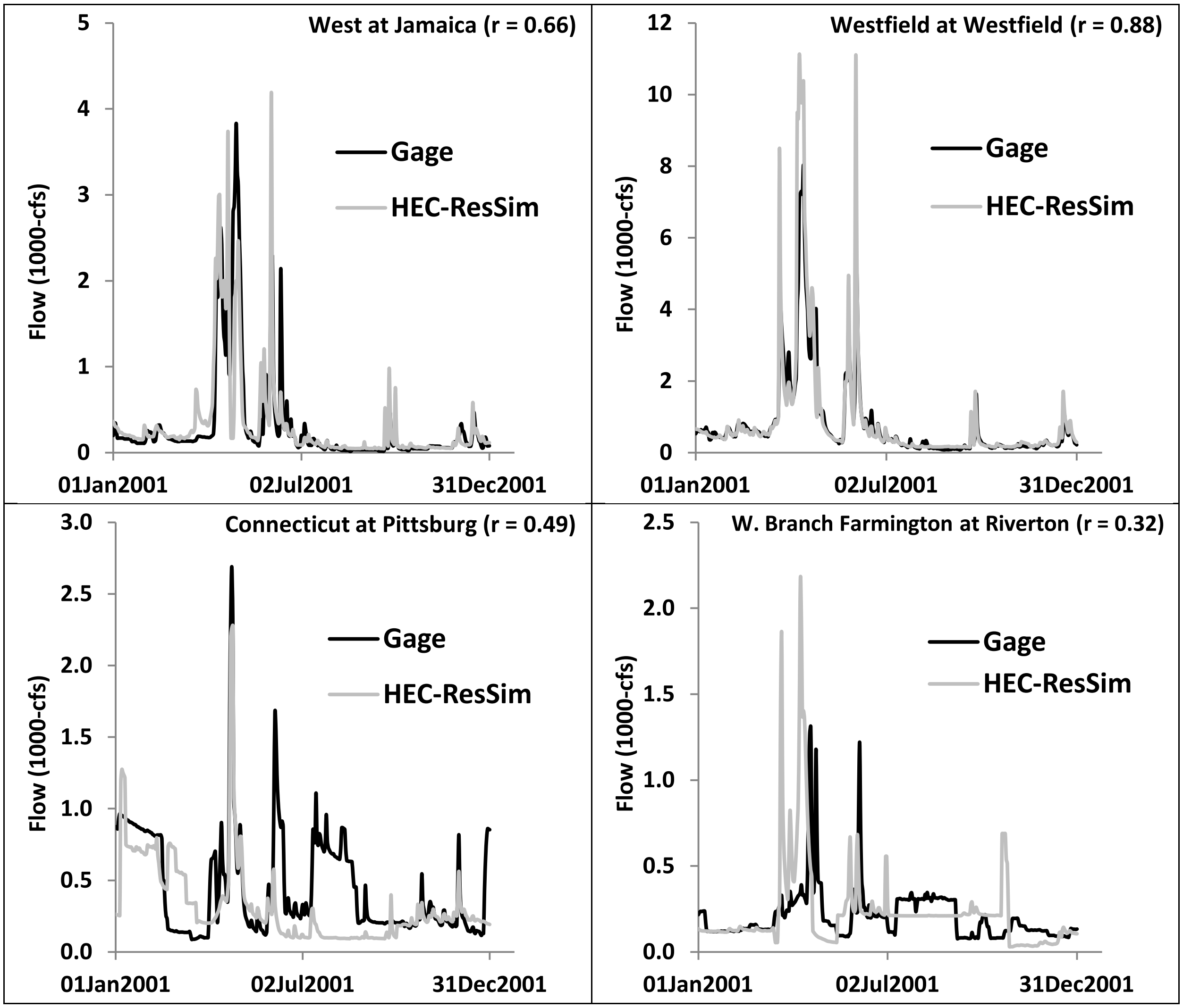


Figure 12. Comparison of HEC-ResSim generated hydrographs versus USGS gauge hydrographs (continued)

Chapter 5
HEC-EFM and HEC-RAS Applications

Two additional software tools, HEC-EFM (Ecosystem Functions Model) and HEC-RAS (River Analysis System), were applied to the Connecticut River to support analyses for ecosystems. HEC-EFM is a planning tool that aids in analyzing ecosystem response to changes in flow regime. CEIWR-HEC is developing HEC-EFM to enable project teams to visualize existing ecologic conditions, highlight promising restoration sites, and assess and rank alternatives according to the relative change in ecosystem aspects[12].

At the watershed scale, HEC-EFM was used to calculate flow statistics that were compared to ecological flow targets determined by expert elicitation. These flow targets were developed in a workshop hosted by TNC in 2011 that brought a variety of aquatic and riparian ecologists together[13]. Flow targets were developed for a wide variety of species types including diadromous fish, tiger beetles, freshwater mussels, resident cold and warm water fish, and floodplain forests. The flow targets are performance measures that can be used evaluate alternatives in the HEC-ResSim model from an ecosystem perspective.

HEC-EFM was also used to calculate specific flow needs of two ecological communities, floodplain forests and diadromous fish, for use in both measuring performance of alternatives and habitat mapping using inundation grids generated with HEC-RAS. HEC-RAS is hydraulic modeling software that can perform many functions, including simulating water surface elevations and inundation for one-dimensional steady and unsteady flow analyses[14]. Three different sections of the watershed had HEC-RAS models created for them: the Farmington River between Simsbury, CT and Rainbow dam, the Connecticut River mainstem at North Hampton, MA, and the Connecticut River mainstem from Hartford, CT to East Haddam, CT. Chapter 6 illustrates in more detail an example of how HEC-EFM and HEC-RAS were used for habitat mapping.

[12] USACE, 2013. *HEC-EFM Ecosystem Functions Model Quick Start Guide*, Hydrologic Engineering Center, Davis, CA.
[13] Flow targets were taken from a spreadsheet provided by TNC that was a product of the workshop.
[14] USACE, 2010. *HEC-RAS River Analysis System User's Manual, Version 4.1,* Hydrologic Engineering Center, Davis, CA.

Chapter 6
Example Analysis Using the Decision Support System

The following is from an example application of the Connecticut River HEC-ResSim model in conjunction with the HEC-EFM and HEC-RAS applications described in Chapter 5. The analysis focused on ecological metrics for floodplain vegetation flow needs and diadromous fish ecological flow statistics on the Connecticut River mainstem. This is not intended to be a definitive alternatives analysis but rather an example of how this decision support system can be used. The results described here are meant for illustrative purposes only.

6.1 Methods

6.1.1 Ecological Metrics-Floodplains

Several studies have linked annual inundations to the composition of floodplain plant communities[15, 16, 17]. Marks (unpublished data)[18] also linked specific annual durations of inundations to general floodplain plant community types. The annual inundation and Marks's classification of the floodplain plant community type is provided in Table 7.

Table 7. Numbers of days of annual inundation corresponding to 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

To calculate the annual flow that corresponded to the number of days receiving inundation, the 20th, 50th, 200th, and 300th highest daily flows were determined for each year of the period of record (Figure 13). For example, the 20th highest flow represents the maximum area that received 20 days of inundation.

[15]Zimmerman, J., 2006. *Hydrologic Effects effects of flood control dams in the Ashuelot River, New Hampshire, and West River, Vermont,* Northampton, MA: TNC Connecticut River Program.
[16]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.
[17] Nislow KH, Magilligan FJ, Fassnacht H, Bechtel D, & Ruesink A (2002) Effects of dam impoundment on the flood regime of natural floodplain communities in the upper Connecticut River. *J. Am. Water Resour. Assoc.* 38(6):1533-1548.
[18] Marks, C., The Nature Conservancy Connecticut River Program, MA.

The median (2-year flow) of the annual flow values for each of the four durations was then calculated as a metric of typical year conditions. Doing this for both the unregulated and regulated time series generated from the HEC-ResSim model allowed for calculating the percent change from unregulated flow to regulated flow[19].

