Decision Support System for Water and Environmental Resources in the Connecticut River Basin

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Abstract: This paper describes the development and application of a reservoir management decision support system for evaluating floodplain benefits and socioeconomic trade-offs of reservoir management alternatives in the Connecticut River watershed. The decision support system is composed of a reservoir system simulation model, an ecological model, and two river hydraulics models. The reservoir model simulated current operations at 73 reservoirs and flows at locations of interest in the Connecticut River watershed. Regulated flows from the reservoir model were compared with unregulated flows, both statistically and spatially, for a suite of environmental flow metrics based on inundation patterns related to floodplain vegetation communities. Analyses demonstrate use of the decision support system and show how its use illuminates (1) trends in existing hydrologic alteration for the Connecticut River mainstem and one of its tributaries, the Farmington River, and (2) management scenarios that might have ecological benefits for floodplain plant communities. The decision support system was used to test two management scenarios to assess potential floodplain benefits and associated trade-offs in hydropower generation and flood risk. The process described shows the usefulness of large-scale reservoir management decision support systems that incorporate environmental considerations in assisting with watershed planning and environmental flow implementation. **DOI: 10.1061/(ASCE)WR.1943-5452.0000538.** *© 2015 American Society of Civil Engineers.*

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Introduction

Alteration of in-stream flows from natural conditions has greatly affected riverine ecosystems (Bunn and Arthington 2002; Vogel et al. 2007). Native aquatic species are typically adapted to the natural flow regime (Junk et al. 1989). Different aspects of that flow regime, such as seasonal variability and durations of different flows, cue and sustain their various life stages and provide physical habitat (Poff et al. 1997). When flow regimes are changed by dams, diversions, and land-use practices, the distinct environmental cues and habitat to which native species are adapted are altered, thereby disrupting the life stages of native aquatic and floodplain species (Nislow et al. 2002). Additionally, geomorphic processes on which many species rely for habitat creation and maintenance, such as gravel deposition and sediment flushing, may be disrupted (Bunn and Arthington 2002). Reduced connectivity between suitable habitats, such as rivers and floodplains, is yet another consequence of flow alteration (Nislow et al. 2002).

Managed flows that provide ecological benefits are often defined as environmental flows (Hirji and Davis 2009). Historically, reservoir management placed little priority on environmental flows (Petts 2009). Flood control, water supply, and hydropower have dominated reservoir operations with the consequence of degradations to riparian ecosystems (Kopec et al. 2014; Frazier and Page 2006; Burke et al. 2009; Stallins et al. 2010; Johnson et al. 2012). However, efforts are now being made to address and prioritize environmental flows for in-stream flow management (Souter et al. 2014; Olden et al. 2014; Warner et al. 2014).

Managing in-stream flows to restore habitat and ecosystem functions is the subject of considerable research and debate (Arthington 2012; Poff et al. 2010; Richter 2010; Doyle et al. 2005). Environmental flows for specific species are often

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difficult to evaluate, as are the actions needed to implement them.

One approach to estimating environmental flow needs is to characterize the degree to which a river's hydrograph has been altered from its natural hydrograph and then estimating flows that will reduce the degree of alteration (Richter et al. 1996; Bunn and Arthington 2002; Gao et al. 2009; Zimmerman 2006a). This approach assumes that species are adapted to the natural flow regime of a river and that significant deviations from the natural flow regime will have negative consequences for a given species. However, this approach also demands knowledge of the natural hydrograph through stream gauge records or estimating the predam hydrograph through hydrologic modeling, which can be data intensive, computationally difficult, and prone to uncertainty.

Another approach involves linking a specific ecologic function, such as floodplain inundation and sediment flushing, or a specific life stage, such as fish spawning, to a flow statistic (Jowett 1997; Petts 2009; Monk et al. 2006). These ecologically significant flow statistics are often based on empirical research and habitat modeling on a small or limited scale (Bockelman et al. 2004; Hardy 1998; Valavanis et al. 2008).

Many studies have used one of these techniques to estimate environmental flow needs for various rivers worldwide (DePhilip and Moberg 2010; Cain and Monohan 2008; Sandoval-Solis and McKinney 2012; Hughes and Hannart 2003; Apse et al. 2008). This paper explores an approach that quantifies changes from the natural hydrograph (hydrologic alteration) and incorporates environmental flow needs of a specific ecological target, successfully combining the two methods described previously.

Implementing environmental flows often involves changing reservoir operations (Richter and Thomas 2007). Some reservoirs are operated to optimize the production of one or more services (e.g., hydropower), others are operated in accordance with rules, and some are operated with both optimization and rules. Several studies have used reservoir optimization models to balance environmental flows with flows for human use (Pitta and Palmer 2011; Homa et al. 2005; Yin et al. 2010; Harman and Stewardson 2005; Tilmant et al. 2010; Zhang and Qian 2011). Optimization models are useful in directly testing operational changes in reservoirs managed to optimize services and for identifying possible changes in reservoir management using operating rules. Simulation models are also commonly used in reservoir analyses (Draper et al. 2004; Matrosov et al. 2011). These models explicitly represent existing operating rules; operational changes can be tested by modifying those rules and analyzing the corresponding changes in flows and services provided. In complex reservoir systems, containing many reservoirs with a diversity of owners and operating purposes, models can complement each other. Optimization models helping identify opportunities for reservoir reoperation and simulation models assess how existing rules might be changed to realize the desired change.

Simulation models can also help focus reservoir reoperation efforts. Unregulated (no reservoir) and regulated flows, which are common outputs of reservoir simulation models, can be used to calculate hydrologic alteration within a reservoir system. This identifies reservoirs causing the greatest hydrologic alteration and promising changes in reservoir operations (Fields 2009). Socioeconomic trade-offs between reservoir purposes, such as hydropower generation and flood control, also can be quantified. However, the ability to determine the reservoirs and specific operations affecting hydrologic alteration becomes more difficult as the watershed increases in size and complexity. The interactions between reservoirs themselves and their interactions with tributaries cause changes in the hydrologic alteration that become increasingly hard to track. Simulating these interactions in a model with multiple reservoirs and tributaries adds additional complexity. Developing an approach to evaluate the interactions of dams and tributaries and their effect on hydrologic alteration will help dam reoperation efforts to optimize environmental flows in complex watersheds while accounting for other reservoir purposes.

As part of The Nature Conservancy (TNC) and U.S. Army Corps of Engineers (USACE) Sustainable Rivers Project, an ongoing national partnership to advance sustainable water management (Warner et al. 2014), a decision support system for the Connecticut River watershed was developed that incorporated a variety of water management purposes, including environmental considerations. One aspect of this decision support system was the application of computer technologies that simulate reservoir operations, quantify environmental flow needs, and map inundated areas. This paper demonstrates through an example analysis how these technologies can help quantify hydrologic alteration to aid ecosystem management at a watershed scale. The paper focuses on the Connecticut River mainstem and a major tributary, the Farmington River, to contrast ecological changes and opportunities for reservoir reoperation on rivers of different scales. The overall purpose of the paper is to demonstrate how a reservoir simulation model and other tools can quantify hydrologic alteration and other water management trade-offs in support of watershed planning studies and environmental flow implementation.

Study Area

The Connecticut River flows from headwaters at the Canada–New Hampshire border south to Long Island Sound (Fig. 1). Along its 660-km course, many tributaries join the Connecticut River mainstem, draining more than 29,000 km^2 in Vermont, New Hampshire, Massachusetts, and Connecticut. Precipitation occurs year-round with mean annual precipitation ranging from 900 mm in the north to 1,200 mm by the coast. Peak flows usually occur in early spring from snowmelt, and consistent low flows occur during August to September. While high flows can occur in any season, flooding is primarily driven by spring rain on snow events and remnants of hurricanes in late summer and fall. Roughly 77% of the watershed is forested and the remaining 23% of land use is divided among agriculture (9%), wetlands and water bodies (7%), and urban areas (7%) (Hatfield and Lutz 2011).

The Connecticut River watershed is one of the most heavily impounded in the United States based on density of dams (Graf 1999). There are an estimated 2,722 dams spread throughout the watershed, with the oldest dating back to the seventeenth century [national inventory of dams (NID) database and state dam lists]. The dams were primarily constructed for mill ponds and floating logs downstream, but during the Industrial Revolution they started to be used for power generation (Connecticut River Watershed Council 2015). There are 15 dams on the Connecticut River mainstem, the most downstream of which is Holyoke Dam in Massachusetts. The dams along the Connecticut River mainstem are primarily privately owned hydropower facilities. There are 125 hydropower dams in the watershed (Zimmerman 2006b). There were no dams specifically for flood control in the watershed until the floods of 1936 and 1938, which prompted the USACE to construct 14 flood control dams on major tributaries (Connecticut River Joint Commissions 2015). There are no dams specifically for flood control on the Connecticut River mainstem. Water withdrawals are also widespread. Approximately 80 surface water withdrawals as well as an uncounted number of groundwater withdrawals are in the Vermont–New Hampshire section of the watershed (upper

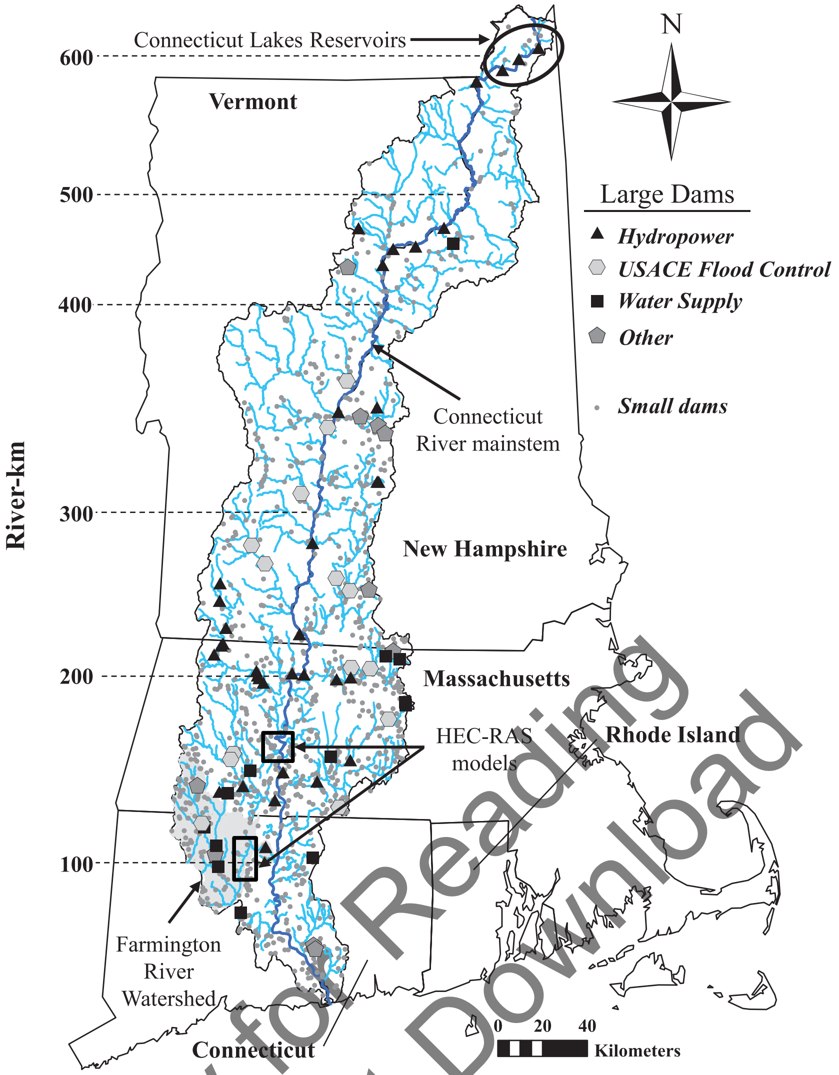


Fig. 1. (Color) Map of reservoirs in the Connecticut River watershed; large dams were defined as either storing more than 10% of annual runoff of the dam's drainage area or having a hydropower generating capacity >1 MW; small dams stored less than 10% annual runoff of the dam's drainage area

watershed), with the overall number of withdrawals unknown (Fallon-Lambert 1998). The states of Massachusetts and Connecticut authorize the withdrawal of 421,190 cm · s (6,676 million gal./day); however, the vast majority of withdrawals are grandfathered in (94% Massachusetts and 85% in Connecticut) and therefore are not subject to environmental review (Gannon 2007).

The Farmington River has its headwaters in northwestern Connecticut and southwestern Massachusetts where it flows 130 km (from its longest tributary) into the Connecticut River mainstem just above Hartford, Connecticut, draining 1,500 km^2 in the process. Its hydrology is similar to that of the whole Connecticut River watershed, except the snowmelt-driven spring high flows are less pronounced. More than 100 dams are located in the Farmington River watershed; however, only seven are considered significant in terms of drainage area impounded, and most of these are used for water supply purposes. Barkhamsted Reservoir, located on one of the Farmington's tributaries, is the biggest in the Farmington watershed and is used as a major water source for the city of Hartford, Connecticut. Colebrook Reservoir is a USACE flood control reservoir and is also used for water supply purposes.

The watershed is home to a wide variety of aquatic and riparian species including 10 listed as endangered [Natural Resources Conservation Service (NRCS) 2008], including shortnose sturgeon (*Acipenser brevirostrum)*, dwarf wedgemussel (*Alasmidonta heterodon)*, Puritan tiger beetle (*Cicindela puritan)*, and the northeastern bulrush (*Scripus ancistrochaetus)* (U.S. Fish and Wildlife Service 2014). The watershed hosts large diadromous fish spawning runs, including American shad (*Alosa sapidissima)* and, historically, the Atlantic salmon (*Salmo salar)*. The populations and ranges of many of these species have declined significantly due to dams (Zimmerman 2006b). The watershed is home to a variety of floodplain forest communities (Bechtel and Sperduto 1998; Kearsley 1999; Metzler and Barrett 2006; Nichols et al. 2000). Specific inundation patterns, high-flow timings, and geomorphic features promote unique combinations of floodplain vegetations (Apse et al. 2008; Marks et al. 2014). Dams, particularly flood control dams, have reduced the number of bankfull flows (nonflood) and flood flows per year, resulting in less inundation of the floodplain downstream and thus a decline in floodplain forest communities (Zimmerman et al. 2008). Reduced flooding downstream of dams can also promote nonnative species invasions (Greet et al. 2013;

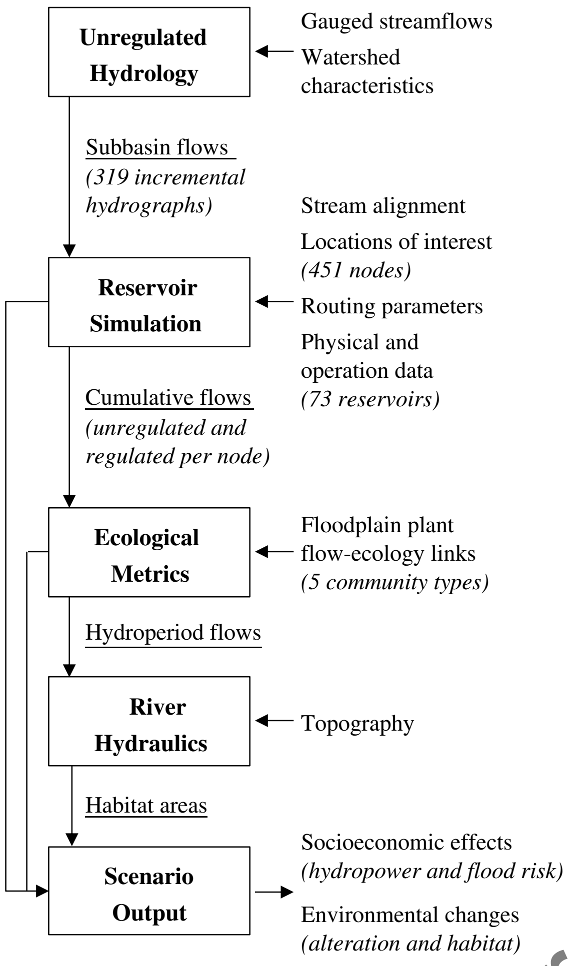


Fig. 2. Decision support process and outputs

Reynolds et al. 2014; Terwei et al. 2013). Dams have increased inundation upstream due to their storage pools, resulting in changes in aquatic and riparian plant compositions in the reservoir zone. In the mainstem sections that are not inundated due to reservoirs, reduction in high flows is the most important driver of floodplain forest decline after agriculture and urban development (Nislow et al. 2002; Carpenter 2007). Channel incision and bank hardening is another important conservation concern for floodplain forests (Shankman and Smith 2004), especially on the tributaries, including the Farmington River.

Methods

Management alternatives were assessed with a linked decision support system capable of translating changes in hydrology and reservoir operations to changes in hydrologic alteration, hydropower generation, reservoir pool levels, and ecological responses (Fig. 2).

Hydrology

Unregulated hydrology for the study was generated using the Connecticut River UnImpacted Streamflow Estimator (CRUISE) tool developed by the U.S. Geological Survey (USGS) (Archfield et al. 2009, 2013). The CRUISE tool estimated unimpaired flow duration curves at ungauged locations using a regression equation based on physical, climate, and watershed characteristics. The nearest USGS gauge time series was also translated into a reference flow duration curve. The two flow duration curves were then compared and the date of the reference flow duration curve at each percentage became the date of the unimpaired flow duration curve value at the same percentage. This translated the unimpaired flow duration curve into an unimpaired flow time series. Through this method, CRUISE produced daily incremental unregulated hydrographs based on physical, climate, and watershed characteristics at a subbasin scale with a period of record from October 1, 1960, to September 30, 2004. Archfield et al. (2009, 2013) describe in detail the methods and available gauges used within the CRUISE tool. The incremental hydrographs were generated for all necessary nodes in the reservoir simulation model, such that flows would be wholly available for all locations of interest. In total, 319 incremental hydrographs were generated and imported to the reservoir simulation model.

Reservoir Simulation

Given the number and regional significance of reservoirs within the watershed, a reservoir simulation model is a central aspect of the decision support system. The model provides flow estimates at 138 points of ecological interest (eco-nodes) that reflect unregulated conditions and current operations of 73 dams. The eco-nodes were determined by TNC and used to assess flows for either individual or combinations of different species or ecological communities: floodplain forests, diadromous fish, tiger beetles, freshwater mussels, resident warm water fish, and resident cold water fish. The model simulated the operations of the 73 largest dams in the Connecticut River watershed (which contains more than 2,700 dams). A reservoir was classified as large if it was able to store 10% or more of the total annual runoff its drainage area received or had hydropower generating capacity greater than 1 MW.

The reservoir simulation modeling platform used was *HEC-ResSim 3.1* (Reservoir System Simulation Model), which was developed by the USACE HEC. Technical information on *HEC-ResSim* can be found in the user's manual (HEC 2011). Inflow time series are input at user-defined locations throughout the model and reservoirs to simulate the release of water based on physical constraints and operating rules. Each reservoir within *HEC-ResSim* has a target pool elevation that the model tries to maintain by storing and releasing inflow.