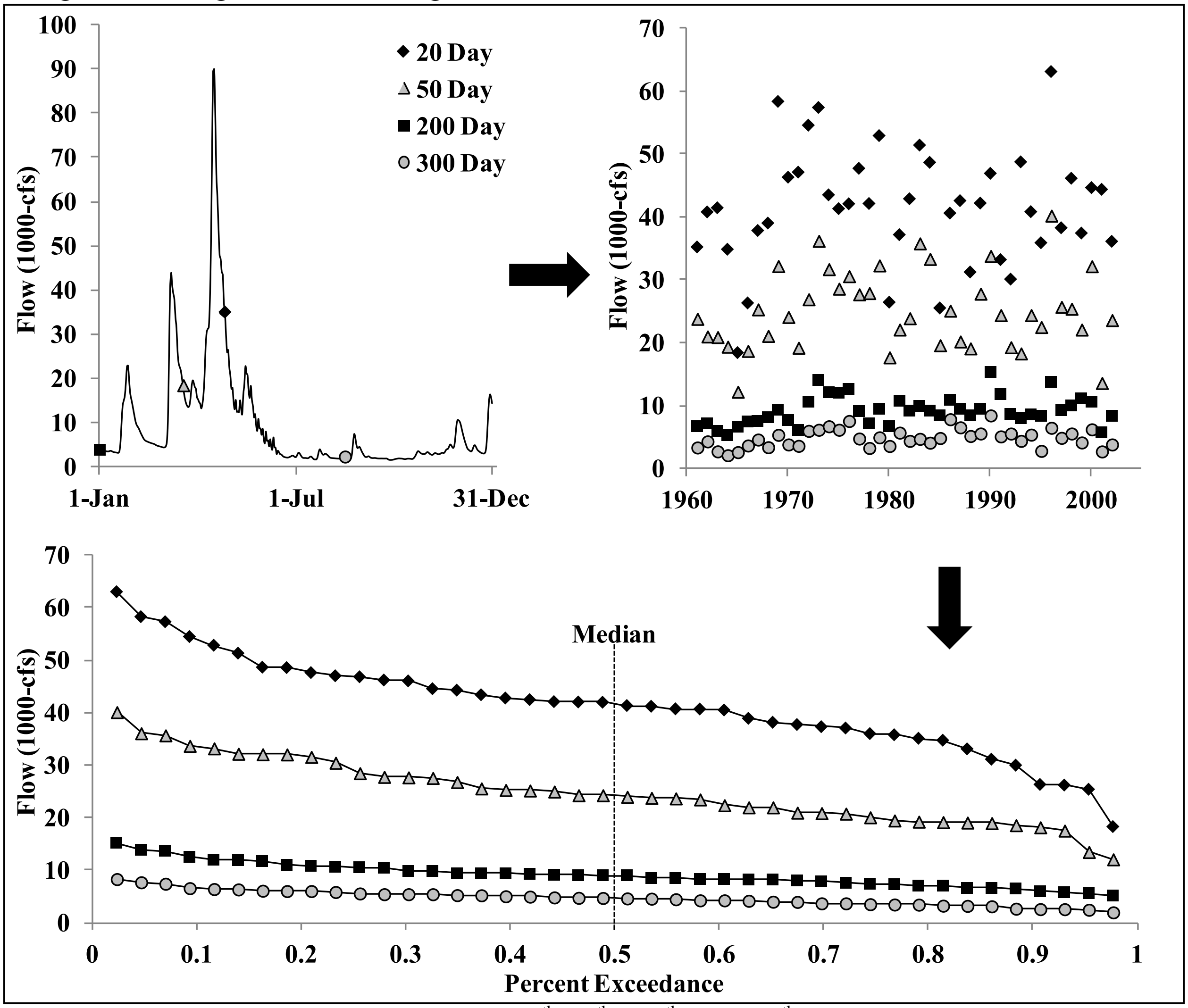


Figure 13. Plot of a hydrograph showing the 20th, 50th, 200th, and 300th highest flows for that year and the annual flows corresponding to the four annual inundation durations over the period of record.

Percent change, instead of actual differences in the flow, was the metric used as it allowed for the comparison of points throughout the watershed, where there are differences in the total flow received. HEC-EFM was used to calculate the median annual inundations as it could calculate the values at many locations quickly.

[19]Unregulated in this section means no dam is affecting the flow (also called unimpaired or natural). Regulated means the flow is being affected by dams.

6.1.2 Ecological Metrics-Diadromous Fish

Several seasonal flow targets were developed in the 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[20]. Comparing flow duration curves shows the changes in variability of the stream flow. The metrics analyzed in this paper are shown in Table 8.

Table 8. Seasonal flow metrics specified by ecological experts as ecological flow targets for diadromous fish

Season	Allowable Percent Change from Unregulated		
	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 the end of May while American Shad can spawn as late as June[13]. September to November is the season when the juvenile outmigration occurs. The experts' flow targets specify that during these two seasons, no change should occur to the lowest ten percent of flows, the Q99-Q90 range of the flow duration curve. At the low to medium range of flows, Q90-Q50, there is a ten percent allowable change from the unregulated flow duration curve. For the medium to high flows, Q50-Q10, the allowable change from unregulated is twenty percent.

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 together. Using more points within the flow duration curve was found to yield overall similar results. This gave an accurate representation of the overall percent change from regulated and allowed the HEC-EFM to be utilized once again to compute the percent change for these different metrics at many locations quickly.

6.1.3 Floodplain Inundation Mapping

In addition to quantifying the percent change in flow, the percent change in the actual inundated area between unregulated and regulated conditions for the annual inundation durations were quantified using a calibrated HEC-RAS model of a seven-mile reach by Northampton, MA[21]. The median 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 (for the Northampton section, the computation point used was MAIN-Floodplain23). The

[20]Vogel, Richard & Fennessey, Neil. *Flow Duration Curves I: New Interpretation and Confidence Intervals*, Journal of Water Resources Planning and Management, 120(4), pp. 485-504, 1995.
[21]An HEC-RAS model was created for this section of river because TNC deemed this section ecologically significant enough to warrant hydraulic modeling.

regulated and unregulated flows were then simulated in a one-dimensional steady hydraulic flow simulation in HEC-RAS, to get the water surface profiles for each flow[22]. Inundation grids for the resulting water surface profiles were then calculated using the RAS Mapper tool in HEC-RAS. The resulting inundation grids gave the total area that received inundation at that flow and were used to calculate the changes from unregulated to regulated conditions in the areas that received the four annual inundation durations.

There are many additional factors that determine floodplain vegetation communities, including depth, velocity, sediment accretion rate, lateral bank migration rate, growing season length, soil pH, and possibly timing of floods. Thus the inundated area 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.

[22]Boundary conditions for the analysis were known water surface elevations taken from a rating curve of the mainstem at the Oxbow. The rating curve was provided by USACE New England District (CENAE).

6.2 Results

6.2.1 Analysis of Connecticut River Mainstem

An analysis was performed to quantify the percent change from unregulated to regulated of the two different types of ecological metrics described in the methods section (i.e., floodplain inundation and diadromous fish) along the entirety of the Connecticut River mainstem. Every dam outflow, tributary confluence, and econode was analyzed on the Connecticut River mainstem, for a total of 106 points (Figure 14).