Locations of interest along the stream network, whether stream junctions, eco-nodes, gauges, or towns and cities, are known as computation points. Flow time series (unregulated and regulated) are generated for each computation point when the model is run. *HEC-ResSim* can simulate controlled and uncontrolled reservoir outlets as well as power plants, taking into account generation efficiency, tailwater, and a variety of hydropower generation types. It also can handle complex reservoir operating rules and many reservoirs and routing reaches. *HEC-ResSim* simulates unregulated flows by routing inflows through the stream network as if no reservoirs were present.

The Connecticut River *HEC-ResSim* model was developed by several USACE engineers from the New England District and HEC. Watershed data, such as stream alignment and reservoir locations, were collected from the USGS's National Hydrography Dataset (NHD).

Due to the large number of routing reaches that had subdaily travel times, a routing strategy was developed to ensure a consistent routing approach that worked within the daily time-step format of the model. Ten points within the watershed, either on the Connecticut River mainstem or on tributaries, were identified where all the flow upstream of those points would reach that point within 24 h. All routing reaches above that point had null routing applied. For the reaches directly downstream of the identified points, a lag of 24 h was applied. This routing approach allowed travel times to be considered (albeit in a coarse way), which was important for tributary reservoirs with mainstem operating objectives while avoiding the numeric averaging of flows that occurs when subdaily travel times are applied in simulations with a daily time step. A consequence of this approach is that the relative timing of the incremental hydrographs is not entirely respected. For example, two streams flowing into the same river at confluences separated by hours of travel time and above the 10 routing reaches were combined by simple addition without any time offset. Any effects of these neglected offsets would become less significant as the combined hydrographs continues downstream through the routing reaches. The incremental hydrographs are composed of daily mean flows and therefore any mode of aggregation that might account for the subdaily offset would require a numeric averaging method that works at a time step finer than that of the data.

Physical and operational data of the reservoirs, including pool elevation-storage curves, outlet elevation-discharge curves, and operating rules, were obtained from the owner-operators of the dams. Where actual water supply and hydropower operations were not specified, general modeling strategies were implemented for water supply withdrawals and hydropower generation. A modeling strategy for USACE flood control dams was also implemented because initial modeling based only on documents provided by the USACE's New England District did not reflect actual operations during most high-flow events. The details of the water supply withdrawals, hydropower generation, and flood control modeling strategies are described subsequently.

Water Supply

Eight dams in the *HEC-ResSim* model had water supply withdrawals simulated. Withdrawals were modeled using negative inflow time series. These time series were approximated using seasonal guidelines developed through conversations with the Metropolitan District of Connecticut, a water supply district that serves Hartford, Connecticut. Negative inflows were applied at the upstream computation point of the eight water supply reservoirs modeled (two of which were on the Farmington River). A majority (75 to 90% depending on the season) of the diverted flow was then returned at the downstream computation point of each reservoir through another time series. While the strategy adopted for water supply withdrawals could be considered crude, the goal of the strategy was to remove some flow volume from the overall system while taking seasonal fluctuations in water demand into account.

Hydropower

The *HEC-ResSim* model simulated hydropower operations at 31 dams. Two of those facilities, Northfield and Turners Falls, had their hydropower operations specifically detailed by their owner-operators. The rest of the hydropower dams, 24 daily run-of-river and five peaking, lacked operational data. Where operational data were lacking, modeling strategies for daily run-of-river and peaking operations were developed. Both strategies were deemed sufficient based on outflow comparisons with available USGS gauges.

Daily run-of-river hydropower dams were assumed to pass all inflow through the turbines when the pool elevation exceeded the conservation pool elevation. If the pool elevation was below the conservation level, 95% of the inflow was passed through the turbines in order to return the pool elevation to the conservation level. Daily run-of-river dams may be peaking hydropower facilities on a subdaily scale; the term *run-of-river* as used in this paper is therefore not an absolute term.

Peaking dams allow their pool elevations to fluctuate daily in order to generate hydropower during peak consumption periods. To model peaking operations in the *HEC-ResSim* model, it was assumed that the amount of flow passed through the turbines each day was a function of the inflow and the current pool volume. If the volume available for hydropower releases was greater than or equal to the equivalent volume to generate hydropower for 4 h, that equivalent daily volume was passed through the turbines. If there was not enough volume for 4 h, then 2 h of hydropower generation occurred. If there was not enough for 2 h, then only inflow was passed through the turbines. It was also assumed that no peaking hydropower was generated on weekends.

Flood Control

Fourteen USACE flood control dams were modeled. Initial rule sets were based only on the standard operating procedures (SOPs) of each dam [USACE Reservoir Regulation Team (RRT) 2013]. Initial results showed that simulated operations poorly matched observed operations. Specifically, simulated outflows dropped too rapidly and were sometimes greater than the peak daily inflow experienced during high-flow events. In reality, USACE New England District's RRT uses operational flexibility in managing high-flow events and considers the storage, inflow, downstream conditions, and forecasts before making release decisions for each reservoir. The operational data that were gathered from the SOP of each dam are the operating bounds within which the flood control dams are operated, but most high-flow events do not force operations to those bounds. To better simulate actual operations during high flows, two operating rules were added that are not specified in the SOPs.

The first additional rule was a measured drawdown of releases based on the maximum stage at specific points on the Connecticut River mainstem. The USACE flood control dams are located on tributaries but are operated also to reduce flooding on the mainstem. The SOPs specify the stage at specific locations on the mainstem when outflows should start to reduce in order to prevent flooding. In practice, the RRT slowly reduces releases from the dam rather than immediately reducing releases to minimum flows. The actual amount of flow reduction varies with the unique nature of each storm. To mimic this, a linear drawdown that was a function of the maximum allowable release (channel capacity) was implemented for each flood control dam such that as stage at the downstream locations increased above the initial target stage, simulated outflows from the dams were decreased.

The second additional rule prevented the maximum reservoir releases from exceeding maximum inflows of high flow events. In practice, the RRT does not allow outflows to exceed the maximum inflow experienced during a high-flow event. The SOP made no mention of this aspect of flood control operations. To incorporate the RRT's guideline, 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 during spring (March to May) generally lasted at most 3 weeks.

Implementing these two rules brought the model results closer to matching observed data. The outflows were decreased more gradually when stage on the mainstem reached flood levels and maximum outflows did not exceed maximum inflows during high-flow events.

Model Testing

To test the model, simulation results at 40 computation points were compared with USGS observed flows using a standard correlation for the 1960 to 2004 period of record. Seventy-five percent of the computation point and observed comparisons had correlations greater than 0.8, indicating good overall agreement between simulated and observed results. The computation points that exhibit larger differences from observed flows were points below reservoirs that had significant knowledge gaps in their operations and below the USACE flood control dams. 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 as described in the previous section.

Ecological Metrics: Floodplain Plant Community Hydroperiods

Several studies have linked annual inundations to the composition of Connecticut River floodplain plant communities (Metzler and Damman 1985; Nislow et al. 2002; Marks et al. 2014). Marks et al. (2014) quantified specific annual durations of floodplain inundation (hydroperiods) associated with particular floodplain plant species and habitats (Table 1), which the decision support system incorporates into quantifying floodplain benefits. Aquatic plants dominated where flooding exceeds 255 days/year. Herbaceous marsh plants dominated in the zone with flooding between 142 and 255 days/year. Shrub swamp dominated in the zone receiving flooding between 95 and 142 days/year. The transition in dominance from upland forest tree species to floodplain forest species occurred at 4.5 days of flooding per year. Although no longer dominant, floodplain tree species do occur at elevations where flooding is less than 4.5 days/year. However, such flood-dependent species as silver maple (*Acer saccharinum* L.), black willow (*Salix nigra* Marsh.), and cottonwood (*Populus deltoides* Bartram ex Marsh.) rarely occurred where flooding is less than 1 day/year. Thus a 1-day hydroperiod indicates the upper elevation limit of the habitat for flood-dependent plant species (hereafter referred to as floodplain habitat extent). For a more detailed list of plant species distributions in relation to floodplain hydroperiod, please refer to Marks et al. (2014).

Changes in hydroperiod flows allow the extent of hydrologic alteration to be compared for different water management scenarios (i.e., unregulated versus current or alternative management conditions). An important caveat of this approach is that hydroperiods do not fully explain ecological conditions. Many variables could potentially be considered when investigating hydrologic alteration due to reservoirs. The work described in this paper was fortunate in two regards. First, significant research had been done in the watershed to identify and quantify key ecological variables related to positioning of floodplain plant community types, including hydroperiods. Second, the key variable determined (hydroperiod) was directly affected by the operations of reservoirs and therefore inherently described by the decision support system.

To calculate the 1-, 4.5-, 95-, 142-, and 255-day hydroperiods corresponding to important transitions in floodplain vegetation type, the 1st, 4.5th, 95th, 142nd, and 255th highest flows were determined for each year of the period of record [Fig. 3(a)]. Annual results were ranked [Fig. 3(b)] and the median (50% exceedance) of those annual values was selected as the statistical result for each hydroperiod [Fig. 3(c)]. The decision support system allows for many different flow exceedances and flow duration criteria to be analyzed. The median flow exceedance value was chosen because it is representative of typical year conditions and for use as an example criterion. The process was done for both unregulated and regulated flows. Percent change from the unregulated hydroperiods were then calculated as the metric to quantify hydrologic alteration [Eq. (1)]

$$\text{Percent change} = \frac{Q_{\text{regulated}} - Q_{\text{unregulated}}}{Q_{\text{unregulated}}} \times 100\% \qquad (1)$$

Percent change allows for comparison between different points in the watershed where there are significant differences in total flow received (Richter et al. 1998). The median year 1-day hydroperiod is the same as the 2-year recurrence interval (RI) flood. The 2-year RI flood is important for geomorphic processes that affect floodplain habitats (Magilligan et al. 2008).