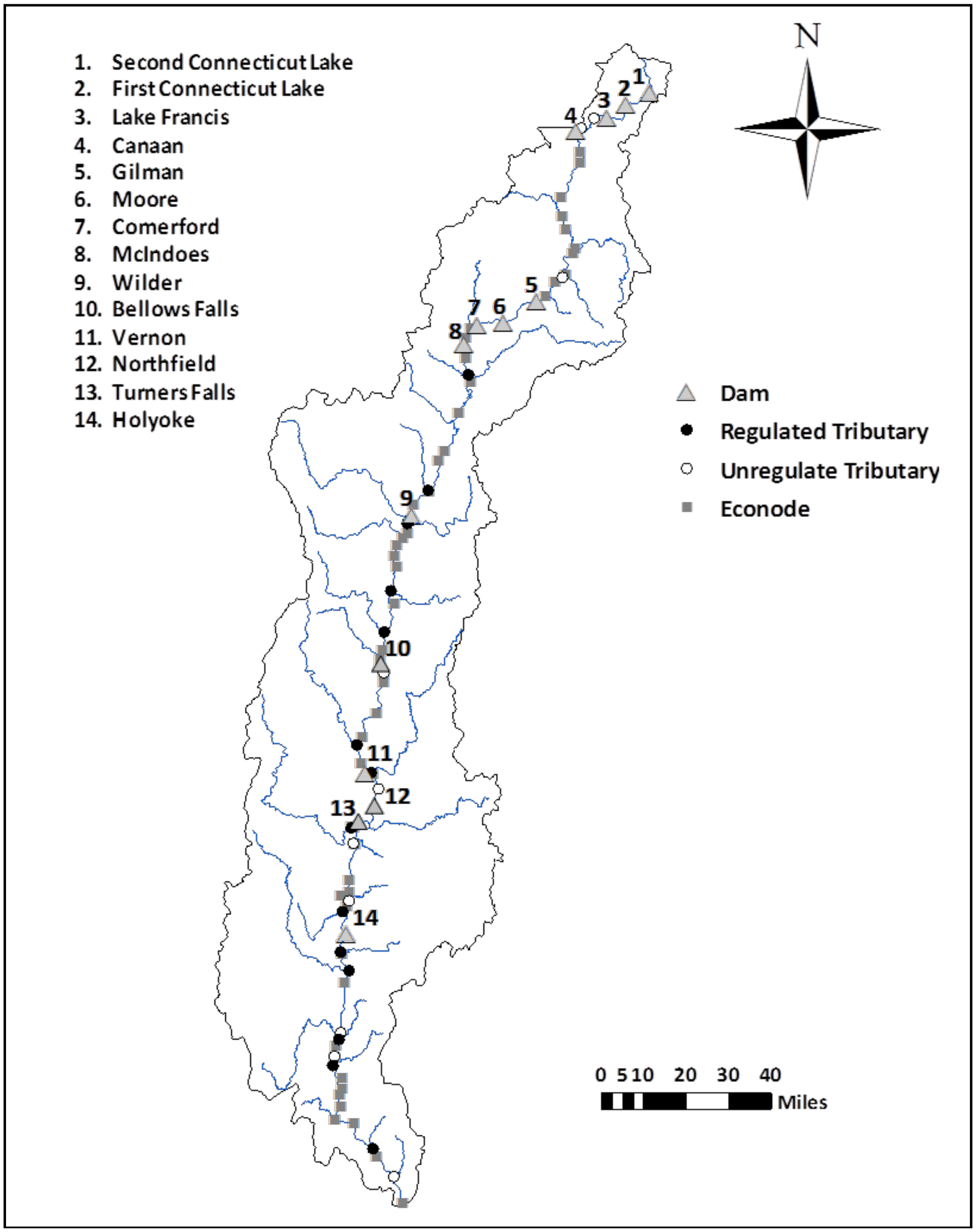


Figure 14. Map of points along the Connecticut River mainstem analyzed for changes in the ecological flow metrics.

6.2.1.1 Current Conditions

i. Floodplains

The percent change from unregulated to regulated in the median 20-day, 50-day, 200-day, and 300-day annual duration flows at the 106 points along Connecticut River mainstem are displayed in Figure 15. The four annual durations of flow correspond to transitions between floodplain plant communities.

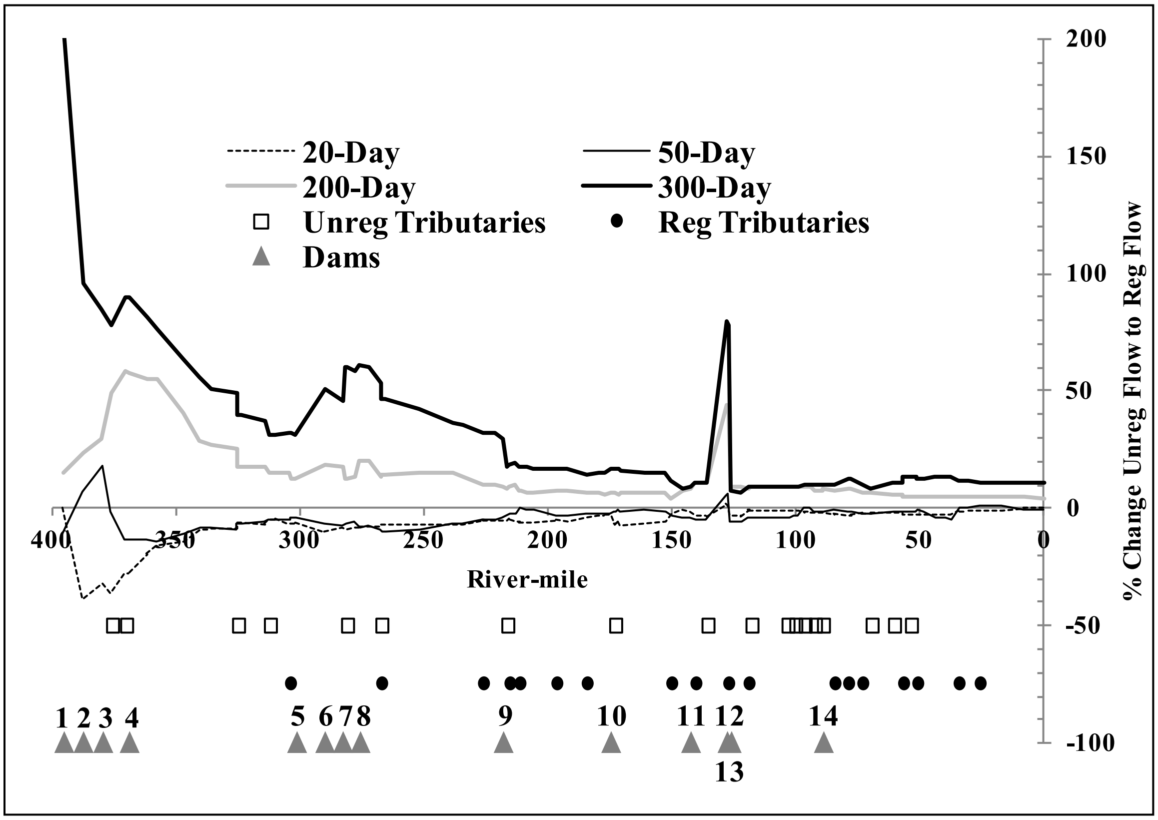


Figure 15. The percent change from unregulated to regulated in the median annual flow for four different durations at every dam outflow, tributary confluence, and econode on the Connecticut River mainstem. The dams are labeled by their number from Figure 14.

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 also primarily contribute to a 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 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 could potentially be important for mitigating the large effects of Northfield on the median annual floodplain inundation flows. Moore, at river-mile 290, causes the largest relative increase in environmental alteration after Northfield. The run-of-river hydropower dams cause negligible 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 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 at which 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. Consequently, it is likely that 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 areas of floodplain forest. Higher up in the watershed, these differences are more pronounced than in the lower watershed.

The topography of each section of the river determines how this percent change in the different annual durations of flow translates to percent change in inundated area. Table 9 shows this translation from percent change in annual duration of flow to inundated area for the seven mile stretch of the Connecticut River mainstem where hydraulic data was present by Northampton, MA.

The relatively large percent change in the expected annual 300-day inundation flow does not correspond to a large percent change in the amount of acres receiving 300 days of inundation. It translates to an eleven acre increase because the stage at this flow has not reached high enough to spill onto the much larger floodplain. The 200-day inundated

Table 9. Percent change from unregulated in both flow and inundated area of four annual inundation durations for a seven river mile stretch of the Connecticut River mainstem by Northampton, 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	952	11	1.2

area gained more acreage than the 300-day, despite having a smaller percent change in the flow. At the less frequent (i.e., higher) flows, the smaller percent changes in flow reflect more inundated area lost or gained. At a 0.8 percent change in the median annual twenty-day inundation flow, over twice the amount of inundated area is lost as was gained by the 300-day inundation flow. The fifty-day inundated area lost about the same amount of acreage as the twenty-day inundated area, despite twice as much change in flow. The loss in acres receiving twenty days and fifty days of inundation were concentrated in a few small patches. A map of the actual changes in habitat area for the twenty-day and fifty-day annual inundation durations is provided in Figure 16.

Since all of the 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 per loss of hydropower output, the average annual hydropower generated from each dam was divided by the difference between the percent change of each median annual inundation at each Connecticut River mainstem dam and the percent change at the point preceding the dam. 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 10 provides the difference in percent change from the preceding point on the Connecticut River mainstem and the average annual hydropower generated. The absolute value of the percent change per megawatt of the four inundations averaged together is shown in Figure 17[23].

Higher values in Figure 17 indicate higher tradeoffs of hydrologic alteration and hydropower generation among the Connecticut River mainstem hydropower dams. Based on the percent change and its hydropower generating capacity (shown in Table 10),

[23] Canaan was excluded from the percent change per megawatt analysis because its megawatt capacity is much lower than the rest of the Connecticut River mainstem dams. Turner Falls was excluded because it works in tandem with Northfield and thus its hydropower generation is heavily influenced by Northfield.

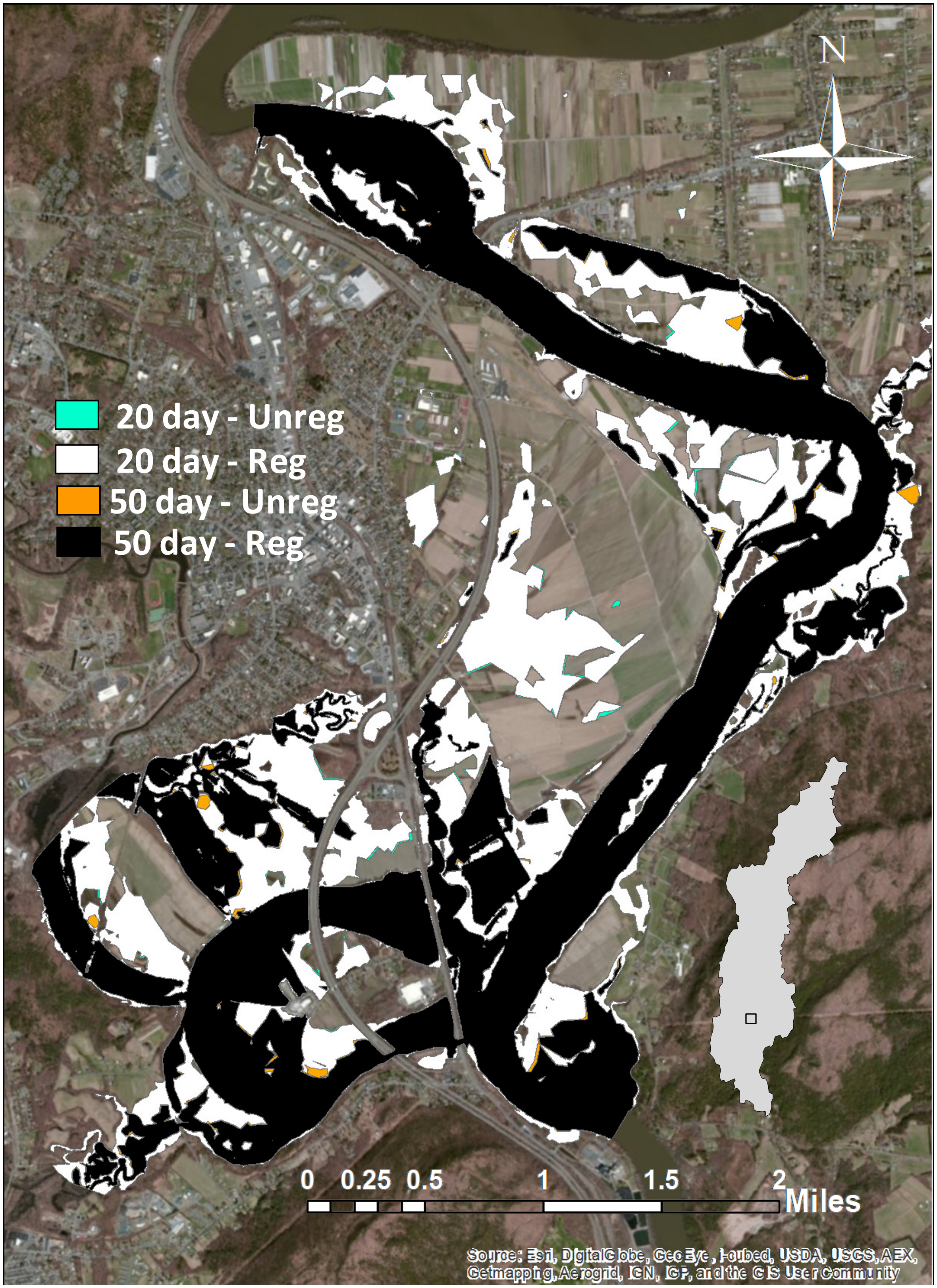


Figure 16. Map of a seven-mile section of the Connecticut River mainstem by North Hampton, MA showing the change in area receiving fifty and twenty days of annual inundation due to the change in unregulated flow.

Table 10. 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.

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

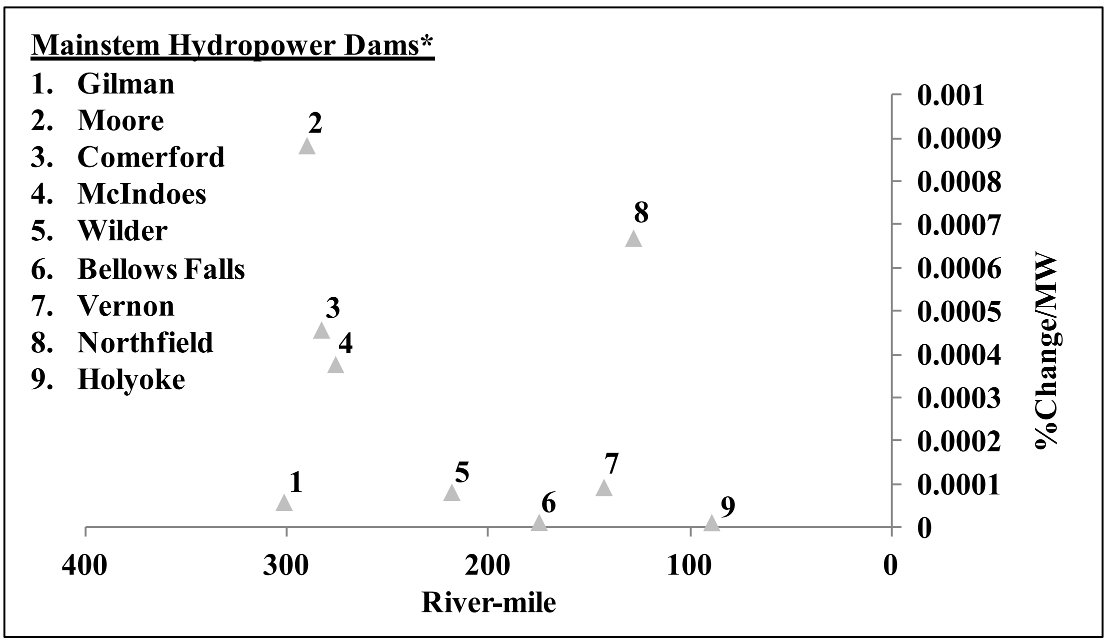


Figure 17. Average percent change of the four annual inundation durations caused by each Connecticut River mainstem hydropower dam per megawatt generated by each dam. *Excluding Canaan and Turners Falls.

Moore has a slightly higher value than Northfield, and even though Northfield generates almost ten times as many megawatts, the proportion of percent change per megawatt is the same. This would indicate that Moore and Northfield have the same tradeoff of hydrologic alteration and hydropower. The fact that these two reservoirs are not operated as run-of-river for their hydropower generation is most likely a factor in these results. Comerford is also a peaking hydropower facility but it generates enough annual megawatts to have its percent change per megawatt be comparatively lower than Moore and Northfield. Thus, re-operating Comerford would potentially lose more hydropower generation per percent change reduction. Ultimately, these results point to Moore and Northfield as offering the most promise for more detailed analysis for hydropower and environmental tradeoffs in revising operations for floodplain plant community restoration on the Connecticut River mainstem. Also based on data from Table 10, more benefits would be realized for lower flows than higher flows.

ii. Diadromous Fish

The same analysis for the floodplain inundations was applied to the seasonal flow metrics for diadromous fish. A plot of the percent changes from unregulated in the Fall and Spring Low, Medium, and High flows at different points along the Connecticut River mainstem is shown in Figure 18. Unlike the floodplain forest impacted area, diadromous fish eco-nodes were only present downstream from Mile 265 of the Connecticut River mainstem.