The HEC Ecosystem Functions Model (HEC-EFM) software tool was used to calculate flows corresponding to different hydroperiods. HEC-EFM was developed to link hydraulic and hydrologic time series with ecosystem flow relationships: season, flow frequency, flow duration, and rate of change (Hickey et al. 2015; HEC 2013). The program takes a time series and ecosystem flow relationship and calculates a specific flow value based on the criteria in the relationship. HEC-EFM can handle many time series and relationships and the compute time is rapid, which was useful when calculating these values at many points throughout the watershed.

River Hydraulics

In addition to quantifying the percent change in flow, areas inundated by the hydroperiod flows were simulated with two river hydraulics models to map the habitat areas of the floodplain plant communities on two river reaches. The section of the Connecticut River mainstem was an 11.3-km reach by Northampton, Massachusetts (river-km 160-149). The section of the Farmington River was a 13-km reach below Simsbury, Connecticut.

The river hydraulics modeling platform used for this study was the HEC River Analysis System (HEC-RAS), which simulates

Table 1. Hydroperiod Associated with Dominance of Different Floodplain Vegetation Types (Data from Marks et al. 2014)

Range in hydroperiod (days)	Floodplain plant community type	Important plant species
<4.5	Rich high terrace and other upland forests	Sugar maple (*Acer saccharum* Marsh.), black cherry (*Prunus serotina* Ehrh.), and white pine (*Pinus strobus* L.)
4.5–95	Floodplain forest	Silver maple (*Acer saccharinum* L.), green ash (*Fraxinus pennsylvanica* Marsh.), pin oak (*Quercus palustris* Münchh.), and sycamore (*Platanus occidentalis* L.)
95–142	Shrub swamp	Buttonbush (Cephalanthus occidentalis L.) and speckled alder [*Alnus incana* (L.) Moench. ssp. *rugosa* (Du Roi) R. T. Clausen]
142–255	Herbaceous marsh plants	Arrowheads (*Sagittaria* species), cattails (*Typha* species), smartweeds (*Polygonum* species), wild rice (*Zizania aquatica* L.), and pickerel weed (*Pontederia cordata* L.)
255	Aquatic plants	Water milfoil (*Myriophyllum* species), water lilies (*Nuphar* species), and bur reeds (*Sparganium* species)

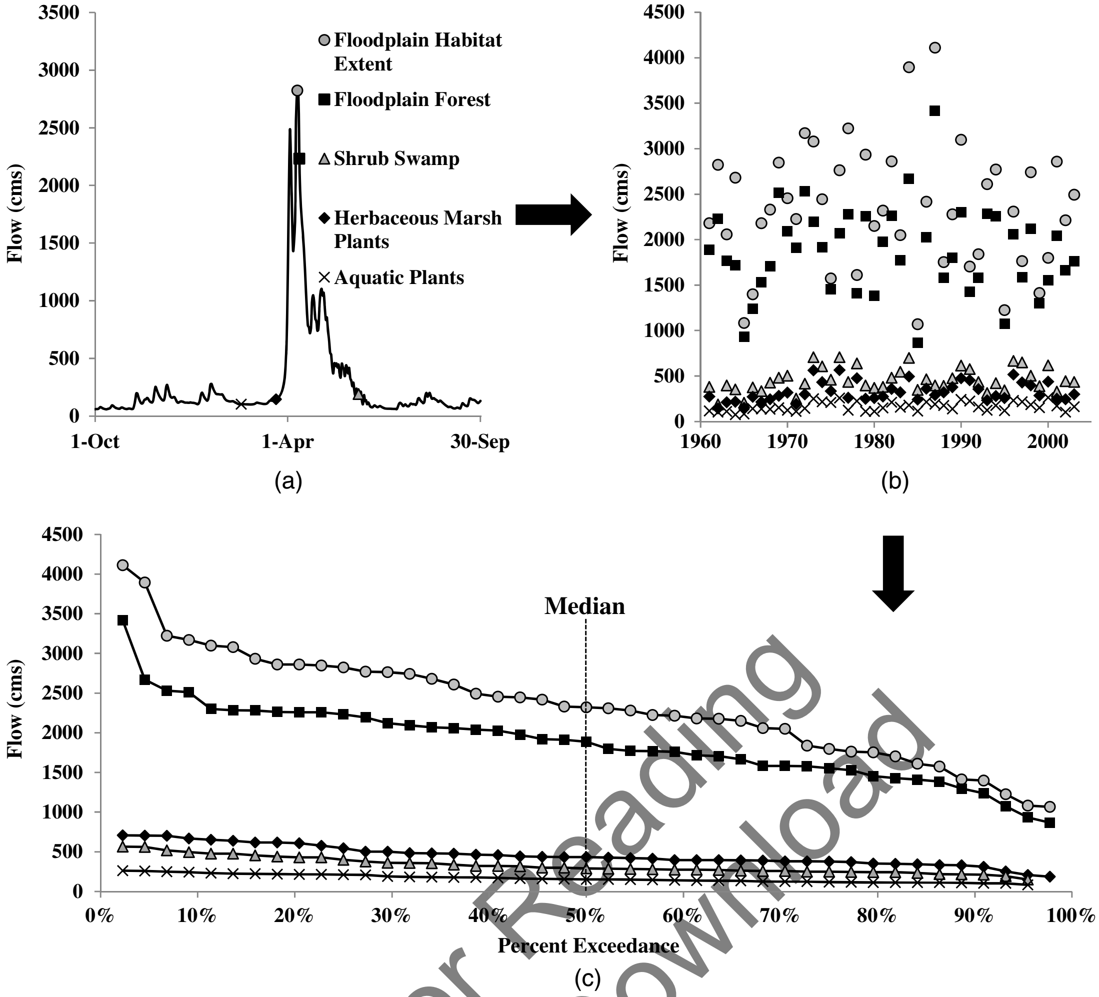


Fig. 3. Method of how the five hydroperiod flows were determined; (a and b) the 1st, 4.5th, 95th, 142nd, and 255th highest flows were pulled from each year and (c) then ranked, with the median selected for this analysis

water surface elevations and floodplain inundation for 1-day steady flow, as applied for this work, as well as 1-day 2-day unsteady flow (HEC 2010). The median unregulated and regulated flows of the hydroperiods and open water were calculated at a computation point that was closest to the midpoint of each modeled section of river. The annual inundation results computed by HEC-EFM were input to HEC-RAS and simulated to compute water surface profiles of each hydroperiod flow for unregulated and regulated conditions. Inundation shapefiles for the resulting water surface profiles were then calculated using the RAS mapper tool in HEC-RAS and then rendered in Environmental Systems Research Institute's (ESRI's) *ArcMap* software. HEC-GeoEFM, an *ArcMap*-based habitat mapping tool, was then used to calculate habitat areas of the hydroperiods.

Habitat areas were calculated by taking the difference between the inundation shapefiles generated for the different hydroperiods. The floodplain forest, shrub swamp, and herbaceous marsh plants habitat areas were the total inundated area of the 4.5-day hydroperiod flow minus the total inundated area of the 95-day hydroperiod flow, the 95-day minus the 142-day, and the 142-day minus the 255-day, respectively. The aquatic plant habitat area was the 255-day minus the area that was always inundated (open water). The flow that represented open water within the river reach was assumed to be the median flow of the annual minimum 7-day average flows, calculated using HEC-EFM. The floodplain habitat extent area was the total inundated area of the 1-day hydroperiod flow minus the open water area. Resulting habitat areas were translated to a percent change from unregulated in habitat areas for the two river reaches. Fig. 4 shows a map of these habitat areas for the stretch of the Farmington River modeled with a HEC-RAS model.

Socioeconomic Trade-Offs

Socioeconomic metrics in this study were defined as changes in hydropower generation and flood protection on the Connecticut River mainstem. Hydropower generation was defined as the mean annual power output of each of the 11 hydropower dams on the Connecticut River mainstem.

Flood protection was defined as 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. The flood stages for North Walpole, Montague City, and Hartford are 9.1, 9.1, and 6.7 m, respectively (USACE RRT 2013). This is a simplistic approach to quantify flood protection and is used in this paper as an example flood protection trade-off. In general, flood stage is defined from a regulatory perspective. Damage to people and property does not usually occur until well above flood stage. A more in-depth socioeconomic analysis would quantify flood damage as a function of stage at these three locations.