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 flow for both seasons saw an increase from unregulated to regulated and the magnitude of percent change was much greater than the medium and high flows. This would indicate that regulated low flows are higher than unregulated flows and that the magnitude of alteration is higher for low flows compared to medium 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 extent of alteration of lower flows than higher flows. The percent change in the highs is negative, indicating lower high flows for the regulated condition, which is also consistent with the floodplain inundation results.

The differences in the seasons of the flow metrics appear to make a major difference. The Spring high and medium flows have almost the same shape and magnitudes of alterations of the Connecticut River mainstem, which might be an indication that there is not much spread between the medium and high Spring flows. The Fall high flow is lower than the Spring high flow 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 flow is also significantly smaller compared to the Spring medium flow.

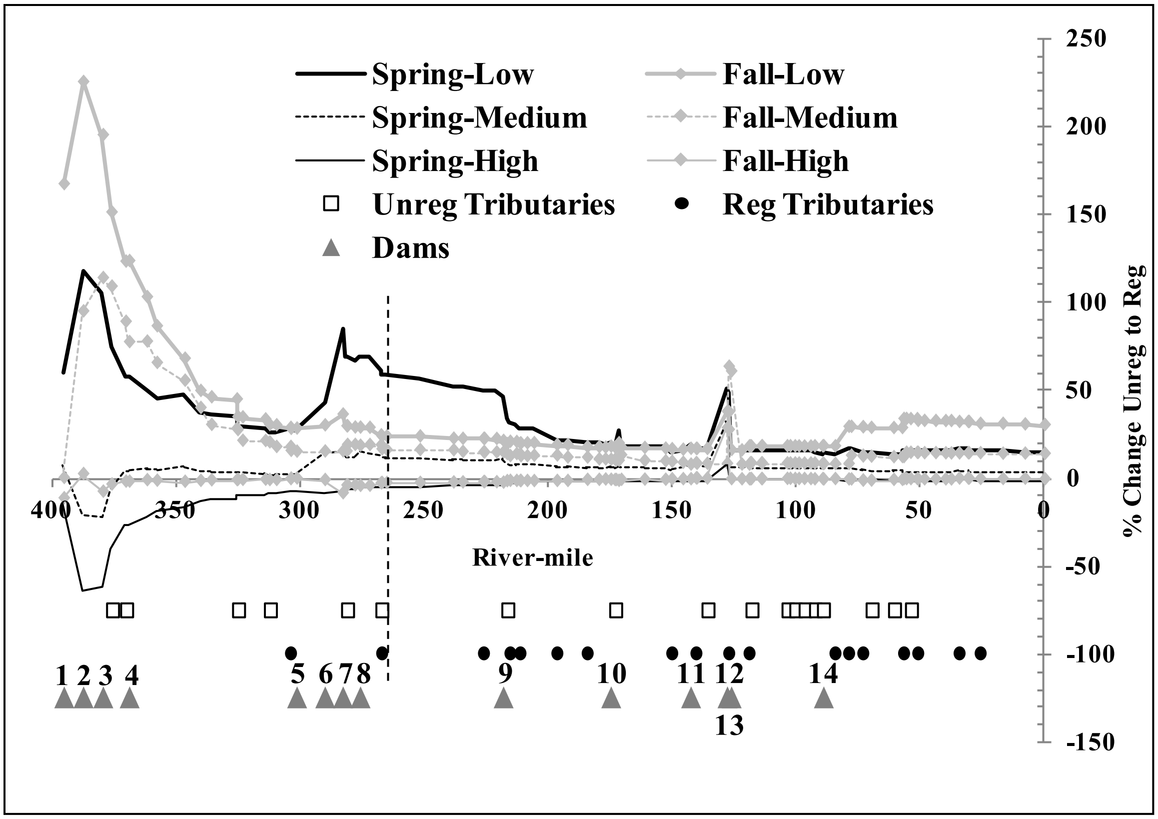


Figure 18. The percent change from unregulated to regulated in the six seasonal flow metrics for diadromous fish at every dam outflow, tributary confluence, and econode on the Connecticut River mainstem. The line delineates the range of the diadromous fish.

However, the seasonal differences of both the medium flows are basically negligible on the Connecticut River mainstem below the Connecticut Lakes projects. The seasonal differences are a factor for the low flows. The Fall low flow appears to be unaffected by dams or tributaries below Station 265 (with the exception of Northfield), gradually decreasing in percent change until the Chicopee and Farmington Rivers enter the Connecticut River mainstem, where small increases in the percent change occur at Station 79 and 57 respectively.

A similar hydropower analysis to the one done for the floodplain plant communities was also done for the two seasonal diadromous fish metrics; however, instead of average annual hydropower, average seasonal hydropower was evaluated. 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 and allows for the Connecticut River mainstem hydropower dams to be compared to see which dams would have more seasonal benefits gained per loss of seasonal hydropower. Table 11 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. The absolute value of the percent change per megawatt of the metrics per season averaged together is shown in Figure 19. Turners Falls and Canaan are excluded from Figure 19 for the reasons described in the floodplain hydropower analysis.

Table 11. Average seasonal hydropower generated and the percent change in the six season diadromous fish flow metrics caused by the hydropower generating dams on the Connecticut River mainstem.

	Spring				Fall			
	Hydropower Generated (MW)	Low (percent change)	Medium (percent change)	High (percent change)	Hydropower Generated (MW)	Low (percent change)	Medium (percent change)	Low (percent 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

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.

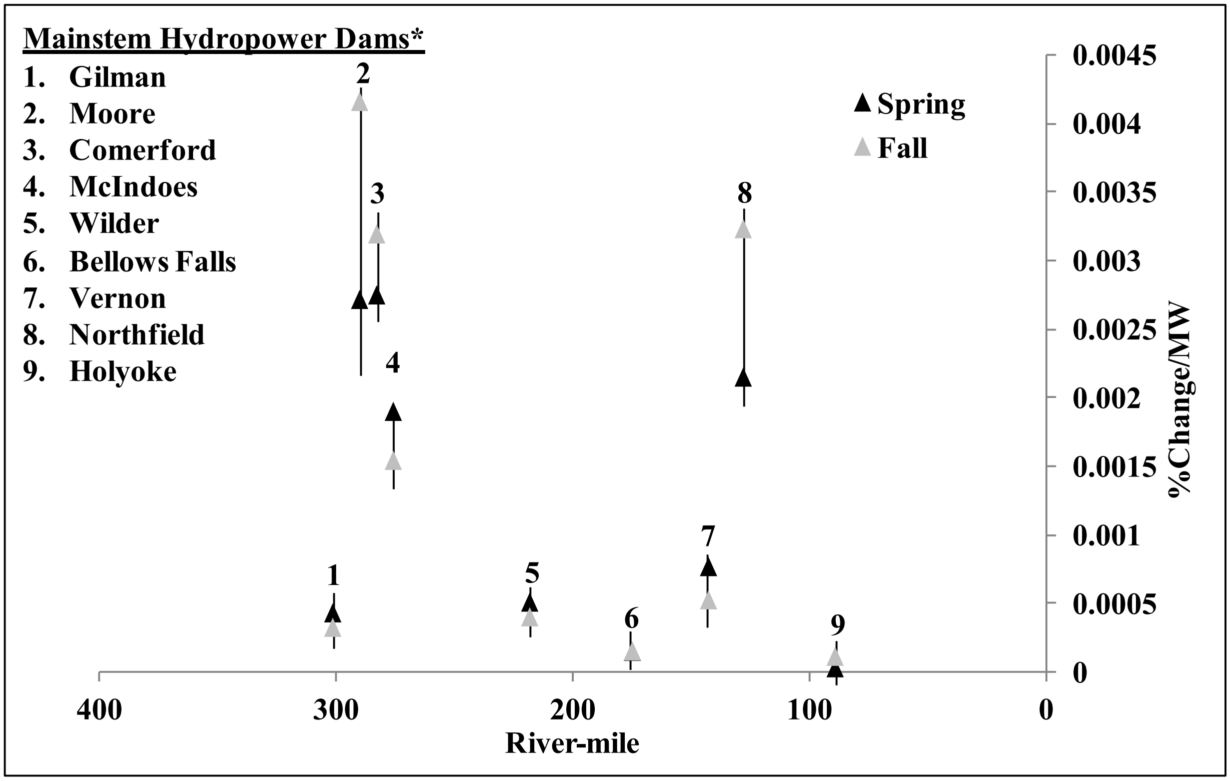


Figure 19. Average percent change of the diadromous fish flow metrics for March-May and Sep-Nov seasons caused by each Connecticut River mainstem hydropower dam per megawatt generated by each dam.
*Excluding Canaan and Turners Falls.