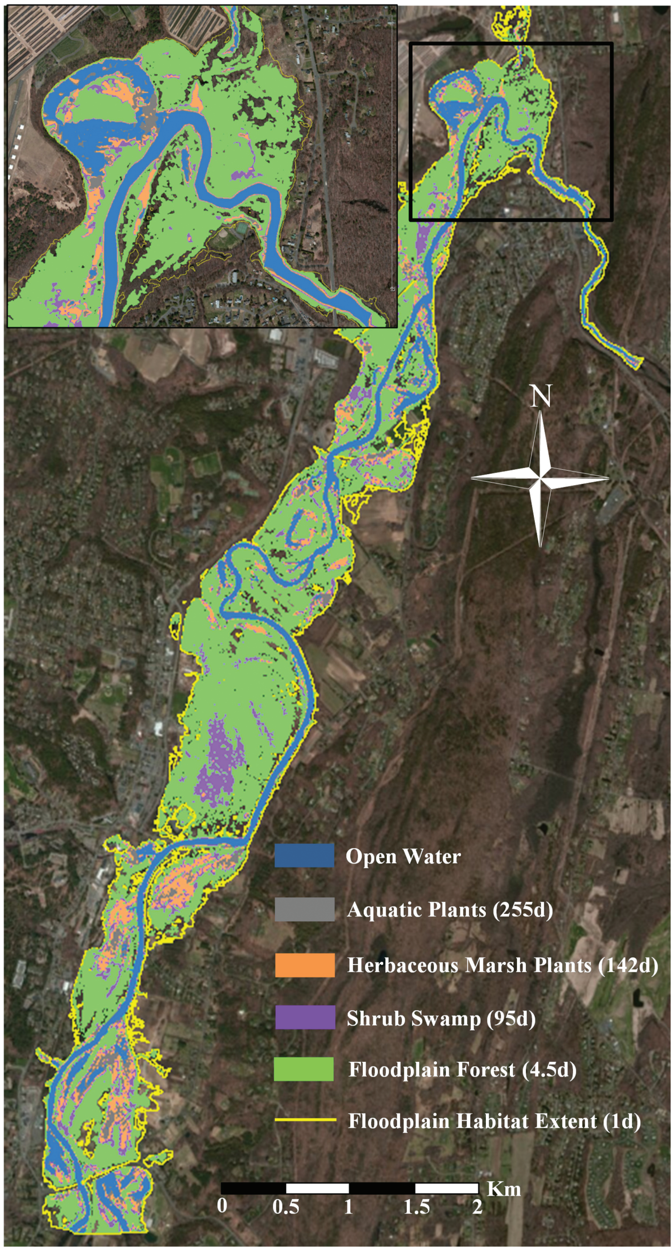


Fig. 4. (Color) Map of habitat areas of the different hydroperiods over the 13-km stretch of the Farmington River by Simsbury, Connecticut (base map courtesy of ArcGIS, Earthstar Geographics, CNES/Airbus DS)

Decision Support System and Results

Following the decision support system process (Fig. 2), unregulated hydrographs were accumulated, managed, and routed by the reservoir simulation model, and subsequently assessed by ecological and river hydraulics models to compute the percent change of each median floodplain plant hydroperiod flow along the Connecticut River mainstem and the Farmington River. This was done for current operating conditions and two management alternatives. Current conditions were analyzed to calculate the existing extent of hydrologic alteration from unregulated conditions. Management alternatives were analyzed to quantify floodplain benefits (defined here as reductions in hydrologic alteration) and associated socioeconomic trade-offs. Because only one criterion (median) was used in the following analysis, the results and observations described are not definitive. A more thorough analysis would incorporate additional criteria using the process of the decision support system.

Current Conditions

Alteration of the five floodplain hydroperiods was assessed at every dam outflow, tributary confluence, and eco-node in the *HEC-ResSim* model along the Connecticut River mainstem (106 points) and Farmington River (18 points), respectively.

Connecticut River Mainstem

Hydroperiod alteration was most pronounced at the top of the watershed due to the three dams of the Connecticut Lakes Project (Fig. 5). Alteration generally decreased longitudinally downstream as more drainage area contributed flow. Alteration also generally appeared to stabilize (the magnitude of alteration did not fluctuate) below river-km 350. Larger decreases in hydroperiod alteration downstream of the Connecticut Lakes Project dams were due primarily to unregulated and lightly regulated tributaries or local inflows at eco-nodes. Increases in alteration were caused by more highly regulated tributaries and the operations of mainstem dams.

The percent change from unregulated of the 255-day hydroperiod was considerably higher at the top of the watershed compared to the other hydroperiods. The regulated 255-day hydroperiod also stabilized at a higher percent change than the other hydroperiods. The regulated 142- and 95-day hydroperiods had an initial large increase in percent change at the top of the watershed but then quickly dropped to near zero for the remaining extent of the Connecticut River mainstem. Percent changes in the 4.5- and 1-day hydroperiods were greater at the top of the watershed but decreased soon afterwards and ultimately stabilized near zero alteration.

The largest relative increase in alteration, at river-km 209, was due to the Northfield Mountain pumped storage facility; however, the large increase was reduced at the Turners Falls dam (river-km 203) computation point downstream. Moore dam (river-km 467) also caused relatively large increases in hydrologic alteration of the hydroperiods, but the other mainstem dams had minimal effects.

Generally, the hydroperiod flows associated with the extent of habitat for flood-dependent plants (1-day) and floodplain forest dominance (4.5-day) were reduced by the operations of reservoirs, and to a much greater extent on the upper Connecticut River. This might indicate an overall decrease in floodplain forest habitat area along the entire mainstem, especially in the upper reaches. Hydroperiod flows associated with shrub swamp (95-day) and herbaceous marsh plants (142-day) were increased on the upper third of the mainstem and were relatively unchanged in the lower two-thirds, indicating potential increases in shrub swamp and herbaceous marsh plant vegetation along the upper mainstem river channel only. The hydroperiod flows associated with aquatic plants (255-day) were increased along the entire mainstem, again, to a much larger extent at the top of the mainstem, like the other vegetation types. Overall, these changes indicate a potential expansion of aquatic plant vegetation along the entire mainstem and a decrease in floodplain forest species dominance and habitat extent. Potential changes in shrub swamp and herbaceous marsh plants may only be noticeable in the upper section of the mainstem. Below river-km 350, the degree of alteration is modest, indicating conditions of floodplains along the Connecticut River mainstem below this point may be largely independent of reservoir influences.

Farmington River

In terms of alteration of the hydroperiods, results on the Farmington River were similar to results on the Connecticut River mainstem (Fig. 6).

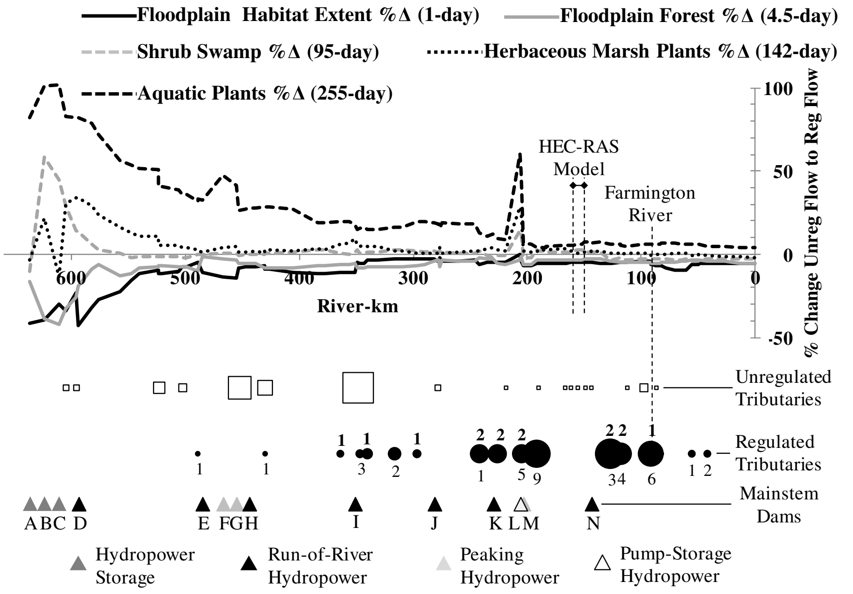


Fig. 5. Hydrologic alteration of five hydroperiod flows on the Connecticut River mainstem; confluences of unregulated (squares) and regulated (circles) tributaries are indicated on the plot and are sized according to their contributing drainage area; the number of USACE flood control dams, if any, on each regulated tributary is indicated by the number above regulated tributary points and the number of non-USACE dams, if any, is indicated by the number below; mainstem dams are labeled as follows: A = Second Connecticut Lake, B = First Connecticut Lake, C = Lake Francis, D = Canaan, E = Gilman, F = Moore, G = Comerford, H = McIndoes, I = Wilder, J = Bellows Falls, K = Vernon, L = Northfield, M = Turners Falls, N = Holyoke; river-kms 160–149 were analyzed with an HEC-RAS model

Percent change in the 255-day hydroperiod was much higher than the other hydroperiods along the entire river (~30%). The percent change in both the 142- and 95-day hydroperiods was small at the top of the Farmington but trended toward zero for the rest of the river, similar to the Connecticut River mainstem. The percent change in the 4.5-day hydroperiod both increased and decreased along different parts of the river, but to a small degree. The 1-day hydroperiod decreased along the entire river. Colebrook dam and the regulated tributary at river-km 75 (which has Barkhamsted water supply reservoir) appeared to be the primary drivers of alteration in hydroperiods. Alterations generally decreased longitudinally downstream due to contributions from unregulated and minimally regulated tributaries and local inflows. Alterations on the Farmington River indicate a potential expansion in aquatic plant