Changing Moore and Comerford conservation pool elevation targets in both seasons may lead to ecological benefits. Also, the result for the run-of-river hydropower dams indicates few benefits will be gained by changing their hydropower operations.

The current conditions analysis indicates several insights about the current state of hydrologic alteration due to dams. These are not meant to be formal observations but rather examples of the potential knowledge that can be gained through the use of the decision support system for analyzing current operating conditions in the watershed.

1. Hydrologic alteration from unregulated conditions is much higher on the upper half of the Connecticut River mainstem than the lower half in that reservoir storage volume is more significant compared to total flow volume.

2. Inundated areas corresponding to durations of 300 and 200 days are generally higher and those corresponding to durations of 50 and 20 days are generally lower for regulated than unregulated conditions along the entire Connecticut River mainstem because reservoir operations dampen out the lowest and highest flows.

3. The alterations in the annual inundations translate into small changes in actual inundated area for the seven-mile stretch of the Connecticut River mainstem by Northampton, MA. These results are preliminary and are meant for illustrative purposes only.

4. Spring and Fall low flows are higher for regulated than unregulated conditions and outside the allowable deviations from natural flows specified for diadromous fish. Fall medium flows are higher for regulated than unregulated conditions, while Spring medium flows are for the most part unaltered. Spring and Fall high flows are slightly lower for regulated than unregulated conditions. Both the medium and high flows for regulated conditions stay within the tolerance specified for diadromous fish.

5. Dams causing the largest hydrologic alteration appear to be the Connecticut Lakes Project dams, the 15-Mile falls Project dams, and Northfield.

6. Moore and Northfield, present the most promising opportunities for detailed trade-off analysis based on hydropower generation versus reduced hydrologic alteration.

6.2.1.2 Run-of-River Scenario Analysis

To analyze the maximum reduction in hydrologic alteration of both the flow needs of the floodplain plant communities and the flow targets of the important diadromous fish species, which could be gained by changing operations for different scenarios, two scenarios of the HEC-ResSim model were run where different dam(s) had run-of-river operation. Each simulation had a different dam(s) removed:

- The Connecticut Lakes Project (Second Connecticut Lake, First Connecticut Lake, Lake Francis)
- All 14 USACE Flood Control Projects

Performing a simulation with the dams removed represents modeling the reservoir operations as if they were completely run-of-river, with no hydropower generation.

i. Hydropower and Flood Control Changes

The change in the average annual hydropower generation, as well as the average Spring and Fall hydropower generation (the seasons for the diadromous fish metrics), for each Connecticut River mainstem hydropower dam was calculated for the two scenarios. The USACE Flood Control scenario caused negligible 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, for which the Connecticut Lakes operate to augment hydropower generation at those dams, saw reductions in annual hydropower generation at two of the three dams: 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 Connecticut Lakes scenario had a decreased total Spring hydropower generation of 167 MW for the Connecticut Lakes scenario.

To measure changes in flood protection, 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 12 shows these results. The flood stage for North Walpole, Montague City, and Hartford is 30 feet, 30 feet, and 22 feet respectively[24].

Table 12. 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 different run-of-river scenarios.

	North Walpole (days)	Montague City (days)	Hartford (days)
Unregulated	15	92	51
Current Conditions	11	58	21
Connecticut Lakes	11	60	21
USACE Flood Control	12	79	37

The total number of days the unregulated hydrograph exceeded flood stage was significantly higher than the current conditions at all three locations, showing that all the dams combined in the watershed do reduce flooding. The USACE Flood Control Projects scenario shows that the flood control dams reduce flood stage more than the other projects. The results of the Connecticut Lakes Project scenario indicates that little to no increase in flood stage will occur at the three control points, indicating that flood risks are not necessarily a concern for re-operating those dams to be more run-of-river.

ii. Floodplain

Figure 20 shows the percent change from unregulated in the median annual inundation duration flows moving down the Connecticut River mainstem of the four annual inundation durations for the current conditions scenario and the two run-of-river scenarios.

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

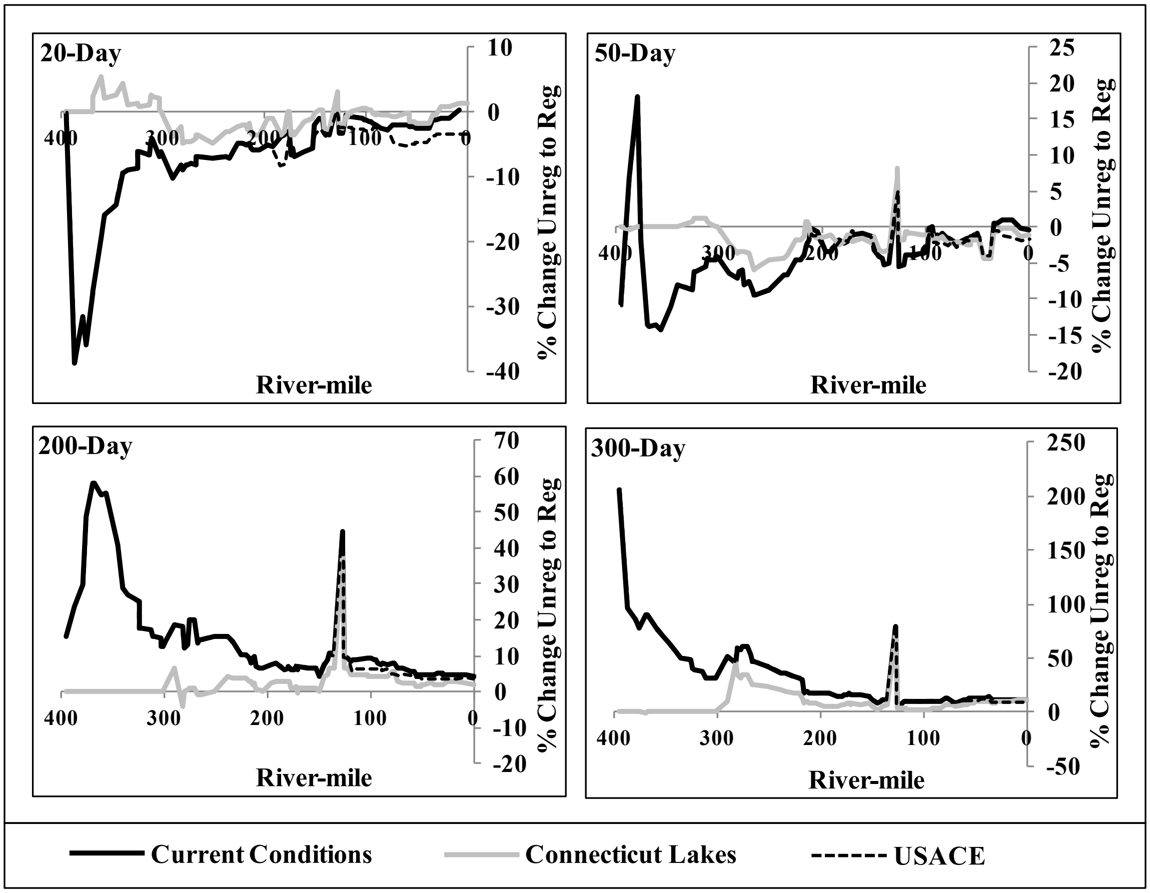


Figure 20. Comparison, between current conditions and the two run-of-river scenarios (USACE Flood Control dams and the Connecticut Lakes Project dams), of percent change from unregulated flow of the four annual inundation duration flows moving down the Connecticut River mainstem.

The Connecticut Lakes Project scenario reduces the percent change from unregulated to regulated conditions substantially for the upper half of the Connecticut River mainstem compared to current conditions and the USACE Flood Control scenario. It still reduces the percent change for the lower half but in a much lower fashion, with that reduction decreasing as a function of distance from the dams.