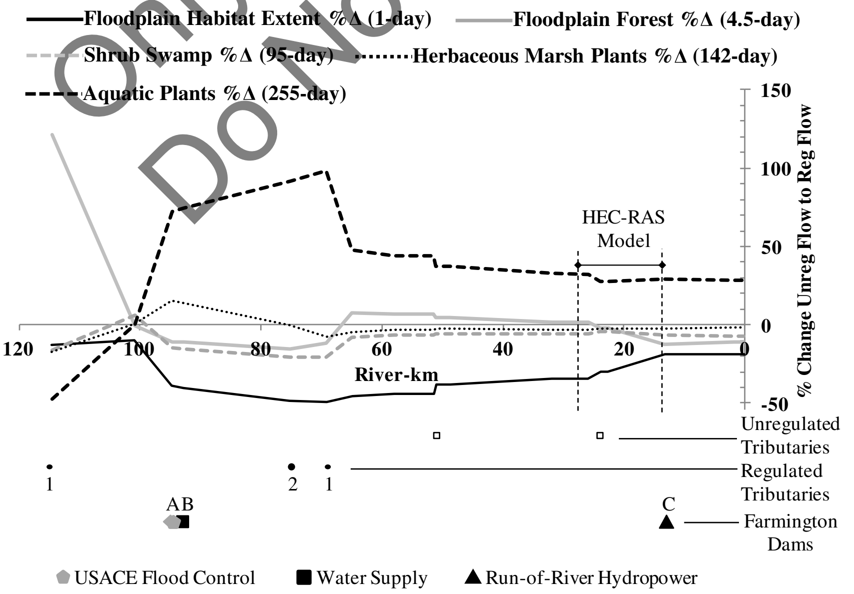


Fig. 6. Hydrologic alteration of five hydroperiod flows on the Farmington River; confluences of unregulated and regulated tributaries are indicated on the plot and are sized according to their contributing drainage area; the number of dams on the regulated tributaries is indicated by the number below the point; the dams on the Farmington are labeled as follows: A = Colebrook, B = West Branch, C = Rainbow; river-km 27–14 were analyzed with a HEC-RAS model

Table 2. Hydrologic and Spatial Changes from Unregulated for Floodplain Plant Communities, Connecticut River Mainstem in Northampton, Massachusetts (11.3-km Section), and Farmington River in Simsbury, Connecticut (13-km Section)

Floodplain plant community	Unregulated flow (cms)	Regulated flow (cms)	% change flow	Unregulated area (km^2)	Regulated area (km^2)	Actual change area (km^2)	% change area
Connecticut River Mainstem in Northampton, Massachusetts							
Floodplain habitat extent	2,490	2,364	−5.1	18.99	18.57	−0.42	−2.2
Floodplain forest	1,983	1,921	−3.2	13.97	13.52	−0.45	−3.2
Shrub swamp	439	449	2.4	1.18	1.24	0.06	5.1
Herbaceous marsh plants	299	301	0.7	1.24	1.20	−0.04	−3.2
Aquatic plants	148	157	6.3	0.73	0.73	0.00	0.0
Open water	49.7	63.0	26.8	3.72	3.78	0.06	1.6
Farmington River in Simsbury, Connecticut							
Floodplain habitat extent	493	325	−34.1	6.83	5.99	−0.84	−12.3
Floodplain forest	153	155	1.3	3.45	3.63	0.18	5.2
Shrub swamp	31.4	29.6	−5.5	0.73	0.63	−0.10	−13.7
Herbaceous marsh plants	22.0	21.3	−3.1	0.74	0.51	−0.23	−31.1
Aquatic plants	9.9	13.1	32.3	0.34	0.29	−0.05	−14.7
Open water	3.7	7.5	106.2	0.56	0.78	0.17	35

(255-day) vegetation and a reduction in floodplain habitat extent. Shrub swamp and herbaceous marsh plant area appears to not have changed compared with unregulated. Floodplain forest area fluctuates between potential expansions and reductions from unregulated, depending on the section of river.

Regarding influence of the Farmington on the mainstem, alteration of the Farmington effected only minor shifts in alteration on the Connecticut River mainstem. Percent change in the 1-day hydroperiod flow changed from −4.1 to −6.0% (1.9% decrease), the 4.5-day changed from −4.7 to −5.5% (0.8% decrease), the 95-day changed from −2.9 to −2.7% (0.2% increase), the 142-day changed from 0.5 to −0.4% (0.9% decrease), and the 255-day changed from 5.8 to 6.0% (0.2% increase). This indicates that the inflow from this significantly large regulated tributary does little to the alteration on the Connecticut River mainstem this far downstream.

Spatial Effects

The topography in each section of river determines how changes in the hydroperiod flows translate to changes in habitat area. For example, an increase in the 255-day flow will not result in an equally large increase in herbaceous marsh habitat area if there are few surfaces at those low floodplain elevations that could be inundated. Table 2 shows this translation for the hydraulic model sections of the Connecticut River mainstem in Northampton, Massachusetts, and the Farmington River in Simsbury, Connecticut.

For the mainstem in Northampton, Massachusetts, small changes in the hydroperiod flows translated into small changes in habitat areas. The overall floodplain habitat extent and floodplain forest area saw the largest absolute decrease in area (>0.4 km^2), but the percentage of area lost was relatively small. The shrub swamp area saw the largest relative increase in area (>5%). Even though herbaceous marsh hydroperiod flows increased, herbaceous marsh area decreased. This was most likely due to encroachment by the two surrounding habitat areas (shrub swamp and aquatic plant areas), which had larger percent changes in their hydroperiod flows. Aquatic plant area saw no net change in area due to the increased open water area. The decrease in the floodplain habitat extent and the increase in open water suggest an overall narrowing of the floodplain, although the change in area was modest (Table 2).

For the Farmington River, results were qualitatively similar to the mainstem, but greater in magnitude (Table 2). The floodplain habitat hydroperiod flow and respective area were reduced substantially. The shrub swamp and herbaceous marsh plants had small reductions in hydroperiod flow, but relatively large reductions in area. Aquatic plants had a large increase in the hydroperiod flow but an even greater reduction in area, most likely due to the large increase in open water area encroaching on what would be aquatic plant area. The floodplain forest hydroperiod flow increased, which resulted in a slight increase in floodplain forest area. This is counterintuitive based on the known operations of Colebrook reservoir, which acts to reduce the highest flows by cutting the peak and then releasing the flood outflows gradually. This is the result of the statistical analyses and an example of why many different metrics, such as different percent exceedances, should be analyzed when doing a definitive analysis using this decision support system. Overall, the relatively large changes in area for most of the floodplain plant communities showed that floodplain plant compositions along the Farmington River were highly influenced by reservoir operations, both in terms of actual floodplain habitat area lost or gained and percentage of floodplain habitat area lost or gained.

Reoperation Scenario Analysis

To quantify floodplain benefits that might be achieved on the Connecticut River mainstem and Farmington River through reservoir reoperation, two scenarios were simulated in which the operations of combinations of dams were changed to be completely run-of-river. The two scenarios consisted of daily run-of-river operations for the following reservoirs:

1. The Connecticut Lakes Project reservoirs: Second Connecticut Lake, First Connecticut Lake, Lake Francis; and
2. All 14 USACE flood control projects: Union Village, North Hartland, North Springfield, Ball Mountain, Townshend, Surry Mountain, Otter Brook, Birch Hill, Tully, Knightville, Littleville, Barre Falls, Conant Brook, and Colebrook.

In these simulations, no water was stored and no hydropower was generated at the dams tested. The Connecticut Lakes scenario was chosen because the three Connecticut Lakes reservoirs appeared to be the primary regulators of flow on the mainstem. The USACE flood control scenario was chosen because, based on the number of projects, the USACE is one of the primary operators in the watershed. These scenarios do not reflect realistic reoperation scenarios but are used for demonstrative purposes.

Floodplain Benefits

Percent change from unregulated was calculated for the Connecticut Lakes and USACE scenarios and then compared with the