The USACE Flood Control Projects scenario actually increased the percent change from unregulated to regulated for the twenty day and fifty day inundations. The reason for this is that the flood control dams reduce the highest peaks during a high flow event and then release that flow at a higher constant rate during the receding limb of the event.

Table 13 shows the change in inundated area of the four annual inundation durations for the different run-of-river scenarios.

Table 13. Comparison, between current conditions and the two run-of-river scenarios, of percent change in area and actual acreage change from unregulated for of the four annual inundation durations for the seven river-mile stretch of the Connecticut River mainstem by Northampton, MA.

	% Change in Area			Change in Area (acres)		
	Current Conditions	Connecticut Lakes	USACE Flood Control	Current Conditions	Connecticut Lakes	USACE Flood Control
20-Day	-1.2	-0.8	-2.5	-40	-30	-91
50-Day	-2.5	-1.8	-0.5	-54	-38	-12
200-Day	1.7	1.1	1.9	26	13	22
300-Day	1.2	0.2	1.2	11	3	11

The Connecticut Lakes 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 compared to current conditions. However, little additional floodplain forest area overall is gained or lost from either scenario.

iii. Diadromous Fish

Figure 21 displays the percent change from unregulated to regulated conditions of the six seasonal diadromous fish metrics for the current conditions and the two run-of-river scenarios. The stations start at mile 265, which is the furthest station upstream that represents the range specified by the experts.

For the Spring low flows and medium flows, the Connecticut Lakes scenario has little effect. 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, only the Connecticut Lakes scenario had any significant reductions in percent change. The elimination of the Fall releases to augment hydropower generation during low periods is the cause of this reduction.

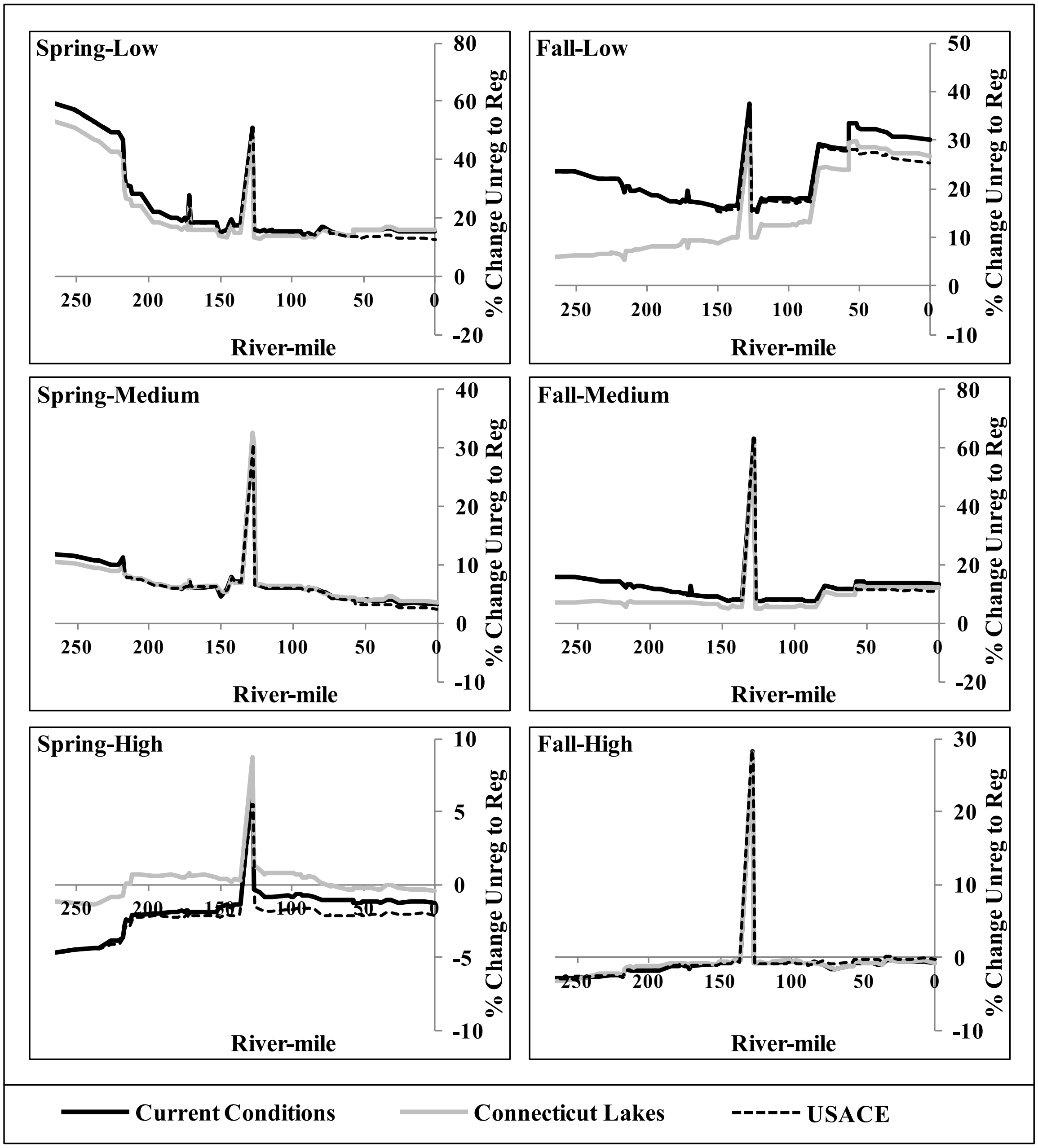


Figure 21. Comparison, between current condtions and two run-of-river scenarios, of percent change from unregulated in the six seasonal diadromous fish metrics. The stations start at mile 265, which is the most upstream point of the Connecticut River mainstem for diadromous fish stipulated by the experts.

The run-of-river scenario analysis offers some insights about potentially re-operating reservoirs to reduce hydrologic alteration. These are not meant to be formal observations but rather examples of the potential knowledge that can be gained through the use of the decision support system for alternatives analysis.

1. Based on the described ecological metrics, large reductions in hydrologic alteration, particularly in the upper watershed, could be achieved through re-operation of the Connecticut Lakes dams.

2. Re-operating the USACE Flood Control dams to be run-of-river could lose additional 20-day inundated area at least on the Connecticut River mainstem by Northampton, MA.

3. Re-operating Connecticut Lakes would cause a relatively large reduction, in comparison to the USACE scenario, of the Fall alteration.

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

Chapter 7
Using the Connecticut River HEC-ResSim Model

Included with this report are all the required files necessary to run the Connecticut River HEC-ResSim model. These files are:

1. A folder labeled "*HEC-ResSim Builds*" which contains the files and executables for HEC-ResSim Version 3.1 for both 32-bit and 64-bit computers.

2. A folder labeled "*base*" which contains a folder labeled "*Connecticut _River_Watershed*"[25]. This folder contains all the files, called a "watershed", required to run the Connecticut River HEC-ResSim model. Among these files are:

   a. A DSS file, *SYE Data_10_07_2011.dss* that contains all SYE generated inflow time series.
   b. A DSS file, *CT Water Supply.dss* that contains all water supply time series (located in the "*shared*" Folder).
   c. Shapefiles required to render the map of the watershed as well as additional shapefiles aspects of the watershed, such as gauge locations and the watershed states, that are not necessary but can help with visualizing the watershed.

Detailed and specific information about the different files included in the watershed folder as well as help on getting started with HEC-ResSim can be found in the HEC-ResSim User's Manual and Quick Start Guide, which can be accessed from the "Help" menu in HEC-ResSim.

HEC-ResSim has three modules that it uses to create and simulate watersheds: the "Watershed Setup" module, the "Reservoir Network" module, and the "Simulation" module. The "Watershed Setup" module is where the physical watershed is constructed into what are called Configurations. A configuration is the physical body that the model is constructed onto. The configuration used for the Connecticut River model is called "Existing", and represents the current conditions state of the watershed. It is possible to add new reservoirs to the configuration that were not originally included, but it is recommended that the revised configuration be saved as a different configuration. It is strongly advised that no reservoirs be deleted from any configuration.