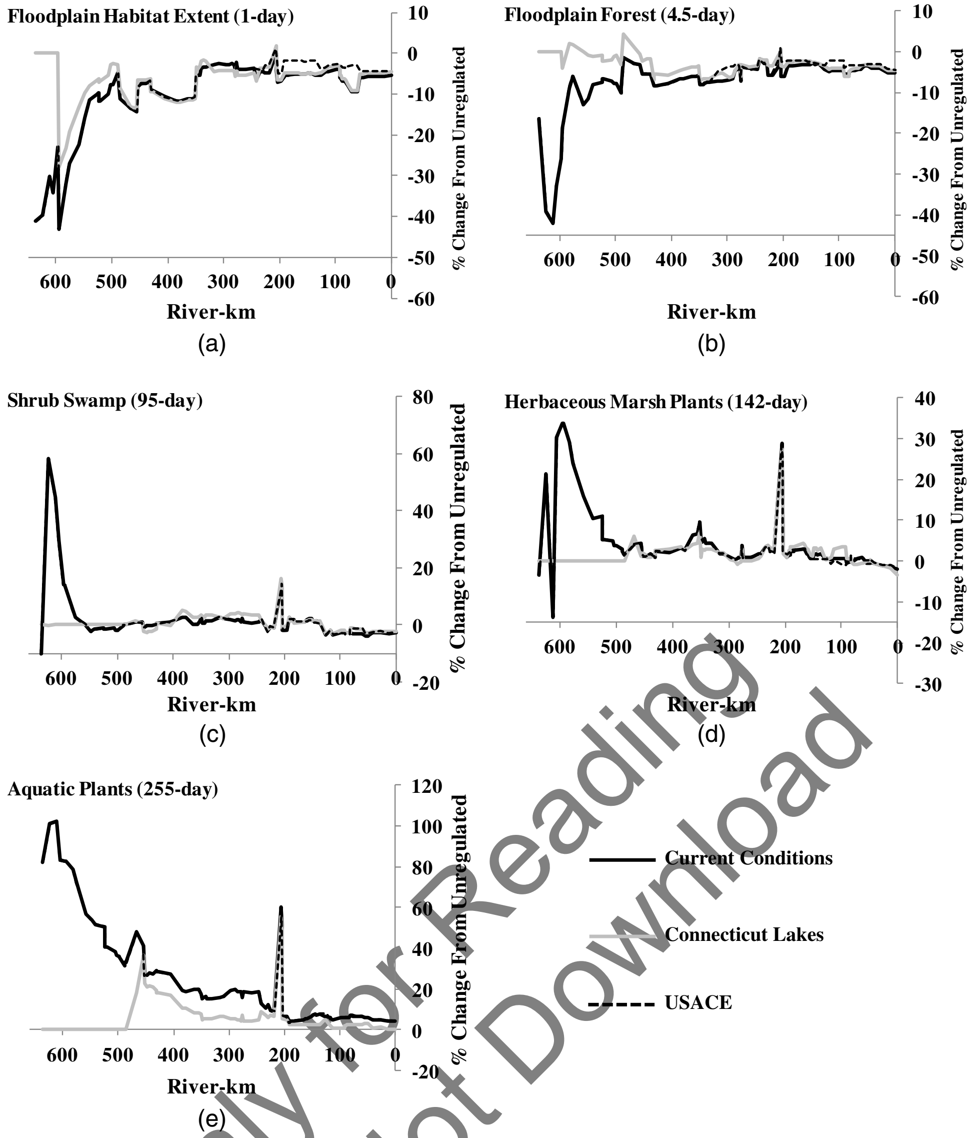


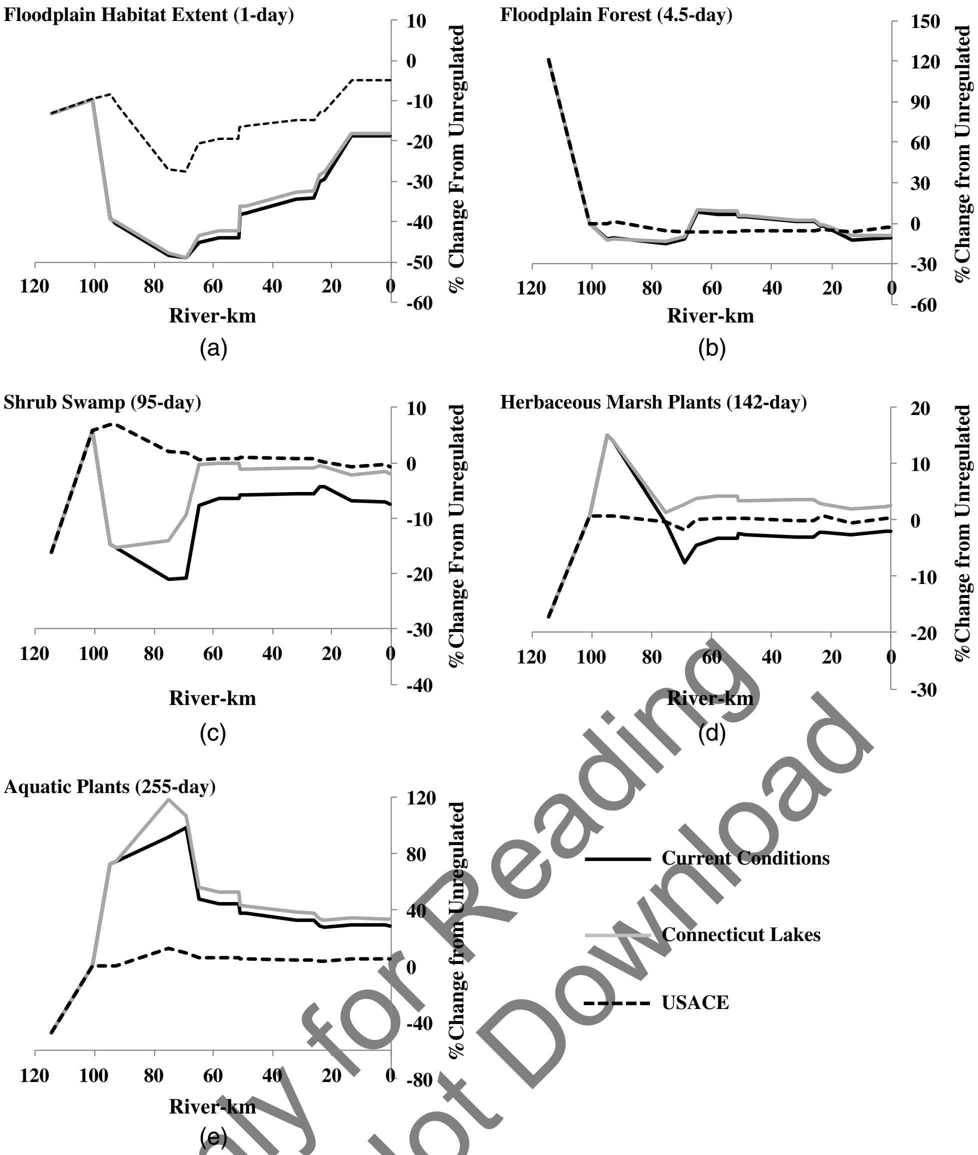
Fig. 7. Comparison of hydrologic alteration moving down the Connecticut River mainstem of the five floodplain vegetation communities between the current conditions and run-of-river scenarios: (a) floodplain habitat extent (1-day); (b) floodplain forest (4.5-day); (c) shrub swamp (95-day); (d) herbaceous marsh plants (142-day); (e) aquatic plants (255-day)

current conditions. The Connecticut Lakes Project scenario reduced hydrologic alteration of all five floodplain hydroperiods substantially for the upper half of the Connecticut River mainstem (Fig. 7). It reduced alteration for the lower half to a lesser extent, with that reduction decreasing as a function of distance from the dams. This indicates that reoperations of the Connecticut Lakes may yield more floodplain benefits in the upper half of the Connecticut River mainstem.

The USACE scenario saw no reductions in alteration along the upper half of the mainstem (where there are no USACE flood control reservoirs) but did see a relatively small reduction in alteration of the floodplain habitat extent and floodplain forest hydroperiods along the lower half of the mainstem. This indicates that flood control reoperation to be more run-of-river could slightly increase floodplain habitat extent and floodplain forest area, but would have minimal effects on the other three hydroperiods.

The USACE scenario reduced hydrologic alteration on the Farmington River substantially for all five hydroperiods, in some cases reducing alteration to zero along the majority of the river (Fig. 8). This was due to the Colebrook reservoir and dam, indicating that Colebrook is the principal driver of flow on the Farmington River and is therefore a good candidate for reservoir reoperations for floodplain benefits on the Farmington. The Connecticut Lakes scenario caused small changes to floodplain habitat extent, floodplain forest, and aquatic plant hydroperiods and slightly more substantial changes in shrub swamp and herbaceous marsh plant hydroperiods. This is due to the operation of Colebrook to control points on the mainstem that have changes in flow due to the Connecticut Lakes run-of-river operations. The change in flows resulted in slightly more flood operations at Colebrook, which reduced the floodplain habitat extent slightly while increasing Colebrook's lower flow releases.

For the HEC-RAS section of the Connecticut River mainstem in Northampton, Massachusetts, the Connecticut Lakes scenario had negligible effects on most of the floodplain vegetation areas compared to current conditions (Table 3) as one might expect given that the Connecticut Lakes and Northampton are far apart in the watershed. Only open water and aquatic plant area moved closer to



(a) (b) (c) (d) (e)

Fig. 8. Comparison of hydrologic alteration moving down the Farmington River of the five hydroperiods between the current conditions and run-of-river scenarios: (a) floodplain habitat extent (1-day); (b) floodplain forest (4.5-day); (c) shrub swamp (95-day); (d) herbaceous marsh plants (142-day); (e) aquatic plants (255-day)

unregulated conditions, indicating current Connecticut Lakes operation may affect low flows along the lower half of the mainstem. Floodplain areas closer to the Connecticut Lakes might be more affected. The USACE scenario did appear to have a small effect on floodplain habitat extent area but appears to have little effect on the other floodplain hydroperiod habitat areas.

For the HEC-RAS model on the Farmington River, the Connecticut Lakes scenario appeared to bring all the floodplain vegetation areas slightly closer to unregulated conditions, except open water, which saw a slight increase in area. The USACE scenario generally brings all the floodplain vegetation areas closer to unregulated, indicating that reoperating Colebrook has the potential to return floodplain composition to its unregulated state.

Socioeconomic Trade-Offs

The socioeconomic trade-offs for hydropower generation and flood protection were calculated for the current conditions and the two scenarios to measure trade-offs between the scenarios.

Table 4 shows the mean annual hydropower generated by each hydropower dam for current conditions and the difference in hydropower output (actual difference and percent change) for both scenarios. The USACE flood control scenario caused negligible changes in the hydropower outputs of any of the dams. The Connecticut Lakes scenario caused minor reductions in hydropower output for a majority of the hydropower dams but also some increases in output for the downstream dams. However, overall the changes in hydropower output caused by both run-of-river scenarios were minor.

Table 5 shows the number of days above flood stage of the period of record for the current conditions and two scenarios. As expected, the total number of days the unregulated hydrograph exceeded flood stage was substantially more than the current conditions at all three locations. The USACE scenario showed a significant increase in days above flood stage; for the Connecticut Lakes scenario, the days above flood stage increased at only one location and to a minor degree, indicating little change from current conditions.

Table 3. Percent Change from Unregulated in Hydroperiod Flow, Calculated from the HEC-EFM Model, and Area, Calculated from the HEC-RAS Models, of the Five Floodplain Vegetation Communities for the Current Conditions and Run-of-River Scenarios

	% change in hydroperiod flow			Absolute change in area (km^2)			% change in area		
Floodplain plant community	Current conditions	Connecticut Lakes	USACE flood control	Current conditions	Connecticut Lakes	USACE flood control	Current conditions	Connecticut Lakes	USACE flood control
Connecticut River mainstem in Northampton, Massachusetts									
Floodplain habitat extent	−5.1	−5.0	−2.0	−0.42	−0.41	−0.20	−2.2	−2.2	−1.1
Floodplain forest	−3.2	−2.2	−2.3	−0.45	−0.31	−0.31	−3.2	−2.2	−2.2
Shrub swamp	2.4	2.0	1.5	0.06	0.03	0.03	5.1	2.5	2.5
Herbaceous marsh plants	0.7	1.3	0.5	−0.04	0.01	−0.04	−3.2	0.8	−3.2
Aquatic plants	6.3	2.7	6.3	0.00	−0.02	0.00	0.0	−2.7	0.0
Open water	26.8	20.9	25.1	0.06	0.05	0.06	1.6	1.3	1.6
Farmington River in Simsbury, Connecticut									
Floodplain habitat extent	−34.1	−32.4	−14.6	−0.84	−0.81	−0.32	−12.3	−11.9	−4.7
Floodplain forest	1.3	1.8	−5.5	0.18	0.05	−0.11	5.2	1.5	−3.2
Shrub swamp	−5.5	−1.0	0.7	−0.10	−0.07	0.02	−13.7	−9.6	2.7
Herbaceous marsh plants	−3.1	3.6	−0.1	−0.23	−0.15	−0.02	−31.1	−20.3	−2.7
Aquatic plants	32.3	37.7	4.0	−0.05	−0.03	−0.07	−14.7	−8.8	−20.6
Open water	106	112	39.4	0.17	0.20	0.02	18.9	22.2	2.2

Table 4. Average Annual Hydropower Generated by the 11 Connecticut River Mainstem Hydropower Dams and the Change in Hydropower Generation for the Two Run-of-River Scenarios

Mainstem hydropower dam	Current conditions (MW)	Connecticut Lakes [MW (%)]	USACE flood control [MW (%)]
Canaan	257	−45 × (−17.5)	0
Gilman	1,371	−96 × (−7.0)	0
Moore	4,200	55 (1.3)	4 (0.1)
Comerford	9,422	−235 × (−2.5)	32 (0.3)
McIndoes	2,039	−58(−2.8)	1 (0.1)
Wilder	6,133	−86 × (−1.4)	−6 × (−0.1)
Bellows Falls	9,313	−115 × (−1.2)	2 (0.02)
Vernon	5,945	−57 × (−1.0)	10 (0.2)
Northfield	40,217	149 (0.4)	−193 × (−0.5)
Turners Falls	594	15 (2.5)	3 (0.5)
Holyoke	7,148	387 (5.4)	202 (2.8)
Total	86,639	−661 × (−0.01)	55 (0.001)

Table 5. 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 Two Run-of-River Scenarios

Scenario	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

Discussion

Hydrologic alteration of floodplain hydroperiods is relatively minimal on the lower two-thirds of the Connecticut River mainstem based on the current conditions and scenario analyses. Therefore, efforts to restore floodplain community composition by changing the flow regime on the lower Connecticut River mainstem may not warrant the potential costs and trade-offs associated with reservoir reoperation. However, results on the Farmington River show that benefits to the floodplain plant community along this entire tributary may make reservoir reoperation more promising. It could be easier to gain floodplain benefits on the Farmington compared with the Connecticut River mainstem because one dam (Colebrook) is the principal driver of flow. In a general sense, reservoir reoperation for floodplain benefits may be more feasible and effective on tributaries due to the smaller numbers of dams and owner-operators and the higher degree of alteration.

There are three primary avenues for reservoir reoperations: (1) existing operational flexibility, (2) minor reoperations, and (3) significant reoperating policies. Reoperations usually require a formal opportunity to rethink policy. For USACE reservoirs, minor operational changes can often be entertained by local offices, so the policy opportunity is there for those willing to navigate the policy processes of a large governmental organization. In the Connecticut River watershed, Federal Energy Regulatory Commission (FERC) licensing is also an important policy opportunity. In FERC licensing, nonfederal dams with a hydropower purpose receive a new license to generate hydropower. This is the principal time when operations of these dams can be changed for environmental purposes. Five projects on the Connecticut River mainstem will undergo FERC relicensing in 2018: Wilder, Bellows Falls, Vernon, Northfield, and Turners Falls. However, the scope for floodplain benefits on the Connecticut River mainstem from reoperating these five dams to reduce flow alteration may be relatively small, based on the results of the described analyses. Changing operations to benefit floodplain plant communities as part of this FERC relicensing should probably focus more on the impacts of operations on floodplain and wetland communities within the impoundments. Reoperating the Connecticut Lakes dams would achieve some floodplain benefits but they will not undergo relicensing for several decades. Changing operations at Moore would achieve some floodplain benefits as well but it also recently had its FERC license renewed (as did the other dams in the 15-Mile Falls Project). FERC licenses last for 30 to 50 years so it may be many years before another hydropower policy opportunity arises again.

There are several limitations to the overall hydrologic alteration approach described in this paper. The amount of data, time, and resources needed to construct and use this decision support system was challenging, even with the attention given to process automation. Compiling input data for the reservoir simulation model was a substantial effort, including the preparation of unregulated flow data as well as physical and operational data to characterize the dams and reservoirs, which required extensive coordination with owner-operators. Development of the river hydraulics models required field surveys and the creation of the models for multiple river reaches. Environmental flow definitions had to be translated into ecological metrics that could be calculated using the decision support system. And finally, all the pieces of the decision support system had to be linked, calibrated, automated where possible, and then exercised to be capable of analyzing reservoir management alternatives.

Another issue is the use of a synthetic inflow data set as both driver of the model and representation of the unregulated hydrograph. When comparing CRUISE to gauge records, there were differences in volume and peak magnitudes in the CRUISE data set from gauge records that varied in significance between subwatersheds (Archfield et al. 2009). These can be explained by the uncertainty associated with using the methods to develop the CRUISE data set as well and local inflows between the gauge locations and the points where CRUISE flows were calculated adding additional volume. This adds uncertainty to the results. However, the use of CRUISE methods is currently one of the most robust approaches to creating daily, unregulated streamflow. Also, in a hydrologic alteration analysis, relative change between unregulated and regulated should determine conclusions. However, the uncertainty of using a synthetic inflow data set must be acknowledged and would be problematic if ecological metrics and habitat areas were correlated with field observations.

Additional uncertainty occurs because the model is a daily time-step model, which masks operations, environmental dynamics, and alteration at a subdaily time step. Simulating the CRUISE period of record at a subdaily time step is currently more or less computationally prohibitive due to the already long compute time of *HEC-ResSim* for the daily time step and the methods utilized by CRUISE. Again, software and hardware upgrades may make this possible.

Further work to improve on the analyses described in this paper would be to incorporate additional ecological knowledge as well as extend the analyses to other ecological guilds, such as for diadromous fish and freshwater mussels. Another interesting extension of the inundation mapping analysis described would be to incorporate additional variables, such as depth, velocity, and soil type. The habitat area analysis described herein is not a comprehensive evaluation of the variables that influence the distribution and success of floodplain plant communities. Additional considerations, such as depth and velocity, could be incorporated into future floodplain vegetation mapping that uses this approach. Also, the reservoir pool can cause changes in upstream floodplain plant compositions. This was not accounted for in this analysis but could potentially have a major effect due to the number of reservoirs in the Connecticut River watershed. Future work could account for these upstream inundations using hydraulic models that could be developed for the reservoir pool areas.

Conclusion

This paper described the development and example application of a linked decision support system to investigate environmental opportunities and socioeconomic trade-offs along the Connecticut River mainstem and one of its tributaries, the Farmington River. The methods and software that comprised the decision support system helped identify potential reservoir reoperations that would generate floodplain benefits while also measuring potential hydropower generation and flood protection trade-offs. Based on the example analysis, changing operations of the Connecticut Lakes Project and the USACE Flood Control Projects has potential to provide modest floodplain benefits but would require trade-offs in terms of hydropower generation (Connecticut Lakes) and flood control (USACE flood control). It is difficult to determine whether the floodplain benefits would be worth the changes in hydropower and flood risk without an in-depth trade-off analysis that includes more refined scenarios (i.e., those that do not wholly remove the storage and hydropower roles of involved reservoirs) designed to optimize environmental and socioeconomic benefits. The alternatives considered herein investigated restoration potential, which highlights areas that are significantly altered. Process output is also useful for conservation interests, which may be better served by investments in areas with larger stream orders, such as the lower Connecticut River, where alteration is low and resilience to flow alteration is high. An advantage of the decision support system is that it is capable of testing many more, and more involved, scenarios than the ones demonstrated in this paper.

Changing reservoir operations for management of aquatic and riparian ecosystems at the watershed scale is challenging in watersheds with many dams of disparate ownership. Understanding which reservoirs have the most potential to achieve ecosystem management objectives with fewer consequences to important societal values, such as hydropower generation and flood control, allows for a better and more focused formulation of management strategies. The general ecosystem management focus here is the flow regime, where benefits are framed in terms of reduced alteration from the unimpaired flow regime and the corresponding shifts in spatial extent of floodplain plant communities. Depending on the reservoir's location within the watershed, size, and purposes, changing operations at one reservoir may increase benefits for ecosystems across a long stretch of river, whereas changing operations at other reservoirs may only have localized benefits. Also, in a watershed with multiple types of operations, including hydropower generation and flood control, changing operations at one reservoir may influence operations at other reservoirs. This may lead to inadvertent gains, losses, or offsets in ecosystem benefits as reservoirs compensate to continue meeting other water management objectives. In addition, when analyzing an entire watershed to identify areas of ecological opportunities, it is important to have metrics that quantify ecosystem change that can be applied universally throughout the watershed as well as metrics that can measure trade-offs in hydropower, flood control, or other purposes. The reservoir simulation model, ecosystem metrics, and software technologies described in this paper illustrate an approach to analyzing regulated watersheds that incorporates environmental considerations and measures water management trade-offs to assist in watershed planning and environmental flow implementation.

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