[25] In order for HEC-ResSim to indentify a "watershed", the folder containing all the watershed files must be in the "*base*" folder, thus the inclusion of the "*base*" folder.

The "Reservoir Network" module is where the reservoir model resides and where all the data for the model, such as the inflow time series, reservoir physical and operational data, is entered. The network for the Connecticut River model is named "Current_Conditions_Network". This network contains all the information described in this report.

The "Reservoir Network" module is also where alternatives are defined. Alternatives are the inputs for a simulation. One alternative is linked to one reservoir network and once created, this link cannot be changed. The alternative "Curren_Alt" is the alternative linked to the "Current_Conditions_Network" reservoir network. There are four requirements for an alternative so that a simulation will run.

1. **The Time Step and Flow Computation Method.** The "Curren_Alt" alternative has a one-day time step. The focus of the model development was on a daily time step model. It is not recommended that the time step or flow computation method be changed for this model.

2. **Operation Sets.** The "Curren_Alt" alternative initially lists the operation sets described in the individual project descriptions.

3. **Lookback values.** The Lookback values are the boundary conditions required to start the model. Lookback values must be specified for the pool elevation and outlets. The "Curren_Alt" has the Lookback values for the pool elevation set at the conservation pool elevation and the outlets at 0. No problem will be created by changing the Lookback values; however, this will not change the simulation results much.

4. **Time Series.** The Time-Series tab lists all the local flow names that were specified at each computation point. All local flow must have a time series associated with them. The "Curren_Alt" alternative has all its local flow in either the "*SYE Data_10_07_2011.dss*" file or the "*CT Water Supply.dss*" file. All time series files must reside within the watershed folder or any of the folders within the watershed folder. To remove local flows, delete the local flow at the computation point, which will make that location local flow disappear from the list in the Time-Series tab.

The "Simulation" module is where simulations are actually run and the results can be viewed. Creating a simulation involves setting a Start and End Date as well as a Lookback date which must come before the Start Date. The Lookback Date is the date at which the Lookback values are applied and gives the simulation time to “warm up”. It is possible to edit the reservoir network and alternative in the "Simulation" module; however, that will only change that particular simulation. It will not change the reservoir network or alternative in the "Reservoir Network" module or any other simulation that has the same reservoir network or alternative. If the user wants to apply those changes to the reservoir network or alternative in the "Reservoir Network" module, right click on the alternative name in the Simulation Control window and select "Save to Base Directory…". This will update the reservoir network or alternative in the "Reservoir Network" module. If the user wants to update an existing simulation after making changes to the reservoir network or alternative in the "Reservoir Network" module, right click on the alternative name and select "Replace From Base Directory…". This will update the reservoir network and alternative for that simulation.

There are three additional reservoir networks (and corresponding alternatives) included in the watershed: Simplified_Reservoir_Network, No_Connecticut_Lakes_Network, and No_USACE_Network. The Simplified_Reservoir_Network is a simplified version of the Current_Conditions_Network reservoir network. It only models the reservoirs that are modeled in UMASS's optimization model[26]. The No_Connecticut_lakes_Network and the No_USACE_Network are the reservoir networks that were used to do the example scenario analysis described in Chapter 6.2.1.2. The two networks are the Current_Conditions_Network with the specific dams removed from the watershed for each scenario (and replaced with a routing reach). These reservoir networks are not meant for a dam removal analysis but to model the conditions of the watershed if those dams were perfectly run-of-river as an example analysis by the Decision Support System.

There are many different ways to analyze scenarios in HEC-ResSim. Several approaches are recommended here, depending on the kind of scenario to be analyzed.

1. **Changes in Operations with SYE Inflows**
   To analyze changes in operations, it is recommended that the user create a new Operations Set within the "Current_Conditions_Network" reservoir network and continue to use the "Master_Alt" alternative. Remember to switch the operation set in the alternative editor.

2. **Physical Changes to the Network**
   To analyze changes in the Network, such as the removal of a dam, there are two recommended approaches.

   a. One approach is to do a Save As of the "Current_Conditions_Network" network and then begin to delete reservoirs (remember to reconnect any nodes with a routing reach). This will involve creating a new alternative that is linked to the new network and having to reenter all the operation sets, Lookback values, and time series[27]. The No_Connecticut_Lakes_Network and No_USACE_Network were created in this fashion.

   b. The other approach is to duplicate the entire watershed folder. This way, the user can make edits to the " Current_Conditions_Network " network and no new alternative will have to be made (the "Curren_Alt" alternative will update automatically). However, this will take up a considerable larger amount of computer storage as the watershed folder can be several gigabytes in size.

3. **Changes in Inflow**
   To analyze changes in inflows, such as climate change scenarios, the two approaches for analyzing physical network changes are also recommended for analyzing changes in inflow. To change inflows, changes must be made at the

[26] The Simplified_Reservoir_Network includes 57 reservoirs while UMASS's optimization model has 54 reservoirs. The three differences are; 1) UMASS models Turners Falls as one reservoir while HEC-ResSim models it as two reservoirs, 2) UMASS does not model Northfield but scripted rules in HEC-ResSim for Turners Falls requires knowledge of Northfield's operations, 3) UMASS models Mare Meadow and Bickford as one reservoir.
[27] It is possible to copy/paste the Lookback values and time series from another alternative. Remember that the deleted reservoirs will no longer be in the Lookback values list and thus the order will be different.

computation points. Delete the name from the "Local Flow" tab and then input a new name (make the factor one). New time series DSS files will have to be linked to the new Local Flow names[28].

Other Files Provided

Also included is an HEC-EFM project file that contains the ecosystem flow targets described in Chapter 6 and the three HEC-RAS models as well as the terrain files necessary to do inundation mapping. The software tools are free and available for download at www.hec.usace.army.mil/software.

The HEC-EFM project file also includes the unregulated and regulated flow time series output from the current conditions simulation of the HEC-ResSim model. All computation points within the model are included in the HEC-EFM project file. To analyze different water management alternatives using HEC-EFM, the only requirement is to change the input DSS file, which would be the Simulation.dss file generated from simulating that alternative in HEC-ResSim. In HEC-EFM version 3.0, this must be done one flow regime at a time. In development version 3.1, all input DSS files can be changed at the same time using the “Replace input files” feature.

[28]There is one time series called Dummy that should be left alone. It is required to make HEC-ResSim run.

Chapter 8
Conclusion

This report describes the development and an application of a reservoir simulation model of the Connecticut River watershed using HEC-ResSim. The model simulates the current operations of 73 reservoirs, using data provided by the USGS and the owner/operators of the reservoirs and general modeling strategies for hydrologic routing, hydropower, and water supply. The reservoir system model was developed as part of a study for the USACE and TNC Sustainable Rivers Project for the Connecticut River watershed, and is a main component in an overall decision support system that incorporates ecosystem health as part an objective for water management in the watershed. Along with software tools HEC-EFM and HEC-RAS, the decision support system is capable of generating output such as hydropower generation, compliance with ecosystem flow targets, flood stage, and habitat acreage for select sections of the watershed and can be used to analyze many different reservoir operating scenarios. The goal of this report is not to make operational recommendations but to document the development of the decision support system and describe an application of the decision support system as an example of its potential use. Through this process, several conclusions were reached.

- Despite the challenges related to the scale and complexity of the watershed and the number of reservoirs modeled, a comprehensive decision support system is practical to develop and run.

- The model results are most affected by the inflow data and the uneven knowledge of operational practices.

- The decision support system can provide quantitative estimates of operational tradeoffs such as hydropower and ecosystem services.

- The system is scalable, allowing for analyses at both the watershed and sub-watershed scale.

This decision support system was developed to work in concert with the other models, optimization and climate models, as part of the Connecticut River Watershed Study. It can be used for a variety of other purposes, such as FERC relicensing and planning studies. Ultimately, it is hoped that stakeholders within the watershed will make use of this decision support system to evaluate future water resource management alternatives.

Appendix
Modeled Reservoirs for the Connecticut River Watershed Application of HEC-ResSim

Separate from this report is an appendix document with information about each reservoir modeled in the HEC-ResSim model. Information for each reservoir includes descriptions and sources of all physical and operational parameters in the model. This appendix is to serve as the reference guide in case changes to the model occur and could be used for setting up models at the sub-watershed and individual reservoir scale. The appendix document is separate but can be accessed by clicking here.